### 08.00H REGISTRATION

### KEYNOTE SESSION

**8:45 – 9:30 H**

Mobile Robotic Systems Facing the Humanitarian Demining Problem: State of the Art (SOTA)
December 2007 ITEP 3.1.4 Task

**Prof. Yvan Baudoin**
RMA - Belgium

**Chairman:**

**Prof. Maki K. Habib (AUC)**

### SESSION F1. MOBILE ROBOTICS SYSTEMS - I

**Chairman:**

**Prof Y. Baudoin (RMA)**

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<th>Authors</th>
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| 09.30-10.00H | Mechanical Design of a New Locomotion Concept for Humanitarian De-mining | Prof. Dr. Dr.h.c.mult. Peter Kopacek  
Lukas Silberbauer  
Institute of Handling Devices and Robotics  
Vienna University of Technology  
Favoritenstraße 9-11  
1040 Vienna, Austria |
| 10.00-10.20H | Development of a Semi-Autonomous De-mining Vehicle                  | Daniela Doroftei, Yvan Baudoin  
Royal Military School (RMS)  
Department of Mechanical Engineering (MSTA)  
Av. de la Renaissance 30, 1000 Brussels, Belgium |

### 10:20 – 10:40 COFFEE BREAK

### SESSION F2. MOBILE ROBOTICS SYSTEMS - II

**Chairmen:**

**Prof P. Kopacek (Vienna University of Technology) and Prof. E. F. Fukushima (Tokyo Institute of Technology)**

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<th>Time</th>
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| 10.40-11.00H | Remote Operation of the Mini MineWolf in High-Threat Mine Environments           | Christoph Frehsee  
Director Products and Services  
MineWolf Systems AG  
Seedammstrasse 3  
8808 Pfäffikon SZ  
Switzerland |
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<tr>
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| 11.00-11.20H | De-mining Techniques of Improvised Explosive Materials by the Usage of Mobile Robots. | Arbnor Pajaziti, Jakup Berisha, Xhevahir Bajrami  
Faculty of Mechanical Engineering, University of Prishtina  
Kosova.  
Arbnesh Ajvazi  
Improvised Explosive Device Disposal Unit, Kosovo Police Service  
Kosova. |
| 11.20-11.40H | Humanitarian Demining Robot Gryphon - an Objective Evaluation                  | Marc Freese, Edwardo F. Fukushima and Shigeo Hirose  
Tokyo Institute of Technology |
| 11.40-12.00H | Agricultural Derived Tools for Ground Processing in Humanitarian De-mining Operations – set up of Testing Facility in Jordan | Emanuela Elisa Cepolina (1) & Bassam Snobar (2),  
(1) PMARlab, Department of Mechanics and Machine Design (DIMEC), University of Genova,  
Italy  
(2) Professor at the Department of Horticulture and Crop Science, Faculty of Agriculture,  
University of Jordan, Amman, Jordan. |
| 12:00-13:40 | LUNCH                                                                          |                                                                         |
| 13.40-14.00H | Nuclear Quadrupole Resonance for Explosive Detection                          | Hideo Itozaki and Go Ota  
Osaka University Graduate School of Science Engineering  
1-3 Machikaneyama Toyonaka, Osaka 560-8531, Japan |
| 14.00-14.20H | Exploitation of Nonlinear Dynamics in Ferromagnetic and Ferroelectric Materials for Novel High Performances B-field and E-field Sensors | B. Andò, S. Baglio, N. Savalli, C. Trigona  
Facoltà di Ingegneria, Univ. degli Studi di Catania,  
DIEES  
Viale A. Doria 6, 95125 Catania, Italy.  
V. In, A. R. Bulsara  
Space and Naval Warfare Systems Center  
49590 Lassing Road A341, San Diego, CA 92152-5001, USA |
Carlos Parra(1) and Michel Devy(2)  
(1) Pontificia Universidad Javeriana, Carrera 7° No. 40 – 62, Bogotá, Colombia  
(2) Laboratoire d’Analyse et d’Architecture des Systèmes (LAAS-CNRS), 7, Avenue du Colonel Roche, 31077 Toulouse Cedex 4, France |
| 14.40-15.00H | Fuzzy Template Based Automatic Landmine Detection from GPR Data              | Zakarya Zyada(1), Takayuki Matsuno(2) and Toshio Fukuda(3) |
### SESSIONS Keynote, S1-S3 and Conclusions: 29th March 2008, Saturday

#### KEYNOTE SESSION

8:45 – 9:30 H  
Humanitarian Demining and the Challenge of Technology  
**Prof. Maki K. Habib**  
The American University in Cairo  
**Chairman:**  
**Prof. Y. Baudoin (RMA)**

#### SESSION S1. DATA PROCESSING, CONTROL and SIMULATION - I

**Chairman:**  
Prof Maki Habib (AUC) and Dr. Munsang Kim (KIST)

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<th>Time</th>
<th>Topic</th>
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| 09.30-09.50H | Legged robot - Animal cooperation to trace smell gradients in minefields | Thrishantha Nanayakkara(1), Tharindu Amal Dissanayaka(2), Lasitha Piyathilaka(3)  
(1) School of Engineering and Applied Science, Harvard University, USA, Email: thrish@deas.harvard.edu  
(2) Department of Mechanical Engineering, University of Moratuwa, Sri Lanka  
(3) Department of Electrical Engineering, University of Moratuwa, Sri Lanka |
| 09.50-10.10H | Data Association for Robot Localization in Satellite Images | Sid Ahmed Berrabah, Yvan Baudoin  
Mechanical Department, Royal Military School, Avenue de la Renaissance 30, 1000 Brussels, Belgium |
### 10.20 – 10.40 COFFEE BREAK

#### SESSION S2. DATA PROCESSING, CONTROL and SIMULATION - II

**Chairmen:**
*Prof. Andrzej Maslowski (PIAP) and Dr. Ayman Abbas (BUE)*

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<th>Time</th>
<th>Session</th>
<th>Speaker(s)</th>
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| 10.40-11.00H | **Cognitive Theory – Based Approach for Inspection using Multi Mobile Robot Control** | Janusz Bedkowski, Andrzej Maslowski
Research Institute for Automation and Measurements
PIAP, Warsaw, Poland |
| 11.00-11.20H | **Framework for Creation of the Simulators for Inspection Robotic Systems** | Janusz Bedkowski, Grzegorz Kowalski, Andrzej Maslowski
Research Institute for Automation and Measurements
PIAP, Warsaw, Poland |
| 11.20-11.40H | **A Fuzzy Approach for the Control of Autonomous Vehicles Operating in Hazardous Terrain Environments** | Dr Ayman Abbas
British University in Egypt (BUE) |
| 11.40-12.00H | **Virtual Training System for Teleoperation of ROBHAZ-DT2** | Dongseok Ryu, Sungchul Kang, Munsang Kim
Korea Institute of Science and Technology
Center for Intelligent Robotics, Korea. |

### 12:00 – 13:30 LUNCH

#### SESSION S3 : RISKY INTERVENTION-ENVIRONMENTAL SURVEILLANCE

**Chairmen:**
*Prof G. Muscato (DIEES) and Prof. V. G. Gradetsky (Russian Academy of Sciences)*

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<tr>
<th>Time</th>
<th>Session</th>
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| 13.30-13.50H | **Heterogeneous Robot Cooperation for Interventions in Risky Environments** | C. Bruno, D. Longo, D. Melita, G. Muscato, S. Sessa, G. Spampinato DIEES Università degli Studi di Catania
Viale A. Doria 6
Catania, Italy |
DIEES Università degli Studi di Catania
Viale A. Doria 6
Catania, Italy |
| 14.10-14.30H | **AMARANTA: Modular Platform for a Mine Hunting Robot** | Snaider Carrillo(1), Carlos Santacruz(1), Diego Botero(1), Carlos Parra(1), Alvaro Hilarión(1), Martha Manrique(1), Camilo Otañor(1) and Michel Devy(2)
(1)Pontificia Universidad Javeriana, Carrera 7 No. 40 – 62. Bogotá, Colombia
(2) Laboratoire d’Analyse et d’Architecture des Systèmes (LAAS-CNRS).7, Avenue du Colonel Roche, 31077
Toulouse Cedex 4, France |
| 14.30-14.50H | **Demining in Shallow Inland Water Areas** | Viktor Kálmán, Miklós Vogel researcher, László Vajta
Budapest University of Technology and Economics
Department of Control Engineering and Information Technology |
<p>| 14.50-15.10H | <strong>Robotic Assistance in Extreme</strong> | Professor V. G. Gradetsky |</p>
<table>
<thead>
<tr>
<th>Conditions</th>
<th>The Institute for Problems in Mechanics of Russian Academy of Sciences</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.10-15.30H</td>
<td>Model-Based Soil Parameter Identification For Wheel-Terrain Interaction Dynamics</td>
</tr>
<tr>
<td>Suksun Hutangkabodee, Yahya H Zweiri, Lakmal D Seneviratne, Kaspar Althoefer</td>
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<tr>
<td>Department of Mechanical Engineering, King’s College London, Strand, London WC2R 2LS, UK</td>
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<tr>
<td>15.30-15.50H</td>
<td>Robotised Combine to Demining of Mine Fields</td>
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<td>Marin Midilev</td>
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<td>40-A-10, Badema str</td>
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<td>6300 Haskovo</td>
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<td>Bulgaria</td>
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CONCLUSIONS : IARP WS'HUDEM'2009 OBJECTIVES – ITEP CONTRIBUTION

HUDEM’ 2008 Workshop Dinner

HUDEM 2008’s Half Day Tour: Morning 30th March 2008, Sunday
Abstract - Robotics solutions properly sized with suitable modularized mechanized structure and well adapted to local conditions of dangerous unstructured areas can greatly improve the safety of personnel as well as the work efficiency, productivity and flexibility. Solving this problem presents challenges in robotic mechanics and mobility, sensors and sensor fusion, autonomous or semi autonomous navigation and machine intelligence. This 7th IARP workshop will review and discuss the available technologies, their limitations, their adaptability to different environmental natural or artificial calamities (humanitarian de-mining obviously but also Earthquake, fire, chemical pollution, natural disaster, CBRN-E threat, etc) and discusses the development efforts to automate tasks related to de-mining / detection / interventions processes wherever possible through the use of Robotics Systems and other technologies. The paper summarizes the information of the six previous IARP workshops, complemented by some progresses achieved at the RMA.

1. INTRODUCTION : THE PROBLEM [1]

The mines have been used for the first time during the American Civil War in the United States (1861-1865). Antitank mines were later ameliorated and laid on the battlefields of the First World War: the mine-clearing operations didn’t pose major problems with those visible or easy-to-detect ATK-mines, reason why Anti-personnel mines have been conceived and systematically used on the ATK

minefields during the Second World War: such mines prevented the enemy from easy de-mining of the defence system. But the anti-personnel mines are today more and more used as offensive weapons and for sowing the terror among the civilian population of a country affected by guerrilla war: the marking of the minefield does no more exist and the anti-personnel mines, often buried in the ground, remain active after the war: about 60 millions AP-mines infest today more than 80 countries all over the world, two-third of them in Africa and South-East Asia...AP mines and Unexploded devices of the Second World War still exist in all the countries of Europe and North-Africa

Example: Due to the central geographical location between Africa, Asia and Europe, Egypt was a location for many battles. During the Second World War, the most known El-Alameen battle, Western Desert, (Fig.1) was between the British and German troops. As a result of this fighting, a numerous number of anti-tanks and anti-personnel mines have been left. The total number of mines (19,711 Million mines) that was buried in the Egyptian land is considered to be about 21% of the total number of mines that buried in the whole world . The presence of such active mines caused many problems to Egypt [2]

Fig.1: Location map for landmines distributions in Egypt
In 1994, the United Nations Mine Action Service or UNMAS was founded, with as objectives the mine awareness and risk reduction education, the minefield survey, mapping, marking and clearance, the assistance to victims, the advocacy to support a total ban on AP-mines, and, in 1999, the treaty of Ottawa (the Convention on the Prohibition of the use, stockpiling, production and transfer of AP-mines and their destruction) entered into force. The next map summarises the actual status of the Signing Countries.

The European Commission launched several programmes to encourage the Scientific Community to develop research activities allowing to improve the de-mining tools, according to the next priorities:

<table>
<thead>
<tr>
<th>Priority</th>
<th>Description</th>
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<tbody>
<tr>
<td>Priority 1</td>
<td>the development of reliable sensors allowing the detection of minefields and, on those minefields, the detection of the mines (or similar explosive devices)</td>
</tr>
<tr>
<td>Priority 2</td>
<td>the development of data processing algorithms confirming the detection and leading to the identification of the parameters needed for the next actions</td>
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<tr>
<td>Priority 3</td>
<td>the development of fast removal techniques or neutralization techniques</td>
</tr>
<tr>
<td>Priority 4</td>
<td>the development of the mechanical assistance</td>
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</table>

The military de-mining operations accept low rates of Clearance Efficiency (CE). For these purposes it is often sufficient to punch a path through a mine field. But, for the humanitarian de-mining purposes, on the contrary, a high CE is required (a CE of 99.6% is required by UN). This can only be achieved through a ‘keen carding of the terrain, an accurate scanning of the infested areas’: that implies the use of sensitive sensors and their slow systematic displacement, according to well-defined procedures or drill rules, on the minefields. At present, hand-held detectors seem still to be the only and most efficient tools for identifying all unexploded ammunitions and mines: but this first step doesn’t solve the problem: the removal task and/or the neutralisation and/or destruction task must follow: those last two tasks are time-consuming actions.

II. SENSOR TECHNOLOGY

A. Remote Sensing

In order to avoid a considerable waste of time, a first essential objective lies in the delimitation of the mines polluted areas: local information on observed explosions, craters, injured animals and/or on hospital casualty reports already allow the sending of local technical teams in charge of minefield-marking: this marking may never be precise: the suspected area may be very larger or very smaller, even if performance ground sensors are used: therefore, research efforts have been funded by the European Commission encouraging the airborne survey with colour, colour infrared and thermal cameras, multi-spectral sensors and other promising sensors.

Different projects have been initiated in this context (ARC, MINESEEKER, etc, see EUDEM2 website, [5], for more information). Let us limit to a very short description of one of the most promising projects on this matter, i.e. the SMART project [3, 4]. The goal of the SMART project is to provide the human analyst with a GIS-based system - the SMART system - augmented with dedicated tools and methods designed to use multi-spectral and radar data in order to assist him in his interpretation of the mined scene during the area reduction process. The usefulness of such image processing tools to help photo-interpretation has already been studied: the possibility to process automatically a large amount of data and help a visual analysis is among their advantages. The use of SMART includes a field survey and an archive analysis in order to collect knowledge about the site, a satellite data collection, a flight campaign to record the data - multi-spectral with the Daedalus sensor and polarimetric SAR with the ESAR from DLR - , and the exploitation of the SMART tools by an operator.
to detect indicators of presence or absence of mine-suspected areas. With the help of a data fusion module based on belief functions and fuzzy sets the operator prepares thematic maps that synthesise all the knowledge gathered with these indicators. These maps of indicators can be transformed into danger maps showing how dangerous an area may be according to the location of known indicators and into priority maps indicating which areas to clear first, accounting for socio-economic impact and political priorities. These maps are designed to help the area reduction process. Figure 2 shows the detection of hedges and trees on a polarimetric SAR image. Existing hedges and tree alignments are, in dangerous areas, possible places where mines are laid. Figure 3 gives an example of danger maps. Preliminary results obtained with SMART showed a global substantial area reduction rate of 20% and a miss-classification rate of 0.1% for what SMART considers as not mined and is actually mined. The approach has also its limitations. The general knowledge used in SMART is strongly context-dependent. It has been currently derived from the study of three different test sites in Croatia chosen to be representative of South-East of Europe. In the case of another context a new field campaign is needed in order to derive and implement new general rules. Before using SMART the list of indicators must be re-evaluated and adapted. For instance it has been noted that the assumption that a cultivated field is not mined, although quite valid in Croatia, may not apply in other countries such as Africa or Colombia. It must also be checked if the indicators can be identified on the data and if the new list is sufficient to reduce the suspected areas.

B. Close-in Detection

Assuming the borders of a minefield have been defined, a systematic scanning of the field must follow: in order to assure the desired CE, the use of combined will be necessary: the most known or proposed multi-sensor platform under investigation combines the metal detector, the ground penetrating radar (GPR) or an Ultra-Wide-Band radar (UWB) and an infrared camera. But, added to the possible use of other combinations, the optimisation of existing sensors and/or the development of new sensors (NQR or Nuclear Quadrupole Resonance detection of nitrogen bonding in explosives), the simultaneous use of several sensors induce a certain number of problems that have to be solved: the fusion of the quite-different data provided by the sensors, the mutual interaction or inter-compatibility of the sensors, the control of the positioning of the sensors above the inspected ground. The next table [3] summarises the actual state-of-the-art of the detectors and their relevant characteristics if de-mining automatic technologies are envisaged (i.e. mounted on robots or vehicles).
For each type of sensor, specific signal processing techniques are used in order to extract useful information. The techniques used mainly include signal conditioning or pre-processing (e.g. signal detection, signal transformation, noise reduction, signal restoration and enhancement which are very important steps before further processing) and pattern recognition techniques aiming at increasing the expertise of each sensor separately. Nevertheless, it has been shown that no sensor is perfect for all scenarios and all conditions (moisture, depth, cost, etc.). The analysis of the principles of operation of different sensors, their complementary information, and the factors that affect their operability, have led to the conclusion that their fusion should result in improved detectability and reduced number of false alarms in various situations (different types of mines, soil, vegetation, moisture, etc.). The Japan Science and Technology Agency recently organised a test and evaluation for anti-personnel landmine detection systems using ground penetrating radar and metal detector mounted on robotic vehicles: the test results showed that combining GPR with MD can improve the probability of detection (PD) around a depth of 20cm, where it is difficult to detect targets by using only a metal detector and that there is a room for further improvement in the PD, for instance by feeding back the test results to testers to learn typical target images, where targets were not able to be detected in the blind tests (no pre-knowledge of the locations of the buried mines). It has also been learned that positioning control must be improved in scanning the ground with a sensor head, which is a key to making the best use of MDs mounted on vehicles (argument pro-robotics) [5].

<table>
<thead>
<tr>
<th>Sensor family</th>
<th>Sensor type</th>
<th>Maturity</th>
<th>Cost</th>
<th>Speed</th>
<th>Effectiveness</th>
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<tr>
<td>Probes &amp; Acoustic</td>
<td>In Use</td>
<td>Low</td>
<td>Very Low</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Smart Probes</td>
<td>In Use</td>
<td>Low to Medium</td>
<td>Very Low</td>
<td>High</td>
<td></td>
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<tr>
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<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
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<td>EMI devices</td>
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<td>Low to Medium</td>
<td>Low to Medium</td>
<td>High</td>
</tr>
<tr>
<td>Magnetoacoustics</td>
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<td>Low</td>
<td>High</td>
<td></td>
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<tr>
<td>Groundpuls</td>
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<td>Low to Medium</td>
<td>High</td>
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<td>EW</td>
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<td>In Use</td>
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<td>Medium</td>
<td>Medium</td>
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<td>Medium</td>
<td>Medium</td>
<td></td>
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<td>Main &amp; Hyperpectral</td>
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<td>Medium</td>
<td>Medium</td>
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<td>LIDAR</td>
<td>R&amp;D</td>
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<td>Medium</td>
<td>Low</td>
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<td>Terahertz</td>
<td>R&amp;D</td>
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<td>Medium</td>
<td>Low</td>
<td></td>
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<td>SDVS</td>
<td>R&amp;D</td>
<td>Very high</td>
<td>Medium to high</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Biosensors</td>
<td>Dog</td>
<td>In Use</td>
<td>Medium to high</td>
<td>Medium to high</td>
<td>Medium to high</td>
</tr>
<tr>
<td>Rodents</td>
<td>In Use</td>
<td>Medium to high</td>
<td>Medium</td>
<td>Medium to high</td>
<td></td>
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<td>NQR</td>
<td>R&amp;D</td>
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<td>Medium</td>
<td>Medium</td>
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<td>Medium</td>
<td>Medium</td>
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<td>MAL</td>
<td>R&amp;D</td>
<td>Medium to high</td>
<td>Medium</td>
<td>Medium</td>
<td></td>
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<tr>
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<td>R&amp;D</td>
<td>Medium to high</td>
<td>Medium</td>
<td>Very high</td>
<td></td>
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<td>High</td>
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<td>Medium</td>
<td></td>
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<tr>
<td>Chemical detectors</td>
<td>R&amp;D</td>
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<td>Medium</td>
<td>Unknown</td>
<td></td>
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</tbody>
</table>

III. MECHANICAL ASSISTANCE AND ROBOTICS SYSTEMS

A. The mechanical mine-clearance

The mechanical assistance consists into the use of motorized mine-clearers: adapted military vehicles or armoured vehicles of the same or similar type, with same or reduced size, may be used on large areas (agricultural areas, for instance) for so far their access is granted; some mine-clearers now combine clearance and detection tools: the HITACHI landmine disposing machine illustrates this kind of system, combining a Rake-Grapple to cut the vegetation (fig 4a), a Mount-type metal detector for avoiding the Rotary-cutter’s hitting (fig 4b), a Magnet System to remove the metal fragments (fig 4c): intensive tests were realised in Cambodia and Afghanistan and proved its efficiency: about 15000 m² (300 times more than a human operator) may be cleared per day; 100 % ATK-mines are removed and destroyed, 90 % AP-mines only: although other clearance techniques (e.g. heavy tooted road rollers) already lead to higher efficiency (98 %), some AP-mines may be
pushed on size or deeper buried or partly damaged (thus more dangerous)

Fig. 4a, b, c: Yamanashi Hitachi Construction Machinery Co., Ltd, Japan

B. Vehicle mounted mine detector

Conventional vehicle-mounted mine detector systems employ an array of sensors elements to achieve a detection swath typically 2–4m wide. Some systems employ more than one type of sensor technology. These systems are typically expensive, unsafe, complex and inflexible.

Fig. 5: Modular description of a Robotics System for the Detection of Explosive Devices

C. Vehicle

Several mobile remote controlled platforms have been described, some ones illustrated by the figure 6.a to 6.f [1, 6, 8, 10, 11, 12]: the motion control needs to be highly sophisticated. General motion in difficult terrain needs advanced adaptive control. Closely controlled motion is required to deliver sensor packages to accurate positions when detection is in progress. The motion of the vehicle demands by far the highest power requirements. Whilst some scenarios allow the use of an umbilical, many need more autonomy so an on-board power supply is needed. Thus efficiency of motion is most important, requiring advanced control algorithms. On the other hand, speed is unlikely to be paramount since detection will take time and will probably limit forward motion. The modes of operation need to be specified. Most requirements have a man-in-the-loop operation and there is a direct line of sight operation at a safe distance. This safe distance has to be specified and as is the method of ensuring that the safety restraints are carried out correctly. Typically, current methods for remote control from close in up to 1-2 km distance use Tele-operation. Examples of the advantages of Tele-operation are that the task can be carried out by a single operator...
and that camera positions are easily selectable using a microwave link or fibre-optic for a line of sight video transmission from the machine to the remote command station. To carry out complex tasks, the numbers of cameras needed and their positions have to be considered. It is likely that at least two fixed or one rotational camera need to be fitted to the vehicle to give all round viewing during operation and allow the modelling of the ground. Operator control units can be fitted to display single or multi-image options. The communication link might be a 1.4 GHz video link. Fibre optic links that offer high bandwidth can be used but the trailing of cables can be a problem over long distances. A communications link to carry control and sensor feedback signals is also required.

In summary, machines to carry out de-mining activities in place of human de-miners are generally likely to be wheeled or tracked. However, there is a possibility that in certain terrain, walkers will add value. Such machines are likely to be light in weight. The control and communications system is likely to be of a nature which will facilitate the addition of higher order functionality such as sensor fusion, HMI, navigation, etc. The complete system will need to integrate the vehicle control and navigation systems with a data fusion system that will discriminate, to a high degree of confidence, between mine and ‘no-mine’ conditions.

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**Fig 6.a.** Gryphon-IV remote maneuvering experiment. The system can be remote-controlled in a range of about 150 meters, Tokyo Institute of technology, JP [8]

**Fig 6.b.** Mine detection robot COMET-III – Chiba university, JP [6]

**Fig 6.c.** Mine detection robot Hunter Royal Military Academy, BE [7]

**Fig 6.d.** 16-wheeled (each tube tire able to support about 25 daN without explosion – most sensitive AP-mine is 0.064 bar) Sensing Vehicle, Tohoku University, JP [10]

**Fig 6.e.** AMRU-4, eight-legged electro-pneumatic sliding robot, RMA, BE [11]

**Fig 6.f.** Mine Hunter Vehicle, equipped with a teleoperated hydraulic manipulator, Chiba University, JP [12]

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**D. Control**

The adaptive control usually implies the use of Tele-operation, Tele-presence and distributed intelligence: the Tele-operation is the extension of a person’s sensing and manipulating capability to a remote location implying communication channels from and to the human operator; the Tele-presence defines the techniques allowing the human operator to feel himself physically present at the remote site; the intelligence combines the sensory...
Processing, the world modelling, the behaviour generation and the value judgement to perform a variety of tasks under a-priori unknown conditions. Combination of Tele-operation, Tele-presence and human-machine distributed intelligence often defines the supervisory control. Through the introduction of AI techniques and use of the virtual or pseudo-virtual reality, the robotics system’s teams try today to develop the concept of adaptive autonomy and virtual symbiosis. As deduced from the figure 5 (top-down approach from the right side to the left side), an optimal approach in Humanitarian de-mining should consist into providing a supervised autonomous UGV that can remove excess vegetation and then deploy a multi-sensing detector with sufficient precision to provide a reliable mapping system of detected mines. This will involve a combination of several different sensors, including:
- a sensor to determine the location of the robot vehicle within the area to be cleared
- an explosives proximity sensor to enable safe navigation
- a multi-sensing mine detector, incorporating for instance a 3D metal detector and a GPR
- a sensor to determine the position and orientation of the multi-sensing detector.
- sensors to control the attitude of the vehicle
- a vision sensory to allow the supervised autonomy (HO in the loop)

E. Control Station (Top):

The Application related Control and Command has to implement three primary activities, defined in the blocks ‘Mission Management, Data Fusion and HMI’. Concerning the Mission management, one has to make a clear distinction between the High-Level Mission Management (HLMM) or Mission Planning and the Robotics System Mission Management (RSMM).

- HLMM.

Several problems are inherent to the process of supporting Humanitarian De-mining campaigns with useful data. Within the framework of a de-mining campaign, contaminated areas are often very large and represent a lot of information. This huge amount of data has to be compiled and safely stored in a central repository to avoid loss or corruption of data. Also, these data need to be represented in an explicit manner, in order for the user to work with them as effectively as possible. Maps are key elements for campaign management and field work; however, as de-mining campaigns generally take place in developing countries, there is often a lack of accurate and recent maps for the zone of work. Information systems have been developed in order to solve those problems and are now used in countries affected by Explosive Remnants of War (ERW). IMSMA, the UN-standard information system for Mine Action, addresses this problem. It consists mainly of a database located at the Mine Action Centre (MAC) of a specific country or region, into which all Mine Action related data are centralized. It also contains management and planning tools that process the information in the database in order to help decision makers. PARADIS [9] addresses the problem by compiling and organizing the data related to the campaign in a geographic database (GeoDb). As PARADIS is built on a GIS, it presents the data to the user on a map rather than on a form (x, y coordinates) (fig 7a). The user is able to enter the data in the PARADIS system, then export them to IMSMA using the MAXML (Mine Action eXtended Markup Language - http://www.hdic.jmu.edu/conference/casualty/maxml_files/frame.htm). The manager interface is located in the MAC and is built on a full-featured GIS. As it needs to access the central Geographic database and may run big processes while manipulating the data, it is based on a desktop –or laptop- computer (the Desktop Interface). The field operator or the RS controller could or will work on a lightweight GIS interface called the Field Interface. The latter is running on a Personal Digital Assistant (PDA), which small size and light weight make it the ideal tool for the field work or could run on the RS laptop containing in this last case the Field-Manager Interface as well as the Human Machine Interface. A complete procedure of Information exchange (Manager to Field, Field, fig 7b, Field to Manager, MAC to IMSMA) is currently developed, exploiting the advantages of the Internet Facilities.
RSMM

The RSMM comprises (a) the planning process including the valuation of the environmental conditions compared to the available data (for instance, primary map of the minefield from an aerial detection, with some information on natural relief, obstacles, PARADIS information ..) in order to generate a series of tasks (path-planning, cutting of the vegetation, inspection mode – choice of the sensor, sensor deployment -....), (b) the directing process which defines with a high precision and on unambiguous way the operations (a set of operations or sub-tasks defines a task) that will be controlled by the Field Users and (c) the monitoring process involving the Tele-operation aspects. The intelligence of the system lies essentially in the first two processes: an Expert-System (ES) will assist the local field manager (and, indirectly the field user during the monitoring process). Such an ES includes a comprehensive database (HLMM derived GIS, Geological information, Mines and UXO information/description, characteristics of the UGV, of the Sensors, etc), a set of rules and a strategy allowing the best choice of rules according to the objective (minefield delineation, precise scanning of well-defined area, etc). The monitoring process imposes a correct design of the HMI. As an example, the next figures describe the control-architecture of the RMA-Hunter as well as the HMI (CORODE software) including the visualisation of the signals delivered by the detection sensors (fig 8.a, 8.b)
HLMM and RSMM or IMS

Both management tools may be combined as well and form an Information Management System (IMS) [10] that makes a planning the for de-mining procedure and controls the sensing mobile robot(s), but also provides the information of the current status or past de-mining results in order to share the information with operators and other de-mining organizations. The information management system is composed of three subsystems as follows: the controller of the sensing unit entrusted to the supervisor, the mine detection support system displaying the image processing results, an integrated information interface for mine action (I’MA) based on the international standard “Mine Action Extensible Mark-up Language: maXML.

The first IMS has been implemented by the inter-university team Nagoya, Tsukuba, Tohoku under the sponsorship of the Japanese National Institute of Advanced Industrial Science and Technology (AIST) and with the support of the Mitsui Engineering and shipbuilding Company (Fig. 6.d). The next two figures describe the Hard/Software of the Control Station (right side of fig.5).

Fig. 9. Controller of the Advanced Mine Sweeper (fig 6d) and IMS

F. Robot Control (DOWN)

In the supervised mode, the safety and the performances of the communication (particularly non-line-of-sight) as well as the computing speed capabilities of the Informatics systems play a major role: a considerable literature (a.o. for military Ground missions) describes the constraints related to those factors: example: standard 19.2 Kbit/s (need of compression for the High-Bandwidth, typically 20 MHz for one vehicle in frequency modulation mode, Video signals). The vehicle control network and the data network impose the development of High Level - Low Level control software: here also a considerable literature suggests solutions: as an example, the ANCEAEUS control system [13] adopted on the JINGOSS mine-detection system developed by the Canadian Forces (DRES Defence Research Establishment Suffield) and mounted on a 8x8 wheeled vehicle ARGO (used in Somalia): the Vehicle Supervisor includes its own navigation module (semi-autonomous navigation, vehicle status monitoring, DGPS positioning functions,...) and its own application module (detection/marking).

The objective of the supervised control is clear: to free the human operator(s) to concentrate on a higher level of Control and optimally achieve the planned mission. No any supervised control may be successfully implemented without having satisfied to the next requirements: (a) the use of a UGV adapted for the mission (adapted mechanical structure, locomotion mode, actuation, sensory, etc.), (b) the training of the human operators (all ranks, thus including the Commando levels) through an appropriate series of courses on the emerging information and control technologies) thanks to on-the-field simulations, then on-the-dummy minefield trials under varying environmental conditions including uncertainties or randomly occurring events, (c) the pursuing (and funding) of R&D activities related to the next issues: optimal allocation of information processing (interactive planning and control at the mission level (the above described TOP level),
timely reactions on observed deviations), *optimal allocation of control functions* (High Level/Low Level motion control of the UGV and orientation/positioning control of its sensors), *Multi-Vehicle Control* (Integration of navigation, task, sensory modules under predictable structured conditions, - Idem under Uncertainties)

The first R&D results related to some of those issues, in real-time outdoor conditions, are still stammering.

- **Navigation**

Robots use sensors to perceive the environment. Generic robot sensors are ultrasonic sensors, laser range scanners, stereo camera systems, inertial measurement systems, GPS receivers and of course metal detectors. All but the last one of these sensors return positional and perceptual information about the surroundings. This sensor data has to be fused in a correct way to form a coherent “image” of the environment. Hence the need for an intelligent sensor fusion algorithm to combine the often erratic, incomplete and conflicting readings received by the different sensors, to form a reliable model of the surroundings. Sensor fusion has been subject to a lot of research. Most of the proposed methods use Kalman Filtering and Bayesian reasoning. However, in recent years, there has been a tendency to make more and more use of soft computing techniques such as artificial neural networks and fuzzy logic for dealing with sensor fusion.

An autonomous mobile agent needs to reason with perceptual and positional data in order to navigate safely in a complex human-centered environment with multiple dynamic objects. This translation of sensory data into motor commands is handled by the robot navigation controller. Its design is closely related to the design of the control architecture which describes the general strategy for combining the different building blocks. The basis for this reasoning process is often a map, which represents a model of the environment. These maps can be simple grid maps, topological maps, or integrated methods. The used path planning technique depends highly upon the type of map chosen before. In [14], a behavior-based control architecture is proposed to navigate while modeling (mapping) the environment in 3 dimensions, using vision as a primary sensing modality.

The control architecture describes the strategy to combine the three main capabilities of an intelligent mobile agent: sensing, reasoning (intelligence) and actuation. These three capabilities have to be integrated in a coherent framework in order for the mobile agent to perform a certain task adequately. The control architecture has to be translated into a software architecture which manages the building blocks on a software level. This software architecture has to provide the flexibility of modular design while retaining a thorough structure, enabling an easy design process. All the different processes (sensor measurements, measurement processing, sensor fusion, map building, path planning, task execution ...) must be coordinated in an efficient way in order to allow accomplish a higher goal. A number of control strategies can be set up, varying from simple serial sense-model-plan-act strategies to complex hybrid methods. An interesting approach here, is to use fuzzy behaviors, partially overriding each other, to build up complex navigation plans.

During the design of all these sub-aspects, the outdoor nature of the demining robot has to be taken into account. Outdoor robots face special difficulties compared to their indoor counterparts. These include totally uncontrolled environments, changing illumination, thermal, wind and solar conditions, uneven and tough terrain, rain, ...

The working principle of the control architecture proposed in [14] is sketched on Figure 10. There are three distinctive modules to be discriminated: Navigation (on the right side on Figure 2), Mine Detection - Scanning (in the middle on Figure 2) and Metal Detection (on the left side on Figure 2). These three processes are controlled by a watchdog, the robot motion scheduler, which manages the execution of each module and decides on the commands to be sent to the robot actuators.

*Navigation* goes out from data from different Sensors providing input for a Simultaneous Localization and Mapping module. These sensors can be:

- **GPS** (Global Positioning System) for absolute positioning
- **IMS** (Inertial Measurement System) for acceleration (and speed and position by integration)
- **US** (Ultrasonic sensors) for distance measurements to obstacles
- **IR** (Infrared sensors) for distance measurements to obstacles
- **LASER** for line 3D data
- **Mine Sensor:** The mine imaging module will return locations of mines, which have to be represented on the map and which are obstacles themselves

As the map-building module works with a global map, it doesn’t have to re-calculate the whole map from scratch every time, but the map can just be iterated to improve the different estimates, hence the loopback arrow. The map-building module outputs a global map with obstacles and also with mines, thanks to the input from the mine imaging module. This map is used by the navigation module to calculate a safe path. The safe path is given as an input to the robot motion scheduler which will transform it into a motor command and execute it.
unless another module has a higher priority task (and trajectory) to perform. *Mine Detection* uses a Cartesian scanning mechanism to make a 2D scan with the metal detector. Mine imaging tools determine the likelihood of mine occurrence and the exact position of eventual mines. If a mine is found, this will be reported to the robot motion scheduler, which will take the appropriate actions. In addition to this the Mine detector acts as a sensor for the SLAM-algorithm, as it will return the locations of mines, which have to be represented on the map and which are of course obstacles themselves. *Metal Detection* relies on the metal detector scanning for metal in the soil. If no metal is found, it keeps on doing this and the robot keeps on moving. If a metal is found, this will be reported to the robot motion scheduler, which will take the appropriate actions.

The robot motion scheduler needs to arbitrate which of the modules is executed and which of them can influence the robot actuators through robot commands. Therefore, there are two main paths through the robot scheduler, one for the (normal) situation of exploring while avoiding obstacles and while detecting metals and one for the situation where a metal is found and more thorough investigation is needed (mine detection) while the robot is standing still.

Figure 5 shows the graphical interface which was developed for controlling the mine detection process. This computer interface enables the user to control the robot scanning mechanism or to order the robot to scan the suspected area for mines. It also shows the map of suspected mine locations (red leds), as detected by the robot.

The described framework shows that by the integration of extensive navigation, map-building and path-planning techniques, a demining robot can be developed which can navigate semi-
autonomously in an unknown environment while searching for mines. These results will be further integrated in a behavior based reactive-reflexive framework, such that the robot can at the same time react quickly to dynamic changes in the environment, and perform high-level reasoning on a 3D model (map) of the environment.

**Sensor Positioning**

The signal of GPR (normally used in combination with a Metal detector) is strongly affected by a ground surface. If it is not flat and even, a reaction from ground surface varies much stronger than that from landmines. In addition, this variation of reaction from a ground surface disturbs an imaging of landmine, occasionally cancels it out. It’s consequently mandatory to design an adaptive scanning of the ground surface to reduce the effect of a bad positioning on the useful reflection signal. Proximity sensors attached directly to the sensor head can be a very simple solution for a reflexive control scheme to automatically adjust the vertical distance of the sensor head to the terrain. However, although technically more complex and expensive, in order to make possible a more efficient mapping and scanning of wider areas in a minimal time, cameras and/or laser range finders have to be used. The next table [8] summarises the types of topographical map acquisition systems.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Cost</th>
<th>Accuracy</th>
<th>Acquisition speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active stereo vision</td>
<td>expensive</td>
<td>very good</td>
<td>Fast</td>
</tr>
<tr>
<td>Passive stereo vision</td>
<td>affordable</td>
<td>good</td>
<td>Fast</td>
</tr>
<tr>
<td>1D Laser range finder</td>
<td>expensive</td>
<td>very good</td>
<td>slow*</td>
</tr>
<tr>
<td>2D/3D Laser scanner</td>
<td>expensive</td>
<td>very good</td>
<td>Fast</td>
</tr>
</tbody>
</table>

The passive stereo system has been selected for the GRYPHON-IV (fig 6.a), working in two steps: first the generation of a regular grid that will be overlapped to the terrain image, then the computation of the commands to the actuators of the 5-DOF manipulator carrying the multi-sensor-head, as illustrated by the next figures:

![Fig.12. Stereo system results on GRIFFON-IV, Mono system results on RMA-Hunter](image)

Depth from defocus is another original method used to recover information distances from textured images to displace mine detection sensors above the ground at a given distance without collision. If one uses a fixed focal length camera the image of the object placed at a point will produce a sharp picture of the object in the focal plane. The more the object moves from its position, the more the image is blurred. The Depth from Defocus method uses the direct relationship between the depth, the camera parameters and the amount of blurring in images to derive the depth. Because the blurring in an image can be caused by either the imaging or the scene itself, at least two images taken under different camera configurations are generally required to eliminate the ambiguity. The practical implementation of this principle gives promising results too.

**Robot Positioning – Tracking**

The ability to track the pose of a mobile robot, relative to its environment, while simultaneously building a map of the environment itself, is a critical factor for successful navigation in a partially or totally unknown environment. Simultaneous localization and map building (SLAM) has therefore been a highly active research topic during the last decade. While most existing approaches to SLAM make use of sonar or laser scanners, the use of vision sensors, both stereo and monocular, has also been studied, mainly because vision can yield a much richer information about the environment when compared to other kinds of range sensing devices. It must be noted, however, that SLAM is intrinsically an incremental process, and
consequently almost all the published approaches use recursive statistical techniques (Kalman or Bayesian filtering) which, although successful on the short term, suffer from error accumulation over time. A. Cumani [16] proposes an approach to SLAM which uses a panning stereo head as sensor, and an occupancy grid to store the acquired map. At regular intervals along its trajectory (in our case, at each detection-scanning step), the robot stops and "looks around", i.e. acquires a set of stereo pair images by panning its head. Point and line features from each image pair are matched and their 3D estimated positions are used to build a local occupancy grid map, which is then merged into a global map after registration to the global reference frame, using the current estimate of the robot pose. Relative robot pose for registration is estimated by correcting the a priori (dead-reckoning) position estimate by map cross-correlation in x and y, while the heading correction is obtained by applying standard ego-motion estimation techniques to the images acquired while the robot moves between two consecutive stops. Combining the visual heading estimate with the translation estimate from map correlation, yields a good compromise between speed and accuracy, by avoiding the need to perform a costly correlation search also in the angular domain. Instead of placing the camera on the mobile platform, a fixed camera may be used, located at a safe proximity of the scanned area: this is the approach followed by our research-group: P.Hong [17] proposed the use of a colour camera (fig 12.a.) and the choice of the HIS model: in the HIS colour model, the characteristics used to distinguish one colour from another are brightness (I), hue (H), and saturation (S). Brightness embodies the chromatic notion of intensity, Hue is an attribute associated with the dominant wavelength in a mixture of light waves. Saturation refers to the relative purity of the amount of white light mixed with a hue. A red target is put on the top of the tracked robot and algorithms have been defined to track the target, parameterized by its position, size and apparent diameter, with a good resolution (0.2%). Finally, let us also mention that a good positioning accuracy can be obtained with commercial systems such as DGPS (Differential Global Positioning Systems) for so far the communications allow their use.

**Multi-agent control**

As previously mentioned, and as clearly pointed in the fig.5, a Robotics System is not limited to a mobile platform, but includes proprioceptive and exteroceptive sensors allowing the precise actuation of the mechanical parts of the robot as well as the precise positioning of the robot self, and, in the case of Humanitarian de-mining, the detectors of the explosive devices. Furthermore, even if this solution may not be expected at short term, several robots may be used on the same minefield with dedicated de-mining tasks (brush-cutting, detection, removal, etc)

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Fig. 12.a. Pan-Tilt colour Camera, Sony EVI-371D color CCD (see also fig 8.a)

Fig 12.b. Configuration System

Fig.12.c. The HIS model

Computer systems are the backbones of all robotic applications. Since many years, researchers have developed ad-hoc programs for every new system. It is consequently difficult to build on existing systems and to reuse existing applications. There is a crucial need for reusable libraries, control framework and components. Efforts in this direction have focused on autonomous systems while we are also targeting Tele-operation. Some are based on proprietary communication libraries; others are based on CORBA (Common Object Request Broker Architecture). The RMA chose this last base to develop COROBA, specific multi-robot-control software: such a control has to be based on robust communication libraries and to
claim to be open it must subscribe as much as possible to existing standards. When considering communication libraries it appears that one communication middleware has been present for more than 10 years and has now reached its maturity, this middleware is CORBA. Beside the development of the architecture and to improve its capability, a simulator MoRos3D written in Java already proved the consistency of the chosen middleware. The next figure describes the basic structure of the Robot Control and a view on the treated scene. Tri-dimensional elements have been divided in different categories: robots, obstacles and terrain. Elements geometry can be read from files or directly created using Java code. At this stage, real implementations are realized on a outdoor robot ROBUDEM and an indoor one NOMAD [15]

IV. CONCLUSIONS

The development of a Robotics System not only depends on the technical aspects and modular components allowing the correct design of the remote controlled platform(s): the application related constraints have also to be carefully analysed in order to achieve the success of the whole system. Technically, the next scheme (proposed by the European Consortium CLAWAR) perfectly describes the hard- and software modules.

We have to focus on. The constraints related to the Humanitarian De-mining, and more generally to outdoor applications, may be summarised as follows: a high level of protection against the environmental conditions (dust, humidity, temperature, etc.), protection and resistance against vibration and mechanical shocks, long and continuous operation time between battery charging/charging or refuelling, wireless communication range depending on the terrain and minefield location, low cost, affordable prices by use of off-the-shelf components (typical constraint for HUDEM due to the lack of a real commercial market), high reliability, fail-safeness, easy maintenance, easy to use, application of matured technology. An ISO SC2 Technical Committee started the study of standards for mobile ROBOTICS (Catania, 23 Oct 2005 – final Clawar meeting). The next annexes, based on informations collected during the IARP workshops and allowed by their POCs, summarise the actual status of Robotics Systems. Test and Evaluation criteria are proposed as well, as result of WS discussions.
V. ACKNOWLEDGEMENTS

I want to mention that this paper includes the contribution of my colleague, Marc Acheroy, Director of the Signal processing Centre of the RMA and our searchers involved in the HUDEM (humanitarian de-mining) project. I also want to thank my partners from the European Network CLAWAR (Climbing and Walking Robotics) and from the WG HUDEM of the IARP (international Advanced Robotics Programme), as well as all the partners of our European funded projects (DG Education/OIC-R³-D², FW6-IST VIEW-FINDER, EDA/NMRS, MoD MB07).

VI. REFERENCES

A new Locomotion Concept
for Humanitarian Demining Robots

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Abstract – Landmines are most often laid in rough terrain which is difficult accessible for mobile robots. This paper outlines a new approach to build a locomotion system capable of traversing through difficult terrain to facilitate humanitarian demining. The overall costs for a demining robot have to be low enough to compete with wages in war-torn, mine affected countries. Therefore the proposed locomotion concept consists mainly of cost efficient commercially available components.

I. INTRODUCTION

Landmines continue to be a burden for 78 countries [1] and a challenge for mobile autonomous robots used for detecting and clearing them.

Although robots are less error prone, not affected by heath or other environmental conditions and much more accurate than their human colleagues they still suffer from inferior locomotion systems in rough terrain.

Unfortunately there is no typical landmine field, but it can be stated that mines are seldom laid in flat, even terrain. Generally speaking, there is no restriction where landmines cannot be laid. Obstacles like stones, rocks, trees and are frequently encountered.

Another serious problem hindering accessibility of landmine fields is vegetation, especially in warm, humid climates. As minefields cannot be harvested or gazed they are frequently overgrown by thick vegetation which has to be removed before the field can be cleared. Vegetation removal is beyond the scope of this paper, it is assumed that the terrain is already accessible by humans or robots.

II. REQUIREMENTS

During interviews with demining experts we derived the following requirements which are mandatory for a demining robot’s locomotion system [2]:

• Reliability, Robustness
  The whole system needs to operate very reliably, thus minimizing costly periods where the robot is out of service. Appropriate environmental protection (water tightness, dust tightness, vibration protection, etc) is considered to be mandatory.

• Maneuverability
  As stated in the introduction minefields are frequently littered with obstacles. The robot has to decide which objects can be surmounted and which obstacles need to be circumnavigated.

• Low Ground Pressure
  Ideally a demining robot should be light enough to avoid triggering a landmine even if it accidentally drives over it.

• Endurance
  Operation time should be at least two hours before the energy source is recharged or refueled. This should not take longer than 30 minutes [3].

• Cost Effectiveness
  Mine affected countries do not have the means to afford expensive high-tech solutions. A typical deminer with two years of experience makes 140 US Dollars per month in Afghanistan. For countries like Cambodia or Angola wages are even lower and the costs for a deminer are around 200 - 1.000 US Dollars a year. In order to compete with these low wages a robot has to be reasonably cheap [4].
III. LOCOMOTION CONCEPT

Prior to constructing a prototype a virtual obstacle course has been built using simulation software. Such an environment facilitates the evaluation of different locomotion concepts and design alternatives.

In the early stages of our simulation the idea was developed to use the concept of articulated wheels for propulsion. The term articulated wheeled vehicle refers to a vehicle which is able to change its suspension configuration or vehicle geometry and thus repositioning its Center of Gravity (CG). Historically this locomotion type has become popular in the 1990ies when the first Unmanned Land Vehicles (ULVs) for exploration of the planet Mars were commissioned.

During a planetary explore mission high demands are posed on a robot’s locomotion system. First there is very little knowledge of the exact terrain type the robot is going to operate in. Therefore the rover should be able to cope with steep, rocky terrain. Autonomous operations can easily result in loss of wheel traction, leading to entrapment, loss of stability and even tipover [5]. The mission’s success depends on avoiding such situations. As an example Fig. 1 depicts the Mars rover “Spirit”.

Using a vehicle with articulated wheels seems very promising for demining operations: The maneuverability is unmatched, obstacle surmounting capability is excellent and energy consumption is moderate [7].

In an iterative simulation process the mars rover’s Rocker-Bogie suspension design was used to generate a new suspension geometry by successive simplification and evaluation while maintaining its advantages (Fig. 2). Instead of having a fragile set of arms holding the wheels on each side of the body the wheels are directly connected to a segmented body. This prevents the robot from entanglement by vegetation.

The front and rear body segments are connected by a free pivot which allows the whole vehicle to adapt passively to the ground along its driving path.

To improve the vehicle’s traction and to allow its adaption to lateral terrain irregularities it was planned to use active suspension (e.g. pneumatic shock absorbers) for all six wheels. As this idea was about to be implemented in the simulation environment it turned out that passive suspension (i.e. regular shock absorbers) worked flawlessly, eliminating the need for more sophisticated (and potentially error prone) pneumatic components.

IV. OPTIMIZATION

Next the question arose: How efficient is the newly developed geometry? In order to optimize the position of the pivot, the length of the front section and the length of the rear section a metric had to be found which offers to measure the robot’s all terrain performance.

An effective method for doing so was to constantly reduce the maximum motor torque and observe if the vehicle was still able to climb all virtual obstacles while modifying its parameters (i.e. position of pivot, length, etc). In the simulation it is a matter of seconds to change these parameters and the effect is visible immediately. Therefore it is possible to achieve many iterations in a short amount of time and constantly optimize the geometry.

This optimization process could also be automated by using an evolutionary approach: The vehicle’s parameters are mutated and recombined while selection pressure is established by constantly reducing the motor torque and...
eliminating the individuals who cannot climb all virtual obstacles anymore. Although it would be very interesting to implement such an algorithm the optimization process was done manually for reasons of time and effort.

V. DESIGN PROCESS

During the design process a low cost method for rapidly building robot prototypes using commercially available components has been applied.

The robot developed during the simulation phase is segmented into a front and rear section. These two sections are interconnected by a passive joint which allows the robot to adapt passively to the terrain. Four wheels are located in the front section and two wheels in the rear section. Each wheel is driven by a high torque gear motor. Six servos allow setting each wheel’s steering angle individually. As the front section has to carry the weight of the mine detector and its rotating mechanism the asymmetric wheelbase enables an equal weight distribution among all wheels.

The chassis frame represents the skeleton of the robot, holding its core parts together. Its dimensions and geometry define the key characteristics of the locomotion system. As with cars a chassis frame’s quality is of utmost importance for the overall quality of the vehicle. In order to reduce effort and costs commercial aluminum profiles are used wherever possible. This approach is state of the art for plant engineering and construction. Aluminum profiles are available in a wide variety of different shapes and sizes. For the demining robot’s chassis frame 20 mm profiles were selected as base material. Great care has to be taken that a metal detector is placed sufficiently far from any metal parts in order to prevent interference.

For the suspension and steering linkage commercially available parts from R/C monster trucks were used. They have been designed to withstand high forces and shocks; they are easily available and cheap compared to a custom made solution. The construction is durable and proven in use for several years. As the weight of the resulting vehicle is significantly higher than the weight of the monster truck the standard suspension springs need to be replaced by stiffer springs. The vehicle’s total weight (including payload) was anticipated with 20 kg.

The equilibrium length of the monster truck suspension springs is 117 mm. If the vehicle is standing still the suspension springs should not be contracted more than 10 percent of their total length to maintain enough ground clearance. This means that the spring constant has to be 1.21 N/mm. A qualified spring would have a diameter of 19 mm, 20 wraps with a wire diameter of 2 mm. These springs were custom made on a turning lathe.

A demining robot’s tires need to provide excellent grip for propelling the robot forward. They should be low inflated to minimize ground pressure and have a wide diameter to increase the robot’s ground clearance. These needs are once again covered by R/C monster truck parts. For the robot prototype 200 mm tires of a 1:6 scaled truck are selected.

VI. STEERING GEOMETRY

In order to calculate the individual steering angles the Ackermann geometry depicted in Fig. 3 was applied.

As Fig. 3 indicates, for a vehicle which drives around a given turning point T all wheels need to be perpendicular to a straight line connecting the kingpin (main pivot) of the wheel and T. Furthermore the individual wheel speeds need to be adjusted to emulate a mechanical differential.

A demining robot’s tires need to provide excellent grip for propelling the robot forward. They should be low inflated to minimize ground pressure and have a wide diameter to increase the robot’s ground clearance. These needs are once again covered by R/C monster truck parts. For the robot prototype 200 mm tires of a 1:6 scaled truck are selected.

The 7th IARP International WS HUDEM’2008, AUC, Cairo, March 28-30, 2008
normal cars a tie rod connects the two steering arms, which lie on a line between the steering kingpins and the center of the rear axle. Therefore the Ackermann steering geometry is implemented mechanically (Fig. 4).

In addition to setting the correct inner and outer wheel angles the tie rod has also another very important function. It neutralizes forces acting from an alongside direction on the steered wheels. Reasons for the occurrence of such forces are frictional resistance, bumps on the way and obstacles to be traversed.

This implies that for individually steered wheels the steering servos have to tolerate shocks and vibration due to the absence of a tie rod. Furthermore the servos needs to be able to provide high torque to overcome the tires’ moment of friction when driving at low speeds. Fig. 5 shows a rendering of the chassis frame, the suspension parts and the steering linkage.

VII. EVALUATION

In order to evaluate the prototype’s rough terrain capabilities a series of field trials in the backyard of the VUT and on a nearby construction site were performed. Both areas were littered with natural and artificial obstacles and posed an ideal playground for the demining robot’s locomotion system. The obstacles resembled those from the simulation. Therefore a comparison between simulation and prototype performance is possible.

The outside obstacle course for the locomotion system evaluation was slightly covered by ground vegetation. This did not affect the robot’s maneuverability and entanglement by plants was not an issue.

The total rough terrain evaluation drive lasted more than 60 minutes and during that time the robot showed no signs of battery weakness. The batteries last for about 90 minutes continuous driving when fully charged. During a demining mission the robot will not constantly drive around as it has to locate and mark the mines as well. These actions drain far less energy than driving and thus it is concluded that the robot fulfills its endurance requirement of 2 hours total operation time.

Concluding it can be stated that most properties established during the simulation phase hold under real circumstances. As the focus of these experiments was laid on the locomotion system’s performance, all trials were made without landmine detector and additional payload. Fig. 6 shows the prototype “Humí” climbing an artificial concrete obstacle. Fig. 7 depicts the fully assembled vehicle including the landmine detector and a landmine marking unit.

VIII. OUTLOOK

It is anticipated that robots will take over the work of humanitarian deminers in the future. Currently much research effort is spent to use robot swarms or Multi Agent Systems (MAS). Such a system consists of multiple robots.
performing different tasks, such as localization of landmines, excavation of the potential threat and transport/disposal.

One of these tasks, most probably the localization of landmines can also be accomplished by humanoid robots. These robots are expected to have the same or even better locomotion and climbing abilities as humans and are therefore an interesting alternative to wheel based vehicles in rough terrain. A humanoid robot called “Archie” is currently under development at our institute.

IX. CONCLUSION

Rough terrain poses a major challenge for deming robots and their locomotion system. By using mainly commercially available parts we were able to build a cost effective prototype capable of navigating through rough terrain and surmounting obstacles of various sizes and forms.

X. REFERENCES


Abstract—Humanitarian demining is still a highly labor-intensive and high-risk operation. Advanced sensors and mechanical aids can significantly reduce the demining time. In this context, it is the aim to develop a humanitarian demining mobile robot which is able to scan semi-automatically a minefield. This paper discusses the development of a control scheme for such a semi-autonomous mobile robot for humanitarian demining. This process requires the careful consideration and integration of multiple aspects: sensors and sensor data fusion, design of a control and software architecture, design of a path planning algorithm and robot control.

Index Terms—Autonomous robotics, demining robots, mobile robot navigation, robot control and software architectures

I. INTRODUCTION

The goal of this research project is to prepare the ROBUDEM, an outdoor mobile robot platform as shown on Figure 1, for a humanitarian demining application. In this setup, the robot navigates and searches for mines by moving and sensing with the metal detector for suspicious objects in the soil. Once a suspicious object is detected, the robot stops and invokes its Cartesian scanning mechanism. This scanning mechanism performs a 2D scan of the soil, allowing mine imaging tools to make a reliable classification of the suspicious object as a mine or not. This paper describes partial aspects of this research work and focuses mainly on the design of the control and software architecture.

II. CONTROL ARCHITECTURE

The control architecture describes the strategy to combine the three main capabilities of an intelligent mobile agent: sensing, reasoning (intelligence) and actuation. These three capabilities have to be integrated in a coherent framework in order for the mobile agent to perform a certain task adequately.
The control architecture has to be translated into a software architecture which manages the building blocks on a software level. This software architecture has to provide the flexibility of modular design while retaining a thorough structure, enabling an easy design process. All the different processes (sensor measurements, measurement processing, sensor fusion, map building, path planning, task execution …) must be coordinated in an efficient way in order to allow accomplish a higher goal [2]. A number of control strategies can be set up, varying from simple serial sense-model-plan-act strategies to complex hybrid methods. A discussion of some of these control strategies can be found in [13]. An interesting approach here, is to use fuzzy behaviours, partially overriding each other, to build up complex navigation plans, as discussed in [9][10][11][12]. This research work aims at implementing such a hybrid control strategy.

During the design of all these sub-aspects, the outdoor nature of the robot has to be taken into account. Outdoor robots face special difficulties compared to their indoor counterparts. These include totally uncontrolled environments, changing illumination, thermal, wind and solar conditions, uneven and tough terrain, rain, …

As the map-building module works with a global map, it doesn’t have to re-calculate the whole map from scratch every time, but the map can just be iterated to improve the different estimates, hence the loopback arrow. The map-building module outputs a global map with obstacles and also with mines, thanks to the input from the mine imaging module. This map is used by the navigation module to calculate a safe path. The safe path is given as an input to the robot motion scheduler which will transform it into a motor command and execute it, unless another module has a higher priority task (and trajectory) to perform.

A. General Architecture

The working principle of the proposed control architecture is sketched on Figure 2. There are three distinctive modules to be discriminated: Navigation (on the right side on Figure 2), Mine Detection - Scanning (in the middle on Figure 2) and Metal Detection (on the left side on Figure 2). These three processes are controlled by a watchdog, the robot motion scheduler, which manages the execution of each module and decides on the commands to be sent to the robot actuators. This robot motion scheduler is explained more in detail in Figure 3 and is discussed here more in detail for each of the three modules.

1. Navigation

Different Sensors provide input for a Simultaneous Localization and Mapping module:
B. Robot Motion Scheduler

The robot motion scheduler (Figure 3) needs to arbitrate which of the modules is executed and which of them can influence the robot actuators through robot commands.

Therefore, there are two main paths through the robot scheduler, one for the (normal) situation of exploring while avoiding obstacles and while detecting metals and one for the situation where a metal is found and more thorough investigation is needed (mine detection) while the robot is standing still.

In a normal situation, occurring e.g. in an initial situation (default inputs), or when the “no mine found” or “mine found” trigger are given, the scanning metal detection is turned off. The Navigation module gives at all time instances a safe path and trajectory, as this module loops infinitely without interaction with the other modules. This Trajectory is set as the trajectory to be executed, but with a low priority. The Metal detector module is activated.

If the “metal found” trigger is given, the metal detector is switched off. The trajectory for the robot is set to a predefined movement, more specifically, to back off a little. This is done to be able to centre the scanning metal detection better around the suspicious object. This trajectory has a high priority. When this movement is completed, the robot is halted, by giving a “no movement” trajectory with a high priority. Finally, the scanning metal detection module is activated.

III. SOFTWARE ARCHITECTURE

As control architectures which aim to mimic human thinking risk of becoming highly complex, the choice of a flexible, extendable and real-time capable software architecture is very important. This software architecture has to ease the use of reusable and transferable software components. The chosen software architecture, MCA (Modular Controller Architecture) [14] achieves this by employing simple modules with standardized interfaces. They are connected via data transporting edges which is how the communication between the single parts of the entire controller architecture is managed. The main programs only consist of constructing modules that are connected via edges and pooled into a group. This results in an equal programming on all system levels. As modules can be integrated both on Windows, Linux and on RT-Linux without changes, they can be developed on Linux-side and then transferred later to RT-Linux. As errors in RT-Linux lead to system hangs this development strategy prevents from many reboot cycles and results in faster software development.

The proposed MCA software architecture, as it is depicted on Figure 4, consists of three main groups: one for sensor-guided robot control (using a behavior based navigation method and SLAM), one for scanning metal detection and one for metal detection.

The robot motion scheduler controls which of the three groups is executed and with which parameters. Each group consists of several modules and/or subgroups.

Each MCA module is determined by four connectors with the outside world: Sensor input (left below), Sensor output (left top), Control Input (right top), Control Output (right below). As a result sensor data streams up, control commands stream down. The Sensor input and output are connected through a Sense procedure which enables to process the sensor data and the Control input and output are connected through a Control procedure which enables to process the control commands. Sensor data flow is shown in yellow, control command flow in red.

For now, the scanning and metal detection modules are implemented and operational. The X-axis of the scanner has been removed in the mean time, so scanning is only performed in the Y-direction. The whole architecture contains interfaces that can be used via TCP-IP (Ethernet). In this way all sensors values can textually or graphically be presented on a second PC. A common graphical user interface has been developed to
simplify the procedure. Figure 5 shows the graphical interface which was developed for controlling the mine detection process. This computer interface enables the user to control the robot scanning mechanism or to order the robot to scan the suspected area for mines. It also shows the map of suspected mine locations (red leds), as detected by the robot. As the map building and path planning modules are not implemented yet, the robot is currently still restricted to follow predetermined trajectories.

Fig. 5: Graphical Interface of the Control Program, showing the Map of Suspected Mine Locations

IV. CONCLUSIONS

In this paper, we have proposed a solution for the control problem of a mobile humanitarian demining robot. The results so far are encouraging: the robot is able to follow a predetermined trajectory and find mines along this path, as illustrated by Figure 5. Future research will enable the robot to find its way semi-autonomously, by the integration of extensive navigation, map-building and path-planning techniques. These will be integrated in a behaviour based reactive-reflexive framework, such that the robot can at the same time react quickly to dynamic changes in the environment, and perform high-level reasoning on a 3D model (map) of the environment.

REFERENCES

Remote Operation of the Mini MineWolf in High-Threat Mine Environments

By Christoph Frehsee and Carl Fenger

The increasing demand for safe and rugged robotic mine clearance vehicles for high-threat environments has resulted in the development and deployment of a light-weight, robust, armored demining machine, the Mini MineWolf. Introduced in 2006, the machine has been designed and proven to fulfill four crucial requirements for humanitarian demining operations:

1) Provide a safe operating environment for deminers, even in high-threat environments, e.g. high concentration of Anti Personnell (AP) mines, and/or presence of Anti Tank (AT) mines.
2) Increase the rate that contaminated land is cleared and returned to civilian use as compared to manual demining alone.
3) Achieve superior cost-effectiveness on a per-square meter cleared basis as compared with purely manual techniques, e.g. metal detectors and mine detection dogs.
4) Remain operational and repairable in remote regions and in high-risk environments far from a logistical supply chain.

Currently 8 Mini MineWolfs have been produced and deployed in 6 countries (Afghanistan, Bosnia-Herzegovina, Croatia, Jordan, Sudan), clearing over 2 million square meters in a wide range of challenging terrain and harsh environmental conditions during 2006-2007.

The machine is a light-weight (8.1 tons), robust, armored demining machine designed to provide maximum safety for human operators via remote control. It has also been designed and proven during German Army trials to achieve a high rate of Anti-Personnel (AP) mine clearance (≈99%) while surviving harsh environmental conditions and Anti-Tank (AT) mine detonations up to 13.5 kg TNT with only minor damage to the working tool, repairable in the field.¹

Providing a safe operating environment for deminers

To insure maximum safety, the Mini MineWolf has been designed as a remote-controlled vehicle. It is equipped with a Remote Visual Guidance System and automatic depth penetration system allowing operation from a secure distance (>500 m) with close-up, high-quality visual guidance of the ground and working tool. The system also provides a comfortable operating environment reducing fatigue and human error. A patented tiller design channels dust away from the camera allowing effective visual quality control. Optional tiller or flail working tools can be interchanged in minutes.

To reduce the risk to manual deminers during area verification, the Mini MineWolf has demonstrated its effectiveness against AP mines in a variety of soil conditions during German Army trials. The result: due to the design of the working tools, a tight ground strike spacing of 4 cm can be achieved resulting in an average AP mine neutralization effectiveness of approximately 99% to a depth of 20cm.¹ The result is already very close to the 99.6% clearance rate mandated by the United Nations Mine Action Service (UNMAS) for humanitarian demining.

¹ “Final Report, Testing of the Mini MineWolf According to ITEP Workplan 3.2.10” German Army Centre for Weapons and Ammunition, WTD-Nr. 91-300-160 (2007).
Testing of the Mini MineWolf took place at the German Army’s Centre for Weapons and Ammunition in Meppen, Germany with technical support from the Canadian Centre for Mine Action Technologies (CCMAT). The 4 week trial was held in September 2007 to determine the effectiveness of the Mini MineWolf using both tiller and flail attachments against simulated AP mines, as well as survivability against live Anti Tank mines. AP mines were physically simulated using computer-controlled “WORM” mines (Wirelessly Operated Reproduction Mine) which are able to detect and report damage inflicted by the machine to a remote computer via a wireless link.

The results of the trial were excellent, with the Mini MineWolf achieving impressive results of approximately 99% with both flail and tiller attachments against small AP mines, as well as survivability against heavy AT mines of up to 13.5kg TNT. According to the official report: “…the repairs, mainly welding work, could be performed on site the same day.”

The trial verified the Mini MineWolf’s effectiveness against AP mines, as well as its ability to survive occasional AT mine blasts. According to Col. Radlmeier, Chief Development Division of the German Army Engineering School, “The ability to provide safe clearance capabilities in areas contaminated with explosive remnants of war is becoming increasingly significant to the future tasks of the German Army’s Corp of Engineers… The Mini MineWolf is, based on real-world tests and its convincing results, a very interesting option to fill this gap.”
The Mini MineWolf was also successfully tested by the Croatian Mine Action Centre for Testing and Development (CROMAC) against 19 live AP mines including PMA-1A, PMA-2, PMA-3, PMR-2A, and PROM-1 during November 2006. All mines were successfully cleared with only superficial damage to the machine.²

Increasing the rate that contaminated land is cleared and returned to civilian use

Manual demining with metal detectors and Mine Detection Dogs (MDD) is a laborious, dangerous and painfully slow process. According to the report “A Study of Manual Mine Clearance” published by the Geneva Centre for Humanitarian Demining³, manual deminers can typically clear between 8 and 75 square meters per day depending on ground conditions. Accidents frequently occur inflicting severe injury or death. The Mini MineWolf can safely achieve outputs of between 5000-12000 square meters per day, a considerable increase even with manual verification factored in.

**Mini MineWolf Track Record as of End 2007**

<table>
<thead>
<tr>
<th>Country</th>
<th>Time Period</th>
<th>Operator</th>
<th>Area cleared (est.)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afghanistan</td>
<td>Delivered Dec. 2007</td>
<td>Danish Demining Group (DDG), 1 unit</td>
<td>-</td>
<td>Machine is en-route to Afghanistan</td>
</tr>
<tr>
<td>Bosnia-Herzegovina</td>
<td>2006-2007</td>
<td>Norwegian People’s Aid (NPA), 2 units</td>
<td>1,040,000 m²</td>
<td>Clearance tasks in various regions (AP, AT mines and EOD):</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>▪ Donje Dubravice, Brcko District</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>▪ Vidovice, Orasje, Posavski Kanton</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>▪ Ladjevici, Ilijas, Kanton Sarajevo</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>▪ Obudovac, Samac, Republika Srpska</td>
</tr>
<tr>
<td>Croatia</td>
<td>Oct. 2006-2007</td>
<td>Tornado d.o.o., 1 unit</td>
<td>915,000 m²</td>
<td>Clearance tasks in various regions</td>
</tr>
<tr>
<td>Germany</td>
<td>Sept. 2007</td>
<td>German Army</td>
<td>-</td>
<td>Tests and trials against AP and AT mines</td>
</tr>
<tr>
<td>Georgia</td>
<td>Delivery planned Mar. 2007</td>
<td>MOD Georgia</td>
<td>-</td>
<td>Planned deployment in Georgia</td>
</tr>
<tr>
<td>Jordan</td>
<td>Nov 2007</td>
<td>NPA, 1 unit</td>
<td>100,000 m²</td>
<td>Clearance tasks along Jordan-Syria and Jordan-Israel borders (AP and AT mines)</td>
</tr>
<tr>
<td>Sweden</td>
<td>Delivered Nov. 2007</td>
<td>Swedish Rescue Services Agency (SRSA), 1 unit</td>
<td>-</td>
<td>Planned deployment to Congo</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>2,055,000 m²</td>
<td></td>
</tr>
</tbody>
</table>

Achieve superior cost-effectiveness
The cost of manual mine clearance depends on many factors, and is difficult to quantify. However, what is clear is that the majority of operational costs in humanitarian demining are due to direct and indirect cost of staff and their infrastructure: deminers, managers, advisors, support staff, headquarter staff and associated costs such as insurance, office rental, travel and accommodations etc. By integrating a demining machine into manual demining teams, overall cost can be significantly reduced via reduction of required personnel. A recent statement by the Croatian Mine Action Centre following demonstration of mechanical demining machines at the “Humanitarian Demining 2007” conference in Sibenik, Croatia stated “…one machine together with 3 manual deminers produces the equivalent output of 63 manual deminers”.

According to the Geneva International Centre for Humanitarian Demining (GICHD), “The mine action community is increasingly aware of the benefits of mechanical demining equipment in the field. Appropriate application of mechanical demining equipment leads to cost-effective clearance and, as a result, to the safe return of cleared land to communities…it is beyond doubt that a well-balanced mechanical component can greatly improve the effectiveness of a mine action programme." 4

Remaining operational and repairable in remote regions
An important aspect of mechanical demining is reliability and reparability of the machine in the field. Once shipped to remote regions, the machine should not require factory repairs or shipment of replacement parts from abroad.

To meet this requirement, the Mini MineWolf, and indeed all MineWolf Systems machines are delivered with an integrated workshop and spare parts package. Based on extensive experience of demining operations on 3 continents, typical requirements for routine wear (e.g. example wear-down of chisels or chains), consumables (e.g. lubricants, filters) and blast damage (rotor) have been established and are included in the package.

The mobile Workshop Container concept renders mine clearance operations self-sufficient and flexible providing a comprehensive maintenance, repair, transport and service solution which greatly facilitates the scope of operations.

The Workshop Container can be either designed as a stand-alone solution or as an attachment to a service truck or trailer. The workshop is equipped to accomplish all standard maintenance and service tasks including servicing and changing of wear parts, engine and drive train maintenance, repair and replacement of working tools, welding and blast damage repair.

For the Mini MineWolf, the 20-foot mobile workshop container version may also double as a transport container for the machine without having to remove the tiller or any of the workshop tools or equipment. This facilitates transportation of the machine to remote regions via truck, ship or air.

Conclusion
Important criteria for humanitarian demining operations include safety, clearance speed, cost-effectiveness, and maintainability of the machine in the field. The Mini MineWolf with its remote-control capabilities has demonstrated its effectiveness in all 4 areas via field and 3rd party testing in high-threat environments.

De-Mining Techniques of Improvised Explosive Materials by the usage of Mobile Robots

Pajaziti A., Berisha J., Bajrami Xh., University of Prishtina, and Ajvazi A., Kosova Police Service

Abstract—This paper demonstrates the de-mining techniques of the Improvised Explosive Device Disposal Unit (IEDD) that are in use for the neutralization of improvised explosive materials. The IEDD is a specialized unit, which operates within the Department of Specialized Units of Kosova Police Service (KPS) and is responsible for identification, training, transportation and neutralization of improvised explosive materials. The IEDD members are involved only in cases of presence of the improvised explosive materials (suspicious bags, doubtful mines, deadfall mines, chemical explosives and explosives in general, as well as forays of high risk). Improvised explosive materials can be of different shapes, but usually they are stored in different packages and with the first contact, they do not give the impression that could present any danger, in particular for human being or surrounding, except in cases when the terrorists who place those mines with intention to achieve considerable effect on threatening, rather than causing the eventual victims. Since, the cases of emergency situation with mines have to be treated in specific way regarding the reaction methods as well as different scenarios, the IEDD Unit has applied the usage of mobile robot, carrying the mine detectors, could play here an important role. Among the different ways robots could help IEDD Unit, the scenarios described in this paper regarding the detection and removal of mines are the most realistic.

I. INTRODUCTION

THE IEDD is a specialized unit that is functioning within the Department of Special Units of Kosova Police Service and is responsible for identification, training, transport and neutralization of improvised explosive materials.

Participants of the IEDD are engaged only in cases of appeared improvised explosive materials (suspicious bags, doubtful mines, deadfall mines, chemical explosives and explosives in general, as well as forays of high risk).

Explosive materials of military character (EOD) and UXO un-explosive materials are not responsibility of the IEDD treatment.

The duties and responsibilities of the IEDD unit are as following:

- Building foray with high risk;
- Identification of improvised materials and consisting parts of it;
- Formulation of minimal distances and security general regulations;
- Reaction in case of bomb threatening;
- Assistance for investigation in the place after explosion;
- Operation action in order to ensure and avoid the doubtful packages, doubtful bombs, deadfall bombs, chemical explosives and other explosives;
- Legal treatment, secure transport and material deposit in and from the place of event;
- Training assurance for anti-terrorist foray units.
- Security with dignity for all the citizens;
- Control of the place of event after explosion and keeping the evidence.
- Preparing and participation of the training programs with regard of explosives;
- Cooperation with Emergency Department on plan developing for bomb threatening to IEDD and crime scene caused by bombs;
- Technical support to special operations, for instance, special foray of objects for very important persons;
- Keeping and material disposal for operational and training purposes;
- Preparing and training of special teams for anti-terrorist foray;
- Supervision on the work of Anti-terrorist Foray Unit in terrain;
- Command of Anti-terrorist Foray Units in operations of high importance;
- Coordination of activities and maintenance of the Anti-terrorist Foray Unit Standards;
- Maintenance, stocktaking and proper storage of equipment of IEDD Unit.

II. THE EXPLOSIVE MATERIALS IN GENERAL

The improvised explosive devices (IED) present a great risk for police and citizens in general. Therefore, the warning of improvised explosive devices and materials should be treated very seriously without exception. IED are produced in different shapes and magnitudes, with different methods of functioning, content and different method of distribution.

Timer can activate IED from distance, by vibration, by pullback etc. They are unique in nature, since the producer of IED should improvise with combined materials manually handled.

IED can be of different shapes, and they are usually
placed in different packages, and in first sight they can not give the impression that could express any danger for the people and environment, except in case when terrorists place them to demonstrate the risk in particular for people and environment to achieve the threaten and cause eventual victims. In those cases, terrorists intentionally warn about the installed explosive and in first sight, this material could be identified as explosive material. Therefore, the Emergency Situations Cases with bombs have particular specifics, in the manner of reaction as well as the method of treatment.

The application of robots to the above-mentioned activities is of a great importance, since from one side, the IEDD operator could be away from the danger, while to another side; there will be the increase of precision of doubtful material treatment.

The key of success for accomplishment of the IEDD tasks is the combination of operator’s experience with application of the proper and reasonable usage of robot [1].

III. PRACTICAL USAGE OF THE ROBOTS

The IEDD Unit is employing the robots for the following tasks:
- Control of environment for doubtful reported devices;
- Recording the doubtful materials;
- Recording the explosive materials initializing even the environment around the materials;
- Monitoring the environment around including supervision through the windows of buildings of the vehicles to have control the inside environment of object;
- Visual control of vehicles and opening the door with explosive materials;
- Force opening the door of vehicles and neutralization of doubtful materials inside the vehicle;
- Deliverance of wave frequents blocker to the explosive material, before the technician for neutralization approaches to the explosive material;
- Usage of a disruptive emptiness for neutralization by the robot;
- The doubtful material’s pullback in different ways from one place to another enabling better approach for neutralization;
- Control the place where the explosion took place due to secondary danger before the operator physically controls the environment;
- Different material removing close to explosive material, with intention to forensic treatment before the explosion;
- Taking and placing the explosive material on trailer for the explosive transport to the safe place to non-activate and remove the explosive material from the trailer to the out of action place.

A. The VANGUARD MK-2 robot

Advantages of MK-2 robot with (fig. 1.) regard to human are as follow:
1. precision during the mission
2. safety (eliminates risking human life during the mission)
3. identification of the IEDD objects without risking the human life
4. records and gets photos of the IEDD objects without risking the human life

![Fig. 1. VANGUARD MK-2 robot](image.png)

1) Features:
The MK2 is the newest version of the Vanguard robot voted best performing and most applicable system in a major performance evaluation of competing systems conducted by Battelle, for the Technical Support Working Group (TSWG) of the National Institute of Justice. The MK2 incorporates the enhancements recommended by Battelle-and more-making it “a major asset for bomb squads” and law enforcement personnel [2].

2) General Capacities:
- Lift Capacity (arm extended) 8.0 kg (17.6 lbs.)
- Lift Capacity (arm retracted) 18.2 kg (40 lbs.)
- Vertical Reach 132 cm (52.0 inches)
- Horizontal Reach 96.5 cm (38.0 inches)
- Ground Clearance 5.75 cm (2.25 inches)
- Overall Length 91.5 cm (36.0 inches)
- Overall Width 43.5 cm (17.0 inches)
- Stowed Height 40.5 cm (16.0 inches)
- Overall Weight 48.0 kg (105.6 lbs.)
- Mission Duration 2-3 Hours +(quick change battery pack)
- Stair Climbing Angle 40 Degrees
3) **RF System P/N 3VCS10580:**

The RF system refers to both, the data and video system to make the MK2 completely remote, fig.2. The data transceivers work on 900 MHz. The video system works on 2.4 GHZ. The data system is, internal, only exposing the antenna. The video transmitter is protected by the rear cage and has a flexible mount for the antenna to avoid damage if uprighted [3].

![Fig. 2. RF System](image1)

4) **Recoilless PAN Disrupter Mount P/N 3VOE500000:**

Firing the PAN Disrupter has never been easier, with the new recoil system from Ideal Products Inc. Allen-Vanguard provides a mounting system for the PAN disrupter with the recoil adapter tube, which also includes a color CCD camera and dual flashing lasers for pinpoint accuracy. The Recoil system is a simple add-on to any PAN disrupter, fig. 3.

![Fig. 3. The PAN disrupter](image2)

5) **IR Camera P/N 3VOE210000:**

The IR Camera is light sensitive and automatically changes from a color CCD to a B&W camera in low-light situations, fig.4. This camera is mounted on the upper arm and becomes the forth camera. This camera is great for surveillance when searching poorly lit areas.

![Fig. 4. IR Camera](image3)

6) **20 MM Recoilless Disrupter P/N 3VPA15840:**

The 20mm recoilless disrupter from Prop arms mounts to the upper arm, and has a color CCD camera and laser as part of the mount, fig. 5. Ammunition is bought directly from Prop arms and requires an end user certificate.

![Fig.5. Recoilless Disrupter](image4)

7) **Command & Control Unit (CCU):**

One of the most important units is CCU unit since this is the operators or human interface with the robot, which is very important during the mission, fig. 6. User-friendly CCU can have important role to operate efficiently during the mission, which often can be key of success during the mission.

![Fig.6. CCU unit](image5)

The above photo shows most of the CCU features. The CCU is portable and ready to go at all times. You can choose from AC or DC power. The DC power source can run from 3 to 5 hours before recharging. The batteries and charger are...
To charge the system, plug it into the AC receptacle to charge the batteries and laptop.

8) Software user friendly & easy to use Interface:
The user interface is a guide to operating your robot, by matching the function you want to use in the interface menu and the keys on the laptop keyboard. For example, on the above screen, in the Drive box you will see “F1.” This tells you that by pressing your “F1” key you will activate the Drive function of the robot. All motor functions use the arrow keys on your keypad or joystick to operate the function. Other functions are toggle on/off such as the lights “F9”. After choosing your function, use the Help menu for instructions until you are fully familiar with all the functions and operations, the help menu changes with each key pressed. The interface is the source for your robot’s information; the laptop automatically boots up into the interface screen.

From this menu screen, you can check battery status of the robot, communication link, what functions you are using and so on. Along with the visual information, selecting the “P” button activates your speech feedback, giving you audio confirmation of what button was pressed.

When the laptop is first turned on, it automatically loads the MK2 software. There are other features on the desktop you may want to access. You can minimize the MK2 interface either once the software is loaded or close the software completely.

As we can see on this picture, with function keypads we can control most of the robot features like, drive, robot-arm, camera, lights, and laser and make a photo. We can use keypads or Joystick to operate with the robot.

We need to choose first with the function keys for the operation and then we can manipulate or operate with keypad arrows.

These are the files (fig. 9) you may need or want to access:

1) MK2 Software-should you close the software for any reason and want to start again press this icon.
2) MK2 Manual- the operating manual in PDF format.
3) My Documents file- here is where your photos are saved from the MK2 interface. When you press F11, the image you are viewing is stored by date and time.

IV. ACTION PROCEDURES – ENGAGEMENT RULES

The IEDD Unit is engaged in cases of foray with high risk in case of threaten with bombs, as well as in cases of improvised explosive material treatment [4].

The IEDD Unit on daily basis is engaged in case of reporting about the doubtful explosive, and in particular in cases of discovering of improvised explosive materials.

In figure 10 is shown the organizational scheme of IEDD Unit intervention including all the actions of the involved teams.

When the IEDD receives the information from the citizens in case of finding the explosive materials through the Operating Center, the IEDD Unit starts with the action. The IEDD Unit is the unique unit inside the Kosova Police Service that covers all the Kosova’s area.

There is the all responsibility of the IEDD Unit operator whether to use or not the robot from case to case.

In order to manage the robot manipulation, at least two people should be employed: the technician for manipulation and the technician for neutralization. These two operators work closely and all their activity work is in coordination with each other. In addition, there are other units that their
work is to help about the incident place and of all activities in general. The direct manner of manipulation and the neutralization’s techniques are classified like confidents.

The IEDD Unit has employed the robot to operate in different functions as: manipulation task: relocation packages to other area (fig. 11), inspection and disruption task (fig. 12), and mobility task: climb short run of stairs (fig. 13), [5].

Robot platform performance, in most areas of concern, satisfied a large percentage of the requirements specified by the IEDD. The robot completed successfully the tasks commonly encountered by the technicians.

V. CONCLUSIONS

Mobile robot Vanguard MK2B have been used in performing the adopted techniques in civilian mine clearance. Since, in the humanitarian de-mining, a high Clearance Efficiency (CE) is required, it can be achieved through the usage of robots supplied with cameras and sensitive sensors and their slow systematic displacements, according to well-defined procedures on the real terrain.

From the performed tasks in the terrain, one can conclude that Robotic Systems can help the de-mining teams to improve the cost effectiveness and the safety of de-mining operations. However, based on the obtained results, it is expected in the future the robotic systems should be equipped with more open and reusable applications in completion the detection tasks in complex and dangerous areas.

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Humanitarian Demining Robot Gryphon – An Objective Evaluation

Marc Freese, Toshiaki Matsuzawa, Takatoshi Aibara, Edwardo F. Fukushima and Shigeo Hirose

Abstract—Assisting human deminers or trained dogs in the mine searching task is challenging and expectations are high: the automation of the scanning increases safety for demining personnel and allows sensor imaging and automatic target recognition. This implies a new dimension for a more informed data evaluation with current landmine sensors and will represent at the same time an enabling technology for new sensors to come. Additionally, it is expected that this will increase demining pace and this at reduced cost. This paper presents a semi-autonomous mine searching robot named Gryphon that was developed with above goals in mind. It is made-up by a vehicle-mounted robotic manipulator capable to scan its surrounding terrain and generate precise sensor images. An operator remotely located monitors the scanning sequence and generated images, then registers suspect spots with GPS coordinates or with on-board marking systems. Gryphon was tested with two different metal detectors and various ground penetrating radar systems. Gryphon has gained the attention of researchers in recent years (see [12] for a survey). In particular, ground penetrating radars (GPRs) have been identified as a promising complement to the metal detectors (MDs). Where the MD detects buried metallic objects, the GPR detects bigger heterogeneities in the ground. The combination of both in a single sensor, or dual-sensor, allows performing discrimination, and so effectively reducing the number of false alarms.

Sensors like the GPR, producing at each measured position a large amount of data, can also be integrated into a hand-held device, however they typically see their performance decupled by having their scanned positions tracked and generating sensor images. An image – versus simple “beep” sounds like the MDs are producing – allows to visually identifying the precise position of the searched object. Not only does this facilitate data evaluation, it also allows saving recorded data for offline evaluation (potentially by an unlimited number of different deminers). Moreover, recorded data can be a posteriori corrected and improved by running various processing algorithms on it (e.g. noise removal, a posteriori soil compensation, automatic target recognition, etc.). This also holds true for traditional MDs which can see their performance increased in that way.

Sensor position tracking can be performed by several means, one of them is by having the scanning process mechanized. Several attempts have also been made in that direction by automating or assisting human deminers in the scanning process; legged robots [2][3][4], wheeled vehicles [5], tracked vehicles [6] and even suspended inspection tools [7] have been researched. Unfortunately, research is often focusing on one particular aspect (e.g. locomotion or sensing) leading to weak system integration. Also often, real-world conditions are abandoned for controlled laboratory conditions, and testing performed by researchers themselves. This produces devices difficult to objectively evaluate regarding their practical use. Direct comparison between a hand-held device like an MD and its mechanized version have not been carried out up to date but seems essential in the device evaluation process.

The Tokyo institute of Technology developed a semi-autonomous mobile robot to assist the mine detection process. Its manipulator is able to automatically scan over a 2 m2 surface with attached sensors, record data and present the
resulting sensor images to the operator who then can mark suspect spots. Additionally, a novel algorithm based uniquely on the acquired data from an MD has been tested, and shows promising results in extracting more than just the position of buried metallic objects; next to identifying the depth at which a metallic object is buried, it allows also performing discrimination. The developed robot was tested in several field trials on test minefields in Croatia and Cambodia.

II. GRYPHON - OVERVIEW

As shown in Figure 1, the developed robot named Gryphon is based on an All Terrain Vehicle (ATV) to which a custom long-reach hybrid robotic manipulator is added. The robot is equipped with a stereo vision camera to acquire topographical information of its surrounding environment. The so modeled terrain is then used to autonomously move a mine-detecting device (hereafter called mine detector) at close distance from the ground – that is not required to be flat – and describing a precise scanning motion over an effective surface of 2 square meters. The recorded mine detector data is then presented to the operator who, after careful inspection and evaluation, can indicate suspect spots that will be marked directly onto the minefield with an onboard paint- or plate-marking system. Additionally an optional RTK-GPS localization system records the location of the acquired data and marked spots.

For maximum safety, Gryphon always operates along the minefield borderline and from the cleared side. Only the mine detector and a part of the manipulator are operating over the dangerous area – hovering at close distance to the ground without ever touching it – during the scanning motion. Additionally, most operation steps are fully automated and Gryphon can be operated and monitored from a safe distance through a control box.

From very soon on, Gryphon was built with the idea to undergo practical tests in near-to-real-world-conditions. Particular attention was given to system integration, robustness (water-proof, extended temperature range, etc.), cost and easy operation/maintenance.

Following sections briefly describe Gryphon’s main composing elements and operation procedure.

A. The Mobile Platform

The mobile platform is a commercially available 4-wheeled ATV powered by a gasoline engine. It was modified for remote operation [8], and is equipped with mechanisms to actuate its steering, throttle, brakes and gear change by remote control. The engine’s alternator also provides all the electric energy needed onboard (manipulator, mine detector, control system, etc.).

B. The Manipulator

The manipulator consists of a 3 degree of freedom counter-balanced pantographic arm [9]. This configuration allows taking advantage of a reduced power consumption and improved insensitivity towards the ATV’s suspension (the ATV’s inclination when the arm reaches far out is drastically reduced). The arm is completed with a 2 degree of freedom wrist mechanism that allows positioning most mine detectors over the terrain in the best-possible way, following the curvature of the ground. Taking into account the possibility of using a metal detector as mine detector, the front part of the manipulator is entirely free of metallic parts to avoid reducing sensing sensitivity or influencing data reading; the wrist mechanism is mainly made of polyoxymethylene, while the front link is made of glass fiber reinforced plastic. Wrist actuators are remotely located and linked through two rods.

An alternative 3 degrees of freedom wrist mechanism can also be attached to the manipulator and is meant to be used when carrying heavier mine detectors (>8 Kg).

C. The Stereo Vision Camera

In order to compute the trajectory of the mine detector over the terrain, a model of the terrain to scan is constructed by make usage of a stereo vision camera. The camera is located on the first link of the manipulator and allows, by taking several depth maps of the terrain surrounding the ATV, to build a model of the latter upon which all trajectory calculations will be based. See [10] and [11] for further details.

D. The Mine Detector

Currently, the default configuration of the mine detector is based on commercial hand-held MDs. Two types are available and have been thoroughly tested: the CEIA MIL-D1 and the Minelab F3. Both are statically operating MDs, they however differ from their generated signals and how their respective image interpretation should be performed. Figure 2 shows two scan passes performed with Gryphon equipped successively with the two MD types over the same 2 m² area. While the MIL-D1 outputs signed values that produce a
typical 2-lobe pattern centered over metallic objects, images produced by the F3 are more intuitive to interpret.

Fig. 2. 2 m$^2$ MD images of 7 buried metallic targets from MIL-D1 and F3 respectively.

The attached MD coil can be completed with a GPR antenna to form the dual-sensor configuration. Two different types of GPR are currently supported: an impulse radar (Taugiken, Yokohama, Japan) and a stepped-frequency radar [12]. Figure 3 illustrates the stepped-frequency radar data output. GPR is able to generate 3 dimensional images so that data is represented as a distinct image for a given depth level. In figure 3, only relevant GPR layers have been displayed. While the MD allows identifying targets 1 to 5, the GPR can identify targets 2, 3, 4 and 6.

Fig. 3. MD and corresponding GPR imaging of a 2 m$^2$ scan. Buried targets are: 1: PMA-2 at 5 cm depth, 2-4: PMA-1A at 12.5 cm depth, 5: metallic fragment at 5 cm depth and 6: bigger stone at 10 cm depth.

Additionally, Gryphon was also used to carry an array-type GPR antenna and a Nuclear Quadrupole Resonance sensor (NQR), attached on the heavy payload wrist mechanism.

E. The Marking Systems

Once Gryphon scanned a portion of terrain, mine detector data will be shown to the operator who can then decide to mark suspected mine locations. This allows decoupling the mine detection and prodding procedure. Two different marking systems have been developed for Gryphon. The first one, based on water-soluble color paint, has a nozzle attached to the mine detector and allows not only marking suspect spots, but also to write additional information on the terrain. The second marking system operates by having the manipulator fetch a marking plate from a marking plate dispenser and dropping it onto the correct position.

Fig. 4. Paint marker and marking plate dispenser.

Both marking alternatives operate fully automatically and require only the operator to indicate the appropriate spot by a click on the control box screen. An optional marking system based on Real-Time Kinematics GPS (RTK GPS), if present, will additionally record marked spots with a precision of 4-5 cm.

The plate marking system was developed mainly to have a versatile marking systems on test sites; indeed, often one given requirement is to leave the terrain unmodified so as to allow additional blind tests on the same day. The system is however inappropriate to use on real minefields since the plates can be shifted from their original position accidentally or by natural cause (e.g. wind). The paint marker on the other hand is much more robust to such influences, but the best is to use it in conjunction with the RTK-GPS for additional safety and conserve recorded data validity over a longer period.

Fig. 5. Paint-marked spots and marking plate dropping.

F. The control Box

The control box (cf. figure 6) is the remote user interface unit of Gryphon. It allows to remotely operating the ATV and the manipulator. The manipulator higher control software runs on a tablet PC embedded into the control box: terrain mapping, trajectory generation and mine detector data is calculated and displayed on the tablet PC. The control box is linked to Gryphon through modem communication and wireless LAN.
G. Operation Procedure

The standard operation procedure of Gryphon can be described in 4 steps, which are repeated for each scanning position:

1) The ATV is driven into position (through manned or unmanned operation). Since Gryphon operates along the minefield borderline, the vehicle is positioned so as to be able to scan on its left or right side.

2) The surrounding terrain is geometrically modeled by acquiring several depth maps with the stereo vision camera.

3) Autonomous scanning is executed, detector data processed and visualized in the control box.

4) After evaluation of acquired data, suspected mine locations are marked using one of the two onboard marking systems.

Individual Gryphon machines can also be used conjointly, where each entity would be in charge of a specific detection/discrimination task. Three Gryphon robots successively scanning the same area, once with an MD, then with an array-GPR, and finally with an NQR sensor for instance, is a scenario that becomes possible. This modularity allows for a very flexible detector configuration with distributed detection characteristics. Data overlap between individual machines is guaranteed by the RTK-GPS localization systems.

III. FIELD TRIALS

Since 2005, several field tests and trials have been carried out to evaluate Gryphon as a minefield access vehicle and mine detector carrier. Gryphon has endured most weather conditions (heat, cold, rain, snow, strong wind) and terrain configurations (flat, bumpy, dry, muddy). Over the years, the various tests and trials, and the numerous discussions with demining personnel have helped to concentrate on the essentials (e.g. simplicity in use), to gradually improve the various aspects of Gryphon. Following trials were conducted up to date:

2) Benkovac, Croatia, Feb. 2006 [14]
4) Benkovac, Croatia, October 2007

The minefields that Gryphon approached were prepared test-minefields with deactivated landmines. Testing Gryphon on real minefields is the next logical step. Hereafter, results from the last trial performed in Croatia in 2007 are discussed.

A. The Test Site

The test site in Benkovac, Croatia, is constituted of 6 main test lanes, each one of them 1 meter wide and 28 meters long (cf. Figure 8). Forming 3 pairs of lanes, each pair has a different soil type, namely Obrovac, Sisak and Benkovac soil, corresponding to cooperative homogeneous, uncooperative homogeneous and uncooperative heterogeneous respectively.
B. The mine detector

Two Gryphon machines, one equipped with an F3, the other one with an array-type GPR (cf. figure 9), were used in a dual-sensor configuration. While the first machine scans for and marks only metallic targets, the second machine inspects the spots marked by the first machine and decides whether it is a landmine. And so the mine detection task is divided into detection (with the MD) and discrimination (with the GPR). Recorded data overlap between MD and GPR is guaranteed by the RTK-GPS.

Scanning is performed 2 m² at a time, starting with the MD-Gryphon. Distance between individual scan passes is 4 cm and the scanning speed is 50 cm/s. Upon completion of the MD-Gryphon’s scan which takes approx. 3 minutes, the GPR-Gryphon moves into the same position previously held by the MD-Gryphon and scans the same surface at a speed of 7 cm/s. Distance between individual scan passes is 45 cm in that case (the array-type GPR scans a width of more than 45 cm at a time) and task completion requires less than 2 minutes.

Marked spots were then scanned and evaluated by the GPR-Gryphon operator. The lack of clear signal in the GPR images would allow discriminating targets. Once the entire lane was scanned and evaluated, a total station would acquire marked spots. This allowed evaluating the performance of the Gryphon dual-sensor system by matching Gryphon-identified target coordinates with the real target coordinates. Official results of the dual-sensor evaluation have not been released by the time this paper is written. At the same time overall performance of the dual-sensor Gryphon system doesn’t say much about the effect of automation; when looking at MD results only, is Gryphon able to attain the same performance than the handheld version in terms of probability of detection or false alarm rate?

To answer this question, data recorded with the MD-Gryphon during the trials was reprocessed with improved algorithms and re-evaluated, taking into account only clearly visible signals. Target locations were then compared against real target locations and performance evaluated for all 6 lanes. Table 1 summarizes results for the MD-Gryphon.

![Fig. 9. Gryphon dual-sensor system, composed by an MD-Gryphon and an array GPR-Gryphon.](image)

![Fig. 10. MD images as recorded with the F3-MD-Gryphon. Based on RTK-GPS coordinates, images are automatically appended with the right position/orientation. The adjusted contrast reveals deeply buried objects (indicated with the circle), but at the same time, noise levels also increase.](image)

<table>
<thead>
<tr>
<th>Lane</th>
<th>Probability of detection (POD)</th>
<th>False alarm rate [m⁻²] (FAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>76%</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>86%</td>
<td>0.07</td>
</tr>
<tr>
<td>3</td>
<td>93%</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>86%</td>
<td>0.04</td>
</tr>
<tr>
<td>5</td>
<td>93%</td>
<td>0.07</td>
</tr>
<tr>
<td>6</td>
<td>90%</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Above results were obtained by using an F3 as sensor payload on Gryphon. The MIL-D1 was also tested on lane 5, but produced much worse results (POD of 45% and FAR of 0.21/m²). This performance discrepancy between the F3 and MIL-D1 doesn’t necessarily tell anything about each MD’s overall performance and could be linked directly to the soil type on that lane (some MDs perform better or worse depending on the soil type).

Details about the number of targets, type or their burial depth or position were not disclosed to the testees at the time of the tests.

The performance of any MD should not be degraded by integrating it into Gryphon. In the worst-case scenario, the MD attached to Gryphon should perform as well as its standard hand-held version. Unfortunately at the time the Gryphon machines carried out the trials, no hand-held MDs were tested so that a direct comparison is not possible. However, the ITEP project of Systematic Test and Evaluation of Metal Detectors (STEMD), carried out in September-October 2006 on the same test site, produced a report [15] comparing several hand-held MDs. Targets in all 6 lanes have remained the whole time in the ground so that a comparison with the MD-Gryphon becomes possible. Figure

C. Evaluation and Results

Each time a scanning sequence finished, the operator in charge of the MD-Gryphon would evaluate the recorded data, and then mark suspect spots with marking plates. Evaluation is performed by appropriately adjusting the MD image’s contrast and colors in order to also detect deeply buried targets.
11 shows comparative results obtained on each soil type.

a) Lanes 1 and 2 (Obrovac soil)

![Fig. 11. FAR VS POD diagrams for lanes 1-6. “+” indicates performance of Gryphon equipped with an F3, “O” indicates performance of a hand-held F3, and “-“ indicate performances of other hand-held MDs tested during the STEMD.](image)

b) Lanes 3 and 4 (Sisak soil)

c) Lanes 5 and 6 (Bencovac soil)

From above diagrams, it can be seen that the vehicle-mounted F3 systematically performs better than its hand-held version in terms of false alarm rate. The probability of detection is also improved except on the Sisak soil, where results are slightly inferior. The generally very good result of Gryphon illustrates the strength obtained from data visualization. Performance could even be further improved by optimizing image processing algorithms or by scanning at closer distance to the ground. These tests confirm previous tests’ good repeatability and good data consistency, coming from a reduced human factor effect.

IV. MD-BASED LANDMINE DISCRIMINATION

Having the ability with Gryphon to easily generating precise sensor images, a method was developed that is able to discriminate for a certain landmine-type, based uniquely on an MD. The algorithm takes advantage of an MD’s sensitivity profile that is precisely measured for a searched landmine type. This landmine fingerprint is then matched against data from a blind scan, which, if unsuccessful, allows discriminating the target. Best results were obtained by using the MIL-D1. Figure 12 shows the MIL-D1’s sensitivity profile for a PMA-2 landmine simulant.

![Fig. 12. Cut through sensitivity profile of a PMA-2 landmine simulant at various depths. Each image at a given depth has been normalized for better visualization.](image)

It can be seen that a specific signal amplitude and image pattern can be associated with each metallic target and each burial depth. The algorithm’s effectiveness was tested during the field trials in Cambodia. 5 metallic targets (cf. figure 13) were tested at various depths in 3 different soil types (sand, laterite and clay). The algorithm was trained to identify the PMA-2 landmine simulant (itop).

![Fig. 13. Metallic targets tested for the discrimination algorithm.](image)

As can be seen from figures 14 that illustrates results obtained in sand-soil, the algorithm was able to determine for each tested object a discrimination value (or itop-likeliness). Taking a safety margin, it is possible to safely identify the
searched itop with little false alarms. The method also allows identifying the burial depth of metallic objects in the ground, which can improve safety of mine removal/neutralization procedures.

![Fig. 14. Discrimination experiment result for in-sand buried targets. The shaded area indicates that the target has higher similarities with the searched object (e.g. itop), and should therefore be handled like a landmine (not discriminated).](image)

V. CONCLUSION

A machine for semi-automatic scanning operation with a large variety of landmine sensors was developed. It can assist a human deminer by guaranteeing his safety through remote operation, and by generating precise sensor images. The device has been thoroughly tested in several field trials and results indicate that its imaging capability can improve the probability of detection and reduce the false alarm rate. In case of metal detectors, soil compensation procedures become less crucial and can potentially be performed afterwards, in a more effective way.

Additional image processing methods can extract more specific information about a target and allows for MD-based discrimination. The developed method shows good potential but still needs confirmation in further tests and trials.

The Gryphon system is proposed to be used as a complement to traditional metal detectors. A portable version of Gryphon’s manipulator has also been developed, and is ideally suited as a sensor testing platform, reducing the human factor during comparative tests to a minimum.

REFERENCES

Agricultural derived tools for ground processing in humanitarian demining operations: set up of testing facility in Jordan

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Abstract—As often acknowledged, humanitarian demining is mainly a gardening process. Because of its intrinsic threat, it requires extreme care, but the tools and the machines used for demining are very similar to equipment used in agriculture as the aim in the end is always ground processing. Nevertheless, mechanical technologies available on the humanitarian demining market are extremely expensive, the price of the cheapest machine being approximately 120,000 US$. Gardening tools as shovels and shears are used in support of manual demining operations but exceptions exist in which they become the prime demining technologies. This is the case of Sri Lanka and Jordan, where, due to particular environmental characteristics of soft sandy soil and small plastic anti personnel landmines, Norwegian People's Aid (NPA) has implemented the rake system. The method encompasses fully excavation by using simple hand rakes with longed handle. As final stage of the first author's PhD research into Participatory Agricultural Technologies (PAT) for Humanitarian Demining, involving the adaptation of power tillers to demining applications, the test of the module for ground processing tool to be attached to the power tiller - tractor unit will take place in Jordan in March 2008, supported by the Faculty of Agriculture of the University of Jordan and NPA Jordan.

After introducing briefly the project, the paper describes the design of the ground processing tool to be tested, the set-up of the testing facility in Jordan including the production of the tool supporting frame and the possible use of such facility for testing new tools derived from agricultural technologies targeting different soil and landmine environments.

I. INTRODUCTION

There is increasing consensus on the fact that landmines heavily affect the development of contaminated countries and that mine action activities need to be integrated into general development initiatives [1].

There is also general acknowledgment that machines have fallen short of expectations: only few are actually employed in the field and are often down for maintenance waiting for spare parts or experienced technicians able to fix them coming from abroad [2].

These reasons are at the base of the idea of adapting commercially available power tillers to demining applications by developing different modules attachable to the main tractor unit using a participatory design methodology.

In fact we believe that involving deminers into the whole design process would allow them to get familiar with the innovation process, which is a key component of the development process, and would help realizing a machine nearer to real needs, sustainable because made of materials available locally and therefore more efficient.

The project presented here therefore regards the participatory design and development of a new small machine for helping removing landmines in the Vanni region in Sri Lanka and in Jordan, where landmines are of the small plastic type containing not more than 50g of TNT. The whole work encompasses the realization of three modules:

- tractor unit
- ground processing tool
- vegetation cutting tool

and the control unit to drive the machine from the safe distance of 20m, set by local authorities.

The tractor unit is the power tiller, opportunely modified to support other modules, provide sufficient traction and adapted to the remote control [3], while the vegetation cutting module can be attached on the front of the machine when vegetation is too thick for the machine to pass through; it is powered by the powertiller engine and it is supported by the same frame of the ground processing tool [4]. This paper focuses on the ground processing tool that is the means by which landmines are lift up on soil surface to facilitate later hand removal by deminers. The ground processing tool is placed on the front of the machine, to allow landmines to be removed before the tractor unit passes over them.

Fig. 1. Digital mock up of robot composed by three modules: tractor unit, vegetation cutting tool and ground processing tool. Picture of tractor unit physical prototype.
II. DEFINITION OF REQUIREMENTS

Before starting the project, a field visit to Norwegian People’s Aid (NPA), the NGO partner of the project, in Sri Lanka was organized; we asked deminers to indicate in which operations they would have liked to be helped by a new small machine. Between standard operational procedures currently in use by NPA, they indicated as more boring and difficult the operations of vegetation cutting, specially palm leaves and hard ground processing [5]. In fact, no metal detectors are employed as soil is ferrous and mines have very low metal content; instead, ground is excavated at the depth of 100mm, specified by local authorities, to expose to eye sight buried landmines. Two simple rakes with handler extended to 2m are used: light rakes to remove loose soil and hard rakes to process more compact and deep soil.

The rake system, currently employed by NPA in Sri Lanka and Jordan, is also known as Rake Excavation and Detection System (REDS) (fig.3). It consists of full excavation, preferably achieved using only the light rake, which no matters how much force is applied on it, due to its numerous and flexible tines, the pressure it exerts on soil is lower than the minimum required to activate landmines (10464Pa, for Type72A, the most sensitive landmine found in the regions).

If soil is too hard and light rake becomes ineffective, the heavy rake is used to scarify ground; deminers place the rake head in front of them in the clearing lane and gently pull it back toward them. The two curved rake tines plough back through the soil; their curvature is such that mines are approached on the side and the pressure plate on top is not touched. The raking action is repeated for the entire width (1m) of the clearing lane. When a mine is discovered, it is exposed using either the rakes or other hand tools.

Fig. 3. Light and heavy rakes general use in REDS (Source: Andy Smith).

Work on the ground processing tool module of the machine started after the work on the tractor unit was already at an advanced state. In fact, two working configurations for the ground processing tool are possible, one with the ground processing tool at the back (G-P-B) and one with it at the front (G-P-F). The choice influences tractor unit performance and simplicity. We have identified parameters that contribute to achieve extreme simplicity and effectiveness, referred to as Simpleffectiveness(fig. 4).

**SIMPLEFFECTIVENESS**

- forward/backward motion (traction)
- steering: 1m curve radius
- energy supply to end-effectors
- stability
- assessment of ground processing depth
- mine disposal
- safety of operator
- shock wave protection for machine
  (and operator, in manual use)

Fig. 4. Simpleffective parameters.

The choice of placing the ground processing tool at the front or at the back is subject to the evaluation of Simpleffective parameters values in the two cases. A matrix reporting “plus” (advantages) and “minus” (drawbacks) related to each parameter for the two configurations has been prepared. Later it was completed by adding other two columns reporting “known effects” and “possible improvements” for both the configurations. Those columns were filled in with the results obtained by tests and simulations on different models, related to each parameter.

After testing the first armoring design we chose to place the ground processing tool at the front. The preferred back position was abandoned as the breakable joint specially designed to fit between powertiller driven wheels and the driving stub axles failed to work as low frequency wave filter. Therefore it did not protect the drive train from unhealthy mechanical vibrations, even if breaking due to the explosion underneath the wheel and allowing the wheel to jump away [6]. Therefore the task of the ground processing tool placed at the front of the machine became to remove landmines before the tractor unit passage and to process the soil at constant depth in order to make demining activities with excavation tools easier for deminers, never pushing mines deeper but possibly lifting them up.

The power tiller we are employing as tractor unit has 7.5kW engine; due its limited capacity, energy consumed by the ground processing module should be as low as possible; other important requirements the tool has to meet are the general ones valid for the whole machine: it should be low-cost, easy to use and maintain, robust, made of few simple parts, easy to find on the local market and able to work in dusty and dirty environment at high temperatures.

III. PRELIMINARY ANALYSES

Because it can be processed with simple rakes, soil can be classified as light or soft both in the Vanni region of Sri Lanka and in the Southern minefields in Jordan at the boarder with Israel, where NPA is using REDS. Landmines mostly found are small, antipersonnel, plastic, blast mines. Due to their small size and low explosive
content, even if accidentally actuated by the action of the hard rake, they don’t cause injuries to deminers wearing proper personal protection equipment. As reference for designing the ground processing tool, we considered the landmine smallest in dimension mostly found in the two countries. In Sri Lanka this is Type72A, while in Jordan it is M14. The explosive content of Type72A is 50g of TNT, while the one of M14 is 30g of tetryl.

Other bigger and more dangerous landmines can also be found in both countries, including fragmentation types and anti-tank mines; the machine is anyhow targeting only small plastic landmines, which are also the most common types, as a major requirement for it is to be low cost and therefore with limited power. Before starting clearance it is generally possible to say in which minefields bigger and more dangerous mines can be found: the machine will not be used in those areas.

To achieve the main goal of processing hard soil, as required by deminers, the ground processing tool has to substitute the heavy rake. Therefore, it has to process the soil at required constant depth and expose landmines by lifting them up on soil surface, without actuating them.

The machine can support manual deminers both in area reduction operations and in landmine clearance, depending on the minefield structure and clearance procedures. In fact, where landmines have been laid in well defined patterns along “mine-belts”, usually for defending trenches during conflicts, such as in Sri Lanka, the most efficient way to employ the machine would be simply to locate the beginning of the mine-belt; deminers can later proceed to the manual clearance of the belt without wasting time working on clear land. The machine could be employed in support of proper mine clearance operations where landmines are found in random locations. This is the case of Jordan, where even if landmines have been used mainly on borders, therefore have been placed in an ordered, patterned manner, the landslide action due to the rainfall caused them to shift location.

To achieve different aims, different ground processing tools have to be designed. Where landmines are found at random locations, the ground processing tool has to lift mines from the soil and collect them, while where landmines are laid in patterns, like in Sri Lanka, the ground processing tool has to lift them up and leave them there in order to allow manual deminers to locate the mine-belt.

The ground processing tool that has been designed and will be tested in Jordan in March 2008 is of the second type: its task is to process the ground at constant required depth, to lift buried landmines, to remove them from the machine lane and to leave them on top of soil on the side of the lane.

Hopefully, more ground processing tools suitable to different environments will be designed, developed and tested in the framework of a research project between the University of Jordan and the University of Genova in Italy, recently submitted to the Arab Science and Technology Foundation.

IV. GROUND PROCESSING TOOL DESIGN

Primary tillage is defined as the process of loosening the soil from an initial compact state by dragging a metal implement through it. This is exactly what the ground processing tool, made out of steel, to be easy repairable in a local workshop by welding, has to do. Therefore, it is of great interest to look into tillage theory before starting the design of a new tool.

Soil is a special example of granular (solid) material, containing in smaller quantities water (liquid) and air (gas). It is a three phase system extremely weak in tension, very strong in compression and in practice it fails mainly in shear [7]. Failure is defined by the Coulomb criterion in which the maximum shear stress is a function of the compressive stress normal to the plane of shear failure (eq.1).

\[ S = C + \sigma \cdot \tan \varphi \]  

Where, \( S \) is the soil strength, i.e. the maximum shear stress the material can hold before failing, \( C \) is soil cohesion, \( \sigma \) is the normal stress and \( \varphi \) is the angle of internal friction.

The strength or resistance to sliding at a soil-metal interface is analogous to the resistance to shear of a soil-soil surface. The soil-metal sliding equation (eq.2) is similar to the soil-soil shearing equation:

\[ S' = C_a + \sigma \cdot \tan \delta \]  

Where, \( S' \) is soil-metal sliding stress, \( C_a \) is tangential adhesion, \( \sigma \) is the normal stress and \( \delta \) is the angle of soil metal resistance.

In designing soil engaging implements it is of main importance to produce efficient tools, which perform the manipulation required with a minimum effort, therefore minimum draft. Parameters that influence the draft force required to pull or push the implement in the soil are: soil/soil parameters, such as angle of internal friction and cohesion, soil/metal parameters, such as polish of the implement surface and soil moisture content, both affecting tangential adhesion, and implement shape parameters. Between these, great importance assumes the rake angle, the angle between the horizontal and the implement blade (fig.6). Draft force increases as rake angle increases [8]. Moreover, during tillage, especially tillage in which the width of cut is very large compared to the working depth, a prism of soil is separated in front of the implement and slides forwards and upwards along the failure surfaces as the implement moves forwards (fig. 6).
The failed soil associated with different failure surfaces build up in front of the implement producing a surcharge effect that is not desirable. This phenomenon can be attenuated if soil moves along the blade, i.e. if scouring occurs. Scouring occurs as long as the resistance at soil implement interface is less than at a parallel soil-soil interface. As generally the angle of soil metal resistance is less than the angle of soil internal friction, an increase in normal load improves scouring. Therefore, slatted implements with less surface area encourage scouring by increasing the normal load.

Low draft is a very important requirement also for the ground processing tool that is only one of the modules driven by the power tiller based tractor unit, a machine with only 7.5kW engine. For our application it is also important to increase scouring to have mines moved on the side of the machine.

In order to achieve an action similar to the one of heavy rakes and process the soil with minimum energy consume we have decided to design an implement with tines.

It consists of two tools: a single blade to cut the soil and tines to sieve soil away and retain mines. It is shaped like an arrow to allow landmines to move sideways from the machine lane. The rake angle is less than 90° to allow approaching the landmine from the side, avoiding exerting force directly on the pressure plate, as well as for lowering the draft force. The risk of actuating landmines exists, if landmines are found upside down or if soil presents a crust on top, but in case of explosion the damage to the tool should be limited to the tines, which are simple steel rods easily repairable at low cost.

There were two important implications in deciding the shape of the tool.

Weight transfer: most soil engaging tools involve a horizontal (draft) and vertical force (fig. 7). When the tool is mounted on the front of the tractor both of these forces, together with the weight of the tool, have the effect of transferring weight from the rear to the front of the tractor. These effects are generally undesirable (on a rear wheel drive tractor) and hence it is important that they do not become excessive.

Depth control: the requirement for good depth control is to avoid the tool working too shallow and missing mines or digging too deep and causing the tractor engine to stall or the tracks to slip. Mounting the tool on the tractor alone is likely to cause a variation in depth as the tractor pitches in the vertical longitudinal plane.

Therefore we decided to fit a depth wheel running in the undisturbed soil ahead of the tool (fig. 7). This reduces the weight transfer effect of the tool and assists in depth control. It is in the form of a cage wheel on the assumption that this will suffer minimum damage if a mine were to explode under it.

Moreover, it is desirable, in the interests of simplicity, that the tool is formed from plane shapes. The simplest form of such a tool is therefore defined by two angles: the rake angle, between the tool and the horizontal (ground) in the longitudinal vertical plane, and a side angle, between the tool and the vertical longitudinal plane in the horizontal plane (fig. 8).

Different low-fidelity prototypes with different rake and side angles were made and tested in a sand bed (fig.8).

Tests showed that a small rake angle allows the soil to flow up the tool in a thin sheet and so encourages sieving, and a small side angle tends to cause the soil to be moved to the side and pass outside the passage of the tool width. Therefore, to achieve mine disposal sideways, we adopted a side angle equal to 50° and rake angle equal to 30°. The rake angle had to be increased to keep the distance of the tool tip from the tractor unit relatively small.

The success of the tool in sieving soil and retaining or shedding mines depends on the form of the tool described above but also on the form of the sieve. Simplicity suggests that the form of the sieve members should either be in the plane of the sides of the tool, either parallel to the spine of the tool (effectively at the rake angle) or alternatively at the
side angle (effectively horizontal). It would seem useful, in evaluative terms, to make one side of the sieve in one form and one in the other (fig. 9). This would provide an immediate and obvious comparison of the two forms and guide future developments. As the tool will be tested in Jordan, distance between tines has been set to be less than 40 mm, the minimum dimension of the smallest landmine M14.

It is understood that some form of active movement of the tool would assist in breaking clods and clumps and so improve the sieving process. This however should not be necessary in sandy soil for which the initial form of tool is being developed. However it is likely to be needed for future prototypes addressing other heavier soils.

To calculate the draft force of the designed ground processing tool designed and compare it with the drawbar pull exerted by the tractor unit (3kN [9]), we used two different empirical models. In fact, the fundamental earth moving equation developed by Reece in 1965 gives the implement draft force as sum of four terms, respectively function of soil cohesion, surcharge pressure on failure surface, bulk density and tangential adhesion at soil metal interface. Each one of these forces can be calculated only if some soil parameters and dimensionless factors are measured in the field. Due to the impossibility to measure them in the field, we used a semi empirical approach.

From Agricultural Machinery Management Data, ASAE D497.5 FEB2006, published by the American Society of Agricultural and Biological Engineers (ASABE), the draft force, defined as the force required in the horizontal direction of travel for tools operated at shallow depths is given by eq. 3.

\[
D = F_i \cdot \left[ A + B(S) + C(S)^2 \right] \cdot W \cdot T
\]

(3)

Where, D is the implement draft, F i a dimensionless soil texture adjustment parameter whose value is given in ASABE tables, A, B and C are machine specific parameters, given in ASABE tables, S is field speed, W is machine width, T is tillage depth. The value for the draft force necessary to push a tool, considered as a sweep plow in primary tillage, 1200mm wide, at 100mm depth, at 1.1 km/h, in fine textured soil, is approximately 2.5kN.

A second estimation of the draft force of approximately 2kN was obtained extrapolating data regarding a 19 tine scarifier fitted with 150mm wide dart points [10]. In both cases, draft force of the ground processing tool is less than the drawbar pull exerted by the tractor unit.

A finite element analysis on the ground processing tool showed that steel plates 8mm thick are suitable to be used as plane shapes for the tool. With a horizontal load of 2.5kN applied on the spine and on side plates, the maximum stress induced, calculated with Von Mises criterion on the plates is less than 140 MPa, while the maximum displacement is less than 4 mm (fig. 10). Yield strength for steel is 235 MPa.

V. SET-UP OF TEST FACILITY IN JORDAN

In the context of first author’s PhD a prototype of the tractor unit and remote control was developed and tested in Italy. A collaboration with NPA Jordan and the University of Jordan made it possible to organize a test of the ground processing tool in realistic minefield conditions in Jordan, in March 2008. Unfortunately, time and money constraints don’t make it feasible to test the ground processing tool and the tractor unit at the same time, as resources and time are not enough either for developing a second prototype of the machine in Jordan or for transporting the Italian prototype in the country. Therefore, a facility for testing the tool has been set up in Jordan. Attention has been posed into the development of a system that could be used later on to test other ground processing tools targeting different soil conditions and compare results. In this way, more details on the performance of the ground processing tools can be understood and the design can be improved in possible further design iterations.

During a recent visit of the first author in Jordan, agreement for manufacturing the ground processing tool in the country was made. A mechanical workshop, located in Irbid in the north of the country, will manufacture the ground processing tool designed for less than 50 US$. Test will take place in the Southern minefields at the boarder with Israel, under the supervision of NPA, in an area already cleared from active landmines. Already neutralized mines will be laid in the ground to observe their translocation at the tool passage. Real mines cannot be used as the prime mover of the ground processing tool will be a small tractor, hired in the country. For connecting the ground processing tool to the tractor we will use a frame, attachable to the three point linkage hitch at the back of the tractor (fig. 11).

As the tractor will be driven forward the ground processing tool will be pulled, not pushed as it will happen in real working configuration when mounted on the tractor unit. Therefore, the frame will have to provide a support similar to the semi mounted hitch in use in the machine. The ground processing tool rigidly connected to the depth control wheel has to be pivoted to a support that allows it to follow ground profile. For doing this we have chosen to employ a parallelogram frame, also called active frame, attachable to the three point linkage hitch, with a rear wheel.

Fig. 9. Ground processing tool final design.

Fig. 10. FEM analyses on ground processing tool (steel plates 8mm thick).
The frame will be produced in the University of Jordan workshop and could be used later on for other tests. This particular structure allows the measurement of draft force using a force cell mounted horizontally between the linkage and the frame (fig. 12).

![Ground processing tool frame mounting for test.](image)

The forces acting on a general tillage tool act in a general direction in space and their measurement is complex and requires several transducers. However, when the tool is symmetrical about the plane of motion it is possible to simplify the system of forces by assuming that there is no force perpendicular to that plane, i.e. no side forces. The point of application and the direction of the single force left, in the plane of motion, are unknown, but they can be resolved in the plane of motion. The vertical component is pushing the tool into the soil and is resisted by wheels on the tillage implement; it does not contribute directly to the force required to move the tool through the soil. The horizontal component of the force, the draft force, is the one against which energy is expended. By an analysis of the static equilibrium of the frame it can be shown that if opposite members have the same length and the force cell is mounted horizontally, the force cell is measuring only the draft force [11].

The active frame presented could also be used for mounting the ground processing tool on the front of the tractor unit when a vibratory motion is needed to push it in harder ground. Where the force cell is now located a cylinder could be placed, providing horizontal forward and backward movement to the tool.

VI. FUTURE WORK

The test facility set up in Jordan will be hopefully re-used for testing new ground processing tools targeting different environments, soil conditions and landmines in the context of a new project whose proposal we have recently submitted to the Arab Science and Technology Foundation. The project aims at establishing a research centre of mechanical technologies for humanitarian demining in Jordan. There, we would like to employ the same participatory design methodology used for the rest of the work, to achieve more sustainable technologies.

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The whole Participatory Agricultural Technologies (PAT) project could not have taken place without the help of the numerous wonderful people, who actually participate to it. Particularly, here, we would like to thank Professor H. Ross Macmillan of the University of Melbourne, who gave us precious support in the whole work regarding the ground processing tool design and test, Andy Smith who knows everything about the REDS system and has always followed the work from the field, Fabio Rossi who spent one week at the University of Genova working on the test of cardboard tools during his high school stage, and NPA Jordan for all the logistic support they give us. Last but not least we would like to thank Exilis Belgium for funding this part of the project.

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Nuclear Quadrupole Resonance for explosive detection

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ABSTRACT

A Nuclear quadrupole resonance detector has been developed. It can clearly detect RDX, a high explosive inside an anti-personnel landmine. It works well in the field. It can be mounted an anti-mine vehicle and mine detection was demonstrated remotely controlled.

INTRODUCTION

Nuclear quadrupole resonance (NQR) is one of distinguished candidates for a landmine detection technique. A widely used metal detector is suffered from high false alarm rate because it is required to detect just 10 grams of metallic object in a landmine. Highly sensitive metal detector as this gives an alarm every time it encounters few grams of metal trash, which results in a bad performance. On the contrary, An NQR detector identifies an explosive inside a landmine by a resonant frequency unique to each material. The technique can distinguish bulk of explosive from metal fragments.

An NQR landmine detector has been developed to detect $^{14}$N nucleus spins of an explosive molecule in a landmine[1-3], but very limited paper have been published about the NQR remote detection of explosive in a landmine. This work reports the development of a prototype NQR mine detector and test result of its detectability.

EXPLOSIVE DETECTION BY NQR

NQR is a kind of interaction between radio frequency (RF) wave and nuclear spins. A schematic view of NQR detection is shown in figure 1.

When RF wave with a specific frequency is irradiated, the wave is adsorbed by the nuclear spins and then re-emitted after the irradiation. Equation (1) shows the NQR Hamiltonian which is the resonant spin in NQR landmine detection [4].

$$H_Q = \epsilon Q \left[ (V_1^z - I_z^2) + (V_1^y - V_2^y)(I_z^2 - I_y^2) \right] \quad (1)$$

$Q$ is the nuclear quadrupole coupling constant of the resonant spin. $I_z$, $I_y$, and $I_z$ are the spin operators and $V_1^z$, $V_2^z$, and $V_2^y$ are the electric field gradients around the spin to each directions. Since the electric field gradient is unique to each molecule structure, NQR frequency is also unique to each molecule.

Figure 2 shows the NQR frequencies of major explosives, RDX (cyclo–trimethylenehexaminitramine), HMX(cyclo-tetramethylenetetranitramine), and TNT.
(trinitrotoluene). The difference of the frequencies allows identifying explosive material. Figure 3 shows one of NQR signals from 300 g of RDX (figure 3 (a)) and 300 g of TNT (figure 3 (b)). Both are detected in an electrically shielded room. 1,000 data were averaged to improve the signal to noise ratio. Measurement pulse sequences are the strong off-resonance comb (SORC) for RDX and the spin locking spin echo (SLSE) for TNT, respectively.

The measurement times were 2 second for RDX and 200 second for TNT. This is due to the difference of the relaxation time of each material. There are two types of relaxation time in NQR. The one is the longitude relaxation, by which the excited spins are relaxed to the equilibrium state with the spin-lattice relaxation. This time constant of the spin-lattice relaxation is written as $T_1$. $T_1$ dominates the interval time between the sequences, i.e., long $T_1$ drastically decreases the efficiency of NQR measurement. The other is the transverse relaxation, by which the coherently excited spins are randomized by the spin-spin interaction and the thermal scattering, resulting in the cancellation of the NQR signal from each spin. The time constant of the transverse relaxation is written as $T_2^*$. Generally $T_2^*$ is shorter than $T_1$. Since NQR signal continues only for $T_2^*$, short $T_2^*$ makes detection period short and it makes difficult to detect the signal.

Figure 4 shows the relaxation times of RDX, TNT, HMT (hexamethylenetetramine), and PNT (para-nitrotoluene). HMT and PNT are the raw materials of RDX and TNT, respectively.

As shown in figure 4, RDX has relatively long $T_2^*$ and short $T_1$, while TNT has extremely short $T_2^*$ and long $T_1$. So RDX is easier to detect than TNT. NQR detector for RDX has been firstly developed to evaluate NQR feasibility in the field.

**NQR MINE DETECTION**

A prototype of an NQR mine detector has been developed by the support of the Japan Science and Technology Agency. The outlook of the developed sensor-head for NQR mine detection is shown in
The detector, W 570 mm × D 285 mm × H 290 mm, consists of a sensor coil, a matching box, and some small electrical circuits such as a pre-amplifier. This sensor-head weighs 10 kg, which is prepared to be used by a mine vehicle.

The performance of the developed NQR detector was evaluated. The NQR signal from RDX buried in the soil was studied. The sample, 100 g of RDX was packed in a cylindrical plastic case with 110 mm of radius and 80 mm of height. The distance from the bottom of the NQR detector to the top of the sample case was set to 7, 12, and 17 cm. The soil moisture was controlled 10 %. 220,000 data were averaged at maximum to evaluate the relationship of the measurement time and the signal to noise ratio (SNR). The developed system is capable to acquire 17,000 data in a minute. The measurement was repeated 7 times every one experimental condition. One of the NQR signal obtained by 7 cm detection and background noise were shown in figure 6.

The NQR signal was clearly detected in figure 6 (a). Since the NQR signal certainly appears at a steady frequency, the signal intensity was evaluated by the output at that frequency. The dependence of NQR signal intensity on the sample depth was then measured and evaluated. The environmental noise data were acquired seven times and the averaged background noise height was calculated in frequency domain. The difference of obtained data and the averaged noise height was normalized by the averaged noise height. The detection result is shown in figure 8. The square dots of each detection depth show the average of the seven data, while the error bars show the maximum and the minimum of the signal intensity. When the square dots are placed higher than zero, the signals were detected.

As shown in figure 8, NQR detection from 7 to 17 cm deep was apparently successful. Especially the sample buried 7 or 12 cm deep seems to be clearly
detected. However, 22 cm detection was almost similar as zero level. This drastic decrease of sensitivity may be due to both of the signal diffusion and the decrease of the excitation field by the increase of the detection depth. The latter may be improved by the arrangement of an antenna design and a system innovation, which will result in the sensitivity improvement of deeper detection.

The result was also analyzed by the receiver operating characteristics (ROC) curve. The possibility of detection and the false alarm rate were evaluated by the noise levels and the signal intensities of seven measurements. The ROC curve of 7, 12, 17 cm detection are shown in figure 9. 22 cm detection was not shown because the data was less outstanding.

![ROC curves](image)

**Fig. 9 ROC curves of the NQR remote detection of 100 g of RDX with the detection time of 13 minutes.**

It is shown in figure 9 that the sample buried 7 or 12 cm deep were perfectly detected. As few results have been ever reported about the NQR detection of 100 g of RDX, this result was a milestone for the realization of the NQR mine detection.

The ROC curve of 17 cm detection was worse than that of 7 or 12 cm detection. This distance seems to be the limit of current NQR remote detection of 100 g of RDX with detection time of 13 minutes.

NQR signals detected in 2 minute are shown in figure 10. The sample was 100 g of RDX buried 5 cm deep (figure 10(a)) and 10 cm deep (figure10(b)).

![NQR signal](image)

**Fig. 10 NQR signal from 100 g of RDX detected in 2 minutes. (a) buried 5 cm deep, (b) buried 10 cm deep. The resonant frequency of RDX is shown by a dashed line.**

Though it is easy to see the NQR signal in figure 10, not so outstanding signal was obtained in figure 10 (b). 100g of RDX buried 15 cm deep in soil was almost impossible to detect using only 2 minutes.

This result shows that the longer time measurement is required for the NQR detection of a deeply buried landmine. Sensitivity improvement will be helpful for improve the deep detection of land mine.

**DEMONSTRATION OF NQR MINE DETECTOR**

The NQR detector was mounted on a mine vehicle developed by Hirose Lab. in Tokyo Institute of Technology [5]. This vehicle can be remotely controlled for the safety of a deminer. Figure 11 shows the outlook. The detectability was demonstrated in September and December, 2007. The integrated mine detection system was so stable that it detected the NQR signal from 100 g of RDX in 1 minute during the demonstration period.
APPLICATION OF NQR DETECTOR

Technologies of the NQR landmine detector is applicable to other fields, such as security inspection. The requirement of security in an airport and a seaport has increased year by year as the response to the expansion of worldwide terrorism. The application of NQR detection technology to a luggage inspection has been recently studied. Prototypes in research are shown in Figure 12. This is developed by National Institute for Materials Science and Thamway by the support of Japan Science and Technology Agency.

NQR detector identifies explosives, which will prevent a terrorist from taking a bomb in an airplane or a ship. Not only explosives, but also several narcotics also expect to be detected by NQR. The realization of these detectors will contribute the social security.

CONCLUSION

Development of an NQR mine detector was reported. NQR can detect as small as 100 g of RDX buried up to 12 cm perfectly. The performance evaluation by the ROC curve shows that 17 cm is the limitation of the detection depth for 100 g of RDX now.

The NQR landmine detection was demonstrated in the field and it worked very well. The reduction of the measurement time and extension of detection depth will remain to be realized. Even though, these results show that NQR Technology is feasible to landmine detection.

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Exploitation of nonlinear dynamics in ferromagnetic and ferroelectric materials for novel high performances B-field and E-field sensors

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Abstract – High resolution sensors for either magnetic and electric fields are of great interest in all those applications where a weak source must be detected. Humanitarian demining can benefit, among other application fields, of such sensors. The exploitation of smart materials and nonlinear dynamics toward the development of innovative transducers is focused in this work; ferromagnetic and ferroelectric properties have been taken into account to develop sensors and actuators for various application fields. Transducers exploiting the properties of FeSiB amorphous ferromagnetic micro-wires are presented. Highly sensitive fluxgate magnetometers that are based on a two-coils structure (excitation coil and detection coil) wound around the ferromagnetic core having a hysteretic input-output characteristic and a very high permeability. Residence Times Difference is used as a readout strategy. A nonlinear dynamical system based on ferroelectric capacitors coupled into a unidirectional ring circuit is considered, with particular interest in developing novel electric field sensors. The focused approach is based on the exploitation of circuits made up by the ring connection of an odd number of elements containing a ferroelectric capacitor. The presence of a weak, external, target electric field induces perturbations of the polarization status in the ferroelectric material, this in turn corresponds to a change in the oscillation frequency of the coupled circuit thus allowing for quantification of the external electric field. The dynamic behaviour of the ferroelectric ring is described by using the equations of the “quartic double well” potentials function, the target electric field is considered as a perturbation in the polarization status of each ferroelectric element. Simulation results show that for a suitable value of the coupling factor, between the ring cells a change in the harmonic content of the permanent oscillation generated in the coupled system occurs. Advanced simulation tools have been used for modeling a system including electronic components and nonlinear elements; moreover, Finite Element Analysis (FEM) has allowed to steer the capacitor electrodes design toward optimal geometries and to improve the knowledge of effects of the external target E-Field on the electric potential acting on the ferroelectric material.

Experimental characterization of the whole circuit, including three cells coupled in a ring configuration has been made. The results confirm the adherence between the models developed and the experimental data. Work is currently in progress for completing the characterization of the sensors proposed for the detection of very weak magneto-static and electro-static field.

Keywords: E-Field detection, ferromagnetic, ferroelectric, nonlinear dynamics, B-field detection.

1 Introduction
The present work focuses on the exploitation of smart materials properties and of nonlinear dynamics for the development of innovative transducers. The paper is organized such to deal with two classes of materials: the former having magnetic properties and the latter having ferroelectric properties. The nonlinear dynamics underpinning the behavior of these materials play a key-role in our approach to develop the sensors.

Magnetic transducers discussed in the following sections include RTD fluxgate magnetometers [1-3] exploiting materials as an amorphous ferromagnetic microwire. These devices have been used by the authors to realize measurement systems for B-field target identification in several different applications ranging from the identification of small magnetic targets to the magnetic immune assay area and including also the monitoring of the volcanic ash fall out. Ferroelectric materials have been embedded in unidirectionally coupled, overdamped nonlinear elements to realize a novel class of electric field sensors. An emergent oscillation occurs in these systems, even in the absence of an applied “target” signal, and the frequency depends on the parameters of each individual element (i.e. the potential energy function when isolated), as well as the coupling strength.

Finally, the onset of a quasi-static target signal makes the system asymmetric and leads to changes in the frequency of oscillation, as well as other characteristics [4] including the “residence times” in the stable stationary states of the active non linear element. These changes are used to quantify the
symmetry-breaking signal which is the amplitude of the target electric field.

2 Magnetic materials and RTD-Fluxgates

We will discuss here the use of a suitable material with interesting magnetic properties. We will deal with soft ferromagnetic materials showing a very sharp hysteresis loop and large saturation field. These materials come in the form of ribbons and wires. Therefore the device we will discuss will exploit both the magnetic features and the mechanical properties. Thin ribbon layers and tiny microwires allow to fabricate small devices with noticeable performances that can also be arranged in suitable geometries to accomplish specific sensing goals.

Fluxgate magnetometers have always been of interest to the technical and scientific communities to sense weak magnetic field with resolution of few picotesla at room temperature. These non linear devices find applicability in fields such as space, biomedical, vehicle navigation, security, military, geomagnetic field measurement and proximity sensors applications.

Recently, Residence Times Difference (RTD) Fluxgate based on innovative core material have been proposed as competitive devices to the traditional second harmonic architectures [1-3]. Low cost, small dimensions, high sensitivity, low noise floor, low power consumption and an intrinsic digital form of the output signal are the main advantages given by the innovative readout strategy based on time domain.

Typically the RTD-Fluxgate is based on two coils architecture (excitation and detection coils) shown in Fig.1a. The coils are wound around a suitable ferromagnetic core showing a sharp hysteretic input-output characteristic which allows to infer that switching between the two stable states of the magnetization occurs almost instantaneously (the formal assumption is to neglect the device dynamics) when the applied magnetic field exceeds the coercive field level $H_c$. A periodic driving current, $I_e$, is forced in the excitation coil and generates a periodic magnetic field, $H_e$, parallel to the main axis of the core. A target field $H_x$ is applied in the same direction of $H_e$; the secondary coil is used as pick-up (detection) coil and the output voltage $V_{out}$ is proportional to the first derivative of magnetization and contains information on the external magnetic field (Fig.1b).

The phenomenological model for the dynamical response of an hysteretic ferromagnetic core, can be described by a bistable potential energy function $U(x)$. The difference between two Residence Times is directly correlated to the target field $H_x$. In the next section the RTD-Fluxgate magnetometers that use 100 $\mu$m ferromagnetic amorphous wires (FeSiB) are presented.

2.1 Amorphous FeSiB: Microwire-Fluxgate magnetometer

Microwire Fluxgate magnetometers are based on 100$\mu$m FeSiB amorphous ferromagnetic material. The microwire ferromagnetic core are produced by rapidly cooling of alloys: 80 % Fe, Ni or Co, and 20 % P, Si, Al, C, B. In particular, FeSiB microwire are obtained using the in-water quenching technique with typical diameter range of 80 ÷ 160 $\mu$m and cylindrical structure. Typically, the solidification process induces two magnetic domain regions: (1) an inner core, easy axis parallel to the wire axis ; (2) an outer shell with radial easy axes [5]. The internal stress induced with the solidification process can be reduced through an annealing process at 350°– 400°.

Fig. 1 (a) RTD Fluxgate structure; b) Output waveform.

A highly sensitive magnetometer exploits the properties of such a magnetoelastic material core to detect and measure the presence of a few magnetic particles, for biomedical and security applications. Such a fluxgate is based on two-coils structure (excitation coil and detection coil) wound around the ferromagnetic core having a hysteretic input-output characteristic. A Residence Times Difference has been exploited as readout strategy. Such a magnetometer shows interesting physical characteristics in term of magnetic performance and flexibility with high spatial resolution. The simplified process description can be summarized as:

- 100 $\mu$m wire-coils (excitation and detection) diameter are wound around a plastic structure (~1.2 mm).
- A cylindrical glass-structure (~1 mm) is used to contain 100$\mu$m FeSiB Fluxgate core.

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Magnetic core is centered with respect to the cylindrical plastic structure.

The research activity on this class of transducers has started from confirming their non-linear behavior, supported by models developed for precedent fluxgate magnetometers, through the characterization phase. Fig. 2 shows the Wirecore-Fluxgate. The primary coil has 1 layer, ~900 wounds, the internal coil radius is ~100 µm, while the coil resistance is 30 Ω; the secondary coil has four layers, each layer has ~900 wounds, the internal coil radius is ~100 µm, and the coil resistance is 30 Ω.

Fig. 2. (a) Picture of the 100 µm FeSiB amorphous ferromagnetic microwire. (b) Wirecore-Fluxgate magnetometer.

The primary coil has 1 layer, ~1000 wounds, the coil length is 0.06 m, the internal radius is ~100 µm, while the coil resistance is 6.5 Ω; the secondary coil has 1 layer, each layer has ~1000 wounds, the coil length is 0.06 m, the internal radius is ~100 µm, and the coil resistance is 6.5 Ω.

Figure 3 shows the evolution of Averaged RTD (\(R_{TD}\)) obtained in the observation time, at \(H_x=0\) A/m.

Finally Fig. 4 reports the calibration diagram for the microwire RTD fluxgate developed.

### 3. Ferroelectric materials and E-field Sensors

A nonlinear dynamical system, based on ferroelectric capacitors unidirectionally coupled to form a ring circuit, is considered here for developing novel electric field sensors. The conceived devices exploit the synergic use of bistable ferroelectric materials, micromachining technologies that allow to address density charge amplification, and novel sensing strategies based on coupling non-linear elementary cells [6]. The presence of the weak, external, target electric field interacts with the system’s elementary cells inducing a perturbation of the polarization status in the ferroelectric material of each cell, that can be indirectly detected and quantified via its effect on the oscillation frequency and on the asymmetry of the coupled system output signals.

Simulation results have shown that for a coupling factor, between the ring cells, greater than the critical one, as related to the external field amplitude, the coupled system shows a spontaneous oscillation and an external target signal will modify the harmonic content of the permanent oscillation generated in the coupled system. Advanced simulation tools have been used for the design, in particular the relations between the external target E-Field and the polarization in the ferroelectric capacitor has been extensively studied. Experimental characterization of the whole circuit, including three cells coupled in a ring configuration has been performed. The results confirm the changes of the circuit oscillation frequency as a function of the coupling factor and of the target signal, as expected from the mathematical models.

#### 3.1 System description

Each active element is realized by a micromachined capacitor whose core is a ferroelectric material that can be polarized through an imposed bias field. The presence of the target electric field will result in a distortion of the polarization status that can be observed as a change in the hysteresis loop.
A suitable external receptor allows for amplification of the target field applied to the sensing element. Each nonlinear ferroelectric capacitor can be modeled by the following differential equation:

$$\tau \dot{P} = aP - bP^3 + cE$$  \hspace{1cm} (1)

The over dot denotes the time derivative, $P$ represents the material polarization, $a$, $b$ and $\tau$ denote material dependent system parameters governing its bistable behavior, finally $c$ is a coefficient that relates the action of the external electric field $E$ applied to the dielectric sample. Thus, the potential energy function for the given material is therefore expressed as:

$$U(P,t) = -\frac{a}{2} P^2 + \frac{b}{4} P^4 - cEP$$  \hspace{1cm} (2)

The presence of a target signal results into the asymmetrization of $U(P,t)$. The detection techniques are aimed at quantifying this asymmetry.

### 3.2 Elementary cell - circuital realization

The ferroelectric capacitors investigated in this work have been realized at the Penn State University Laboratories [7]. Starting from a Silicon substrate a common Silver electrode has been evaporated, the ferroelectric material has been therefore deposited over the bottom electrode and finally several top electrodes have been spotted over the top surface of the ferroelectric in order to both realize the capacitors and the external connections pads. A microscope picture of the ferroelectric sample is reported in Fig.5a.

In order to evaluate the two quantities characterizing the ferroelectric device a suitable circuit has been considered (shown in Fig.5b); it is based on a charge amplifier to realize the topology known as “Sawyer-Tower circuit” [6].

In this circuit the polarization of the capacitor dielectric, $P_{FE}$, is proportionally related to the circuit output voltage. The definition of the polarization as function of the electric field and that of the electric flux as function of the capacitance charge yields to the following equation:

$$V_{out} = -\frac{A}{C_f} P_{FE}$$  \hspace{1cm} (3)

which expresses the proportionality between the circuit output and the polarization of the ferroelectric capacitor, where $A_{FE}$ is the armatures area.

The most important technological issue to be addressed is the realization of an integrated ferroelectric capacitor in which the electrodes configuration is such to polarize part of the ferroelectric sample, while avoiding that part to be shielded by the target electric field, by the electrodes itself.

The hysteretic behavior of the sample material has been confirmed experimentally [6]. These experimental observations were used to identify the parameters of the analytical model reported in Eq. (1) of the system.

### 3.3 Pspice Models

In order to perform numerical simulation of the system, a circuit dynamic model has been developed for ferroelectric capacitors. In particular, the circuit model of a ferroelectric capacitor, through PSPICE, has been developed by using a behavioral representation. Consider the model that schematizes the capacitor as a “displacement current” generator, shown in Fig. 6a, driven by a voltage difference that can be derived from two fundamental equations.
\[ \tau \cdot \frac{dP}{dt} = aP - bP^3 + cE \]  

(7)

where \( a, b, c \) and \( \tau \) are the model parameters and \( E \) is electric field amplitude.

A parallel plate capacitor, with a separation \( d \), has been considered to evaluate the electric field amplitude \( E \):

\[ E = \frac{V_{(2)} - V_{(0)}}{d} \]  

(8)

The previous model may take also into account an external perturbation, to the polarization of the ferroelectric capacitor, induced by the target field through the sensing electrode. An auxiliary input allows for introducing such a perturbation, where the voltage at this node (\( \Delta P \)) is expressed in units (C/m²) and summed to the actual value of \( P \). Thus, we can write equation (7) as:

\[ \frac{dP}{dt} = \frac{1}{\tau} \left[ a(P + \Delta P) - b(P + \Delta P)^3 + cE \right] \]  

(9)

Hence, equation 9 models the representation of the PSPICE circuit displayed in Fig. 6b.

### 3.4 Dynamic Cooperative Behavior in the coupled capacitor system

As pointed out earlier, operating the E-field sensors as a single device, via a reference applied signal to induce switching between the stable polarization states is problematic due to the high coercive fields that are typical in ferroelectric materials. In recent papers \[8\], it has been demonstrated, however, that coupling an odd number of overdamped bistable elements in a ring, with unidirectional coupling and cyclic boundary conditions, can lead to oscillatory behavior when the coupling strength exceeds a critical value.

Typically, this behavior is dictated by symmetry conditions and is generated by Hopf bifurcations; it appears in any coupled system of overdamped bistable elements, none of which would oscillate when isolated and undriven, subject to the appropriate choice of parameters and operating conditions (albeit through different bifurcations mechanisms). The practical importance of this effect lies in the potential sensitivity enhancement when the system is “tuned” very close to the oscillations threshold.

The circuit implementation of this system composed of three elementary cells (one of which is shown in Fig. 6a), each with a ferroelectric capacitor active element.

The complete coupled circuit device is shown in Fig. 7a. In the coupled circuit the \( j \)th element is modeled by:

\[ \tau \cdot \frac{dP_j}{dt} = aP_j - bP_j^3 + cE_j \]  

(10)

where \( j = 1 \ldots N \). From equation (3) the relationship between output voltage and polarization of the \( j \)th element is given by:

\[ P_j = -V_{out} \frac{C_j}{A} \]  

(11)

and:

\[ E_j = \frac{V_{out,j-1} - V_{out,j}}{d} \left(1 + \frac{R_{G1}}{R_{G2}}\right) \]  

(12)

Using relation (10) and equation (11) we obtain:

\[ E_j = \frac{A}{C_j d} \left(1 + \frac{R_{G1}}{R_{G2}}\right) (P_j - P_{j-1}) \]  

(13)

Hence, the coupled dynamics in Fig. 7b has the following form (in the case of three unidirectional coupled circuits):

\[ \begin{align*}
\tau \dot{P}_1 &= aP_1 - bP_1^3 + \lambda(P_1 - P_3) \\
\tau \dot{P}_2 &= aP_2 - bP_2^3 + \lambda(P_2 - P_1) \\
\tau \dot{P}_3 &= aP_3 - bP_3^3 + \lambda(P_3 - P_2)
\end{align*} \]  

(14)

where:

\[ \lambda = c \left(1 + \frac{R_{G1}}{R_{G2}}\right) \frac{A}{C_j d} \]  

(15)

is the coupling coefficient.

The experimental results follow the predicted out of phase behavior as shown in Fig. 7b. Calculations yield the critical coupling (at the onset oscillations):

\[ \lambda_c = \frac{a}{2} + \frac{3}{2} \frac{cE_{ext}}{1 + \sqrt{2a/b}} \]  

(16)
where $E_{ext}$ is the external target electric field. Actually, the system oscillates for values $\lambda > \lambda_c$. 

The frequency dependence of the oscillations as a function of the coupling gain, is shown in the experimental results reported in Fig. 8a. These experimental observations are seen to be in good agreement with the theoretical expectations.

The circuit has been validated, by using an experimental calibration chamber, with regard to the dependence on the coupling gain and on the external field. Moreover, preliminary experimental results, reported in Fig. 8b, show the variation (decreasing) of the output signal frequency as a function of the external Electric Field. The measurement setup included two 3 m by 3m facing electrodes, used to impose the quantity to be measured and the apparatus made up by the microcapacitors and the charge collector, placed in between the two electrodes.

4 Conclusions

In this paper solutions to highly sensitive magnetic and electric field sensors have been presented. The transducers rely on the exploitation of the nonlinear behaviors of some specific material. Experimental prototypes have been realized and several applications have been investigated. In general they have shown their suitability in the case of signal such as those produced by weak perturbations on a large background scenario as in the case of metals in the earth magnetic field. Further efforts are in progress to enhance the sensor performance and to integrate the B-field and the E-field sensors into a single device.

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AMARANTA: Modular Platform for a Mine Hunting Robot

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\textsuperscript{3}Observatory of Colombian Mines (IMSMA), in Colombia during year 2007, 884 people were victims of anti-personnel mines and unused ammunition [1]. Unfortunately 193 people died and 691 were wounded in 30 of the total of 32 regions (provinces) that make up the country [1]. These facts show that humanitarian demining is a necessity in Colombia. Although it is a costly activity, recent studies have shown that besides the benefit of social recuperation of the affected communities it can be justified by an strict economical standpoint [2][3].

Humanitarian demining is a difficult and dangerous activity for human beings. For this reason, investigators have made a great effort to develop robots that may lend assistance in the performance of this task [4].

Mine Hunting robots need to have specific characteristics in order to ensure their own safety to achieve its task. Mobility, modularity, portability, and endurance are important factors that robot designers have to consider to ensure the robot’s performance.

Pontificia Universidad Javeriana has been working on the design of a robot capable of navigating on high risk terrains, especially in semi-structured roads that are very common in the Colombian rural areas where mines are usually planted. Research and development of this type of robotic platform was initiated in 2003. The main objective was to design a modular robot composed of independent systems for mine detection. The product of this research was robot Ursula [5]. It was a six-wheel mobile robot capable of detecting landmines using a metal detector [6] developed at Javeriana University. Ursula could be controlled with a laptop using a graphical user interface or it could be set to an autonomous mode where the robot decided where to go based on a navigation algorithm that followed non-structured roads.

The robot had acceptable performance, but presented the following operation issues: it wasn’t able to overcome obstacles on rough terrains due to its short height and it was too heavy to be portable. These problems became the source of inspiration to design a new robot with better mobility, hence improving its functionality.

Legged robots [7][8][9] have been used for humanitarian demining because they have advantages over wheeled robots such as omnidirectionality, finite number of ground contact points, and robust navigation on uneven terrains [10]. Adding a wheel to the leg mechanism makes the robot faster than a robot with legs. Leg-wheel mechanisms give the robot a flexible traction which is suitable for navigating on rough terrains. That is why institutions like NASA are currently working on leg-wheel rovers that serve as a mobile platform in the moon or other planets [11].

The main objective of the research was to design a light weight robot, equipped with: an onboard metal detector to find buried metallic objects, a vision system that enables the robot to achieve navigation tasks and identification of high risk terrains, and a manipulator arm that facilitates interaction with the environment.

This paper presents the development of robot Amaranta based on leg-wheel mechanisms. One of the main features of the robot is its modular architecture. Amaranta can be adapted to the type of terrain with three, four, five or six leg-wheel assemblies.

The robot’s sensory information is provided by two CCD cameras, a GPS, an electronic compass, a barometric altimeter, 4 force sensors, and 16 quadrature encoders. Amaranta is also equipped with a 4 DOF manipulator arm so the operator has basic manipulation capacities over the environment.

Amaranta has two modes of operation: the first one is a teleoperated mode where an operator can control the robot...
with a joystick or a laptop. The second type of operation is an autonomous mode where the robot’s navigation is based on a vision algorithm that detects semi-structured roads [12]. This paper is organized as follows. In section II the mechanical design and the robot’s specifications are presented. Section III shows the robot’s system configuration. In Section IV the advantages of Amaranta’s design are explained. The preliminary evaluation used to test the performance of the robot is presented in section V. The conclusions and future work are described in section VI.

II. AMARANTA’S SPECIFICATIONS

Figure 1 shows an overview of Amaranta. Amaranta has 12 DOF, it weights 30 kg and it is 40 cm high. It is composed of a main framework and 4 leg-wheel assemblies. Its main framework has hexagonal shape and contains the power system, the control system, the communication system, and the batteries. Up to six leg-wheel assemblies can be adapted on the sides of the robot, according with the type of terrain.

The mechanical design was made in Solidworks® (Figure 2) and COSMOS® was used to do stress analysis of each part. The mechanical structure and the legs are made of aluminum because of its good resistance and low weight.

![Fig. 1. Overview of Amaranta](image)

![Fig. 2. Mechanical design on Solidworks®](image)

Figure 3 shows a picture of one of Amaranta’s leg-wheel assemblies. Each leg-wheel assembly has 3 DOF allowing the wheel to spin, yaw rotation in the wheel joint, and the flexion or extension of the leg. In addition, it has a 4 DOF manipulator that has two main purposes: have a higher level of interaction with the environment (for example grabbing small things that could be in the terrain) and carry the metal detector. Table I shows the basic specifications of Amaranta.

![Fig. 3. Leg-wheel assembly](image)

**TABLE I

SPECIFICATIONS OF AMARANTA**

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>16-bit Digital Signal Controller (x 6)</td>
</tr>
<tr>
<td></td>
<td>32-bit Dual Core DSP (x 1)</td>
</tr>
<tr>
<td>Vision</td>
<td>CCD Camera (x 2)</td>
</tr>
<tr>
<td>Actuators</td>
<td>DC Motor with Reduction Gear (x 16)</td>
</tr>
<tr>
<td>Sensors</td>
<td>Metal detector (x 1), encoder (x 16), force sensor (x 4), GPS (x 1), electronic compass (x1), and barometric altimeter (x1)</td>
</tr>
<tr>
<td>Battery</td>
<td>12 V @ 7A-h (x 2)</td>
</tr>
<tr>
<td>Weight</td>
<td>30 kg</td>
</tr>
<tr>
<td>Height</td>
<td>40 cm</td>
</tr>
<tr>
<td>Width</td>
<td>160 cm</td>
</tr>
<tr>
<td>Depth</td>
<td>160 cm</td>
</tr>
</tbody>
</table>

Amaranta has three different types of actuators. The joint in charge of leg extension is an 11 W motor with a 53:1 planetary gearbox. This motor is connected to a nut-screw mechanism that changes rotational motion to translational motion. An 11 W motor with a 590:1 planetary gearbox controls the wheel’s yaw and a 4 W motor with a 131:1 planetary gearbox drives the wheel’s spin. This last motor is connected to the wheel with a 2:1 conical gear.

The proprioceptive sensors of the platform are 16 quadrature encoders and 4 force sensors. The encoders are used to determine the position and velocity of the motors while the force sensors measure the pressure that each leg is exerting on the ground.

The exteroceptive system has 2 onboard cameras, a GPS, and a metal detector. One camera is installed on Amaranta’s fronthead and it is used for navigation while the other is attached to the arm manipulator. In this way, the operator controls the arm having a direct view of what he is manipulating. Amaranta also has a Garmin® Personal Navigator® that includes a GPS, an electronic compass and a barometric altimeter. The metal detector is used to find landmines which have metal components. It is installed on the tip of the manipulator enabling the robot to scan nearby terrain before advancing, hence ensuring its safety. The detector measures the variation of the induced magnetic field on a coil and compares it with a signal generated on the DSP.
III. SYSTEM CONFIGURATION

Figure 4 shows Amaranta’s control system. The processing unit is composed of six 16-bit Digital Signal Controllers (DSC) and one dual core DSP. The DSP executes a navigation algorithm [12] to find and follow non-structured roads and an algorithm to analyze images of the road in order to detect non-metallic landmines [13]. Non-metallic landmines can be detected analyzing color and texture variations over the image that may signal that the surface has been intentionally modified.

The DSP also receives information from the metal detector and based on hard limiter’s thresholds determines if there is a possible landmine. The metallic objects can be detected at distances up to 20 centimeters underground.

The main Digital Signal Controller receives from the DSP the control string that commands the robot’s motion. This string contains the velocity vector and the robot’s main framework desired height. The velocity vector is obtained by the navigation algorithm or from the operator when it is in teleoperation mode. The main Digital Signal Controller processes this information to calculate wheel velocity and joint positions of each leg-wheel assembly so it can achieve the desired motion.

The main Digital Signal Controller communicates with the other five DSCs via a CAN bus. Each leg-wheel assembly has a DSC that is in charge of performing the control algorithm for the three motors (two position controls and one velocity control for the wheel). The other DSC is in charge of the manipulator’s joints position control and of processing the GPS data. These five DSCs monitor motor current in order to detect excessive torques that could damage the motors.

Depending of the task to be performed by the robot, Amaranta can be controlled using a laptop or a joystick. A graphical user interface installed on the laptop is helpful because the operator can access all the data provided by the sensors. However, in some terrains carrying a laptop can be a problem. In such situations, the operator can control the robot using a remote controller. The remote controller has three modes of operation that enables the operator to control the motion of the robot, to drive the arm manipulator, and to move each leg independently. Figure 5 shows the graphical user interface developed in Visual C#.

Zigbee® protocol enables wireless communication to the main station. The wireless control allows the operator to drive the robot at a distance of 300 m, minimizing the risks for the operator in case of an explosion.

IV. DESIGN HIGHLIGHTS

Amaranta’s design has three mayor advantages for navigation on high risk terrains: flexibility, speed, and modularity.

A. Flexibility

Each leg-wheel assembly has 3 DOF that allows the extension and flexion of the mechanical structure (Figure 6), hence controlling the robots height. This implies that Amaranta’s center of gravity can be lowered down in order to increase stability and it can be elevated to avoid obstacles are present on the road. The robot’s inclination can be controlled with the purpose of navigating on uneven terrains and to emulate the action of a shock absorber.

To achieve stability, the robot has to have a minimum of 3 leg-wheels assembled, this way the polygon of support becomes a triangle. Therefore if the robot has more than 3 leg-wheels installed, each leg can be lifted up individually in case a large obstacle is present across the road.
Amaranta’s configuration is characterized by having no specific front head, therefore it permits the robot to go in any direction in case it gets blocked. In addition, in a flat surface Amaranta can be driven at high speed lowering its center of gravity and applying full power to the motors of each wheel. A robot based only on leg assemblies will not reach high velocities mainly because it depends on its dynamical stability.

Due to its inherent omnidirectonality, if a tall obstacle is present along the road, Amaranta has the ability to achieve 90° turns in order to border the obstacle and continue with its commanded task.

C. Modularity

Mine hunting robots have to navigate on high risk terrains and the priority is to ensure the robot’s safety. This was the reason why the most important design criterion on developing Amaranta was modularity. There is a main DSC that executes main processing but each leg-wheel assembly has its own DSC in order to minimize damages in case of accident. If an explosion takes place, the damaged leg-wheel assembly can be replaced without affecting other parts of the robot. Since the robot may move using three of its four legs, this makes it capable of overcoming obstacles whereas a robot made up of only wheels would be blocked up. This is also an advantage in case a leg-wheel assembly gets ruined by an accident.

Another advantage of modularity is portability because in order to transport the robot it can be disassembled, hence occupying less space. It is important to mention that Amaranta’s main structure is made of aluminum so it is considerable less heavier than its predecessor Úrsula.

V. Preliminary Evaluation

To evaluate its performance, Amaranta was tested on flat and uneven surfaces. It was driven on simple paths like the ones shown on figure 6.

With a laptop, the operator sent speed, orientation and height commands to the robot. Speed can be adjusted from 0 which means stop to 100 which means full power (integer increments). The orientation command consists of an integer angle between 0 and 359. Height command ascends or descends the main framework.

The robot was capable of following straight lines with any startup position. Middle size objects (10 cm diameter) were placed on the road and the robot was capable of crossing over them.

VI. Conclusion

This paper presented the development of a robot for navigation on high risk terrains. The mechanical model is based on a main framework with four leg-wheel assemblies. The electronic and mechanical characteristics of the robot and its advantages for navigation on uneven surfaces were presented.

At the present time the work includes the applicability of the platform such as new vision algorithms and also inclination control algorithms.

Although the nut-screw mechanism in each leg-wheel assembly connects strongly the motor and the leg, in future work a motor with higher torque could be installed directly on the joint in order to achieve a faster flexion or extension of the leg. Additionally, a model with one more DOF can be developed in each leg-wheel and in this way it would allow the platform to walk blocking the tires. Thusly the robot would have two kinds of locomotion and it would be stronger for rough and irregular terrains.

REFERENCES


Fuzzy Template Based Automatic Landmine Detection from GPR Data

Zakarya Zyada, Member, IEEE, Takayuki Matsuno and Toshio Fukuda, Fellow, IEEE

Abstract—in this paper, a 3D fuzzy template based anti-personal landmine automatic detection from GPR data is presented. A 3D template is chosen and a 3D fuzzy template is designed. The choice of the 3D template is decided based on smooth changing position of the maximum amplitude at every C-scan as well as the threshold of its background average intensity. The 3D fuzzy template is extracted from 3D template crisp data. A data point in the 3D fuzzy template is expressed as a trapezoidal fuzzy set which is extracted from experimental data. Landmine similarity for both the 3D template as well as the learnt fuzzy template is examined by a crisp similarity measure and a fuzzy similarity measure respectively. The cross correlation is applied as a similarity measure in crisp case while a membership degree of a fuzzy set is applied as a similarity measure, in the fuzzy template case. Results of similarity applying both methods for automatic landmine detection from GPR processed data are presented. The results show the promise of 3D fuzzy template applying the fuzzy similarity measure in differentiating a landmine from other objects.

I. INTRODUCTION

LANDMINE detection has attracted much attention by many research teams around the world during the last decade. It is estimated that more than 70 million active landmines are scattered in 62 countries around the world. Ground penetrating radar (GPR) provides a recent technique, for sensing objects underground, based on dielectric properties. It is expected to be a good alternative sensor for landmine detection. The output of the signal processing algorithms applying a stepped frequency GPR is a spatial distribution of subsurface reflectivity, [1]. The spatial distribution of subsurface reflectivity is normally presented as C-scan images. The common scenario for landmine detection applying a stepped frequency GPR is manual inspection of those output images by a deminer, [2]. The deminer looks at the processed images and compares many different images and finally takes a decision if there is a landmine or not. The decision is based on the deminer’s experience and his cleverness. It is not only a difficult but also a time consuming task. There is a need to automate decision making of landmine availability to save efforts as well as time, [3]. The need for automating decision making of landmine availability has motivated researchers to apply some computational methods on sensed data. Hasegawa et al, [4], have applied a 2D template matching method stepped frequency GPR data. Realizing that it is difficult to determine the signal attenuation in practical situation, they introduced an adaptive template matching procedure to compensate for signal attenuation at different depths. However, their introduced results show a probability of false alarm (PFA) more than 60%. In this work, a step towards automatic decision making for anti-personal landmine detection from a stepped frequency GPR processed data is presented. We propose a method based on 3D fuzzy template matching as shown in Fig. 1. It is composed of mainly three steps: 1- the choice of 3D reference template; 2- obtaining a 3D fuzzy template; 3- fuzzy matching based on a fuzzy similarity measure.

This paper is organized as follows: the experimental system and signal processing of GPR data are presented in section II. Obtaining a 3D reference template for both crisp and fuzzy cases is presented in section III. Template matching as well as the applied similarity measure for both crisp and fuzzy cases is presented in section IV. Similarity results for both crisp and fuzzy cases are presented in section V. Conclusions and prospects are presented in section VI.

II. EXPERIMENTAL SYSTEM

In this section, robot-manipulation system, the experimental test field, GPR sensing system as well as GPR signal processing is presented.

A. Robot-based manipulation of GPR sensor

It is important to replace a human demining task by an automated robot task. As a simulation of a complete automated demining process, a six-degree of freedom serial manipulator of type PA10-7C, manufactured by Mitsubishi Heavy Industries, Japan, is applied in this study as a sensor manipulator. Manipulator based scanning facilitates a regular step scanning better than a manual based scanning, which
shown in Fig. 2. Its water content is 4.0%, (relative permittivity of about 3.29). EM wave absorber covers all the sidewalls and the bottom of the tank to suppress the tank walls reflection during GPR measurements. A dummy landmine of type PMN2 is the applied one for demonstrating the methodology of this study, Fig. 3b. It has the same dielectric constant and the same metal content as the real one. Its diameter and height is 122 and 54 mm, respectively. A stone of an approximate size like the dummy landmine, Fig. 3c, is also scanned for template matching as will be presented in section IV. The field is relatively flat and the GPR antenna scanned in a path parallel to the surface with a gap between the sensor head and the ground of 10 mm. GPR system is shown in Fig. 3.

B. Ground penetrating radar system

A three-element vector stepped-frequency GPR system, Fig. 3a, developed by Mitsui Engineering and Ship Building Company, (Japan), is applied in this study. It is an ultra-wide bandwidth vector type GPR. Its frequency bandwidth is 7.8125 MHz – 2.0 GHz. Its frequency is changed in 256 steps.

C. Ground penetrating radar signal processing

During the experiments, the scanning area is 400x500 mm\(^2\). The manipulator movement is in 20 mm steps in both Y-Z directions comprising a grid of 26x21 measurement points. The scanning path is as shown in Fig. 4. GPR signal processing includes two main steps to obtain an image spatial distribution from which reference template is extracted. These steps are: local average subtraction and migration, [4]. The output of the processing stage is C-scan slices like that shown in Fig. 5. A local average subtraction is applied for better clutter suppression. The local average subtracted signal \( \phi_i(t) \) is given by \( \phi_i(t) = \phi(t) - \overline{\phi}_i(t) \) where \( \phi(t) \) is the raw data and \( \overline{\phi}_i(t) \) is local average signal at sensing point \( i \); \( \overline{\phi}_i(t) = \frac{1}{n_i} \sum_{k=K_j}^{K_j} \phi_k(t) \) where \( K_j \) is a set of sensing points in the neighborhood of sensing point \( i \) and \( n_i \) is the number of members of \( K_j \). A time series signal is obtained through Inverse Fast Fourier Transformation. A 3-D GPR spatial signal is reconstructed from the time signal. Kirchhoff migration is adopted to reconstruct the spatial distribution of subsurface reflectivity from a set of time series signals acquired on the ground surface by three-element vector radar.

The Kirchhoff migration algorithm gives the output wave field \( \phi(r) \) at a subsurface scatter point of position \( r = (x, y, z)^T \) from the input wave field \( \phi(r_s, m, t_{TR}) \) which is measured at the surface sensed points of position \( r_s = (x_s, y_s, z_s)^T \) for a signal mode \( m \) with transmit ion time \( t_{TR} \). For 3-mode vector radar, the solution used in
migration is given by:

\[
\phi(r) = \frac{1}{2\pi} \sum_{n=0}^1 \left[ \frac{\cos \theta}{r^2} \phi(r, m, t_{n1}) + \frac{\cos \theta}{vr} \frac{\partial}{\partial t} \phi(r, m, t_{n2}) \right] dA \tag{1}
\]

where \( V \) is the RMS velocity at the scatter point and \( r \) is the distance between the input point and the scatter point. \( \cos \theta \) is the obliquity factor, \( 1/vr \) is the spherical spreading factor. The summation is to include effect of the three modes. For more details about GPR signal processing, reader is advised to refer to [1], [5].

Fig. 5 C-scan of GPR processed data

Fig. 6 Spatial position of intensity peak amplitudes

III. THREE-DIMENSIONAL REFERENCE TEMPLATE

Choice of a 3D reference template from GPR processed data as well as a 3D fuzzy template is introduced in this section. The choice of the reference template is based on smooth changing as well as repeatability of horizontal position of the maximum intensity amplitude.

A. Three dimensional reference template’s choice

A 3D reference template is chosen from the reference processed GPR data, C-scans, from which the position of peak amplitude can be obtained for every slice, Fig. 5.

\[
\begin{align*}
|x_i - x_{\text{max}}| &= |x_{i-1} - x_{\text{max}}| \
|y_i - y_{\text{max}}| &= |y_{i-1} - y_{\text{max}}| 
\end{align*}
\]

where \( x_{\text{offset}} \) and \( y_{\text{offset}} \) is a prescribed offset in both \( x \) and \( y \) directions respectively. In the current evaluating algorithm these offsets are chosen to be 2 cm in both directions.

The repeatability of horizontal position of C-scans’ peaks for the chosen depth range is shown in Fig. 7. The color of the figure expresses the repeatability. It is easily extracted that maximum probable horizontal position for the selected data range is at \((23, 23)\) cm. Other probable peaks are to the neighborhood of the maximum probable peak position. Smooth changing of peak positions’ are rechecked again, (applying equations in (2)), and the final depth range of data is chosen.

Trying to get a template better expressing the effect of a landmine, the area of pixels around the peak for a given slice is divided into two areas: a landmine area and a background area. The area is defined by a landmine radius while the background is defined have a radius twice that of the landmine. The average intensity of both areas at different slices is shown in Fig. 8. It is clear that the background average intensity differs from a slice to another. To obtain a

Fig. 7 repeatability of position of maximum amplitude points in the selected range
3-D reference template of a landmine, a threshold at the background average intensity at different slices is applied. The result is a 3D reference template as shown in Fig. 9.

B. 3D fuzzy template
Having obtained a 3D template, Fig. 9, different templates at various landmine depths can be obtained. The 3-D fuzzy template is extracted from different 3D templates. The difference between a fuzzy template and a crisp one is that the element of a fuzzy template is a fuzzy set. To extract a fuzzy template, GPR scans of a dummy landmine is executed at different depths. Some of the GPR-data are applied for defining the fuzzy sets and hence obtaining the 3D fuzzy template while the rest of GPR-data are applied for checking the fuzzy template. A trapezoidal fuzzy set, Fig. 10, has been chosen to express analogous elements, (i.e. similar spatial position), of the different crisp 3D templates. The defining parameters of the trapezoidal fuzzy set, \((a, b, c, d)\), are estimated from experimental GPR-processed data for a landmine scanned at different depths. Defining the intensity to be \(I_j(x, y, z)\) at a given spatial position \((x, y, z)\) in a \(j^{th}\) template, then:

\[
b(x, y, z) = \min(I_j(x, y, z)), \quad j = 1, 2, \ldots, j_{\text{max}},
\]

\[
c(x, y, z) = \max(I_j(x, y, z)), \quad j = 1, 2, \ldots, j_{\text{max}},
\]

\[
a(x, y, z) = \left( \frac{b(x, y, z) - (c(x, y, z) - b(x, y, z))}{2} \right),
\]

\[
d(x, y, z) = \left( \frac{c(x, y, z) + (c(x, y, z) - b(x, y, z))}{2} \right),
\]

\[
j = 1, 2, \ldots, j_{\text{max}}.
\]

Defining trapezoidal function parameters, the fuzzy set at every spatial position of the template can be defined and 3D fuzzy template is obtained. At a specific spatial position, \((x, y, z)\) of the 3D template, the intensity, \(I(x, y, z)\), would be expressed as:

\[
\text{IF position is } (x, y, z) \text{ is THEN } I(x, y, z) = A(x, y, z),
\]

\(A((x, y, z))\) is a trapezoidal fuzzy set whose parameters are defined as mentioned above. The output of this stage is a 3D fuzzy template. Even though only fuzzification of intensity variable is applied here, the spatial position would be fuzzified in future as well.

IV. TEMPLATE MATCHING
Template matching is the process of finding the location of a sub image, called a template, inside an image. Template matching involves comparing a given template, (reference template), with windows of the same size in an image and identifying the window that is most similar to the reference template. In the following sections, first, different similarity measures applied in this study are reviewed, and then, similarity results are presented.

A. Similarity measures
Template matching requires comparison of a given template to windows of the same size in an image and identification of the window which is most similar to it. Different similarity measures are adopted in the literature for both crisp and fuzzy template similarity evaluation. Similarity measures for crisp template would be sum of absolute differences, cross correlation coefficient, geometric
distance, invariant moments and others. Knowing that cross correlation coefficient is resistant to some intensity differences between images, we apply cross correlation coefficient as a similarity measure in crisp template case.

Denoting the template by \( f_1 \) and an image by \( f_2 \), and assuming the size of the template is \( n_1 \times m_1 \times p_1 \) and the size of the image is \( n_2 \times m_2 \times p_2 \), \( (n_2 > n_1, m_2 > m_1, p_2 > p_1) \). Applying a similarity measure, we will get an intermediate image, called a similarity image denoted by \( s_c \). Entry \((x, y, z)\) in the similarity image is indicating the similarity between the template and the window of the same size at location \((x, y, z)\) in the image. Similarity image \( s_c \) will be of size \((n_2 - n_1 - 1) \times (m_2 - m_1 - 1) \times (p_2 - p_1 - 1) \).

Cross correlation coefficient is defined by,

\[
 s_c (x, y, z) = \frac{N}{D_1 \times D_2},
\]

where

\[
 N = \sum_{i=1}^{n_1} \sum_{j=1}^{m_1} \sum_{k=1}^{p_1} f_1(i, j, k) f_2(x+i-1, y+j-1, z+k-1)
\]

\[
 D_1 = \left[ \sum_{i=1}^{n_1} \sum_{j=1}^{m_1} \sum_{k=1}^{p_1} f_1^2(i, j, k) \right]^{1/2}
\]

\[
 D_2 = \left[ \sum_{i=1}^{n_2} \sum_{j=1}^{m_2} \sum_{k=1}^{p_2} f_2^2(x+i-1, y+j-1, z+k-1) \right]^{1/2}
\]

\((x, y, z)\) expresses the coordinates of the front upper left corner of a 3D window in GPR image. In this formula, the denominator is a normalization factor. As the template and the window become more similar, \( s_c \) becomes larger.

According to the above formula and because the intensity is only positive values, \( s_c \) will have a value between 0 and 1.

On the other hand, there are many works on the similarity measures for fuzzy data. These works include the similarity of two elements in a fuzzy set, similarity between fuzzy sets and similarity of an element to a fuzzy set, \([7]\). The algorithm adopted to calculate the fuzzy similarity measure is shown in Fig. 11. For a 3D template of a mine suspect, a membership degree in its appropriate fuzzy set, (be known from the 3D fuzzy template), is calculated. Then the fuzzy similarity measure, \( S_f \), is expressed as the average of membership degrees of template elements as follows:

\[
 S_f = \frac{1}{n_{max} \times m_{max} \times p_{max}} \sum_{i,j,k=1,1}^{i_{max},j_{max},k_{max}} \mu(x+i-1, y+j-1, z+k-1) / N;
\]

\( N \) : number of elements

V. SIMILARITY RESULTS

Both 3D crisp and fuzzy templates are applied for matching GPR images. Images for a dummy landmine at different known depths and of a stone at a specific known depth are tested. The matching algorithm is shown in Fig. 1. The similarity results presented here are based on cross correlation coefficient for 3D crisp template and fuzzy similarity for fuzzy template case. Both the 3D crisp template and fuzzy template are extracted as explained in section III.

A. Similarity results in crisp case

Applying the matching algorithm, we would obtain a value for similarity for matching two templates at a given spatial position. The output will be a 3D similarity matrix. For simplicity, the similarity results at a specific slice of the scanned images, (that is the slice number 9), are presented. That slice includes the maximum similarity results. Cross correlation similarity results are shown in Fig. 12 and Fig. 13 for the images of a stone and a landmine prototype respectively. The reference template in all cases is the landmine prototype template presented in section 3.

Similarity is high as 80% for a stone and as 90% for a dummy landmine. The cross correlation similarity results show the confusion of a stone as if it is a suspected landmine. There is no clear discrimination between a landmine and a stone result.
Fig. 13 Crisp similarity results for a dummy landmine

B. Similarity results in fuzzy case

The matching algorithm shown in Fig. 1 with the fuzzy template designed in section III are applied in this evaluation. A dummy landmine has been scanned at 7 different depths. The data of 4 depths are applied for extracting the fuzzy template. The data of the other 3 depths are applied for testing the extracted fuzzy template. Also the data of scanning a stone, Fig. 3c, is applied for checking the validity of the template and the matching algorithm for discriminating a landmine from a stone object. These testing similarity results are shown in Fig. 14. The presented result is the maximum similarity value for each case, (a landmine at three different depths and a stone). Fig. 13 shows that similarity value in case of a landmine is more than 80% while for a stone case it is about 32%. This result shows that applying the fuzzy template and the proposed matching algorithm, it is possible to discriminate a landmine from a stone. It would enhance the capability for automatic detection of landmines and decrease the false alarm rate.

Fig. 14 Fuzzy similarity results for a dummy landmine at different depths and a stone

VI. Conclusions

In this paper, we have presented 3D-template based automatic landmine detection method from GPR data. Both crisp and fuzzy 3D templates are presented. An element of a fuzzy template is a fuzzy set. The fuzzy set parameters are extracted from experimental data. Cross correlation similarity measure is applied for crisp template matching while a fuzzy similarity measure is applied for fuzzy template matching. The similarity results of a stone and a landmine prototype show the promise of the 3D fuzzy template matching applying a fuzzy similarity measure. In contrast to a cross correlation similarity measure, a landmine suspect can be differentiated from a stone applying the proposed algorithm with a 3D fuzzy template matching and a fuzzy similarity measure.

A. Prospects:

A more general template for a group of landmines, (having similar characteristics), would enhance the proposed automatic detection method in a practical application. It would be the extension of this work.

References


Landmine detection using integration of GPR and magnetic survey

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Abstract
The global landmine crisis is a critical problem facing many countries all over the world. It is estimated that a total of 45-50 million landmines remain to be cleared and more than 80 countries are affected by landmines and/or unexploded ordnance (UXO). Egypt as one of those countries is suffering of this problem and the development plans at the north western part of Egypt are always a matter of delay mainly because of this problem.

Therefore, an attempt to use the GPR and the magnetic gradiometer techniques to detect the land mines was conducted. The main aim was to test these methods of surveying, measuring and inventing a prototype carrier. A special car (ESCALADE) was built for this purpose at the Egyptian Atomic Energy Authority (EAEA) supported by the International Atomic Energy Agency (IAEA). The SIR 20 of GSSI GPR system connected to 1.5 GHz and 400 MHz antennas was used for the test while the fluxgate magnetic gradiometer FM 36 was used to conduct the magnetic survey.

The results of this survey were promising, as the different kinds of the landmines were detectable with considerable resolution, even before reaching the mine itself. The integration of the different techniques helped in enhancement of the recorded signals and represented and tailed with the recommendation for the next phase of the research plan which is the automatic detection and focusing around the position of the object.

INTRODUCTION
Egypt is one among many countries suffering the harmful reward of the existence of the landmines in their soils. In addition to the human organs missing or even soul losses, the development proposals are hindered and prevented whereas the unexploded ordnance "UXO" may exist. Nowadays, the national trends of the country are oriented to purify the planted fields and add them to the reform projects. Therefore, the modern scientific and technological searches had to achieve its duties in solving such a problem.

During the 1990s, modern automated arrays of sophisticated passive and active metal detectors were developed. Digital geophysical mapping has become the goal for UXO searches [1], [2]. Improved detection technologies have been coupled with data analysis systems of varying sophistication to allow either semi-automated or interactive analysis capability [3].

In 1999, the National Research Institute of Astronomy and Geophysics (NRIAG) in cooperation with the Egyptian ministry of defense conducted a test to measure with the GPR over a test site planted with different passive landmines. The experiment resulted in a considerable success of GPR to detect the anti-personal and anti-truck landmines. In 2005, another trial was done in a wider cooperation range; in addition to NRIAG and the Egyptian ministry of defense, the Nuclear Material Authority (NMA), the Center for Eastern Asia Studies of Tohoko University and QMAG of Kyushu University (Japan) jointed the test. The experiment based on carrying the GPR antennas and the magnetic sensor on a balloon and conducting the survey, the result was relatively acceptable, except the wind’s deviation effect on the balloon over the test site.

Around the start of 2007, a research proposal was pointed in cooperation between NRIAG, the Egyptian Atomic Energy Authority (EAEA), and some universities from Europe and South Africa. This research project was approved and particularly, financially, supported by the International Atomic Energy Agency (IAEA). The core of this project could be coaxed around two points; 1)- building an integrated sensor beam including the different detectors capable to pick the landmines, and 2)- constructing a mobile carrier to conduct the survey over the harming fields. The sensor beam included Ground Penetrating Radar (GPR) antenna, vertical magnetic gradiometer (fluxgate), Neutron Back Scattering, and hydrogen detector, in addition to a distance meter and a telemetric transmitter. The first phase of the experiment was started in November 2007 on a test site close to the buildings of EAEA; the results were accepted for the first phase. In the present paper, the results of the geophysical techniques will be represented and tailored with the recommendation for the next phase.

FOCUS ON THE PROBLEM AND THE OBJECTIVES

Egypt is one of the most contaminated landmine countries. The military operations, during the World War II, carried out by the Allied Forces and the Axis Power from 1941–1943 left varieties of about 22 Million landmines and UXO in the western desert nearly along the coast of Mediterranean sea. Not only thousands of civilians victims and injured each year, but also the social, economics and environmental impacts of those mines are disgraceful [4]. Therefore, this work aimed to construct a complete system able to detect the different types of the landmines and UXO with high safety standards. The system utilizes the most modernized geophysical and atomic techniques capable to measure the slight effect of a small object in the physical fields. The sensors of those techniques are carried on a special car constructed by EAEA and called "Escalade". The system is planned to include items, not yet connected, help the intelligent mobility of the carrier to move towards the position of the object and send the data telemetric to a remote control unit.

ESCALADE

ESpecial CAr for LAmdmine DEtection "ESCALADE": is a prototype car that was constructed by the EAEA team to be used during the test. The car (Fig. 1) uses the minimum mechanical forces to move and motivate its parts. It could be divided into three main parts; a) - the controller, is a platform includes the switches, control keys, and the geophysical equipments, b) - the mechanics, is a frame includes the motors, motion gear boxes, axis and spirals, and cables, and c) - the
The Neutron Back Scattering (NBS) technique and the second is proposed (under construction) for the geophysical sensors. Escalade moves forward inline with the profile direction while the carrying units move laterally doing the survey. The minimum speed of the inline motion is 5 cm per minute while the time required for the carrier to move a full lateral track is 60 seconds. It is understandable that the survey resolution is factored by those two speeds. For the now running phase, it is accepted but also recommended that the range of the speeds become more controlled and consequently the survey resolution.

![Fig. 1: A photograph of Escalade showing its elements.](image)

### The Test Site

The test site is prepared by EAEA and located near the laboratory for developing nuclear techniques to detect landmines and illicit materials. The site is located about 60 km northeast of Cairo. Figure 2 shows a picture for the test site. The soil is sand, partly mixed with silt and flint stones. The moisture content of the soil is very low.

![Fig. 2: Photographs of the test site showing its nature.](image)

The prepared site is a test site planted with passive mines at different depths starting from 0cm up to more than a meter. Different exemplars of the anti-persons and anti-trucks mines were planted in the ground and the GPR data was collected over them. The survey grids and profiles were delineated over places on the sites that the tools do not affect each other, since each tool was checked in separate and then integrated on the carrier.

### The Used Techniques and Systems

Two main geophysical techniques have been used to collect the data over the test site; the **Ground Penetrating Radar (GPR)** and fluxgate magnetic gradiometer. The ministry of defense has provided the test with different type of anti-personal mines (APM) and anti-truck mines (ATM); these are detailed as a part of the used system.

**The GPR (Fig. 3);** is considered as a fast and cost-effective electromagnetic (EM) tool which, in favorable condition i.e.
The used mines of the experiment were supplied by the Egyptian ministry of defense, with a group of APM and ATM representing the different types of the mines planted in the Egyptian soil. Figure 5 is a photograph showing these types.

![The landmines used for the experiment and provided by the Egyptian army.](image1)

**Fig. 5:** The landmines used for the experiment and provided by the Egyptian army.

**DATA ACQUIRING**

Firstly, all the used techniques have been applied individually and in a separate place in the site, where a detailed field note with remarks about the mine type, its depth, elevation of the sensor, convergence and divergence to its center, and also the speed of passing over. Then, the sensors were installed on the carrier and surveyed again. Escalade is still in the phase of construction; therefore, the noted remarks could be used as the feedback reform design of its parts, specially the carrier speed and elevation to the ground surface.

**GPR data acquisition;** A series of GPR profiles was measured over the site in free mode. In addition, the measurements were done over 2 nets (4m x 4m (Fig. 6) and 10m x 10m) using the 400 MHz and 1.5 GHz antennas. The profile spacing inside the grids was 20 cm with the 400 MHz antenna and 10 cm with the 1.5 GHz antenna. **Firstly,** these data sets were collected by an operator walking on the ground. The antennas were connected and fixed to be carried by the operator at a simulating elevation to the ground quite close to the elevation of the carrying unit of Escalade. **Secondly,** the two antennas were fixed on the carrier of Escalade former, but separated from, the place of the NBS receiver (Fig. 7). The measurements in this phase were done simply along profiles, while Escalade is not yet flexible to move over a measuring grid, and also, its technology is designed to scan a width in zigzag form.

![The antenna mounted on Escalade](image2)

**Fig. 7:** Photographs of data collection by the free hand and on the Escalade.

**The magnetic data acquisition;** Four landmines of different types (both anti-persons and anti-tracks) were buried in an area of 4m x 4m (Fig. 8). The soil was cleaned from any visible surface metal materials. This area was divided into two sub-grids; each grid was set to be 2m x 4m and the corners were marked by wooden sticks. The fluxgate gradiometer was correctly balanced to null over an area of uniform local magnetic field. The sensitivity was set to 0.1nT. The surveying process was performed along successive parallel traverses separated by 10 cm interval. The readings were then logged every 10cm, with a total 1600 magnetic records acquired over this surveyed grid.

![The measured net with the fluxgate gradiometer.](image3)

**Fig. 8:** The measured net with the fluxgate gradiometer.

**DATA PROCESSING AND INTERPRETATIONS**

The data collected, by both tools, was processed individually and then the results were compared, however, one of the proposed tasks of this research project is to diffuse the different data outputs together to give simultaneous image of the near surface. The object content within this image and its weighted tendency of being a mine is ought to intelligently reorient the carrier of Escalade to focus its position on a control unit and leave a mark on the ground.

**GPR data processing and discussion;** the GPR records, in which the amplitude of the electromagnetic wave is plotted versus the travel time (transmitter - reflecting interface - receiver), were processed using commercial software "Reflex" [10]. A series of processing steps, includes background removal, filtering and migration, was sequenced and applied on the records. The GPR records showed almost all the buried mines. Figure 9 represents the GPR traverses over the landmines planted in the measuring net.

![Free hand measurements](image4)

**Fig. 6:** The survey net (4m x 4m) used for both the GPR and magnetic measurements.
Fig. 9: GPR traverses over the landmines in the test grid.

Figure 10 is a collective representation of some signatures of the difficult landmines, both anti-persons and anti-trucks as follow; a) shows the GPR signature over the mine T-80 and MK ATM at depths of 0.14 m, 0.20 m, and 0.35 m. Their responses at the GPR record were detectable for all the cases; b) represents the GPR record on the Italian landmine VS 50, the material of this mine is plastic, therefore, this result could be considered as an advantage of this experiment, however, the burial hole helped to show the scattering of the wave.

As an experimental phase; both of the 1.5 GHz and the 400 MHz antennas were installed on a sophisticated board, separated but close to the NBS receiver, on the carrier of Escalade, and then the GPR data was collected. The measurements were done while Escalade moves forward, but the carrier is not moving, over a line. The results (Fig. 11) showed the ability to detect the mines using Escalade. The resolution is acceptable in relative to that of the free hand measurements (Fig. 10); however, the forward speeds of Escalade and its carrier are not the only factor to calculate the detectability of the system, but also the lateral tracking of the carrier. Comparing the GPR records on the mines in the free hand and on Escalade showed almost similar signatures; which might mean that the effect of the NBS sensor on the GPR measurements could be neglected.

Fig. 10: GPR signatures over some landmines; a) - T-80 and MK ATM, and b) - VS 50.

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Fig. 11: The GPR records using

**Magnetic data processing and interpretation (Fig. 12);** the resulted magnetic data, showed in its raw form, the ability of the fluxgate magnetometer to detect the anti-trucks mines. Its response to the plastic or the wooden mines is not remarkable; their metal content is not enough to excite the magnetic sensor. The intensity of the detected mine ranges from ~100 nT/m to 200 nT/m and covers an area much wider (unit cube) than the actual size of the mine, i.e. its effect appears on gradiometer sensor former to its place. On the other hand, its integrity to Escalade system did not show success due to the metal mass in the body of Escalade.
The present reported experiment resulted in remarks on the system elements;

1) The sensors; although, the commercial sensors, GPR antenna, showed powerful capability to detect mines, they prevent the flexible motion of the carrier. Therefore, it is highly recommended to build light antenna to be adequate for purpose.

2) The Escalade; its body very heavy and is having a big metallic mass, furthermore, its speed is not completely controlled. Therefore, it is recommended that the body should be lightened, and the side metal rods and the vertical stands should be replaced by a non-magnetic light material to give the possibility of the magnetic sensors to be installed. The speed of body and the lateral tracking should be controlled on an adequate way for the construction purpose.

CONCLUSION

The present work reports the preliminary results of an experimental work to build a system able to detect the landmines. The system consists of three main units; the sensors, the prototype car, and the control unit. The sensors include GPR antennas (1.5 GHz and 400 MHz), the fluxgate gradiometer, and the NBS (its results are not reported within this paper). A test site was prepared for the experiment wherein the different types of landmines, known in the Egyptian soil and provided by the Egyptian army, were planted. Escalade is a prototype car constructed by EAEA and the advisory of the geophysical team. The GPR measurements were done while the antennas were carried in the free hand, but elevated from the ground surface on a level close to the elevation of the carrier of Escalade, and as the antennas were installed on the Escalade’s carrier close to its proposed place close to the NBS receiver. It proofed its powerful ability to detect the mines in both cases. The measurements with fluxgate magnetic gradiometer were carried out on its normal way and could not be installed to the carrier due to the metal mass in the car body, its ability to detect the metal mines (some anti-tanks) is magnificent, while it is limited to detect plastic and wooden ones, it is mainly based on the metal content in the explosion system in the mine.

RECOMMENDATIONS

The present reported experiment resulted in remarks on the system elements;

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Humanitarian Demining and the Challenge of Technology

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Abstract- Landmines undermine peace and stability in whole regions by displacing people and inhibiting the use of land for production while subjecting people life to a continuous danger. Besides this, the medical, social, economic, and environmental consequences are immense. The variety of mines being used is enormous and a number of sources, such as pressure, movement, sound, magnetism, and vibration can trigger a landmine. What happens when a landmine explodes is also variable. Conventional landmines around the world do not have self-destructive mechanisms and they stay active for long time. Modern landmines are fabricated from sophisticated non-metallic materials. Humanitarian demining is a critical first step for reconstruction of post-conflict countries and it requires that the entire land area to be free of mines and hence it is necessary to locate and removes reliably and safely every single mine, and UXO from a targeted ground. Traditional military countermine solutions (techniques and equipment) are not directly applicable to humanitarian demining, largely because the philosophy and the standards for successful clearance are different. The problem associated with humanitarian demining is characterized by an enormous variability in the nature of explosive ordnance to be removed, climate diversity, and in the type of terrain and vegetation. Current demining is a dangerous, time consuming, and costly process. Hence, it becomes urgent to develop detection (individual mine, and area mine detection), identification and removal technologies and techniques to increase efficiency of demining operations by several orders of magnitude to achieve a substantial reduction to the threat of antipersonnel (AP) mines within a reasonable timeframe and at an affordable cost. Applying technology to humanitarian demining is a stimulating objective. To increase mine clearance daily performance by improving productivity and accuracy, and to increase safety of demining operations and personnel, there is a need for an efficient, reliable and cost effective humanitarian mine action equipment with flexible and modular mechanisms with adaptable mobility and equipped with some level of decision making capabilities. Most people in the mine clearance community would be delighted if the work could be done remotely through teleoperated systems or, even better, autonomously through the use of service robots. Detecting and removing AP mines seems to be a perfect application for robots. However, this needs to have a good understanding of the problem. Technologies to be developed should take into account the facts that many of the demining operators will have had minimal formal education and that the countries where the equipment is to be used have poor technological infrastructure for equipment maintenance, operation, and deployment. In addition, it is necessary to overcome the constrain on the resources by developing innovative, cost effective and practical technology inspired by locality and real minefield needs to help in speeding up the demining process and enhance accuracy, productivity, operation and personnel safety, achieve a higher quality of the service, and contribute to local economy.

Keywords: Humanitarian Demining, Mine Detection, Demining Robots, Mechanical Demining, Area Reduction

I. INTRODUCTION

Landmines (antipersonnel (AP) and anti-tank mines) and Explosive Remnants of War (ERW), which include unexploded ordnance (UXO) and abandoned explosive ordnance, represent a major threat to civilian. Landmines are prominent weapon and they are so effective, yet so cheap, and easy to make and lay on or just under the ground surface. A mine is detonated by the action of its target (a vehicle, a person, an animal, etc.), the passage of time, or controlled means. Anti-personnel (AP) mines can kill or incapacitate their victims. In addition, mines represent a substantial barrier to economical recovery and the return to normal life while they deny access to land, and its resources. Besides this, the medical, social, economic, and environmental consequences are immense (O’Malley, 1993; Blagden, 1993; Physicians for Human Rights, 1993; US Department of State, 1994; King, 1997; ICRC, 1998). The removal and destruction of all forms of dangerous battlefield debris, particularly landmines and other unexploded ordnance (UXO), are vital prerequisites for any region to recover from the aftermath of a war.

United Nation Department of Human Affairs (UNDHA) assesses that there are more than 100 million mines that are scattered across the world and pose significant hazards in more than 68 countries (O’Malley, 1993; Blagden, 1993; Physicians for Human Rights, 1993; US Department of State, 1994; King, 1997; Habib, 2002b). Currently, there are 2 to 5 millions of new mines continuing to be laid every year. The annual rate of clearance is far slower. The international Committee of
the Red Cross (ICRC) estimates that the casualty rate from mines currently exceeds 26,000 persons every year. It is estimated that 800 persons are killed and 1,200 maimed each month by landmines around the world (ICRC, 1996a; ICRC, 1996b; ICRC, 1998; Brennan & Woodruff, 2003). The primary victims are unarmed civilians and among them children are particularly affected. Worldwide there are some 300,000–400,000 landmine survivors and the number is increasing. Survivors face terrible physical, psychological and socio-economic consequences. Landmines undermine peace and stability in whole regions by displacing people and inhibiting the use of land for production while subjecting people life to a continuous danger. Besides this, the medical, social, economic, and environmental consequences are immense. The direct cost of medical treatment and rehabilitation exceeds US$750 million. This figure is very small compared to the projected cost of clearing the existing mines. The production costs of AP mines are roughly between 3 and 30 US$. But, the current cost rate of clearing one mine is ranging between 300-1000 US$ per mine (depending on the mine infected area and the number of false alarms).

The variety of mines being used is enormous including many with very small amounts of metal and that may have as little as 30 g of high explosive. A U.S. Army database made available to the United Nations, for example, contains profiles of 750 different types. What happens when a landmine explodes is also variable. A number of sources, such as pressure, movement, sound, magnetism, and vibration can trigger a landmine. AP mines commonly use the pressure of a person's foot as a triggering means, but tripwires are also frequently employed. Most AP mines can be classified into one of the following four categories: blast, fragmentation, directional, and bounding devices. These mines range from very simple devices to high technology (O'Malley, 1993; US Department of State, 1994). Some types of modern mines are designed to self-destruct, or chemically render themselves inert after a period of weeks or months. Conventional landmines around the world do not have self-destructive mechanisms and they stay active for long time. Modern landmines are fabricated from sophisticated non-metallic materials. New, smaller, lightweight, more lethal mines are now providing the capability for rapid emplacement of self-destructing antitank (AT) and AP minefields by a variety of delivery modes. These modes range from manual emplacement to launchers on vehicles and through both rotary and fixed-wing aircraft. Even more radical changes are coming in mines that are capable of sensing the direction and type of threat. These mines will also be able to be turned ON and OFF, employing their own electronic countermeasures to ensure survivability against enemy countermine operations. In addition, new trends have been recognized in having minefields with self-healing behavior. Such minefields will include dynamic and scatterable surface mines used to complicate clearance and preserve obstacles by embedding them with capability to detect breaching and simple mobility to change its location accordingly.

II. HUMANITARIAN DEMINING AND REQUIREMENTS

Humanitarian demining scenarios differ from military ones in many respects. The objectives and philosophy are different. Solutions developed for the military are generally not suitable for humanitarian demining. Humanitarian demining is a critical first step for reconstruction of post-conflict countries and it requires that the entire land area to be free of mines and hence the need to detect, locates, and removes reliably and safely every single mine, and UXO from a targeted ground. It is carried out in a post-conflict context, and the important outcome of humanitarian demining is to make land safer for daily living and restoration to what it was prior to the hostilities. In addition, it is allowing people to use their land without fear; allowing refugees to return home, schools to be reopened, land to be reused for farming and critical infrastructure to be rebuilt (Espirit HPCN, 1997; Bruschini et al., 1999; Habib, 2002b; Goose, 2004).

The standard to which clearance must be achieved is extremely high as there is a need to have at least 99.6% (the standard required by UNDHA) successful detection and removal rate (Blagden, 1993), and a 100% to a certain depth according to International Mine Action Standards (IMAS). The amount of time it takes to clear an area is less important than the safety of the clearance personnel and the reliability and accuracy of the demining process. Safety is of utmost importance, and casualties are unacceptable. Any system to be developed should compliment this effort, not to hamper it or simply move the problem elsewhere. The risks to those carrying out the task must also be maintained at a lower level than might be acceptable in a military situation. Another consideration by humanitarian demining is the use of land for development, i.e., there is a need to reduce the environmental impact that may results from the demining operation. The currently available technologies are not suited to achieve these objectives of humanitarian demining. Until now, detection and clearance in humanitarian demining very often relies on manual methods as primary procedure. The problem resides primarily in the detection phase first, and then how to increase productivity by speeding up demining process reliably and safely.

IV. DIFFICULTIES FACING MINE DETECTION AND CLEARANCE

Landmines are usually simple devices, readily manufactured anywhere, easy to lay and yet so difficult and dangerous to find and destroy. Landmines are remarkably durable, posing a threat years after the wars for which they were laid have ended. They are harmful because of their unknown positions and often difficult to detect. The problem associated with humanitarian demining is characterized by an enormous variability in
the nature of explosive ordnance to be removed, climate diversity, and in the type of terrain and vegetation. There is wide range of terrains (rocky, rolling, flat, desert, beaches, hillside, muddy, river, canal bank, forest, trench, etc.) whereas mines are often laid. The environmental conditions may cover different climate (hot, humid, rainy, cold, windy), the density of vegetation (heavy, medium, small, none), and type of soil (soft, sand, cultivated, hard clay, covered by snow, covered with water). In addition, residential, industrial and agriculture areas, each has its own features and needs to be considered. Landmines are many in terms of type and size. AP mines come in all shapes and colors are made from a variety of materials, metallic and nonmetallic. Metal detector works well with metal cased mines, but metal in modern mines has been increasingly replaced by plastic and wood as countermeasure to metal detector that making them undetectable by their metallic content. There are other methods to detect explosives and landmines. However, most of them are limited by sensitivity and/or operational complexities due to type of terrain and soil composition, climatic variables, and ground clutter, such as, shrapnel and stray metal fragments that produce great number of false positive signals and slow down detection rates to unacceptable levels. AP mines can be laid anywhere and can be set off in a number of ways because the activation mechanisms available for these mines are not the same. Activation methods can be classified into three categories, pressure, electronic, and command detonation (remote control). Mines may have been in place for many years, they might be corroded, waterlogged, impregnated with mud or dirt, and can behave quite unpredictable. Some mines were buried too deep to stop more organized forces finding them with metal detectors. Deeper mines may not detonate when the ground is hard, but later rain may soften the ground to the point where even a child’s footstep will set them off. Trip-wires may be caught up in overgrown bushes, grass or roots. In addition, there is no accurate estimate on the size of the contaminated land and the number of mines laid in it.

IV. HUMANITARIAN DEMINING AND THE CHALLENGE OF TECHNOLOGY

Traditional military countermine techniques and equipment are not directly applicable to humanitarian demining, largely because the philosophy and the standards for successful clearance are different. Humanitarian demining demands that all the landmines (especially AP mines) and ERW affecting the places where ordinary people live must be cleared, and their safety in areas that have been cleared must be guaranteed. The canonical approach to humanitarian demining aims to have efficient tools that can accurately detect, locate and deactivate/remove every single landmine and other UXO as fast and as reliable and safe as possible while keeping cost to a minimum level. Any instrument for this process must be 100% reliable for the safety of the operators and the people whom will use the cleared land. The efficient fulfillment of such task with high reliability represents vital prerequisites for any region to recover from landmines and associated battlefield debris by making land safer and allows people to use it without fear.

Although demining has been given top priority, currently mine’s detection and clearing operation is a labor-intensive, slow, very dangerous, expensive, and low technology operation. Hence, it becomes urgent to develop detection (individual mine, and area mine detection), identification and removal technologies and creative techniques to reduce false alarms, increase efficiency of demining operations to achieve a substantial reduction to the threat of landmines within a reasonable timeframe and at an affordable cost.

Current demining operation relies on careful search of mined areas with a hand held decotor (the most widely used is the handheld metal detector). The other bottleneck in humanitarian demining is often the tedious exploratory probing and delicate excavation, and it that is required after a mine detector has located mine candidates. The current rate of humanitarian mine clearing is about 100 thousand per year. It is estimated that the current demining rate is about 10-20 times slower than the laying rate, i.e., for every mine cleared 10-20 mines are laid. Therefore, to stabilize the mine situation, it is necessary to increase the current capability of mine clearance by 10-20 times.

The diversity of the mine threat points out to the need for different types of sensors and equipment to detect and neutralize landmines. The requirements to develop equipment for use by deminers with different training levels, cultures, and education levels greatly add to the challenge. The solution to this problem is very difficult because, given the nature of landmines and the requirements of humanitarian demining, as any instrument must be 100% reliable for the safety of the operators and the people whom will use the land (Blagden, 1993; Habib 2002b). Hence, it becomes urgent to develop detection (individual mine, and area mine detection), identification and removal technologies and techniques to increase the efficiency of demining operations by several orders of magnitude to achieve a substantial reduction to the threat of AP mines within a reasonable timeframe and at an affordable cost.

Technology has become the solution to many long-standing problems, and while current mine detection and clearance technologies may be effective, it is far too limited to fully address the huge complex and difficult landmine problem facing the world. The challenge is in finding creative, reliable and applicable technical solutions in such highly constrained environment. Applying technology to humanitarian demining is a stimulating objective. Detecting and removing AP mines seems to be a perfect application for robots. However, this need to have a good understanding of the problem and a careful analysis must filter the goals in order to avoid deception and increase the possibility of achieving results (Nicoud, 1996). In order to approach proper and practical solutions for the problem, there is a need for the scientists in each discipline and deminers to share their
knowledge and the results of their experience and experiments in order to design and test viable solutions for humanitarian demining. Technologies to be developed should take into account the facts that many of the demining operators will have had minimal formal education and that the countries where the equipment is to be used have poor technological infrastructure for equipment maintenance, operation, and deployment. Greater resources need to be devoted to demining both to immediate clearance and to the development of innovated detection and clearance equipment and technologies. There is an urgent need to speed up the development to have compact and portable, low cost, technically feasible, fast response, safe, accurate, reliable, and easy to operate mine detector systems with flexible mobile platforms that can be reliably used to detect all types of available landmines and support fast and wide area coverage. Appropriate mine clearance technologies are those inexpensive, rugged, and reliable technical products, processes and techniques that are developed within, or should be transferred for use in mine-affected areas. These technologies should be cheap enough to be purchased within the regional economy and simple enough to be made and maintained in a small workshop. We should favor technologies that can be manufactured in mined countries; technologies that are transferable, and which provide employment and economic infrastructure where it is most urgently required.

V. DEMINING TECHNIQUES AND THE AVAILABLE TECHNOLOGIES

Mine clearance itself can be accomplished through different methods with varying levels of technology and accuracy, but the most laborious way is still the most reliable. Currently, almost all humanitarian mine clearance is still required to apply hand clearance method that uses ‘prodding’ or ‘probing’ within its loop to assure high reliability. Manual probing is slow, labor intensive and extremely dangerous and stressful process.

1. Mechanical Equipment and Tools for Mine Clearance

A good deal of research and development has gone into motorized mechanical mine clearance in which their design is influenced by the military demining requirements. The use of such machines aims to unearth mines or force them to explode under the pressure of heavy machinery and associated tools and to avoid the necessity of deminers making physical contact with the mines. A number of mechanical mine clearing machines have been constructed or adapted from military vehicles, armored vehicles, or commercially available agriculture vehicles of the same or similar type, with same or reduced size (Habib, 2001b). A single mechanical mine clearance machine can work faster than a thousand deminers over flat fields. They are mostly appropriate and cost effective in large and wide areas without dense vegetation or steep grades. In small paths or thick bush, such machines simply cannot maneuver. Mechanical clearance equipment is expensive and it cannot be used on roadsides, steep hills, around large trees, inside a residential area, soft terrain, heavy vegetation or rocky terrain. Mobility and maneuverability where wheeled vehicles cannot travel efficiently on anything other than flat surfaces, tracked vehicles cannot travel in areas with steep vertical walls, machines in general cannot climb undefined obstacles, and machines cannot in general deform to get through narrow entrances. In addition, mechanical clearance has its own environmental impact such as erosion and soil pollution. The logistical problems associated with transporting heavy machinery to remote areas is critical in countries with little infrastructure and resources.

In general, none of the equipment within this category has been developed specifically to fulfill humanitarian mine clearance objectives and for this, there is no form of any available mechanical mine clearance technologies that can give the high clearance ratio to help achieving humanitarian mine clearance standards effectively while minimizing the environmental impact. However, to achieve better clearance rate, these machines can be used in conjunction with dog teams and/or manual clearance team, which double check an area for remaining mines. A number of mechanical mine clearing machines have been tested during the past. The general trend goes from “mechanical demining” towards “mechanically assisted demining”, adaptable to local circumstances. Some examples of mechanical clearance equipment include but not limited, Vegetation cutters, Flails and Light-Flails, Panther mine clearing vehicle, Armored bulldozer, Ploughs and the rake plough, the M2 Surface “V” mine plow, Earth tillers, Mine sifter, Armored wheel shovel, Mine clearing cultivator, Floating mine blade, Rollers, Mine-proof vehicles, Swedish Mine Fighter (SMF), Armored road grader, etc. (US Department of Defense, 1999; Humanitarian Mine Action Equipment Catalogue, 1999; Department of Defense, 2002; Habib, 2002a; Geneva Centre for Humanitarian Demining, 2006).

In addition, vegetation is a large problem facing demining (mainly in tropical countries) and often poses major difficulties to the demining efforts. The vegetation removal can take up a substantial fraction of the time and for this there is a need to properly mechanized vegetation cutting and removal. These machines should be designed to cut down on the time required for demining. In their simplest form, vegetation cutters consist of adequately modified commercial devices (e.g. agricultural tractors with hedge cutters or excavators). There is an urgent need for effective vegetation clearance technology and techniques that avoid detonating mines. Cost effective and efficient clearance techniques for clearing both landmines and vegetation have been identified as a significant need by the demining community.

2. Mine Detection and Sensing Technologies

The main objective of mine detection is to achieve a high probability of detection rate while maintaining low probability of false alarm. The probability of false alarm rate is directly proportional to the time and cost of
demining by a large factor. Hence, it is important to
develop more effective detection technology that speed
up the detection process, maximize detection reliability
and accuracy, reduce false alarm rate, improve the ability
to positively discriminate landmines from other buried
objects and metallic debris, and enhance safety and
protection for deminers. In addition, there is a need to
have simple, flexible and friendly user interaction that
allows safe operation without the need for extensive
training. Such approach needs to incorporate the strength
of sensing technologies with efficient mathematical,
theoretic approaches, and techniques for analyzing
complex incoming signals from mine detectors to
improve mine detectability. This leads to maximize the
performance of the equipment through the optimization
of signal processing and operational procedures.
Furthermore, careful study of the limitations of any tool
with regard to the location, environment, and soil
composition is critically important besides preparing the
required operational and maintenance skills. It is
important to keep in mind that not all high-tech solutions
may be workable in different soil and environmental
conditions. The detection technologies are presently in
varying stages of development. Each has its own strength
and weaknesses. The development phase of new
technologies requires a well-established set of testing
facilities at the laboratory level that carried out in
conditions closely follow those of the mine affected area,
and at the real site. This should be followed by having
extensive field trials in real scenarios to validate the new
technologies under actual field conditions for the purpose
to specify benefits and limitations of different methods.
The work must be performed in close cooperation with
end-users of the equipment and real deminers should
carry out the test at a real site, in order to ensure that the
developments are consistent with the practical
operational procedures in the context of humanitarian
demining, and that it is fulfilling user requirements. In
addition, there is a need to have reliable process of global
standard for assessing the availability, suitability, and
affordability of technology with enabling technology
represented by common information tools that enable
these assessments and evaluations. The benchmarking is
going to enhance the performance levels that enable the
development of reliable and accurate equipment, systems
and algorithms.
Methods of detecting mines vary from, simple in
technology but exhaustive searching by humans using
some combination of metal detectors and manual probing,
to a variety of high biological and electronic technologies.
The effectiveness of metal detectors can be inhibited by
mines with extremely low metal content or by soils with
high ferrous content and hence other detection techniques
have been and are being investigated. Another technique
that is widely used is the direct detection of explosive
material by smell using a dog (Sieber, 1995). Trained
dogs are the best known explosive detectors but they
need excessive training and inherently unreliable because
they are greatly impeded by windy conditions, and have
only 50-60% accuracy.

New technologies are being investigated to improve the
reliability and speedup the detection operation, some of
these technologies are: Electromagnetic Induction Metal
detectors (EMI), Infrared Imaging, Ground-Penetrating
Radar (GPR), Acoustics, Acoustic Imaging, Thermal
Neutron Activation (TNA), Photocoustic Spectroscopy,
Nuclear Quadrupole Resonance (NQR), X-ray
Tomography, Neutron Back-scattering, Biosensors,
Commercial sniffers, etc. (Healy & Webber, 1993; Van
Westen, 1993; Hewish & Ness, 1995; Sieber, 1995;
Currently, there is no single sensor technology that has
the capability to attain good levels of detection for the
available AP mines while having a low false alarm rate
under various types of soil, different weather, all types of
mines, natural and ground clutters, etc. If one sensor can
detect a mine with a certain success rate coupled with a
certain probability of generating a false alarm, could two
sensors working together do a better job? The idea of
developing multi sensor solutions involving two or more
sensors coupled to computer based decision support
systems with advanced signal processing techniques is
attractive and is advocated by many as a fruitful line of
development. Hence, there is a need to use
complementary sensor technologies and to do an
appropriate sensor data fusion. The ultimate purpose is to
have a system that improves detection, validation and
recognition of buried items for the purpose to reduce
false alarm rates and to overcome current landmine
detection limitations. A promising solution will be to
apply fusion of sensory information on various sensor
outputs through the use of advanced signal processing
techniques, by integrating different sensor technologies
reacting to different physical characteristics of buried
objects. Critical to demining is the ability to distinguish
fragments or stones from the target material in real time.
Sensor fusion using soft computing methods such as
fuzzy logic, neural networks and rough set theory must
be further explored and computationally inexpensive
methods of combining sensory data must be designed.
These methods should also have the capability to assess
the quality of the mined area once the mines have been
cleared.

3. Robotized solution for Mine detection and Clearance

Developing and applying technology to humanitarian
demining is a stimulating objective. To increase mine
clearance daily performance by improving productivity
and accuracy, and to increase safety of demining
operations and personnel, there is a need for an efficient,
reliable and cost effective humanitarian mine action
equipment with flexible and modular mechanisms,
adaptable mobility and equipped with some level of
decision making capabilities. Most people in the mine
clearance community would be delighted if the work
could be done remotely through teleoperated systems or,
even better, autonomously through the use of service
robots. Searching and removing AP mines seems to be a
perfect application for robots. However, this need to have
a good understanding of the problem and a careful
analysis must filter the goals in order to avoid deception and increase the possibility of achieving results. Many efforts have been recognized to develop effective multi operational mode robots for the purpose to offer flexible, cheap and fast solutions. It is important to remind ourselves that there is little value in a system that makes life safer for the operators but will be less effective at clearing accurately and reliably the ground. In their current status, they are not flexible and cost effective solution for mine clearance. But, if designed and applied at the right place for the right task, they can be attractive and effective solutions. Three main directions can be recognized in development within this category: Teleoperated machines, Multifunctional teleoperated robot, and Demining service robots.

VI. CONCLUDING REMARKS: HUMANITARIAN DEMINING AND THE TECHNICAL NEEDS

Demining is a time consuming process while it is subjecting deminers to high risks. With the current technology and techniques, clearing all known mined areas would take decades or centuries, even if no additional mine is laid. Based on what has been presented and in order to have effective approach in tackling this complicated problem, with aims to accelerate the demining process, increase daily performance, improving productivity and accuracy, enhance safety of demining operations and personnel, and to achieve cost effective measures, there is a need to have innovative and efficient technology and techniques within the following areas,

1. Demining is very costly and searching an area that is free of mines is adding extra high cost and wasting resources. Hence, to avoid that, the first essential objective in the demining process should be to identify efficiently what areas are polluted by mines. Locating the contaminated land helps to separate the danger from people and makes the uncontaminated land available for use immediately. In order to accelerate the mine clearance process, and save resources new demining methods are urgently needed to detect minefields over large and varied tracts of land in a much more cost effective, efficient, safe and reliable manner. It is important to have reliable methods that can reduce mine suspected areas. Unmanned Aerial Vehicles (UAVs) and Air-ships are integrated with remote sensing technology and sensor fusion techniques to help reducing mine suspected area and isolate the danger of mines while producing important risk assessment maps.

2. The critical element to humanitarian demining is the detection and location of every single mine. Mine detection represents the slowest and the most important step within the demining process, and the quality of mine detector affects the efficiency and safety of this process. Hence, there is a need to have practical and reliable technology that can single out mine from other objects and natural clutters, work under different climate and terrain, while it would be possible to efficiently perform without cutting vegetation.

3. It is necessary increase productivity and efficiency by having reliable and cost effective humanitarian mine action equipment with flexible mechanism and adaptable mobility, multiple operational modes, and some level of decision making capabilities. Such equipment should have selectable sets of mine detectors and work to locate and mark individual mines precisely, and at a later stage to neutralize the detected mines. Such equipment would be useful in quickly verifying that an area is clear of landmines so that manual cleaners can concentrate on those areas that are most likely to be infested. It is important to remind ourselves that there is little value in a system that makes life safer for the operator but which will be less effective at clearing accurately and reliably the ground.

The development of such systems should be done with close cooperation and interaction with deminers in the field, and the resultant system must be inexpensive with possible use of locally available materials, and easy to use with minimal training by locals. In addition, these systems must be flexible and modular with proper logistical consideration to address a variety of clearance tasks and for case-by-case scenarios.

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Legged Robot - Animal Cooperation to Trace Smell Gradients in Minefields

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Abstract

This paper proposes an animal-robot cooperative system to trace smell gradients leading to landmines. The key benefit of the proposed method is that it removes the requirement for a human to be in the minefield. This reduction of risk directly results in a drastic improvement in the efficiency of demining. The animal used in this case is a rodent called mongoose, that exerts contact forces below the general threshold (<7kg) needed to set off anti-personal mines. The legged robot has been designed to navigate under force constraints in tropical minefields with soft terrain conditions. Therefore the system as a whole works within the safety constraints. The overall behavior arbitration is done by a human through a wireless data link. The arbitration involves managing the mutually conflicting objectives of getting the robot to constrain the mongoose’s movements and being complaint to the intuition of the mongoose to trace smell gradients. The system has been tested in a real minefield in Sri Lanka.

1. INTRODUCTION

Among an array of technologies available to detect anti-personal landmines, the most common technology used is metal detection [1]. Since it uses “eddy” currents induced in metal parts of a mine, it is prone to give false alarms for any metallic object such as shell fragments, bullet cases, and other metal debris usually found in mine fields. Furthermore, it is difficult to tune in laterite rich soil or conductive soil (red soil, sea beaches etc.), and there can be false alarms due to electromagnetic interference. Another method is ground Penetrating Radar (GPR) [2],[3]. It uses a microwave that penetrates the ground. The reflected wave can be used to identify differences in the dielectric properties of objects in the soil. However, GPR is seldom used in practice due to it heavy cost. Moreover, it gives false alarms for roots, rocks, water pockets etc. However, the resolution and penetration can be managed by changing the frequency. Resolution is high at elevated frequencies, and penetration is high at low frequencies.

Trace explosive detection systems is also another research area. Here, samples of soil have to be obtained and the detection is done based on a chemical reaction or a mass-spectroscopy measurement [5] – [7]. This method is slow to respond. Therefore, it is difficult to sweep an area as fast as with a metal detector. Other related technologies such as biosensors [8], [9], also suffer from same drawbacks in addition to being too expensive for most demining projects in developing countries. Siesmo-acoustic methods that detect density differences in the ground maybe good for area reduction, though mines with different ages will have different seismic signatures [10].

This work was motivated by the need to have a system that can trace gradients of the smell of explosives from a fair distance to the landmine in order to do area reduction efficiently. Most of the methods discussed above require the user to take the sensor right on top of the mine. This forces deminers to sweep the whole area to ensure safety. Obviously animals whose survival predominantly depends on olfaction use smell gradients to move in hostile environments, and to find food.

The commonly used animal for sniffing is the dog. However, dogs perform well when the master is behind it. It is a well known fact that humans tend to slow down the movement in the minefield due to the heavy risk involved. Rats have been used to sniff and detect Tuberculosis Bacteria in human sputum samples. Rats have limited stamina and tend to prefer dark hiding places. Therefore they can not cover large areas and work continuously. Therefore, we selected a rodent called a mongoose available in abundance in the North and the East of Sri Lanka. It is said to have the third most sniffing ability among animals, only being less than that of elephant and pig. Furthermore unlike dogs, it has a powerful sniffing ability in upward direction. A legged robot that can navigate on soft terrain conditions was designed in order to move the rodent along desired paths in the minefield.

The rest of this paper is organized as follows. Section 2 elaborates the reward based training of a rodent called mongoose to detect explosives, section 3 describes the design details of the legged mobile robot, section 4 discusses the animal-robot combined system, and section 5 presents the experimental results in an outdoor environment and a discussion on future research directions.
2. REWARD BASED LEARNING OF A MONGOOSE TO DETECT EXPLOSIVES

PHASE -1: CONDITIONING SMELL, REWARD, AND SOUND

The objective of phase-1 was to study the general response of the mongoose to the exposure of explosives, a food reward, and a sound. Small amount of C4 explosives (< 1g) wound to one end of a stick was brought closer to the mongoose. If the mongoose came closer to the stick, a “beep” sound was given with a slice of cheese as the reward. This was repeated 20 times a day. Following figure 1 shows how the mongoose improved during the experiment.

Figure 1: The learning curve of the 1st phase. The graph shows the % success rate out of 20 trials a day.

PHASE -2: LEARNING IN A PARADIGM WHERE THE DEGREE OF DIFFICULTY OF CORRECT CLASSIFICATION WAS PROGRESSIVELY INCREASED

In the second phase, 40 trials were tested each day. The number of times a stick with explosives was presented decreased from 26 to 9 out of 40 trials. The cage was covered with a black polyester cloth to remove any biases due to visual cues. Therefore, in this paradigm the difficulty of making a correct detection increased over time. Despite this progressively growing difficulty, the mongoose was able to improve the detection capability to near perfect levels within two weeks as shown in figure 2. To the best of our knowledge, this is the first time such quantified data characterizing the learning curve of the rodent called mongoose has been presented.

Figure 2: The learning curve of the 2nd phase. The graph shows the % success rate out of 40 trials a day.

At present the mongoose has become able to distinguish among several smells.

3. THE LEGGED ROBOT

Legged robots perform better than wheeled or tracked robots in natural environment due to the manner each locomotion method deforms and interacts with soft soil. Wheels tend to deform the soil to make an upward slope just in front of it. Therefore, there is a ground reaction force against the direction of motion. Tracks increase the friction in soft soil. Legs tend to deform the soil to make a ground reaction force in the direction of motion. In addition to the above advantage, it is easy to design legs to integrate energy in spring-like mechanisms to take advantage of the dynamic reactions with different ground profiles. Furthermore, legged locomotion can easily cover the full spectrum of mobility from slow walking, running, galloping, to hopping. Therefore, recently there has been an increased interest on legged locomotion of robots [11], [12].

However, the biggest disadvantage of legged locomotion is the number of degrees of freedom required to have a stable movement and the resulting complexity of the controllers. The unique advantage of the robot being discussed in this paper is that it is driven by just two motors though it consists of eight legs. The robot moves by twisting the body around two Hook joints as shown in figure 3. The robot consists of two identical modules working side by side. Each module is driven by one motor. The robot turns by differential velocity control of the two motors.
Figure 3: The overall kinematic structure of the robot.

Figure 4 shows the relationship between the angular velocity of the motor shaft and the loci of the legs. It is clear from this schematic diagram that this kinematic segment that works as the building block of the robot is a very simple mechanism. It gives rise to a more complex movement when two of them are coupled through a Hook joint. When four of them are coupled as shown in figure 3, the robot has adequate compliance to adapt to the terrain conditions without giving any burden to the controller to adapt the gait patterns to suit the terrain conditions. It could be seen on field trials that the robot’s behaviors were different from one terrain to the other with no additional tuning of the controllers.

\[ \dot{\theta} = N\dot{\alpha} \]

Figure 4: One segment of the leg movement mechanism

Figure 5 shows the detailed configuration of the leg assembly. The axis of the mid segment of the leg goes through the center of the sphere. The sphere rotates around AA axis. Let \( r \) be the radius of the sphere containing the legs of the robot, \( l_1 \) be that portion of the leg above the knee, \( l_2 \) be that portion of the leg bellow the knee, \( AA \) be the axis around which the sphere rotates, \( \beta \) be the angle between the axis that goes through the center of the sphere parallel to that portion of the leg above the knee and the axis \( AA \), \( \theta \) be the angle that the sphere rotated from the vertical axis, \( \gamma \) be the angle between the upper portion and the lower portion of a leg at the knee, \( \alpha \) be the angle rotated by the motor shaft, \( N \) be the gear ratio at the point connecting the motor shaft and the sphere, and \( \delta \) be the twist of one section of one module of the robot relative to the other section when a pair of legs are rotated by \( \varphi \) on the horizontal plane.

Then, the angular speed of one section relative to the other around the axis BB is given by \( \left( \frac{\varphi}{\pi} \right) N\dot{\alpha} \).

Distance between \( O \) and \( p \) is given by

\[ 2[l_1 \cos \gamma + (l_1 + r)] \]

Figure 5: The kinematic relationship of the co-centric leg movement.

Figure 6 shows the finished robot. The box attached to the rear of the robot contains the battery and electronic circuit boards. The chassis is made of aluminium. Figure 7 shows the schematic diagram of the robot’s motherboard. Two embedded microprocessors map perception derived from the angle sensor attached to the mongoose, metal detector,
bumper switches, and the sonar sensor, to behaviors by controlling the two motors.

**Figure 7:** The motherboard of the robot

### 4 ANIMAL-ROBOT COMBINED SYSTEM

The purpose of building an animal-robot integrated system is to derive a synergy out of the individual strengths of an animal and a robot to navigate in a forest environment looking for landmines.

**The strengths of the rodent:**

1. Powerful olfactory capability that enables the animal to walk along smell gradients.
2. Dexterous navigation skills in forest environments.
3. Weigh below the threshold to set off a mine. Furthermore, this allows a light weight robot to restrict its movements.

**Strengths of a walking robot:**

1. Efficient locomotion in soft soil conditions (muddy, sandy, grassy, etc.).
2. Can communicate data and images to a remote location.
3. Can restrict the animal’s movements to desired paths.
4. Can learn from the animal to navigate in cluttered environments.

The detailed navigation algorithm was presented in an earlier paper [11]. The summary is shown in figure 9. The robot uses an array of sonar proximity data to calculate the statistical properties of the environment immediately in front of it. Having obtained the sparcity information of the environment, it classifies the it into one out of a bank of pre-defined classes. Thereafter, it computes the best behaviour in the given environment. Fine details of navigation is negotiated using tactile sensing. In addition to these autonomous behaviours, the robot can continuously tune its internal models by comparing its behaviours with that of the rodent walking in front of it using the potentiometer readings of the relative angle between the heading direction of the robot and the rodent.

**Figure 8:** The animal-robot combined system

**Figure 9:** The navigation algorithm of the animal-robot combined system.

Following figure 10 shows the proposed error feedback based behavior learning paradigm. It works by comparing the behaviors recommended by the internal models of the robot with the actual decisions taken by the rodent. It proved to be a very simple but powerful mechanism. One of the most crucial problems faced by many learning algorithms for outdoor
robot navigation is the difficulty to construct a cost function to be minimized, due to the unstructured nature of the natural environments. For instance, even a very simple task like obstacle avoidance expands to a daunting coding problem if the robot is required to move through trees of a forest, because virtually every plant is an obstacle.

However, the proposed algorithm discussed in detail in [13] only looks at the statistics of the distribution of trees in the environment to classify it into different classes. In each class, the robot implements one out of a bank of behaviors. These behaviors are further tuned by comparing the intricate details of the behavior with that of the rodent.

5. EXPERIMENTAL RESULTS AND DISCUSSION

Experiments were carried out in a typical minefield in collaboration with the 4th engineers’ brigade of the Sri Lanka army. Minute traces of C4 explosives (<1g) were buried within a circle of 2m around a starting point. The ageing of the mines were simulated by watering the ground for one week and allowing it to dry down. We expected this to create a near Gaussian smell gradient in the ground surrounding the buried explosives. The animal-robot combined system was released from the origin. The position data were samples every 1 sec. The following figure 11 shows how the system traced the smell gradients for five different target locations. To the best of the authors knowledge, this is the first time such olfactory guided behavior has been reported for an animal-robot combined system.

Inspections in the minefields of the North and the East of Sri Lanka helped us to understand that landmines are buried according to certain patterns. One such commonly used pattern is shown in the following figure 12. Three lines of mines are buried parallel to a forward defence line (FDL). In a given line, mines are buried in a T-shaped pattern.

This pattern can be modeled by three parameters and their variances given by

\[
p_i^m = R \left[ N \left( \frac{C_1}{2}, \sigma_{c_1}^2 \right) \right]^{N \left( \frac{C_2}{2} (1-(-1)\alpha^*), \sigma_{c_2}^2 \right)}
\]

Where, \( p_i^m \) is the coordinates of the \( i^{th} \) mine, \( \alpha, \sigma_{\alpha} \) are the angle between the FDL and the line of mines and its variance, \( \alpha^* \) is the expected value of that angle, \( C_1, \sigma_{c_1} \) are the horizontal distance between two mines and its variance, \( C_2, \sigma_{c_2} \) are the distance between the top row and the bottom row and its variance. The uncertainty of the locations of mines parameterized by \( \sigma_{c_1}, \sigma_{c_2} \) arise from natural disturbances like rain, tree roots, mud slides, etc. The uncertainty of the angle of the mine front quantified by \( \sigma_{\alpha} \) comes from the loss...
of landmarks due to ageing. Figure 13 shows the case where, \[ \alpha = \pi / 6, C_1 = C_2 = 1, \sigma_{C_1} = \sigma_{C_2} = \sqrt{0.1}, \sigma_\alpha = 0. \]

Therefore, detection of landmines can be accelerated if the above parametric model can be identified as fast as possible. This can be done by a distributed sensing mechanism supported by a swarm of light weight field robots that can traverse in the mine field without detonating mines (< 7kg per contact point). Future research will be directed to estimate the above field parameters on-the-go when a swarm of animal-robot combined system traverses in a mine field.

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DATA ASSOCIATION FOR ROBOT LOCALIZATION IN SATELLITE IMAGES

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ABSTRACT

Autonomous navigation of robots has been of immense research interests since the beginning of robotics. Much progress has been made in the area but a fully functional autonomous navigation system has yet to be developed. To reach a reasonable degree of autonomy, two basic requirements are needed: sensing and reasoning. Sensing is provided by an on board sensory system that gather information about the robot itself and the surrounding environment. According to the environment state, the reasoning system must allow the robot to localize itself in the environment and to seek for free paths.

This paper presents an algorithm capable of combining data from different sensors to localize an outdoor autonomous mobile robot in a user defined global coordinate frame on geo-referenced images. The algorithm uses an Extended Kalman Filter EKF to integrate information data from stereo-camera images, wheel encoders, steering angle encoder, and GPS to build a map for the environment and localize the robot in satellite images. The user can then communicate with the robot to define a final goal (target) using only the satellite images.

1. INTRODUCTION

Localization is the problem of finding out where a robot is, based on sensory data. This problem can be divided into two sub-tasks: global and local localization.

In many applications an initial estimation of the robot pose (position and orientation) is known (supplied directly or indirectly from the user). During the execution of a task, the robot must update this estimate using measurements from its sensors. This is known as local localization [1].

Using only sensors that measure relative movements, the error in the pose estimate increases over time as errors are accumulated. Therefore external sensors are needed to provide information about the absolute pose of the robot. This is achieved by matching the sensors measurements with a model of the environment.

On the other hand, global pose estimation [2, 3] is the ability to determine the robot’s pose in an a priori or previously learned map, given no other information than that the robot is somewhere on the map, i.e., it can handle the kidnapped robot problem, in which a robot is kidnapped and carried to some unknown location. Global localization is considerably more difficult than pose tracking because of the data association problem. The level of complexity of this task varies with the size of the environment, but also with the level of symmetry in the environment. It is only by integrating large amounts of data over time that these symmetries can be resolved.

In this work, we focus on data association from different type of sensors for a more precise global localization of a mobile robot. The robot receives data from a GPS, an onboard stereo-camera, wheel encoders, and an inertial sensor. It uses an Extended Kalman filter to integrate those data and localizes itself in geo-referenced images. The algorithm starts first by extracting useful information from images obtained by the stereo-camera system to recognize places in the scene. The extracted information from images are scale invariant feature transform point SIFT [4]. Those features are saved in the system state vector and their position is updated based on the data from the other sensors.

The rest of the paper is organized as follows: sections II and III give a detailed description of the proposed algorithm. Section III explains the algorithm implementation, and finally a conclusion section encloses the paper and gives some perspectives for this work.
2. Feature Extraction and System Modelling

In our application, a stereo-camera is fixed on the top of a mobile car-like robot "ROBUDEM" (fig.1). The vehicle travels through the environment using its sensors to observe features around it. A world coordinate frame is defined such that its X and Z axes lie in the ground plane, and its Y axis point vertically upwards. The system state vector of the stereo-camera in this case is defined with the 2D position vector \( \mathbf{y}_R = (y_1, y_2) \) of the head center in the world frame coordinates (its position in the Y direction being constant) and the robot's orientation relative to the Z axis, \( \gamma \).

\[
\mathbf{y}_R = \begin{bmatrix} y_1 \\ y_2 \\ \gamma \end{bmatrix}
\]

Fig. 1. The "ROBUDEM" platform

The dynamic model or motion model is the relationship between the robot's past state, \( \mathbf{y}_R^{t-1} \), and its current state, \( \mathbf{y}_R^t \), given a control input \( u^t \):

\[
\mathbf{y}_R^t = f(\mathbf{y}_R^{t-1}, u^t, \mathbf{v}^t) \quad (1)
\]

Where \( f \) is a function representing the mobility, kinematics and dynamics of the robot (transition function) and \( \mathbf{v} \) is a random vector describing the unmodelled aspects of the vehicle (process noise such as wheel sleep or odometry error).

The system dynamic model in our case, considering the control \( u \) as identity, is given by:

\[
\mathbf{y}_R^t = \begin{bmatrix} y_1^t \\ y_2^t \\ \gamma^t \end{bmatrix} = \begin{bmatrix} (y_1^{t-1} + (\nu^{t-1} + \mathbf{v}) \cos(\gamma^{t-1}) \Delta t) \\ (y_2^{t-1} + (\nu^{t-1} + \mathbf{v}) \sin(\gamma^{t-1}) \Delta t) \\ \gamma^{t-1} + (\omega^{t-1} + \Omega) \Delta t \end{bmatrix}
\]

\( \nu \) and \( \omega \) are the linear and the angular velocities, respectively. \( \mathbf{v} \) and \( \Omega \) are the Gaussian distributed perturbations to the camera's linear and angular velocity, respectively.

Usually the features used in vision-based localization algorithms are salient and distinctive objects detected from images. Typical features might include edges, object contours, corners etc. In our work, the map features are obtained using the SIFT feature detector [4], which maps an image data into scale-invariant coordinates relative to local features. These features were contemplated to be highly distinctive and invariant to image scale and rotation. The work of Mikolajczyk and Schmid [5] proved that SIFT features remain stable to age scale and rotation. The work of Mikolajczyk and Schmid [5] proved that SIFT features remain stable to illumination.

Feature are represented in the system state vector by their 3D location in the world coordinate system W:

\[
\mathbf{x}_i = (x_{1,i}, x_{2,i}, x_{3,i})^T
\]

The observation model describes the physics and the error model of the robot’s sensor. The observations are related to the system state according to:

\[
\mathbf{z}_i^t = \mathbf{h}(\mathbf{x}_i) + \mathbf{w}_i^t \quad (3)
\]

Where \( \mathbf{z}_i^t \) is the observation vector at time \( t \) and \( \mathbf{h} \) is the observation model. The vector \( \mathbf{z}_i^t \) is an observation at instant \( t \) of the \( i \)th landmark location \( \mathbf{x}_i^t \) relative to the robot’s location \( \mathbf{y}_R^t \).

Making a measurement of a feature \( i \) consists of determining its position in the camera image. Using a perspective projection, the observation model in the robot coordinate system obtained as follows:

\[
\mathbf{z}_i^t = \mathbf{h}(\mathbf{x}_i) = \begin{bmatrix} x_0 + f \frac{R_{x_{1,i}}}{R_{x_{3,i}}} \\ y_0 + f \frac{R_{y_{2,i}}}{R_{y_{3,i}}} \end{bmatrix}
\]

where \( x_0 \) and \( y_0 \) are the image center coordinates and \( f \) is the focal length of the camera.

\( R_{x_{k,i}} = (R_{x_{1,i}}, R_{x_{2,i}}, R_{x_{3,i}})^T \) are the coordinates of the feature \( i \) in the robot coordinate frame R. They are related to \( \mathbf{x}_i \) by:
The depth coordinate of the detected features is estimated by feature matching between the stereo-camera images. The matching is based on a hypothesis

$$R_{x_i} = \begin{pmatrix} \cos(\gamma) & 0 & -\sin(\gamma) \\ 0 & 1 & 0 \\ \sin(\gamma) & 0 & \cos(\gamma) \end{pmatrix} \begin{pmatrix} x_{1,i} - y_1 \\ x_{2,i} - h \\ x_{3,i} - y_2 \end{pmatrix}$$

(5)

$h$ is the high of the camera.

The depth coordinate of the detected features is estimated by feature matching between the stereo-camera images. The matching is based on a hypothesis

$$\mathcal{H}^t = [h^t_1, ..., h^t_m]$$

associating each measurement $z^t_i$ with its corresponding map feature. $h^t_i = 0$ indicates that $z^t_i$ does not come from any feature in the map. For data association a measure of the discrepancy between a predicted measurement that each feature would generate and an actual sensor measurement is measured by the innovation $\epsilon$ given by (16).

The measurement $z^t_i$ can be considered corresponding to the feature $j$ if the Mahalanobis distance $D^2_{ij}$ satisfies:

$$D^2_{ij} = \epsilon^T S^{-1} \epsilon < th$$

(6)

Where the covariance $S^t$ and the innovation $\epsilon^t$ are given by equations 15 and 16, respectively.

Knowing the characteristics of the stereo system, the depth is then calculated as follows:

$$R_{x3,i} = \frac{b \ast f}{d}$$

(7)

$b$ and $d$ are the baseline and the disparity, respectively.

The state of the system at time $t$ can therefore be represented by the augmented state vector, $x^t$, consisting of the $n_R$ states representing the robot, $y^t_R$, and the $n$ states describing the observed landmarks, $x^t_i$, $i = 1, ..., n$.

$$x^t = \begin{bmatrix} y^t_R \\ x^t_1 \\ \vdots \\ x^t_n \end{bmatrix}$$

(8)

Localization of the robot while kipping references from the scene consists of generating the best estimate for the system states given the information available to the system. This can be accomplished using a recursive, three stage procedure comprising prediction, observation and update of the posterior. This recursive update rule, known as filtering.

Our vehicle uses also a GPS, wheel encoders, and an inertial sensor to help localizing itself. The data from GPS are used to help localizing the robot and features in satellite images. But in some cases, the vehicle may lose the GPS due to buildings or tree canopies, and we seek to maintain an accurate robot positioning even in this case.

The GPS measurement, if existing, and measurement from encoders $\nu$ and inertial sensor $\omega$ are integrated in the measurement block to produce the estimate of the state at time $t$ based on measurements up to time $t$. The robot position and therefore the features position are measured in the universal GPS coordinate system (west-east, south-north).

3. EKF FOR GLOBAL LOCALIZATION

The Kalman Filter is a general statistical tool for the analysis of time-varying physical systems in the presence of noise. A system is modelled by a state vector $x$ which has entries for each of the quantities of interest. The passage of time is divided into small intervals $\Delta t$, and knowledge of the expected evolution of the state vector is encapsulated in the state transition function $f$. The filter permits continuous and efficient estimation of $x$ as the system evolves, incorporating the information provided by any measurements $z$ which are made of quantities depending on the state. The current state estimate is stored in the vector $\hat{x}$, and the covariance matrix $P$, which is square and symmetric with dimension of the number of elements in $x$, represents the uncertainty in $\hat{x}$. If the dependence of both $f$ and the measurement function $h$ on $x$ is linear, and the statistical distribution of noise in the state transition and measurements is Gaussian, then the solution produced is optimal.

The Extended Kalman Filter (EKF) is a simple extension of the Kalman Filter to cope with systems whose state transition and measurement functions are non-linear, or whose noise distributions are non-Gaussian. The EKF acts only as an approximation in these cases, where the downside of its efficiency is oversimplification of the mathematical forms of the functions and distributions involved.

En EKF works in two steps: a prediction step and an
update step. In the prediction step, the filter estimate the system state according to the state transition function $f$ describing the dynamics and the covariance matrix to reflect the increase in uncertainty in the state due to noise $Q$ in state transition function (due to unmodelled aspects of the system). When a measurement is made, the filter improves the estimated state with the new information, and therefore the uncertainty represented by $P$ is reduced. This the update step.

In our application an EKF is used to integrate data from several sensors to estimate the global position of a mobile robot in satellite images. It maintains the state vector $x$ based on sensors measurements. It also maintains a covariance matrix $P$, which includes the uncertainties in the various states as well as correlations between the states.

At each time step of the filter we obtain the predicted state $x$ and covariance $P$ using the state transition function.

$$x^{t|t-1} = \begin{bmatrix} f \left( y^{t-1|t-1}, u = 0 \right) \\ x_1^{t-1|t-1} \\ \vdots \end{bmatrix}$$ (9)

$$P^{t|t-1} = FP^{t-1|t-1}F^T + Q^{t-1}$$ (10)

where

$$F = \frac{\partial f}{\partial x} \bigg|_{x^{t-1|t-1}}$$

is the Jacobian of $f$ with respect to the state vector $x$ and $Q$ is the process noise covariance.

Considering a constant velocity model for the smooth camera motion:

$$\frac{\partial f}{\partial y} \bigg|_{y^{t-1|t-1}} = \begin{bmatrix} 1 & 0 & -\sin(\gamma^{t-1})(\nu^{t-1} + V)\Delta t \\ 0 & 1 & \cos(\gamma^{t-1})(\nu^{t-1} + V)\Delta t \\ 0 & 0 & 1 \end{bmatrix}$$

The update to include a new measurement incorporates the innovation $\varepsilon$, which is the difference between the measurement and its prediction, and its covariance $S$. We also inject the measurement noise via covariance $R$.

$$x^{t|t} = x^{t|t-1} + W^t \varepsilon^t$$ (12)

$$P^{t|t} = P^{t|t-1} - W^t S^t W^t$$ (13)

Where

$$W^t = P^{t|t-1} H^T (S^t)^{-1}$$ (14)

$$S^t = H P^{t|t-1} H^T + R^t$$ (15)

$$\varepsilon = z^t - h(x^{t|t-1})$$ (16)

$Q$ and $R$ are block-diagonal matrices obtained empirically defining the error covariance matrices characterizing the noise in the model and the observations, respectively.

A measurement of feature $x_i$ is not related to the measurement of any other feature so

$$\frac{\partial h_i}{\partial x} = \begin{bmatrix} \frac{\partial h_i}{\partial y} & 0 & \cdots & \frac{\partial h_i}{\partial x_i} & 0 & \cdots \end{bmatrix}$$ (17)

where $h_i$ is the measurement model for the $i$’th feature.

4. CONCLUSION

We presented a Bayesian process to integrate data from different types of sensors to localize robot in the universal GPS coordinate system. The proposed approach is based on an Extended Kalman Filter. The algorithm starts first by extracting useful information from images to recognize places in the scene. The extracted information from images are scale invariant feature transform point SIFT. Those features are saved in the system state vector and their position is updated based on the data from other sensors.

This work will be extended in the future to take into account robot localization using high level features as trees, doors, windows,... This will help robot position initialization using image correspondence matching, if a priori information on the scene is available or has been saved from previous exploration by the robot.

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5. REFERENCES


Cognitive Theory – Based Approach for Inspection using Multi Mobile Robot Control

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Abstract— The following paper describes the Cognitive Theory – Based Approach of multi mobile robot control. The main goal of the approach lays on the implementation of the decision selection which is provided by the model of human supervisor. The application of the model is rendered on its’ cognitive attributes and abilities to control the robot by the vision and chemical sensors based perception which leads the robot to build another property as the sub cognitive system, Robot Inspector Damage Avoidance System (RIDAS). Therefore, the structure of the supervision process from the remotely controlled sophisticated system and the autonomous robots are presented. Hence, along with the autonomous robots system they are cooperating each other to render a new generation inspection system.

I. INTRODUCTION

This paper describes the Cognitive Theory – Based Approach of multi mobile robot control. The main goal of the approach lays on the implementation of the decision selection which is provided by the model of human supervisor. The new generation inspection system is marked by the availability of the human–robot interaction system in the structure. To achieve this interaction, the human machine interface, as a mean to construe the real cognitive interaction system into modeled/simulated interaction have to be implemented. The interfaces are implemented in server–client scheme, because the mobile platforms are prepared to cooperate in distributed control system. All the cooperation shown above requires a kind of complex architecture which can be derived from CORBA. This paper as well, has shown how the architecture is applied and in general inducing an idea of robot teleoperation.

In managing the complexity of the attributes of the system as been described above, then the behavioral conceptual adoption should be applied. This application succeed its’ intelligence system by perpetuating the decision selection system which grounding its operation by the fuzzyARTMAP algorithm system. This skill is a prominent achievement which leads into the perceptual associative memory, as another essential attribute of the systematic cognitive system that this research borrowed it’s concept.

The perceptual associative memory in this system particularly rendered by an ability to interpret the incoming stimuli by recognizing individuals or objects, categorizing them and noting the relationships between the objects and categories. These attributes mentioned above are showing the pertinent robot action which are always consistent with the categories and their relations. So far, the study has able to provide the new approach of the robot’s cooperation system.

In the application, the mobile robot ATRVJR is accompanying the teleoperated robot INSPECTOR with its’ mobile platforms are to be able to execute some autonomous and semi autonomous tasks. Meanwhile, the main goal for the mobile robot itself is to acquire data from the environment and delivers into Command Operation Center (COC) through the wireless communication system. COC is functioned by the existing system of the cognitive modeled of human supervision which perceptually and behaviorally are able to recognize and execute the procedures needed in the case of some risky events, particularly the collision problems. Therefore the two substantial components from the perception and association actions by mapping and localizing tasks are achieved by the system.

II. THE COGNITIVE MODEL OF THE SUPERVISOR

The following paper shows the result of the investigation on the Cognitive Theory – Based Approach of multi mobile robot control. The multi robot system is based on autonomous mobile platform ATRVJr equipped with video and chemical sensors, and remote controlled inspection robot INSPECTOR. The idea of using cognitive model of the supervisor is based on mapping the attributes of human reasoning into computer language. Therefore the advantages of human behavior while supervising the multi robot system are defined and get into account in the cognitive model design. The following scheme shows the interaction between Cognitive model of human – operator and system of the mobile agents.
The Cognitive model of the supervisor (CMS) takes the full control on the mobile inspection robot in case of task execution failure or in case of risky situation prediction. When robots are obtaining goal without problems, CMS is not interfering in control.

The module of the decision selection (MDS) generates the tasks for mobile agents, which execute the goal of environmental inspection.

The system of the mobile agents is composed by autonomous mobile platform ATRVJr and fully teleoperated robot INSPECTOR. The ATRVJr is equipped with chemical sensor array and sensors used in localization and navigation task. The communication between modules is implemented using CORBA (Common Object Request Broker Architecture).

The main functionalities of the cognitive model of the supervisor are listed:
planning, instructing, monitoring, intervening, documenting.

III. THE IDEA OF COGNITIVE MODEL OF THE HUMAN – OPERATOR OF THE MOBILE AGENTS

The design of the Cognitive model of the supervisor is based on the set of defined functionalities of the mental activities. Supervisor is an agent providing orders to another agents. Agents are responsible for the tasks executions. Cognitive model inspects if the task is properly executed, therefore in this case the model is not interfering into the agent system. The main idea of adopting the cognitive model of supervisor is to replace the human with machine applying artificial intelligence to imitate human reasoning while the supervising process occurs. The following scheme shows the multi robot system. The robots connect wirelessly to the base station and each other using a wireless link.

Command Operation Center (COC) is the end point of the system. The Human Machine Interface (HMI) programs allow to manipulate the robots, to choose the task, to record some datum of the robot trial.

The main COC tasks for autonomous mobile robot ATRVJr are defined as:
1. Go to point
2. Follow the line
3. Explore
4. STOP

In the case of a connection lost between COC and ATRVJr, robot will be executing the task autonomously. The main task for autonomous mobile robot is terrain exploration with chemical data acquisition and deliver it to COC.

IV. RIDAS ROBOT INSPECTOR DAMAGE AVOIDANCE SYSTEM

The subsystem of Cognitive model is proposed as Robot Inspector Damage Avoidance System (RIDAS). The subsystem is responsible for taking care of robot Inspector ARM while the remote controlling. The scheme of existing system of mobile robot Inspector remote control is shown on figure 3. The operator block, represents the human operator who is executing real time tasks using control panel. The robot block, represents the robot Inspector chassis.

The new approach of development existing control system is achieved. The scheme of RIDAS is shown on figure 4:
The block RIDAS represent the new communication interface to robot with built-in algorithm of safety supervision. The main idea of RIDAS is based on the ray intersection algorithm applied to detect collision between defined cubes of robot chassis. The example of the set of defined cubes is shown on figure 5.

The RIDAS is predicting collision of robot arm and executes the safety procedure to avoid the robot damage. This approach increases the performance of the teleoperation, therefore the mental functionality of the robot arm safety reasoning is replaced by proposed algorithm.

V. THE AUTONOMOUS MOBILE ROBOT ATRVJr

The essence of the research projects in the area of multi mobile systems applications for risky environment [1,2,3,4] is to integrate Some disparate elements involved in a crisis situation into an info-structure that will allow information to be exchanged readily between all of those elements: crisis centres, relevant forces dealing with the crisis (fire fighters, de-bombing squads, police, etc.), platforms and sensors.

The goal of the development of an intelligent autonomous mobile robot ATRV-Jr is to achieve the new functionality of the control unit and demonstrate all its’ capabilities as a mobile platform with an own autonomy. The basic idea of intelligent control unit building’s is an approach of the following constraints: damage management, adaptability, working with random and the noisy information, parallel processing with low level energy consumption (figure 7).

The human-inspired behavior is taken into the consideration, therefore the control of the mobile platform maps the human like decisions into the robot motion control. The following pictures shows the ATRVJr mobile platform controlled by described intelligent control unit.

The vehicle (figure 8) is compact (0.8 m length x 0.55 m height x 0.64 m width), but powerful with a payload of 25 kg (55 lb). With its rFLEX Control System, the ATRV-Jr can be programmed to complete sophisticated guidance manoeuvres with minimum programming steps. Obstacle avoidance is achieved with 17 sonar sensors positioned around the perimeter of the vehicle. Computations and I/O control are done by a Pentium III class PC running Linux (a UNIX OS). The onboard computing power allows the ATRV-Jr to quickly process large amounts of information; a necessary trait for autonomous robots. It features multiple serial communication ports, thus allowing a host of input and output options.

A. Damage management

Damage management is based on implementation of robust algorithm and duplication of the functionalities. Behavior based obstacle avoidance algorithm is based on the fuzzy sets theories, therefore it is robust in case of noisy data which is generated by improper functioning of the ultrasonic sensors. The SLAM algorithm as the first candidate, is based on traditional odometry and sonars, and second candidate is match scanning algorithm based on laser range finder LMS SICK 221. Therefore, the control unit has 2 inputs of the self local localization algorithms. Each device has its own control unit called server, which serves its’ functionalities. In case of hardware damage, the system is able to reconfigure and serve at least the best configuration to achieve the goal. Each device such as odometry, compass, sonars, video camera and other sensors has an associated program – server with the built-in mechanism called supervisor. This way, the control system is conscious of the usable functionalities of the mobile platform.
platform. The presented approach is the main goal of the implementation of the damage management unit.

B. Adaptability

Adaptability is obtained by implementing robust algorithm based on artificial neural network fuzzy ARTMAP with some modifications, due to its ability to provide real time respond of the network in real environment\[5\][6]. Mobile robot motion is determined by the behavior based algorithm fuzzy ARTMAP. Fuzzy sets are used, to code the information from ultrasonic sensors. The robot path of motion without collision should be as long as possible at the maximum speed. The time of making decision determines the system quality and should be as short as possible. The general idea of the fuzzy ARTMAP was described in [7]. The system is able to learn new association between the set of coded ultrasonic sensor results into the set of the coded values of motors velocities. The algorithm has a high generalization and adaptability, therefore it approaches the goal.

C. Working with random and noisy information

Working with random and the noisy information is achieved by using intelligence computing applied in visual processing, building knowledge of the environment, and self localization algorithms. The noise removal from image operations can be implemented as CNN- Cellular Neural Network [8]. CNNs are often used as fast image processors because they are very efficient in applications such as a noise removal, edge and corner detection, hole filling, operations of mathematical morphology – dilation, erosion. The knowledge building of the environment is obtained by implementing the fuzzy ARTMAP neural network. Self localization algorithm is based on robust graphical operation used in match scanning problem.

D. Parallel processing with low level energy consumption

Parallel processing with low level energy consumption is obtained by using CORBA (Common Object Request Broker Architecture). CORBA is a mechanism in software for normalizing the method-call semantics between application objects that reside either in the same address space (application) or remote address space (same host, or remote host on a network). Each server associated with appropriate device runs independently from others. Therefore, each program from control unit works parallel. The problem with synchronization and action selection has to be obtained [6]. The parallel layer architecture is taken under the consideration. Using CORBA mechanism as a framework of communication between sensors and main computer of the robot allow to fast the reconfiguration of information sources about environment when the same sensor does not work and back to normal work of a robot.

This technology allows to introduce a small multi-agent system on the board of the robot, by creating many servers which the owners are the sensors.

The robot is developed to achieve autonomous tasks such as exploring unknown environment, following defined path and avoid obstacles. The robot is equipped with chemicals sensors, therefore the information about chemical disaster is sent to COC. The robot chassis is shown on picture above:

![Fig. 8. The autonomous mobile robot ATRVJr.](image)

The autonomous navigation is implemented by compounding artificial neural network fuzzyART with IF-THEN-ELSE algorithm. The fuzzyART algorithm allows the knowledge building to the know-how of the obstacles avoidance, following wall and change direction in curve with obstacles. The distance parameter is proposed to obtain the quality factor of the artificial neural network prediction. The IF-THEN-ELSE algorithm obtains high level tasks such as following path or explore terrain using graph method. The new idea is to implement an interface to cognitive model which provide information about the executing task status. The following figures shows the idea of supervising and recording risky situation for ATRVJr. In the case of risky situation defined by large value of distance parameter, the fuzzyART cognitive model takes a full control of the mobile platform and data record for further analysis by operator.

The reason of using cognitive model to solve the problem is the similarity to human behavior while the supervised learning process is on going on the fuzzyART training. Thus, the idea of replacing human by cognitive model is reasonable. Hence, the mechanism of the artificial neural network supervision is obtained. The following figure shows the plot of the fuzzyART distance factor in time function. Red rectangle shows the wrong prediction of the fuzzyART algorithm. Therefore, cognitive model is taking a full situation control.
The HMI Human Machine Interface is proposed for the COC. The idea of HMI is the visualization of the main functionalities of Cognitive Model of the Supervisor, therefore it is possible to observe and to interact into the system.

VI. CONCLUSION

The following paper has described the Cognitive Theory – Based Approach of multi mobile robot control for risky environment inspection. The main goal of the approach lays on the implementation of the decision selection which is provided by the model of human supervisor. The new Robot Inspector Damage Avoidance System ( RIDAS) is presented. Therefore, the safety collision avoidance of the robot arm which is supervised by the cognitive model is achieved. The described model provides some decisions which do not allow the robot damage or risky task execution. The autonomous mobile robot supervision is shown, thus, the idea of providing distance parameter for fuzzyART is investigated. The usage of cognitive approach for multi robot control is proved. The replacement of the operator – supervisor by cognitive model proves the advantages of this idea, therefore the inspection safety is increased.

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Abstract — In the paper research activities concerning framework for creation of the simulators for Inspection Robotic Systems will be described. The goal of the project is to build computer framework which will be used to design simulators for training of the operators for inspection robots and to make software for the simulators.

The use of inspection robots is essential in categories like antiterrorism, crime prevention, safety of the people and their goods. They substitute human in dangerous situations, for example carrying the bomb. Training of the operators of the robots is necessary to improve the process of manipulating the robot and carried package in order to decrease the danger for surroundings and people nearby. Complex training using real machine is very expensive and surely impossible to carry out due to the cost of the robot, its maintenance and variety of possible situations that operator could face. This situation cause that computer simulators are needed. They can be designed and produced using a framework.

This paper describes few steps of the creation of the framework. There are several issues that should be considered, i.e. role of instructors, type of tools needed for creation of the framework, type of information received as result of training, etc, because that kind of frameworks don’t exist (or exist only for private use, not commercial).

At the beginning, methodology of the training should be elaborated. First, information about users’ needs and expectations should be gained. Also recognition if there are any training methods available among the producers and users of the robots is necessary. Following steps are: designing the methodology of the training and initial selection of the simulators, verification of the designed methodology and selection of the simulators with cooperation with users and producers of the robots.

Developing the project of the framework for chosen set of the simulators is the next step. At this stage definition and analysis of user requirements should be done. Then describing the vision of the system could be possible. This part of designing should take into account the information about either commercial or provided by the robots’ manufacturer components of the system. Afterwards the project of the system could be completed.

Last stage of the creation of the framework is to implement and run the software. Technica1 tests and trials are unavoidable, because they show if there are any mistakes, made during the developing, that should be corrected. Designing and creation of the exemplary simulator should be carried out in order to test the functionality of the framework and it would be the final exam for this software.

I. Introduction

TELEOPERATED robots are used to substitute human in dangerous situations, for example [3]: inspection of potential crisis areas, carrying explosives, detection of toxics and chemicals. The use of those robots is growing because the terrorism and crime increase, and they are potential threat to people and their goods. Inspection robots are used mainly in the police and military forces, because these organizations are under the highest risk when handling with dangerous situations.

When the particular robot is being sold its future operators are taught, for example, how to steer, change equipment and maintain the robot. The longest part of the training is the steering part, because maneuvering that kind of device is very hard due to the:

- amount of degrees of freedom of the robot,
- big number of control buttons and joysticks,
- little knowledge of scene, where the robot is working,
- unpredictable problems, for instance: lack of communication range, failure of the part of the robot, “noise” on the vision channel, etc.,
- separation of the robot from the operator.

Above mentioned problems prove that extensive training of the robot operators is necessary. Due to the fact, that the robot and its maintenance are expensive the training should be shortened in order to train as many people as possible. This brings another problem, because some candidates learn longer/worse then other ones, so workload of the robot is huge and it cannot be used on the crisis ground at the same time. Also training using real robot cannot provide even a little amount of possible situations that operator could face.

All these problems cause the fact, that different kind of
training is necessary. Due to the fact that computers are quite cheap and 3D software engines are very developed (realism of view, physics, video and sound effects) several vehicles simulators were developed [5][11]. They bring fast and cheap gaining of experience in steering those devices. That kind of simulators bring functionality of computer games, where players learn particular skills, like handling with input devices, precision of steering, reflex, orientation or planning [2]. Experiments with game Space Fortress proved that operators, which learn not only in real world but also using computer software, were better trained than those, who hadn’t played that game at all [1].

Unfortunately, simulators for inspection robots, on which operators could learn steering, are not commercially available or are developed only for private use. PIAP developed its own robot simulator, which will be described in the next section. Using that software unskilled operator can learn maneuvering the robot using virtual version of robot control console. The operator is able to choose the robot, environment and type of scenario.

Above mentioned simulator has limited number of ground robots, predefined scenarios and environments. Building a new simulator for different type of robot, for example aircraft, brings the whole programming work to the beginning. New types of behaviors of the vehicle, scenarios and ranking methods should be considered from the beginning. To avoid this process available parts (modules) of the simulator system (scenarios, different types of robots, virtual input devices, etc.) should be created and divided into categories, from which only necessary modules would be taken in order to create desired simulator. In this way programming work would be decreased to minimum, because to create a simulator for a particular type of the robot programmer would only point interesting modules from all available to create the software for the operator. This set of simulator modules and linking software we call framework for creation of the simulators for inspection robotic systems.

In this paper we present some aspects concerning creation of the software. First, we present exemplary simulator, which has basic functionality, but is the starting point in our project. Next, the view of methodology of the training will be described, which will later help to describe the vision of the system. At the end implementation ideas and technologies will be presented.

The project is in very early stage now, so there will be no technical solutions described. We will focus on theoretical vision of the system only.

II. PIAP’S ROBOT SIMULATOR

The main goal of presented simulator is training of the operators of the robot INSPECTOR. Program provides functionalities such as full 5 DOF (Degrees Of Freedom) robot arm manipulation, grabbing a bomb, braking glass in the car (Fig.1), steering caterpillar robot. The set of functionalities was designed to obtain the optimal set of events that can happen in real scenario. The idea is to provide robust tool for the robot INSPECTOR interactive demonstration, therefore it is possible to train while presenting main robot features. It is possible to change view from 5 different cameras, also the main pan tilt camera with focus. Some graphic methods are used to create different scenarios, for example while night scenario an operator can use robot’s lights to obtain better viewing of the environment. Additional noise effects are implemented to simulate real noise of analog camera.

Simulator is implemented using MFC (Microsoft Foundation Classes), OpenGL and DirectX libraries. The 3D sound is implemented to provide better effect of rendered scene. The model of the robot INSPECTOR is delivered as the set of basic figures compounded by matrixes defining 5 DOF. The kinematics of robot chassis is implemented using physic equations, therefore it is possible to simulate robot falling down, and changing the centre of the mass while manipulating robot arm. The basics obstacles are delivered, for example the model of 4 wheel drive car is put into the scene. Simulator provides the virtual control panel as an intuitive tool for interacting with virtual scene. More sophisticated training is based on connecting real control panel to virtual world.

![Fig.1. Screen from the simulator of the robot INSPECTOR](image)

III. METHODOLOGY OF THE TRAINING AND THE VISION OF THE SYSTEM

Training using real robot is very expensive and time consuming. It is caused by the fact that only one person can steer the robot all the same time. Training using computers can be cheaper and many people could learn using separated computer training sets. It’s also necessary to improve training process, because big number of hours of learning with different types of the robots and many people is time and money consuming. In order to decrease the costs of training and improve its organization we propose multilevel training. It would be also the factor which would
profile future operators into groups characterized by certain level of skills.

The lowest level of training would involve all potential operators (candidates). This would be the cheapest part of the training, because it would be carried out using low-cost computers with no special extensions, where the particular simulator would be installed (Fig.2).

Preliminary training would reject unskilled/unprepared candidates so higher level of the training could be carried out using more expensive training sets, extended with the real robot operator’s console (Fig.3). Candidates would gain new skills being closer to the robot using mentioned console.

Computer display in Fig.3. could be replaced with Virtual Reality components, like 3D glasses/helmet or 3D display. Then candidates would have more perception of the robot’s overall dimensions and its environment.

New skills gained in previous parts of the training could be confronted with the most complex training set which could consist of computer hosting the software, vision headset, real robot and its control console (Fig.4). Candidates could train their abilities using real console, when work of the robot would be visualized by computer software and displayed in the headset.

In order to choose the types of the supported simulators and profile candidates for operators correctly, the methodology of the training should be elaborated. It should take into consideration types and kinds of the robots, number and skills of the candidates, indexes for ranking candidates. During elaborating the methodology information about training of the operators from other than PIAP companies will be received. Also information about training of the operators different from the robots, for example heavy machines, and training methods using Virtual and Augmented Reality would be very useful. All above mentioned information will be gained using the Internet and through interviews with potential users of the framework and producers of the robots and robot’s parts. This is currently ongoing process.

IV. IMPLEMENTATION

Frameworks for creation of the simulators haven’t been developed so far or they exist in research plans or in non-commercial know-how. This lack of information forces us to design it from the beginning without any starting point. We introduce our framework as a computer system, equipped with different software tools for creation of the virtual models, software for the simulators and visualization modules. We present few technologies and packets we consider to use:

- OGRE (Object-Oriented Graphics Rendering Engine – Fig.5) is a scene-oriented, flexible 3D engine, which provide world-class graphics solutions. It’s available under GNU Lesser General Public License (LGPL). Engine doesn’t contain features like sound, networking, AI, collision or physics so they should be integrated with additional libraries. It supports Direct3D, OpenGL, Windows (C++ and Code::Blocks on Windows version)
and Linux (gcc 3+) distributions, powerful material declaration language, shaders, multitextures, sophisticated skeletal animations, flexible shape animations and many special effects (for example: particle systems, transparency, skyboxes, billboardng) [15][16].

Fig.5. 3D world designed using OGRE [17]

- Havok products – this is the set of SDK modules mainly to create computer games. Functionality and flexibility of its elements enable using it in the simulator project. Interesting modules are: Physics (collision detection, vehicle dynamics, Art Tool support, visual debugger) [6], Animation (highly efficient animation compression/decompression, animation controls, support for Autodesk 3D Max). Havok products were used to create many well-known games, for example: Painkiller, Halo 3, BioShock [7].

- ODE (Open Dynamics Engine) is an open source library for simulating rigid bodies. It has C/C++ API, collision detection with friction, and can be used for simulate vehicles or objects in virtual environments. SDK simulates mechanical systems (solid objects, joints, contact, friction, springs), hydraulics, suspensions and tyres, drivetrains and electric motors, [14].

- CORBA (Common Object Request Broker Architecture) is a mechanism in software for normalizing the method-call semantics between application objects. It uses IDL (infrastructure description language) files to specify the interfaces that objects will present to the outside of the application [18]. Client – server architecture control provides robust information exchange. The communication issue is delivered by TAO implementation of CORBA.

- Matlab is a computing language for algorithm development, data visualization, data analysis and numeric operations [8]. We would like to use following components: Simulink (designing and simulation of dynamic systems, interactive graphical environment, integration with Matlab) [9], VRToolBox (defining and animating objects in 3D environments, insight into the modeled dynamic systems) [10],

- Adams allows importing geometry from a CAD system or build a model from the beginning and when the simulation is started it runs simultaneous equations for kinematic, static, quasi-static and dynamic simulations. The user is informed how pneumatic, hydraulic, electronic and mechanical components interact with each others and what forces are generated during operations [13],

- 3ds Max is an application for integrated 3D modeling, animation and rendering. The software includes tools for modeling and texturing, animation, visual effects, rendering, hair and fur, cloth, tutorials and documentation [4],

- Visual Studio 2005 is a system to aid software developers. It offers tools for all phases of creation of the software: development, testing, deployment, integration and management. It contains multiple coding languages, code editors, wizards [12].

Using above mentioned we could create the framework able to create the 3D models of the robots and their working environment, particular simulators and software for that simulators. The framework will be designed using MDD (Model-Driven Development) methods, which consist in creation and developing models during whole lifetime of the system (designing, implementation, and modification phases).

V. CONCLUSION

Above described vision of the project is unstable due to the fact, that there is no information about any similar products/ projects, so we have no starting point and we are designing the framework from the beginning. The project has already started and during its developing there could appear new ideas or technologies we would consider to use. We will be describing the methodology and choose needed tools in the nearest future, then we will also have some technical solutions to present. Our work will be surely determined by the needs and expectations of the potential users of the simulators (producers and users of the robots). Information from them will also impact on the selection of the type of the robot in exemplary simulator, which will be produced in order to test our framework at the end of the development process.

Our work will create the possibilities for easy creation of the simulators. They are wrongly judged to be nice multimedia gadgets to attract computer-games-knowing potential buyers of the robots. In our opinion, computer training is very important mean in mobile inspection robotics nowadays, because it brings cheap and fast training and enables the robot to do its purposes – carry out the action in the field instead of being training set. Changing
training methods from typical – real world to computer aided is only the matter of time. And a huge designing and programming work.

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A Fuzzy Approach for the Control of Autonomous Vehicles Operating in Hazardous Terrain Environments

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Abstract—The aim of this article is to present a description of the design of a fuzzy based controller for the navigation of autonomous vehicles in hazardous environments, in particular for demining robots. The reason for the selection of a fuzzy based approach is to handle uncertainty in navigational decisions due to the encountering of a mine or to avoid an obstacle. This uncertainty which exists within many autonomous systems is amplified by the unstructured and rough nature of the terrain which may require the vehicle to circumnavigate certain surface features.

The approach is based on a reactive control architecture which reacts towards sensed information about the immediate environs of the vehicle's current position in relation to the target position and makes an intelligent decision of the navigational act to be taken. The system utilizes a fuzzy controller in order to cater for the uncertainty and ambiguity associated with the nature of the surface terrain. Initially, the controller determines the local position of the vehicle in relation to the reference frame. Subsequently, it performs a fuzzification of the target position as well as the fuzzification of a landmine or obstacle distances. The inference mechanism of the controller operates on these inputs through a set of heuristic strategy knowledge rules stored in a rulebase. The set of applicable rules are determined and their results are defined in terms of membership for the fuzzy function. A single navigational decision based on these functions is sought. A fuzzy fusion technique is utilised to combine the results of all valid rules in order to obtain a crisp navigational decision. The output of this fusion process is defuzzified in order to obtain a discrete navigational action for the actuators of the vehicle.

I. INTRODUCTION

The objective of this paper is to present a description of the design of a fuzzy based controller for the navigation of autonomous vehicles in hazardous environments, in particular for demining vehicles. Fuzzy logic control is selected in order to cater for uncertainty in navigational decisions due to the encountering of a mine or to avoid a terrain obstacle. The problem of developing an autonomous mobile vehicle can be broken down into three fundamental tasks; moving the vehicle through its environment, sensing about the environment, and reasoning about navigation strategies. The first task is concerned with the mechanical design of the vehicle in terms of structure, locomotion and drive. The second task is concerned with the development of a sensor system to recognise elements of the environment.

The third task deals with the implementation of a logic controller that operates on input data from the sensors in order to make navigation decisions. This third task is the focus of this current paper.

The paper begins with a discussion of issues related to the development of the navigational strategies and performance of autonomous landmine detection vehicles. It also addresses the features of the desired control system such as, navigational strategy, vehicle intelligence and control system mode. The following section presents a discussion of fuzzy logic control theory as applied to navigation of autonomous vehicles. The final section of the paper presents a description of the developed behaviour-based fuzzy controller in both terms of logic and structure.

II. NAVIGATION AND PERFORMANCE OF AUTONOMOUS VEHICLES

Before autonomous navigation and performance are reviewed in detail, some issues must be acknowledged. The mobility of an autonomous vehicle in unstructured real-world environments dictates the form of locomotion chosen. The nature of the terrain surface in terms of type of soil, density and slope also defines the mechanical construction of the vehicle. Specifically for a demining application, additional parameters affect the design such as the speed of the vehicle and the accuracy of movement.

Generally, there are three levels of control for autonomous vehicles; program control, supervised control, and total control. However, there is no clear cut distinction between these three levels. In program control autonomy, the human operator supplies functions to the vehicle by programming motion instructions into the controller. These instructions are blindly repeated by the vehicle during its operation. Since the vehicle moves directly under its own initiative, this type of control is still considered autonomous albeit of a simple and rigid nature. This contrasts with the tele-operated vehicles in which motion is achieved by remote control operation with no programming. This type of motion is not considered autonomous. In supervised control autonomy, the human operator defines into the controller the path planning techniques to be followed by the vehicle. Usually this level of autonomy possesses simple obstacle avoidance tactics. Although this level of autonomy provides some flexibility, it still requires some form of human supervision [1]. In contrast to the first two levels of autonomy, the most advanced type of autonomy of mobile vehicles is totally independent with no human interaction with the vehicle.
during its operation. This level provides the most flexibility of motion albeit at the expense of complexity of control. It also possesses excellent navigational and obstacle avoidance skills.

Intelligence is expressed as the ability of the vehicle to extract information about the surrounding environment through the use of sensors and to use this knowledge to make informed decisions about actions to be taken. Artificial Intelligence techniques are used to produce knowledge based systems which encapsulate the reasoning and decision making rationale. These knowledge based systems provide an excellent means of extracting heuristic knowledge which is difficult to illicit by conventional algorithmic means. Knowledge based systems also provide a means of machine learning through the accumulation of knowledge to the initially acquired knowledge.

The objective of vehicle navigation is to resolve three fundamental issues; localisation, globalisation, and path planning. Localisation is the ability of the vehicle to determine its position relative to stationary or moving objects in its working environment based on sensory data. It may either be relative or absolute. Relative localisation is achieved through odometry calculations or inertial properties of the vehicle e.g. velocity and acceleration while absolute localisation is based on measuring distance and orientation from a fixed reference point. Globalisation is the ability of the vehicle to relate its current position to derived destination points based on absolute or referenced terms. Path planning refers to the process by which the mobile vehicle determines a suitable course between the current position and target position. It involves being aware of, direction and distance to travel, and of obstacle avoidance techniques.

To achieve navigational and performance goals, a control system which continuously attempts to minimise the gap between the current position of the vehicle and the target position is sought. The control system architecture may be based on one of two modes; model-based and reactive-based. In the model-based architecture, a symbolic representation of the vehicle environment is captured through perception and coded into the control system. The inference mechanism follows a sequential path through the planning task to the execution of motor control based on this representation. The main problem with this control is its inherent inaccuracy due to ambiguity and unreliability of information. Also, as the inference mechanism is sequential in nature, a failure of one layer of execution will fail all subsequent layers leading to a complete failure of the control strategy. This is dissimilar to humans who mainly reason in a non-sequential manner.

On the other hand, a reactive-based control architecture is built as a set of independent but interrelated layers “behaviours” which are reciprocally connected. Based on sensory data, an instantaneous map of the vehicle vicinity is built into the control system which directs the mobile vehicle towards the reaction against perceived environmental situations. The inference mechanism is non-sequential in that each behaviour has access to sensory data and influences actions taken by the control system. The approach is similar to how humans reason, act and react. Outputs from each behaviour are blended together through a weighing factor to obtain the output behavioural action. Although the behaviour-based mode does not suffer from the problems of the model-based mode, careful attention must be made to the issue of information overload which may be contradictory in nature. The adoption of a conflict resolution module addresses this issue through the use of weighting methods.

The required tasks of the intended mobile vehicle are to seek targets and avoid obstacles. The advantages of behaviour-based mode will suffice in this case. The next section describes in detail the developed reactive fuzzy control system for autonomous vehicles.

III. FUZZY LOGIC CONTROL OF AUTONOMOUS VEHICLES

Autonomous vehicles which operate in demining environments face many difficulties. First, the vehicle has no
prior knowledge of the environment in almost all minefields owing to the imprecise location of the mines. This situation results from the lack of, or unreliability of maps and the shifting of mines in the ground with the passing of time. To address this issue, the vehicle must possess some path planning behaviour after the detection of the existence of mines. Also, the need to address the existence of obstacles and how to avoid collision with them is a main concern. Finally, the existence of uncertainties in inputs from sensors and in control actions, in addition to descriptive linguistic uncertainties associated with control reason, constitute a major difficulty for autonomous motion.

There are four types of uncertainties associated with autonomous navigation of mobile vehicles: vagueness, ambiguity, accuracy and reliability. A knowledge statement may be vague when the information conveyed is not clearly defined or is indistinguishable. Ambiguity occurs when a condition may or may not be met. On the other hand, inaccuracy occurs when the information provided is imprecise, inexact or ill-defined. Uncertainty through reliability occurs due to the dynamic nature of real-world unstructured environments. It is expressed as the dependability and consistency of information during the repeated operation of the mobile vehicle. Examples of these four types of uncertainty are illustrated below.

![Figure 3 Types of uncertainty.](image)

Unfortunately, traditional control theory does not provide effective nor efficient methods for dealing with these uncertainties due to the high demand on the control system and increases costs. Fuzzy logic control as a more suitable alternative control method for vehicles has been proposed for twenty years [2-5]. The classic article by Saffiotti [6] presents a review of techniques and trends in the use of fuzzy logic control in autonomous vehicle navigation. The core of such techniques is the design of reactive behaviour-based systems which attempt to encapsulate the tasks and actions of the vehicle. It reacts towards sensed perceptions from the environment and typically performs one or more of three tasks: goal seeking of a target, edge following, and obstacle avoidance in the direction of vehicle travel.

In order to take motion actions, a single decision based on multiple behaviours of often conflicting influences, must be achieved. This process is described as the fusion of behaviours into a discrete motion-action such as speed (move or stop) and orientation. The most common fusion technique is based on the weighing of each individual behaviour [7]. The controller contains a rule base for the fuzzification of the motion parameters i.e. speed, orientation and obstacle distance. Navigation is achieved by combining results from the defuzzification of the weighted behaviours. Another technique is based on the fusion of “allowed” and “disallowed” directions [8]. The allowed direction is based upon the fuzzification of goal-seeking behaviour while the disallowed direction is based on the fuzzification of the obstacle avoidance behaviour. An eliminator factor is used to denote the importance of obstacle avoidance behaviour when the target goal is very near to the vehicle.

A recent development in the area of behavioural fusion is the use of genetic algorithms for the operation of a real-time search-and-fix procedure for obstacle avoidance fuzzy rules [9]. This enables the controllers to fuse behaviours by partial and concurrent activation of individual behaviours. An additional technique used in the design of the rule base is fuzzy perception of the environment. The NASA Jet Propulsion Laboratory project to study autonomous vehicle navigation in planetary terrains uses fuzzy logic to mimic human perception of terrain visibility [10]. This is achieved though the fuzzification of the amount and concentration of rocks to produce a fuzzy set of terrain descriptors. The controller also fuzzifies the inclination of the terrain surface. A fuzzy rule base is used to determine the transversibility of the terrain based on theuzzified data. A different approach by Cuesta utilised fuzzy perception of the environment to deal with planer orientation [11]. Fuzzy perception is used both in the design of behaviours and also in the fusion of behaviours. This method is further refined by using a virtual perception memory in order to take into account the previous perceptions to build new perceptions.

Research has been conducted in the area of path optimisation by providing a learning mechanism for range parameters in order to minimise total vehicle travel distance [12]. Rather than explicitly illicit the fuzzy rule base directly from human experts or by using learning mechanisms, the fuzzy controller is designed to automatically extract the fuzzy rules and membership functions. This process may be preceded by the initial training of the vehicle trajectory by an operator followed by the extraction of the rule base from neuro-fuzzy networks [13]. A fuzzy logic controller which requires no human training at all is described as a type-2 fuzzy logic controller [14]. In conventional type-1 fuzzy logic controllers, uncertainty is described by precise and crisp membership functions that the developer assumes to capture uncertainty. On the other hand, type-2 fuzzy logic controllers are designed based on a fuzzy membership function rather than on crisp values. The approach taken by Novakovic is not to synthesis the fuzzy rule base at all [15]. The approach taken is to analytically synthesise the fuzzy control action by determining the positions of the centres of the output fuzzy sets. Another approach is to use evolutionary self-learning algorithms to illicit the fuzzy rule base. This single rule base is used for both goal-seeking and obstacle avoidance [16].
IV. DESIGN OF THE FUZZY CONTROLLER

The typical design of a fuzzy Logic Controller (FLC) involves four steps; fuzzification of the input variables, definition of a sound fuzzy rulebase, development of a suitable inference mechanism, and defuzzification of the controller outputs.

A. Fuzzification of Variables

The inputs selected to define variables for navigation of autonomous vehicles are the target orientation (TN) and the obstacle or landmine distance parameters (DR, DC, DL). The TN variable indicates a measure of the angle between the vehicle heading and the line connecting the vehicle to the target direction. It is assigned one of 5 values representing overlapping regions measured with respect to the vehicle bearing; Rear Left (RL), Front Left (FL), Front Centre (FC), Front Right (FR), and Rear Right (RR). These overlapping regions and their associated degree of fuzziness are illustrated below.

![Figure 4 Target orientation fuzzy zones.](image)

The landmine distance functions; Distance Left (DL), Distance Centre (DC) and Distance Right (DR), indicate a measure of the closeness of an obstacle or landmine to the current position of the vehicle. For practicality, detection is confined to the space directly ahead of the vehicle heading. Each one of those three functions is assigned either of two values; near or far with a degree of fuzziness associated with them.

![Figure 5 Detected landmine fuzzy distance.](image)

The above mentioned linguistic descriptors are utilised to encapsulate human perception of these inputs. Each input has a fuzzy value assigned to it according to the readings of the sensors. Fuzzification of these inputs represents a transformation of the crisp measurements obtained from sensors to the corresponding fuzzy membership functions. Discrete triangular membership functions are used to quantify the linguistic values. For the target orientation variables, the fuzzification process quantifies the certainty that the target direction is within each of the 5 regions. An example of the membership function for the RR variable is given in equation (1).

\[
\mu_{RR}(x) = \begin{cases} 
\frac{x - 60}{75} & 60^\circ \leq x \leq 135^\circ \\
\frac{10 - x}{75} & 135^\circ \leq x \leq 210^\circ \\
0 & \text{otherwise}
\end{cases}
\]

(1)

![Figure 6 Membership functions for target orientation.](image)

For the landmine distance variables, the fuzzification process quantifies the certainty whether landmine is far equation (2) or near equation (3).

\[
\mu_{far}(x) = \begin{cases} 
\frac{x - 30}{50} & 30 \leq x \leq 80\, cm \\
0 & x < 30\, cm \\
1 & x > 80\, cm
\end{cases}
\]

(2)

\[
\mu_{near}(x) = \begin{cases} 
\frac{80 - x}{50} & 30 \leq x \leq 80\, cm \\
0 & x > 80\, cm \\
1 & x < 30\, cm
\end{cases}
\]

(3)
The output variable of the FLC is the angle that the vehicle is to turn relative to its current bearing. The turning angle (TA) is assigned one of 5 values representing overlapping regions measured with respect to the vehicle bearing: Left Big (LB), Left Small (LS), Left Right (LR), Right Small (RS), and Right Big (RB). These overlapping regions and their associated degree of fuzziness are illustrated below.

The angle is quantified using membership functions similar to those of the TN variable. An example of the membership function for the RS variable is given in equation (3).

\[
\mu_{RS}(x) = \begin{cases} 
\frac{x}{40} & 0 \leq x \leq 40 \\
\frac{80-x}{40} & 40 \leq x \leq 80 \\
0 & \text{otherwise}
\end{cases}
\]  

B. Fuzzy Rulebase

The knowledge base of the FLC contains a set of rules which encapsulate the heuristic and intrinsic knowledge of how humans make decisions about the domain. These rules are represented by implication relationships which are expressed as fuzzy IF-THEN rules which utilize the same linguistic descriptors in order to allow the inference mechanism to match the rules against the inputs. Each rule has one or more input variables as its antecedent and produces a fuzzy linguistic output variable as its consequent.

Fuzzy implications are interpreted by several methods which quantify the fuzzy output variable. The most widely used implication method used in FLC systems is that of Mamdani due to its simplicity and is adopted here [17]. The Mamdani implication is defined using the “min” operator as:

\[
\mu_{R, \text{imp}}(a, b, c, d) = \min\left[ \mu_A(a), \mu_B(b), \mu_C(c), \mu_D(d) \right] 
\]  

(5)

Since each of the landmine distance variables has two possible values and the target orientation variable has 5 possible variables, using the product counting rule, the total number of required rules in the rulebase is 40 rules. Two examples of such rules and their corresponding implication functions are shown below.

Rule R₉:

**IF** DL is far **AND** DC is far **AND** DR is near **AND** TN is FR **THEN** TA is LR

\[
\mu_{R_9}(DL, DC, DR, TN) = \min\left[ \mu_{far}(DL), \mu_{far}(DC), \mu_{near}(DR), \mu_{FR}(TN) \right] 
\]

\forall DL \in \text{far}, \ \forall DC \in \text{far}, \ \forall DR \in \text{near}, \ \forall TN \in \text{FR}

Rule R₃₃:

**IF** DL is near **AND** DC is near **AND** DR is far **AND** TN is FC **THEN** TA is RS

\[
\mu_{R_{33}}(DL, DC, DR, TN) = \min\left[ \mu_{near}(DL), \mu_{near}(DC), \mu_{far}(DR), \mu_{FC}(TN) \right] 
\]

\forall DL \in \text{near}, \ \forall DC \in \text{near}, \ \forall DR \in \text{far}, \ \forall TN \in \text{FC}

C. Inference Mechanism

The inference mechanism of the FLC has to perform two sequential steps; rule matching and rule firing. Rule
matching involves the controller comparing each antecedent of all rules against the input variables. Matching is achieved against all the rules which have the membership function of all of its antecedents greater than zero. For each such rule, the implication membership function is determined by equation (4). The next step is to generate the membership function for the output variables for each matched rule using modus ponens compositional rule of inference. As an example of the inference mechanism, assume that the two above rules are matched for a measured value of input variables from the vehicle sensors to be: DL = 40 cm, DC = 45 cm, DR = 60 cm and TN = 30°. For the rule R₉:

Applying the Mamdani implication:

\[ \mu_{R₉}(DL, DC, DR, TN) = \min\{0.2, 0.3, 0.4, 0.5\} = 0.2 \]

For rule R₃₃:

Applying the Mamdani implication:

\[ \mu_{R₃₃}(DL, DC, DR, TN) = \min\{0.8, 0.7, 0.6, 0.5\} = 0.5 \]

D. Defuzzification of Output

Defuzzification is the process of combining the successful fuzzy output sets produced by the inference mechanism. The purpose is to produce the most certain low-level controller action. Several methods exist in the literature to perform defuzzification, the most popular which is the Centre of Gravity (CoG) method. For discrete triangular linear functions the CoG method is obtained by moments of area as defined by:

\[
\hat{c} = \frac{\sum c_i \mu_c(c_i)}{\sum \mu_c(c_i)}
\]

For the matched rules R₉ and R₃₃, the application of the CoG methods results in a crisp control action of turn angle 28.178° with a certainty of 0.197.

V. CONCLUSION

In order to cater for the uncertainty associated with the autonomous motion of landmine detection vehicles, a fuzzy logic control approach is adopted. The sensed target direction and landmine distance are both fuzzified using overlapping membership functions. Heuristic knowledge of navigational decisions are encapsulated in a fuzzy rulebase. A compositional rule of inference is applied on the rulebase to construct a set of applicable fuzzy navigational decisions. The Centre of Gravity method is used to combine the results of the applicable fuzzy rules and produce a crisp a control action.

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Virtual Training System for Teleoperation of ROBHAZ-DT2

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Abstract

Recently various field robots have been developed for hazardous applications (e.g., explosive ordnance disposal, rescue, security), and most of them employed master-slave system by using teleoperation control scheme. To complete given missions in outdoor environment, the slave robot must have appropriate performance like accuracy and reliability. However, the more functions the slave robots have, the more difficulties can occur because of the complexity of the increased functions. In our previous research the ROBHAZ-DT2, a field mobile manipulator system including an effective user interface was developed. For evaluation and optimization of the field robot system, a lot of test procedures should be carried out. For the field robots are mostly very expensive, it is reluctant to use actual robots for every turns of the verifications. A virtual reality system is useful not only for evaluating slave robots but also for training operators. This paper describes a virtual training system for the ROBHAZ-DT2. The slave robot is simulated in virtual environment, and the operator interacts using the OpenGL based 3D graphics system. Interfacing the developed haptic device to this system operators can be effectively trained by the simulator successfully.

I. INTRODUCTION

For the past decades, many field robots have been developed [1-4] to replace human in hazardous environment such as rescue tasks in disaster, surveillance in airport, even missions in war place. The final goal of the field robot system might be to accomplish these missions autonomously with its own intelligence. For that is still beyond the current technological state of the art, we need proper human intervention in the form of tele-operation.

Basically, a field robot needs appropriate performances such as accuracy, reliability, dexterity and various sensing abilities enough to complete given missions. To meet this requirement, remarkable improvement has been achieved to make the slave robot intelligent. Recent field robots install various sensors (e.g. vision, sonar sensor, inclinometer, etc.) to gather more environmental information, and have specialized mechanisms for manipulation and mobility.

However, the more functions the slave has, the more difficulties the operator may have in controlling the slave robot. The dexterous motion usually requires complicated command sets in operation. Plenty sensing information which is not managed properly is not necessarily good for the operator’s decision. In developing a field robot system, therefore, it gains more importance to design a smart user interface for the easy tele-operation.

The major functions of the user interface are to generate commands to the robot, and to feedback the sensing information to the operator. For the command input, most existing field robots use a joystick-type simple device, and the number of its degrees of freedom is usually too small to control all the joints at a time [4-5]. Therefore in most cases it is impossible to control the robot in Cartesian space. In order to solve this problem we introduced a novel haptic device with two phase force feedback ability and multimodal sensor fusion system for the augmented reality [11].

The ROBHAZ-DT2 was developed as a teleoperated mobile manipulator for hazard environment applications through our past research [6], and a specially designed user interface was also developed for easy operation [10]. It is reluctant to use actual ROBHAZ-DT2 system for tuning the user interface or training novices, because of the expensive maintenance cost.

In this research, a virtual training system for ROBHAZ-DT2 was developed using computer graphics, and some experiments are performed. Section II and III introduce the ROBHAZ-DT2 system, and Section III deals with a control scheme of the teleoperation. Section IV describes the virtual training system for ROBHAZ-DT2 with some experiments, and section VI concludes the research results.

II. ROBHAZ-DT2 SLAVE SYSTEM

The ROBHAZ-DT2 was developed in previous research as a teleoperated mobile manipulator for hazard environment applications, as shown Fig. 1. A mobile base is designed to get high adaptability to uneven terrain using passive double tracks, and a manipulator is equipped on the mobile base. The robot has totally nine degrees of freedom, thus it can move in a hazard environment, and also dexterous manipulation can be performed [6].
As well as unique design in the track mechanism and the manipulator, this robot has some other features for practical deployment in outdoor environment. Between the main body and the front, rear track bodies, hydraulic dampers are equipped for mitigating shock on traveling. A clutch in driving shaft is designed for shifting high and low speed gears trains. The ROBHAZ-DT2 has nine ultrasonic sensors in order to perceive obstacles and a posture sensor to measure its posture during traveling. The ultrasonic sensors can detect not only circumferential obstacles like walls but also a ditch or cliff. The ultrasonic information is used for force feedback and also escaping obstacles in reactive way. As well, a pan-tilt stereo camera is prepared for monitoring a circumference view at a long distance. The feature of the stereoscopic monitoring system enables the operator to view the surroundings of the ROBHAZ-DT2 more realistically by the stereo camera attached on the pan-tilt mechanism. When the operator works at narrow distance such as moving mines or explosives, it gives the remote a more realistic sense. The image information of video is sent to the remote control station via an independent RF channel to reduce the traffic in data communication.

### Table 1. Specifications of the ROBHAZ-DT2 robot

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>External size (W × H × L)</td>
<td>690 × 500 × 910 mm (manipulator excluded)</td>
</tr>
<tr>
<td>Weight (batteries included)</td>
<td>145 Kg</td>
</tr>
<tr>
<td>Max. velocity (m/sec)</td>
<td>2.78 m/sec (10 Km/h)</td>
</tr>
<tr>
<td>Maximum climbing-up angle</td>
<td>32°</td>
</tr>
<tr>
<td>Passive joint limit</td>
<td>+10 ~ -30</td>
</tr>
<tr>
<td>Batteries</td>
<td>actuators : lead-acid controllers : Lithium ion</td>
</tr>
<tr>
<td>Continuous operation time</td>
<td>1hr</td>
</tr>
</tbody>
</table>

A cooling system by means of heat exchange is introduced to ensure the dust-proof cooling for safe outdoor operations. The major specification data of the ROBHAZ-DT2 are listed in Table 1.

### III. Master Interface for ROBHAZ-DT2

In the teleoperated field robot system, the robot is designed to be a faithful slave to face with the dangerous environment, while the operator using a user interface manages the slave in the safe site from a distance. The features of the user interface are classified as follows:

- Command to the robot
- Feedback the situation of the robot to the user.

Ideally, the design goal of a user interface is to make it transparent, as the user feels as if he or she works in the actual spot of the slave. To achieve this transparency, actual design issues are raised as follows:

- **Simplicity**
  - All indicators are unified as one scene.
  - All input button and joystick are integrated into one haptic device.

- **Intuitiveness**
  - High-level command by speech recognition.
  - Human friendly feedback such as graphs indicator, human voice.
  - Motion command matching between the haptic device and the slave in Cartesian space.

With this design factors, the multi-modal user interface has been developed and integrated [10], as shown in Fig. 2. The operator wears the HMD, head tracker and headset to interact with the slave. A six degree-of-freedom haptic master is attached on his waist together with the standalone controller, and the operator grips its handle to tele-manipulate in Cartesian space.

All the control modules with battery are packed into one backpack, so that the user can work around in teleoperation. It includes RF and wireless LAN modules enabling completely wireless communication. It is composed of major three interfaces.

#### A. Speech and Auditory Interface

![Fig. 2 Multi-modal user interface for the ROBHAZ-DT2.](image-url)
In this research, the operator sends two types of commands to the robot. The one is a selection command and the other is a continuous motion command.

For example, the selection between mobile and manipulation mode, the reset of the robot arm and mobile base, the on/off and reset of pan-tilt motors, the speed selection of the mobile, the selection among installed cameras are defined in the selection commands. These commands are executed through the speech recognition. When the operator says a word which has been predefined as a command, the speech interface can be aware of the word. If the speech recognition system successfully recognizes what he says, the recognized command pops up on the HMD for confirmation. Finally, the operator would decide to execute or cancel the command with the confirmation button on the haptic master.

The auditory interface synthesizes the human voice by installed speech synthesis engine. It can warn of the approach of obstacle by sound, or inform of information of a pointed object by a laser displacement sensor mounted in the slave (e.g. direction and distance).

The vision information is sent via a RF channel while the sensed data is feedback via an independent wireless LAN channel to reduce the traffic in data communication. A source for video overlay is prepared with the reported data, as shown Fig. 3(b). The recognized speech command is highlighted on left side to confirm. When obstacle is detected by ultrasonic sensor, it shows around robot icon in the middle of the scene. Other useful and important information (i.e. velocity, heading direction, view direction, arm posture and etc.) are shown by bar graphs. It is overlaid on the remote video source pictures and unified to single scene. Finally the operator sees the stereoscopic picture and the status of the robot at a glance immersivly on the HMD. The overlaid view is shown in Fig. 3(c)

C. Haptic Interface

In most 6-dof haptic devices, all six actuators are activated to create force feedback even when only simple motion is desired, since Cartesian space and the joint space are closely coupled in the device. It is desirable, therefore, that a haptic device is designed so that only necessary degrees of freedom are activated while other degrees of freedom remain inactivated depending on the situations.

In this manner, a new 6DOF haptic device was developed for control of the ROBHAZ-DT2 [11]. The haptic master is composed of upper and lower mechanisms in the consideration of the manipulator and the mobile, as shown Fig. 3. The lower mechanism is designed to be a planar 3-dof parallel manipulator and the planar 3-dof (x, y translation, z rotation) exactly matches the motion of mobile. While the mobile is moving, only the lower mechanism is activated for force reflection. The upper mechanism is designed as a spatial 3-dof (x, y rotation, z translation) parallel manipulator and it is attached on the
lower mechanism, as shown Fig. 3. Finally, the developed device has totally 6DOF. Once the robot reaches the goal, it performs a given task using the manipulator, using its full 6DOF motion.

The complex motions of the ROBHAZ-DT2 are easily commanded by the haptic interface. The continuous command mentioned above, such as the velocity of mobile and the position of arm, is ordered with the haptic master. The operator grips the handle of the haptic device and moves his hand, and the robot exactly moves along the direction. In the navigation mode, the mobile base is operated with the lower mechanism of the haptic master, and only 3 actuators are activated. In the manipulation mode, the operator intuitively control the manipulator with full 6 degrees of freedom. The developed haptic master is newly improved to achieve compactness and lightweight, as shown Fig. 4.

![Fig. 4 compact haptic master](image)

**IV. TELEOPERATION OF ROBHAZ-DT2**

For actual integration of the ROBHAZ-DT2 system, the scaled teleoperation scheme was adopted, and also the compliance control was used for the safety of the manipulator, as shown in Fig. 5.

![Fig. 5 Proposed tele-manipulation system with compliance control](image)

A scaling process matches the different workspaces of the master and the slave. Representing feedback force at the master system was magnified or reduced for minute sensation. The relations of command and force between master and slave command are denoted by

\[
\dot{x}_m = \rho_s \cdot \dot{x}_m, \quad F_s = \rho_F \cdot F_m
\]

where \( \rho_s \) and \( \rho_F \) are the scaling factors.

The kinematic relations between the joint and the Cartesian vectors for each system can be described by

\[
x_m = J_m \cdot q_m, \quad \tau_m = J^T_m \cdot F_m
\]

for master device and

\[
\dot{x}_a = J_a \cdot q_a
\]

for slave arm, where \( J_m \) and \( J_s \) are the Jacobians of the systems.

The communication delay in teleoperation would makes instability, because the force signal is no longer collocated with the corresponding velocity at the slave. When an unexpected collision occurs in the slave arm, there is no way to protect the manipulator during the delay time that the contact force signal reaches the master. Most field robot systems adopt wireless communication, and several tens of milliseconds delay may occur. To protect the manipulator from an unexpected impact by collision, compliance control method was adopted to the slave as shown Fig. 5. The slave faithfully follows the scaled position \( \dot{x}_s \) by the position controller. However, when a contact occurs, the contact force is measured to calculate the displacement vector \( \dot{x}_c \) which presents adequate compliance with given factor \( K \) and \( B \). The relation can be described by

\[
F_s = K \dot{x}_c + B \ddot{x}_c
\]

where the measured force \( F_s \), the position and velocity displacement \( \dot{x}_c \) and \( \ddot{x}_c \). The gains \( K \) and \( B \) are constant symmetric positive definite matrices. The adjusted position and velocity reference \( \dot{x}_a \) is used to control the manipulator. Finally, the contact force is regulated locally at the manipulator side. The measured force signal is also transmitted directly to the operator to inform the contact.

**V. VIRTUAL TRAINING SYSTEM FOR ROBHAZ-DT2**

It is not efficient to use an actual field robot system for training operators due to the burden of the maintenance cost. A virtual training system of ROBHAZ-DT2 was developed for low cost practice. A simulated virtual environment substitutes the slave system as shown in Fig. 6. The virtual field is constructed using OpenGL with the virtual models of trees, stones, and monuments. The virtual ROBHAZ-DT2 can be controlled directly by the developed haptic master.
As the mission starts, the operator controls the ROBHAZ-DT2 to move from the spot A to the spot B in Fig. 6. When the robot approaches near the stones or trees, feedback force against the obstacles is generated and can be used to make the detour path. After arriving at the target position spot B, the operator switches the operation mode from navigation to manipulation. In this scenario, the operator tries to place down a fire extinguisher at one corner under the monument, as shown in Fig. 6(c). If the extinguisher contacts with the wall, reaction force is generated. In real situation, this would protect the manipulator from damage due to an unexpected collision.

Experimental results are presented in Fig. 7. The pose of the haptic handle and the force-feedback command are presented in Fig. 7(a) and (b), respectively. The actual torques of the lower and the upper mechanism are illustrated in Fig. 7(c) and (d). The measured time span $t_{\text{navigation}}$ and $t_{\text{manipulation}}$ in Fig. 7(a) show the total travelling time from the spot A to the spot B, and manipulation time. The trajectory data in Fig. 7(a) and the feedback force data in Fig. 7(b) show that the robot approaches to the obstacles four times during navigation. The trajectory is indicated as a line in Fig. 7(a), and the circles on the line indicate where the obstacles locate. While the robot passes by the obstacles, feedback force is exerted during the sections $S_1$, $S_2$, $S_3$, and $S_4$ in the Fig. 7(b), and the feedback torques are generated as shown in Fig. 7(d). It is noticed that motors of the lower mechanism relating the navigation are only activated. By the force reflection, the motion of handle is adjusted as shown in Fig. 7(a). Especially, the section $S_3$ shows a typical behavior. In the section $S_3$, we can notice that the feedback force to the $x$ direction guides the handle.
to the right direction with regard to approaching to the stone post from left side. The force to \( y \) direction pulls the handle backward not to be near in the beginning of approaching, but it pushes forward so that the robot can get away from the obstacle after passing by. During manipulation, the fire extinguisher bumps against stony walls, and all direction of forces are generated due to the contact. When the feedback force to \( z \) direction is exerted on the stone platform, all actuators for upper and lower mechanism are activated, as shown in Fig. 7(c) and (d). The results are used to tune the scaling factors and feedback gain, and this applies to actual system.

V. CONCLUSION

In this paper a virtual training system for ROBHAZ-DT2 was introduced. Using the virtual training system, even the novice can exercise operating the robot without any hardware burden successfully. Through this training system every operator can define his own operating parameters like scaling factor between master and slave workspaces or feedback gains for force reflection. It was verified that the proposed mode selection method between the navigation and the manipulation mode is very useful for controlling this kind of mobile manipulator system.

REFERENCES

Heterogeneous robot cooperation for interventions in risky environments

C. Bruno, D. Longo, D. Melita, G. Muscato, S. Sessa, G. Spampinato

Abstract— In this work we will present the architectures and some experimental results of two examples of heterogeneous robot cooperation, that have been designed to be adopted to reduce risk for humans operators in intervention in risky environments. In particular we explored the cooperation among mobile terrestrial platforms and climbing robots and of aerial vehicles and mobile terrestrial platforms.

In the first example the cooperation between a climbing robot for inspection of vertical walls and a rover for outdoor operations has been tested. The mobile robot can position the climbing robot on the wall close to the dangerous rough area, allowing human operators to remain at a safe distance while inspecting the wall.

In the second example we propose the adoption of a UAV to help localization and mapping of terrestrial vehicles. In particular an innovative method for aerial target geo-localization is used to determine at the same time the position of the rover and of natural/artificial targets.

I. INTRODUCTION

In most cases, during crisis or emergency in hazardous or dangerous environment, it could be useful to inspect some targets or to have a quick overview of the area. At the same time, it is generally not easy or possible for human operators to perform these operations, for safety or practical reasons.

In past research activity at DIEES Robotic Laboratory, different devices for indoor-outdoor inspection have been developed. Among the others, the outdoor Robovolc rover, the Alicia VTX climbing robot and the Volcan UAV. All these robots were developed for different inspection applications [1], [2], [3], [4], [5], but all of them are very robust and well suitable for outdoor environment. All the three robots are autonomous and/or remotely teleoperated, always allowing safe operations.

While the Robovolc rover can be used by itself in teleoperated mode for inspection of outdoor / hazardous environment, it can be helpful in inspecting vertical wall by deploying the Alicia VTX climbing robot on a wall that is unreachable by human operators, for safety reasons or because of the hostile environment.

Moreover, in some other applications it could be useful to have a full sight of the hazardous area. For this purpose the Volcan UAV can be used in teleoperated way as well as in autonomous way, by programming a target trajectory inside its autopilot. The UAV can be also used to help in rover, natural / artificial obstacles and targets geo-localization.

In the next sections, first a short outline of the different robots will be pointed out. Then, two different situations will be described. In the first, the Robovolc rover helps in deploying the Alicia VTX climbing robot, while in the second the Volcan UAV helps in geo-localize the Robovolc rover and its target.

II. ROBOT OUTLINE

A. Robovolc rover

In the study of volcanoes, a direct approach is required to the volcanologists: on-site inspections are needed for gas and materials gathering, change in the morphology of the terrain analysis, lava flow course observation. It should be noted that observations and measurement of the variables relating to volcanic activity are of greatest interest during paroxismal phases of eruptions, which unfortunately are also the time of greatest risk for humans.

Several studies have been conducted with the intent to develop an autonomous robotic system able to operate in volcanic environment: Dante II by NASA [6], MARSOKHOD by VNIITransmash [7], YAMAHA helicopter [8] are some of the robots built to help volcanologists in their activities.

The DIEES Robotic Laboratory, University of Catania - Italy, is involved in several research projects concerning volcanoes and related problems. Some of these activities are within the Robovolc project [2], [3], [4], whose aim is to develop robotic systems for the exploration and analysis of volcanic phenomena.

Robovolc, shown in Fig. 1, is a tele-operated robot for volcano exploration capable of:

1) approaching an active volcanic vent;
2) collecting samples of the volcanic products erupted;
3) collecting physical and chemical data on the eruptive processes;
4) surveying close to vent openings.
The Robovolc rover is equipped with the following sensors:
1) RTK-DGPS;
2) 6 videocameras;
3) chemical sensors for gas analysis;
4) infrared and thermal vision systems;
5) data loggers;
6) 5 dof SCARA robotic arm; Fig. 2 shows the gripper mounted on the arm.

B. Alicia VTX climbing robot

Climbing robots are useful devices that can be adopted in a variety of applications such as maintenance, building, inspection and safety. These systems are mainly adopted in places where direct access by a human operator is very expensive because of the need for special tools, or very dangerous due to the presence of a hostile environment. Possible applications of these systems are inspection of petrochemical storage tanks, concrete walls like those of dams and bridges pillars, metallic structures and so on.

For visual inspection purpose, the robot can be equipped with a small CCD camera.

Several other systems for similar targets have been developed by our group in the past [9], [10], [11], [12]. Devices based on the principle of sliding suction cups are currently under construction by other universities and research centers. One of these is the robot developed under the Robosense project [13], [14]. The main target of this system was the inspection of concrete walls like those of highway bridges and dams. Other robots are being developed at Fraunhofer IPA [15] and the Technical University of Kaiserslautern [16]; these are very small and light and use a highly efficient sealing system. However, the architecture only allows the system to climb on very flat surfaces like glass walls.

Different kind of climbing robots were built at DIEES Robotic Laboratory; mainly, different methodologies for their adhesion (electromagnets, active/passive suction cups, sliding suction cup) and for their kinematics, were explored. The aim of these studies was to improve adhesion of the system also over rough surfaces and to develop lighter and faster robots.

The Alicia VTX is one of the last systems developed at DIEES. It is a new autonomous climbing robot based on vortex sliding suction cup adhesion. In order to achieve very low system weight and relatively high payload, a new smart active suction cup was designed and built.

The vacuum inside the cup is generated by means of a high speed centrifuge fan that creates a vortex with a low pressure area in the central zone. By using this principle it is possible to use a low power brushless motor to actuate the fan (about 50W). In this way no exhaust air flow is generated, and consequently the process is more efficient with respect to suction cups, where an air aspirator is used instead to generate the vacuum [1].

This kind of vacuum cups can adhere to different kind of rough surfaces because it can sustain vacuum inside without using any sealing. A strong adhesion force is achieved even when a considerable gap (<1cm) between the robot and the surface is present. This allows reducing to zero the friction between the cup and the wall during motion, to save energy and to increase robot speed. Moreover it permits the robot to move over small obstacles or irregularities and to climb from a floor to a wall. The robot uses four independent DC motors and four wheels to move and uses an inclinometer as feedback sensor, in order to follow a reference trajectory during its travel over a surface. The robot is shown in Fig. 3.

The robot has been tested over many different surfaces giving good results and receives its energy from two 11V LiPo battery packs.

C. Volcan UAV

In a recent project INGV (Istituto Nazionale di Geofisica e Vulcanologia) and UNICT have built the Volcan (see Fig. 4 and Fig. 5), an UAV able to analyze gas samples in volcanic areas and to perform visual surveillance [17], [18]. The Airplane has a wingspan of 3.5 m and is actuated by an electric motor to reduce gas sensor contamination.
An autopilot has been realized with the aim of making Volcan UAV autonomous: the avionic system allows performing autonomous operations in following predefined trajectories, while take-off and landing operations are supervised by a human operator. A simple click’n place procedure allows to set the waypoints of the mission on a georeferred map in the base station PC; a GUI has been realized to monitor and modify the mission course and to display in real-time all parameters and measures of interest, such as attitude and position of the plane, level of the batteries, measures coming from the on-board chemical sensors. Data are sent to / from the UAV by means of a radio modem.

An Hardware in the Loop (HIL) architecture has been implemented to develop, test and tune involved control algorithms: based on the use of a commercial flight simulator (X-Plane by Laminar Research), this testing-bench allows to decrease costs and risks related to the development phases before the execution of the flight trials with the real plane. Moreover the UAV can carry a CCD camera in order to gather images of the area under inspection. The images can be sent over a radio frequency channel in analog mode.

III. COOPERATION BETWEEN ROBOVOLC AND ALICIA VTX

In the first example the cooperation between a climbing robot for inspection of vertical walls and a rover for outdoor operations has been tested.

A typical scenario can be an area were some kind of disaster happened. The area can have some risk of explosion and / or hazard of pollution and some operators may have to inspect the condition of some buildings because there could be the possibility of a collapse. In this situation could be useful to have a teleoperated rover that can deploy an autonomous or teleoperated climbing robot.

In order to simulate this situation, a particular test was performed by using the mobile outdoor robot Robovolc that deploys the climbing robot on a vertical surface, while operators stay at a safe distance.

The rover Robovolc was teleoperated from a remote base station by using several cameras on the rover. Once a contact with the wall was achieved, a command was given to the climbing robot that could start climb the wall. On board of the climbing robot another camera with a radio link was present in order to permit a careful inspection of the surface.

![Fig. 3. The Alicia VTX climbing robot.](image3)

![Fig. 4. A representation of the Volcan UAV.](image4)

![Fig. 5. The Volcan UAV during a trial at the sea level.](image5)

![Fig. 6. Robovolc approaching the wall.](image6)
In Fig. 6 the Robovolc rover while approaching the wall is shown. In this situation the remote operator control the robot through the base station, using the video feedback of the cameras mounted on board the robot. When the robot reaches the wall, the operator can send a command to the climbing robot by means of a radio modem, in order to start it (see Fig. 7). Now the robot can start inspecting the wall in a teleoperated or autonomous way, as shown in Fig. 8.

IV. COOPERATION BETWEEN ROBOVOLC AND VOLCAN

The main objective of this project is the development of an integrated network of systems to improve monitoring and exploration of volcanic environments and to reduce risk for the involved operators. The network will be based on Unmanned Ground Vehicles (UGVs), on Unmanned Aerial Vehicles (UAVs) and on one base station for the control of the system by the operators. UAVs will be adopted as first response to quickly make observation of the area, perform measurements and to coordinate motion of terrestrial platforms, while maintaining human operators at a safe distance. Terrestrial mobile platforms will be adopted for on-site close measurements and / or intervention.

To achieve such objectives, it is necessary to develop algorithms that allow a precise localization of the modules and terrain reconstruction. In this way it will be possible to implement autonomous navigation methodologies.

In the literature only few results exist concerning the adoption of UAVs in volcanic area, very few results concerning the adoption of unmanned ground vehicles and there are not published results concerning the cooperation between aerial and ground vehicles [19], [20]. This kind of integrated UAV/UGV network allows to obtain a “cooperative perception” that increases the information content of the data collected by the single robot [21], [22], [23].

A. Simultaneous localization and mapping through UAV/UGV data fusion

In the last year the interest in probabilistic algorithms for localization of mobile robots increased constantly. One of the main problems in all kind of mobile robots is localization, and this problem is more important in presence of unstructured terrain. When unstructured terrains are present, small errors in localization could lead to erroneous or dangerous maneuvers or to the mission interruption. Due to weight and space limitations, UAV cannot have on board precise DGPS or other big or heavy sensors. On the other side UAV are very useful to give a wide map of the interested environment that could be really useful to plan a mission.

It is proposed to develop SLAM algorithms that could merge precise localization information from the UGV with aerial information of the UAV. In this way we could reach two goals:

1) improved localization of the UGV in presence of loss of information from DGPS;
2) precise localization of the UAV and georeferenced aerial map reconstruction.

A precise localization is the first step towards autonomous navigation.

In particular an innovative method for aerial target geolocalization is used to determine at the same time the position of a rover and of a natural / artificial target [24]. The enhancement proposed in this work is represented by the use of the information provided by the Differential GPS mounted on the rover to increase the precision in the estimation process of the targets positions. The proposed approach uses the knowledge of rover position to correct the transformation matrixes. The parameters of transformation matrixes are used as state variable in a Kalman Filter. Rover position is well known by using a Kalman Filter based on sensor fusion between DGPS and odometry raw data. In such a way, to enhance the accuracy in the estimation process, the camera has to collect just few frames of the ground robot.

Once the transformation matrixes are corrected, the position of the landmarks can be well estimated; for example it is possible to estimate the destination point of the Rover path.
Fig. 9 shows the localization and camera parameters correction process, while Fig. 10 represents the involved estimation algorithms.

B. Terrain reconstruction through UAV images

Terrain elevation maps or almost traversability maps from the flying platforms will be built using the acquired images, to improve motion planning of the UGVs. This will be done through a deeper investigation of what has been done in other research activities, as for example in the COMETS project [21], [22]. Through the information gathered from the vision systems onboard the UAV, some estimation of three-dimensional terrain maps are build, to allow a localization of the main exploration points (presence of survivals or other interesting points) and motion planning, avoiding obstacles or particularly rough places.

Moreover, in [25] a method to detect safe landing areas for an UAV from monocular images is proposed. The same approach could be used to detect an obstacle free path for Robovolc. The fusion of information coming from aerial imageries, GPS, ground sensors network and maps databases, will allow to reconstruct the morphology of terrain and to plan an obstacles free path for the UGV.

V. CONCLUSION

In complex situation as operation in risky environment or intervention during emergency in urban, volcanic or industrial area, could be of primary importance to gather as much as possible information in order to better plan an action. A system composed by a network different kind of robot could be a good solution, because it can take advantage from the ability of each robot.

Real practical examples of robot cooperation are still at the beginning. There are still many open problems on individual robot behavior, in order to really think about the cooperation among colonies of robots. Robots are still specialized to particular applications; our principle that was on the basis of this work was to try to get the best of each system and to exploit its peculiarities.

For example, aerial vehicles are able to take a global vision of the area and to collect data of gas pollution. Moreover, from the image taken by the plane, it is possible to obtain geo-localization of the ground vehicle and of the targets or obstacles. Another situation taken into account is the exploration of a vertical wall in an area not safe for operators (for example, because of pollution, poisons or risk of crashes). In this case, a ground vehicle could deploy a climbing robot on the wall to be inspected. A remote operator, using the on-board camera of the climbing robot, can inspect the wall.

To implement this kind of networks, suitable software and algorithm tools are under development in order to obtain for example, rover or target geo-localization, traversability map and so on.

Several practical examples of heterogeneous cooperation have been carried out and a simulator environment has been developed, in order to test new algorithms more rapidly.

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HIL tuning of UAV for exploration of risky environments


Abstract—In this paper the latest results of an HIL architecture, optimized to develop and test UAV platforms are presented. This architecture has been used to realize the different devices involved in the navigation and stability control of the Volcan UAV, a plane designed to operate in volcanic environments.

The proposed architecture is strongly modular and flexible and allows the development of avionic hardware and software, testing and tuning the involved algorithms with non-destructive trials. A flight simulator (X-Plane) with a suitable plane model and plug-in, has been adopted to simulate the UAV dynamics. The flight simulator, interfaced with the real electronic boards, allows an easy tuning of all the control parameters and data collecting for test and validation.

The effectiveness of adopted methodology was confirmed by several flight tests performed subsequently by using the designed avionic modules on the real UAV.

Index Terms—UAV control and navigation, volcanic environment, HIL architecture.

I. INTRODUCTION

This paper describes the latest results of the methodology used in tuning the new autopilot board developed for the Volcan UAV and its architecture.

The DIEES at the University of Catania, Italy, is involved in several research projects concerning volcanoes and related problems. Some of these activities are within the Robovolc project [1][2][3], whose aim is to develop robotic systems for the exploration and analysis of volcanic phenomena.

The goal of the Volcan Project [4][5][6] is the realization of an autonomous system able to perform aerial surveillance and analyze the composition of gas inside volcanic plumes. In situ gas sampling is one of the more reliable techniques to obtain information about the concentration of the main components of the fumes[7][8][9][10]; for this reason the adoption of a flying machine seems to be the right choice[11][12]; all the required instrumentation can be carried directly into the plume to obtain measures collected before contamination due to the interaction with the atmosphere.

Besides application in volcanic environment, the Volcan UAV represents an efficient platform in all those situations where the direct intervention of human operators could bring high risk[13][14][15][16]; typical applications are:
1) intervention in industrial plants;
2) forest fire-fighting services;
3) natural disasters intervention;
4) cooperation with other ground robots in demining operations, through aerial mapping [17].

The payload of the Volcan UAV can be easily changed as each case requires: the implemented plug and play architecture allows easily mounting for example mono and stereo cameras, chemical sensors, infrared and thermal vision systems, data loggers.

After all, the main advantages of the adoption of the Volcan UAV are:
1) reduction of the number of needed operators;
2) reduction of the risk for the involved operators;
3) better identification of the causes and effect of the crisis;
4) reduction of intervention time => faster response.

Fig. 1. The Volcan UAV during the launch phase in a volcanic site on the top of Mt. Etna (2900m).

The environmental and working conditions in which the plane has to carry out the mission, suggested the adoption of an autonomous navigation system for the plane. There are two main problems that do not allow using a classic remote controlled UAV.

The first one is the long distance between a safe place and the volcanic plume. The volcanic scenario is very rugged and often it is not possible to find a runway in proximity to the crater; so, lift-off is usually executed in safe areas from where the teleoperations are very difficult due to the distance between the take-off area and the target plume.

The second problem is related to the loss of the line sight...
when the plane flies into the fumes: the gas within the plume is usually very dense and does not allow a visual recognition of the vehicle flying inside it.

In designing such a kind of system, several features must be taken into account. Among the others, problems related to high altitude flight and gas sampling technique. More details about Volcan UAV design and related problems can be found in [4][5][6].

A navigation system was developed with the aim of making Volcan UAV autonomous; a set of avionic modules that allow configuring the plane in every state of the flight and make the UAV capable of autonomous flight and payload control, was realized.

To develop the different devices involved in the navigation and stability control of the vehicle, a Hardware in the Loop (HIL) technique has been adopted: this architecture allowed realizing, testing and tuning each of the modules of the system. The implemented testing-bench based on the use of a commercial flight simulator, allowed to reduce the number of field trials with the real UAV, with a considerable reduction of development costs and time.

In the following section the control and navigation system architecture is presented. In Section III the implemented HIL architecture is described together with the development procedure used to realize the Air Data Attitude and Heading Reference System (ADAHRS) module of the autopilot. Several results will be presented at the end of the paper.

II. AUTONOMOUS NAVIGATION SYSTEM ARCHITECTURE

In order to plan and monitor an entire flight mission, a complete navigation and stability control system has been realized.

Several features make the implemented autopilot versatile and flexible, allowing to reconfigure the system and to adapt its behavior to the mission requirements; the main peculiarities are:

1) the type of control can be selected between a full waypoints based autonomous navigation and a pilot in the loop (PIL) mode. In the first case the autopilot takes care of both navigation and stability of the plane: the mission is planned via waypoints, placing on a georeferred map the position of each waypoint at the beginning of the mission. The mission can be easily modified during its execution by adding/changing/removing waypoints in the map. In PIL mode, the plane can be teleoperated from the control station by using a control-stick while the on-board autopilot attends to the stability of the aircraft;

2) a user-friendly interface and a radio link allow a continuous exchange of data between the plane and the control station; a user friendly interface is used to display the plane position in real time on a map during the mission, to monitor some UAV parameters such as battery levels, speed, position and orientation, the sensors measurements.

3) on line setting of navigation and stability algorithms parameters allows to reconfigure the autopilot, adapting its response to new supervened conditions. This important feature is fundamental in volcanic environments, where changes in the weather are very frequent.

The block diagram of the avionic architecture is represented in Fig. 2.

The system consists of the on-board modules and the ground control station: the avionic devices constitute the real autopilot, while the ground equipment is the base station from where to plan and monitor the mission.

Volcan UAS modules are:

1) **FCCS - Flight Control Computer System**
   This module represents the core of the autopilot, since it attends to automatic flight navigation and stability control: data coming from Air Data Attitude and Heading Reference System are processed by control algorithms, to provide output commands to the Servo Actuator Control System (SACS).

2) **ADAHRS - Air Data and Attitude Heading Reference System**
   This is the sensor board: it combines tri-axial angular rates, tri-axial linear accelerations, tri-axial magnetic field measurements, air data and GPS to provide a complete 6DoF attitude and pose solution.

3) **SACS - Servo Actuator Control System**
   This module is connected to the R/C receiver to drive the servo commands and supplies them electrical power, derived from the onboard batteries. Opto-isolated servo signals increase power supply noise immunity. Every SACS can control up to 8 servos or other peripherals and allows to activate manual override, through a normal RC Radio command.

4) **GDLS - Ground Data Link System**
   This module provides for the radio link between on board electronics devices and the ground station; it is...
based on the MHX2400 COTS transceiver by Microhard System:
- 2.4000 - 2.4835 GHz ISM band;
- transparent, low-latency communication, providing true 115 kbaud operation;
- 60 miles, line of sight, with gain antenna.

5) GCI - Ground Control Interface
The ground control software allows to set-up the FCCS, configuring the control loops parameters. GCI permits easy “click and fly” operations, facilitating powerful mission planning, monitoring and in-flight adjustment on a notebook PC.

The communication between the functional units, which constitute the system of autonomous guide, is based on CAN bus and CANaerospace protocol; the latter exalts the characteristics of robustness and reliability, typical features of the CAN bus.

III. HARDWARE IN THE LOOP ARCHITECTURE

A. Simulation phase
The Hardware in the Loop architecture represents a powerful and cheap technique, that allows to develop and tune hardware, software and firmware of all of the modules that will be used in the real UAS [18][19][20][21][22]. The trials executed on the testing bench are not a complete substitution of real flight tests, however HIL architecture is very helpful in the preliminary phases to find and solve bug and problems of both hardware modules and developed algorithms.

After all, the main advantage of this type of approach is the reduction of development time, costs and risks.

In Fig. 3 the architecture adopted in the development of the FCCS module is shown. In our case, X-Plane by Laminar Research [24] has been used to simulate the flight dynamics of the Volcan UAV: a model of the plane has been realized by using a professional CAD software and imported in the simulator, to obtain a more reliable and accurate behaviour. A developed communication plug-in acts as an interface between the simulator and the real hardware: telemetry data concerning plane pose are sent through CAN bus to the autopilot board. Once attitude and position of the aircraft are known, the control algorithms implemented on the FCCS board compute the signals for the servo commands that are sent to the simulator to actuate the mobile parts of the plane.

In [6] an exhaustive description of the HIL architecture adopted in the working out phase of the FCCS module, was presented: the implemented control algorithms are described together with the complete hardware in the loop architecture, adopted to tune and test the real hardware device.

A similar architecture, shown in Fig. 4, has been implemented to develop the ADAHRS module. The X-Plane simulator supplies the data coming from the onboard Inertial Measurement Unit (IMU) and sensors: tri-axial angular rates, tri-axial accelerations, ground and air speed, GPS data are sent over CAN bus by the communication plug-in. Moreover, attitude and position of the simulated plane are recorded for an off-line comparison with the reconstructed pose.

Fig. 3. Hardware in the loop architecture adopted in the development phase of the Flight Control Computer System. The red square represents X-Plane simulator together with the communication plug-in realized to allow data exchange between the simulator and the real FCCS hardware.

Fig. 4. Hardware in the loop architecture adopted in the development phase of the Air Data Attitude and Heading Reference System.

In this first phase ADAHRS was implemented on a development board with an 8bit Microchip PIC, implementing a sensor fusion algorithm based on an extended Kalman filter. Sensors raw data, coming from the simulator, are processed to obtain noise-free, compensated and stable data: roll, pitch and yaw angles, heading, latitude and longitude, air speed, barometric altitude, sensors compensated data. Signal filtering parameters are totally configurable through the user friendly PC interface via CANaerospace fieldbus[25][26].

Reconstructed data are then compared with the attitude data obtained from the simulator.

Since sensors data coming from the simulator are noise free and almost ideal, a special plug-in was implemented; in
Fig. 4 the block “Artificial Noise” takes noise-free sensors data coming from the simulator as input and gives noise-added data as output. To obtain a reliable response from the simulated sensors, the real IMU was characterized. Several tests have been executed to test sensors behavior: vibration dependence, static and dynamic responses have been analyzed to introduce artificial noise with properties similar to the real one.

Moreover, these tests allowed implementing in the real hardware ad-hoc digital filters, able to guarantee high performance in all conditions and environments.

In Fig. 5 the true and estimated roll angles are shown: blue line represents roll angle coming from X-Plane simulator, red one is the angle estimated by the ADAHRS board by using the noise-added sensors data.

Maximum values of error committed in the estimation of roll and pitch angles are:
- |E_roll|_{MAX} = 3°
- |E_pitch|_{MAX} = 2.2°
while average values are:
- |mean{E_roll}| = 1.5°
- |mean{E_pitch}| = 1°

B. ADAHRS board

The next step was the implementation on the real ADAHRS hardware of the sensor fusion algorithms tested by using the development board. Once sensor fusion algorithms were completely designed and tested in simulation, raw data coming from real noisy sensor have been used.

The real implemented board (Fig. 6) is a strapdown low cost inertial navigation unit characterized by:
- Freescale MMA 1220D accelerometer for the Z axis;
- Freescale MMA 2260 accelerometers for X and Y axes;
- Tokin tri-axial piezo gyros;
- Freescale MPX 5010 differential pressure sensor for air speed measurement (Pitot tube);
- Freescale MPXAZ4115A absolute pressure sensor for altitude determination;
- 10 bit AD converter;
- 2nd order hardware filters for analog sensors filtering;
- commercial GPS receiver.

The same sensor fusion algorithms used during the HIL simulation phase, have been used on the microcontroller of this board; just a replacement of the simulated sensors data with the value coming from the real sensors, was needed.

Fig. 7 and Fig. 8 show a comparison between the developed ADAHRS and a commercial inertial measurement unit, the MTi by Xsens.
- \( |\text{mean}\{E_{\text{pitch}}\}| = 0.5^\circ \)

![MTI vs ADAHRS (Pitch)](image)

Fig. 8. MTi pitch angle (blue line) vs. ADAHRS estimated pitch angle (red line).

IV. EXPERIMENTAL FLIGHT RESULTS

The validity of adopted methodology was confirmed by several flight tests performed by using the designed autopilot on a real UAV.

Fig. 9 shows the aircraft response when it was flying in level flight and 30° roll angle was assigned to the autopilot as reference: the blue line is the measured roll angle, the red one is the reference angle. The sampling time was 10ms.

![Assisted mode - Roll](image)

Fig. 9. Aircraft response when the plane was in level flight and 30° roll was assigned as reference to the autopilot: the blue line is the measured roll, the red one is the reference roll angle. The sampling time was 10ms.

Fig. 10 shows the roll angle when a wide change in roll angle was executed; while plane was flying with a roll angle of -30°, a 30° roll angle reference was assigned to the autopilot. The blue line is the measured roll angle, the red one is the reference angle. The sampling time was 100ms.

![Mission 3 - Roll](image)

Fig. 10. Measured roll angle (blue line) when aircraft was flying with a roll angle of -30° and a roll reference value of 30° (red line) was assigned to the autopilot. The sampling time was 100ms.

V. CONCLUSION

The implemented testing-bench based on the use of a commercial flight simulator and of a hardware in the loop architecture, allowed reducing the number of field trials with the real UAV, with a considerable reduction of development costs and time.

This kind of architecture permitted the realization of a complete navigation and control system, based on the use of an implemented low cost strapdown inertial measurement unit, able to furnish stable and accurate measures even in presence of great noise and disturbance.

The effectiveness of adopted methodology was confirmed by several flight tests, performed subsequently by using the designed avionic modules on the real UAV.

ACKNOWLEDGMENT

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A COMPLEMENTARY MULTISENSORY METHOD FOR LANDMINE DETECTION

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One of the main needs for the humanitarian demining procedures is to find complementary sensing methods to fuse data supplied by multiple sources in order to maximize the detection of landmine and minimize the false positives. In this paper, a development of a multisensory method for a landmine detector is presented. This method is based on a multisensory fused data analysis on an embedded DSP, taken from an onboard camera and a metal detector.

The metal detector specially created for the application has the capacity to detect the landmine presence only if the mine has at least some small metallic components. This fact makes necessary to integrate another complementary sensory method with respect to the metal detector, given that the main goal is always to ensure the robot’s safety, while false alarms rates are decreased.

In order to do that, the onboard camera along with the embedded DSP have two purposes; first, to implement a navigation algorithm to find and follow non-structured roads, which is extremely necessary due to the special characteristics of the Colombian territory and to perform tasks like ‘demining along a road’. The second purpose is to analyze images of the road by taking account the color texture. Based on the color texture analysis, this research shows that it is possible to determine the presence of a non-metallic landmine within the image, achieved by finding the image regions whose color and texture features variations are considered anomalous. A color and texture variations over the image are an indicator that the surface has been intentionally modified and therefore it could be a landmine. This image processing strategy is being developed, in order to be implemented in ‘Amaranta’ robot, designed at Javeriana University - Colombia.
Demining in Shallow Inland Water Areas

Viktor Kálmán, Miklós Vogel, Dr. László Vajta

Abstract — According to studies[1], out of the 70 million mines deployed worldwide 15% are laid in shallow inland water areas. As these areas pose a serious mobility challenge to vehicles and humans as well - due to deep mud and low visibility under water - they deserve special attention. Some of these areas regularly freeze over in the winter making it possible for lightweight robotic vehicles to traverse them. Moving on low definition surfaces such as ice or sand, vision based teleoperation becomes difficult, and special methods have to be applied. Operating metal detectors, or ground penetrating radars in waterlogged areas can also be challenging. In this paper a special case study is presented, an ice rover[2], capable of moving around on the ice and carrying equipment, enabling it to map metallic objects in the water such as mines, unexploded ordnance and historic artifacts. The main problems associated with the task at hand, teleoperation and navigation issues, sensor suite and data processing problems, and contemporary research on these problems are presented.

I. INTRODUCTION

Many of the world’s waters, seas and lakes alike contain large amounts of wreckage and/or unexploded ordnance and mines, the remainder of various armed conflicts. Some of these areas are of considerable historical interest, others pose a potential threat to those that encounter them. In some cases even urban and touristic areas are cluttered with unexploded bombs and shells underground, that have become unstable during the years and are best handled by experts. Sometimes the terrain itself, such as a swamp might make searching very difficult. Under water, visibility and attainable speed are of consideration. A lot of the fighting has taken place near lakes, rivers and the seaside where the water is usually shallow, thus the sediment of the bottom is easily disturbed by waves and currents, considerably lowering underwater visibility. Also lakes and rivers tend to flow over, forming swamps around them, where mobility problems make exploration a strenuous task. Explorer robots can reduce the load on the research crew by helping to pinpoint the area of interest where further investigation by expert humans is necessary and by keeping them at a safe distance from potentially hazardous substances. Since the locations to be searched are often considered as difficult terrain these robots have to be well adapted to the circumstances both in their mobility and control. The most widely used method for controlling explorer robots is teleoperation, because a human operator is more likely to find a traversable path in challenging terrain, however for underwater explorers due to low visibility and a less cluttered environment autonomous and semi-autonomous operation is a feasible option. No matter what approach is being used, it is desirable for the robot to be aware of both its internal state and its surroundings.

II. SEARCHING IN WATER

Manual searching by metal detectors is by far the most widespread method for wreck and UXO exploration, because - if done by experienced personnel - it is very reliable. The great disadvantage is that the search is very laborious and potentially dangerous for those involved. For example currently, almost all humanitarian mine clearance is still required to apply hand clearance method that uses ‘prodding’ or ‘probing’ within its loop to assure high reliability. Manual probing is slow, labor intensive, extremely dangerous and stressful process [3]. Also in shallow lakes or rivers when visibility is low, orienteering becomes an issue for divers, so systematically searching an area becomes very difficult. When moving close to the bottom, the diver might disturb the sediment, making visibility even lower. This is the case when robotic explorers might outperform humans.

Detectors need not to be special, simple underwater metal detectors or proton magnetometers can be used.

III. EXPLORER ROBOTS

A. Underwater robots

The advance of robotic technology made it straightforward to employ robotic vehicles to do the dirty work. Robots are expendable, can be faster than humans, able to work around the clock tirelessly, and might be equipped with sensors that are more adequate for the task than the human eye, such as radars and metal detectors. However, the cost of applying robotic aids must be justified by the benefits they provide. There is no doubt that one of the major benefits would be safety, removing the operator from the hazardous area. It is clear that the development of a unique and universal robot that can operate under wide and different terrain and environmental conditions to meet requirements is not a simple task. Also there is little value in a system that makes life safer and easier for the operator but which will be less effective at exploration [3]. Well established commercial
technologies exist for marine mine detection, for example Double Eagle. This ROV is manufactured by Bofors Underwater Systems (Saab) and is widely used in countermine operations by various navies around the World. A serious problem with Double Eagle and similar robotic vehicles is their price.

B. Ice rover

When the climate permits, an ice rover can be a cheap alternative to underwater robots. Also in many cases, when the area to be searched is a swamp or a shallow lake, it is not possible to use robots developed for deep waters. The biggest advantage is that cheap proven technologies can be used without the limitations in mobility and communication imposed by underwater operation.

IV. Teleoperation

A. Levels of cooperation

Explorer robots are seldom totally autonomous because of the unpredictability of the terrain they might encounter. Various levels of autonomy are being used on the robots depending on the necessities of the task at hand. The robot can be totally teleoperated, or it can be semiautonomous, meaning that it is switched to autonomous mode when it loses the communication signal or when the operator is not able to control it properly because of being too busy or too slow to perform certain maneuvers. Underwater vehicles are somewhat special in this aspect. In order to teleoperate them a cable or acoustic link is needed. Sometimes dragging a cable is not an option and an acoustic modem is only useful up to a certain limited range. This is the case when autonomy is of high importance.

Teleoperation is a well researched discipline. State of the art teleoperation methods use virtual reality devices to immerse the user in the surroundings of the machine being controlled. These methods employ head-mounted displays, force feedback steering wheels and haptic devices. Besides the devices needed to physically control the robot, the philosophy and the model of interaction is also an active area of research and development. The following paragraphs give a short non exhaustive overview of these topics.

The drive behind the development of more sophisticated teleoperation systems is that the common exploration task can be a lot more effective if several robots are used simultaneously. To be able to do that currently one or more operators per robot are needed, when several robots are involved in the exploration, the number of operators controlling these robots becomes unacceptable, so methods other than direct teleoperation have to be considered.

In these cases it is desirable that the robot be more independent, either because the operator has other tasks to attend to, or there is a communication delay in the control loop, as it is the case when the link is noisy or the robot is far away. In these cases certain level of autonomy is desirable and the robots are controlled with telecommanding, supervisory or collaborative control. In the literature [4] a classification of different levels of autonomy is described, from these somewhat overlapping categories three levels can be derived:

The most basic level is simple teleoperation when both engine states and kinematics control are queried and set by the operator, this is in some respects similar to the direct control paradigm that we find in a car driven by a human. For certain systems this method continues to be the state of the art, because it is a cheap proven technology.

On the second level usually an internal closed loop velocity control on the vehicle allows representing a common motion behavior which is independent from the vehicle itself, or the operator may issue a sequence of elementary steps to perform a plan (such as waypoint path following). The vehicle simply reproduces these actions under the supervision of the operator. This control scheme is also called advanced telecommanding [5]. Also this category is more or less coincident with supervisory control defined in [6]. Although supervisory control has been around since the 1960’s some issues still remain open. Some argue that taking out the human from the actual control loop makes, detecting and diagnosing problems more difficult. Another problem is the lack of an objective method to decide the capabilities of a certain platform and the difficulty in deciding how to share the work between the human and the robot, even when several robots are being used.

On the highest level the robot operates autonomously, and the operator intervenes only in specific phases of the task, when the cognitive role in the execution is fundamental. The vehicle is independent form the user and only interacts with the operator at the level of strategy decision and initiative. These most advanced methods are called robot companion, or collaborative control. In case of collaborative control the robot cooperates with the human operator by using him or her just like any other ordinary resource. [7]

B. Enhanced methods

Teleoperation at its simplest is usually done using a simple medium quality 2D display. Many of the vehicle control problems arise from the fact that it can be difficult to judge clearances and terrain characteristics from a 2D image. Also sensory information processed by the robot has to be presented in a conceivable form to the human (co)operator. Fortunately several methods exist to enhance perception. By using the sensors of the robot extra information about the environment can be extracted, and sent back to the operator. For example overlaying extra information on the display, such as obstacles color coded with their distance, the edge of a road, bumps or other items of interest as sensed by the robot might help to understand the scenario better. Another problem is that the operator usually lacks feedback about the internal state of the vehicle such as the inclination of the ground, acceleration of the
chassis and available traction. Without this information it is hard to drive at higher speeds without running the risk of tipping over. The display of artificial horizons and rollover warnings might help the situation. Another approach gives more control to the robot and lets it deal with choosing the correct speed and heading. To be able to do this the robot has to be equipped with an internal state observer that decides the safe operating parameters for the vehicle. The observer relies on information such as the dynamic and kinematic model of the vehicle, acceleration of the chassis in 6DOF, true ground speed, wheel speed, available traction and a good internal model that fuses sensory and apriori information together to create an instantaneous state estimate and decide on the proper operating parameters to remain under the threshold for safe operation.

Some researchers are trying to solve the problem of time delay with predictive displays, more or less in a simulation – execute sequence of actions. Other technologies are aimed at immersing the operator into the environment via a virtual environment that effectively surrounds the user and supplies feedback by force feedback and tactile devices.[8]

C. Problems related to ice

Ice is inherently very slippery making dead reckoning navigation based on wheel rotation very unreliable. The solution for the problem is to use non contact displacement measurement technologies, such as GPS or Doppler radar. A cheap non contact method is described in [13], where an optical correlation technique is used to measure vehicle speed, much like in a conventional computer mouse. The method relies on ground texture as it compares subsequent images and calculates displacement in the patterns. Because of the low texture density in snowy conditions the use of stronger lights and enhanced resolution is necessary.

In low contrast surfaces, such as ice and snow make the perception of terrain features difficult. Skiers often encounter this problem; when the weather is cloudy it is very hard to recognize bumps on the trail with the naked eye, one has to rely on goggles or his or her knees. When teleoperating a robot using only a small flat screen one has no idea about the surface quality. The problem has its origins in the theory of human depth perception, because in low reflectance circumstances some of the most important depth cues, like shape from shading do not work [14]. This emphasizes the significance of the augmented reality and display overlay technologies and the need for the use of the on-board sensors outlined in the previous section.

V. BALARO

A. Terrain

Lake Balaton is the largest freshwater lake in Central and Western Europe in the Carpathian basin. Its average depth is 3.3 m. The region close to the south shore is particularly shallow (with around 0.8 meter depth). The lake is frozen during practically every winter. The long term average presence of continuous ice cover is 57 days a year with an average thickness of 20-25 cm [9]. According to historians, during WWII approximately 1600 aircraft were shot in Hungarian airspace. Approximately 20-30 of these fell into Balaton, 5-7 in the Tisza River and 10-12 in the Danube. On the 3rd of December 1944 the Russians reached the lake and fallen aircraft were no longer reported to the authorities. That’s why it is such a difficult task to locate and identify many of the wrecks [10]. Experts say that today there are 5-7 aircraft remaining in the water. The Balaro ice rover (Fig. 1.) is a semi-autonomous vehicle with a range of 8 km. The robot's dimensions are 80 x 80 x 60cm, its weight is approx 60 kg. It is powered by a gasoline fuelled generator. A pair of rubber tracks is driven by two 3-phase electric motors, allowing the robot to reach a top speed of approximately 10 km/h. This hybrid propulsion method offers long operating time maintaining the good controllability of the electric driving mechanism.

B. Theory of operation

The robot can be controlled via wireless ethernet link. To maintain useful bandwidth a parabolic antenna - deployed on the shore - transmits and receives signals from the robot. The antenna is mounted on a pan-tilt mechanism, and follows the robot automatically by calculating its relative position from the coordinates provided by the onboard GPS receiver. The robot has a forward looking camera which allows video to be sent back to the base station.

Only the sensors for navigation are directly mounted, others are towed. Sensors needed for safe navigation are GPS, electronic compass, monocular camera, tilt sensor, and odometer. The mobile platform is not fully autonomous in order to reduce on board navigation equipment and control processing needs. The vehicle is able to detect and avoid obstacles, follow preprogrammed path, reach specified points on its internal map.

The default towed equipment of the robot contains an ice drill, underwater camera, acoustic sonar and magnetometer. The drill may require a large amount of power from the generator, but, evidently, it is never operated together with the 3-phase motors of the main platform. The basic concept for the robots control is that the research crew teleoperates it from the shore, while the robot moves around on the potentially dangerous ice. When there is an unexpected scenario, such as communication link disruption, component failure etc. the vehicle follows its own path back to the shore.
Since usually there are no obstacles on the ice, save for built up snow getting from A to B is straightforward. GPS can be used extensively, because there are no obstacles to disturb the signals. In autonomous mode the mission can be planned and executed much like in a precision farming [11] or aerial surveillance scenario, by zig-zagging over the area of interest. The robot uses a hierarchical control scheme. On the highest level the human operator decides the area to be scanned, this is given to the robot in GPS waypoints. The second level is responsible for waypoint navigation and plans the path between neighboring points and replans when an obstacle is detected. The lowest level is responsible for speed control of the individual tracks. In teleoperated mode, the human operator can take the role of the second level, the path planner and give velocity commands to the tracks with a pedal and a steering wheel while following the preset route. Obstacles can be detected with the on board camera. In order to carry out its task successfully the robot has to carry various sensors and tools. Apart from the sensors needed for navigation of the platform, the robot needs sensors to locate objects of interest under the ice. The most widely used sensor that can operate in a waterlogged environment is a proton magnetometer. Since the average depth of the lake is more than three meters the sensor needs not to be special. Also to a certain extent ground penetrating radar can be used, when the water content is relatively small (in a swamp). [12]

C. Actuators

The robot also needs a drilling mechanism such as a conventional electric ice-fishing drill, or a simplified version of a Philbert probe, which is an electrically heated bullet shaped device designed to melt its way through ice. The thickness of the ice - depending on weather conditions – may vary from five to twenty five centimeters. We have conducted experiments to apply a controlled thermite reaction to burn a hole into the ice, eliminating the need for complex drilling mechanisms. However the quantity of the thermite has to be calculated carefully, so that the reaction ends before the mixture reaches the bottom. Also a reliable automatic ignition method and some safety measures have to be implemented before this technology can be applied in practice.

Depending on the task at hand the robot may lower the magnetometer, an array of sonars, or an underwater camera into the hole for further examination of the area.

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Fig. 1. The Balaro ice rover on Lake Balaton during a test run
Robotic Assistance in Extreme Conditions

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ABSTRACT

Robotic assistance in hazardous conditions is analyzed on the base of some Russian organizations experience. The suggested robots are intended for humanitarian de-mining, fire-fighting and decontamination applications.

Last years robotic activities for hazardous conditions are growing as an often dangerous incidents origination. Some results of the research, development and testing of extreme robotics are delivered.

The mobile robot design on the base of mechatronic approach is one of important tendency to improve the adaptivity to environments and to increase main working parameters. Multifunctional mobile robot complex of light and superlight classes are under consideration. Mine detecting methods examine in relations with applications in robotics.

Special attention concentrate on modular fire-fighting robot design because of several modifications of such robots are manufacturing and applied depends on fire solved tasks.

New design solutions are discussed for robotized fire complexes application, providing automatic fire extinguishing of high-floored buildings by water and foam, where application of traditional technical equipment is ineffective and unacceptable.

1. INTRODUCTION

Modern mobile robots have possibilities to produce various important tasks such as fire-fighting, demining, removing of radioactive accidents, decontamination of horizontal and vertical surfaces for example on the areas of Nuclear power stations [1, 2].

The special requirements are needed to apply satisfy the robot’s actions and robotic assistance in such extreme conditions. The additional demands exhibit on dynamics, reliability, control, maneuverability, fast velocity, high degree on autonomous, miniaturization, possibilities for decision making depends on quickly changing of environments [4,5,6].

This paper presents examples of the functional operations increasing by means of new robot design for the motion over horizontal surfaces, vertical or slope ones, and combine motion, using several platforms, multilink structures or “sliding sealing” systems [6,7].

Experience on robot design and application leading organizations in Russia is analyzed. Some examples of robotic activities are presented for firefighting tasks solving, for demining and decontamination.

The results were receiving by such organizations activities as the Institute for Problems in Mechanics, VNIIPo, Bauman State Technical University, Sankt-Petersburg Institute for Technical Cybernetics and Robotics and FR design and Manufacturing Company [1-6].

2. INTEGRATED ROBOT’S ASSISTANCE IN EXTREME CONDITIONS.

Integrated mobile robots consist of multilink or multiplatform mechanical transport systems, control systems with sensory fusion measuring-information possibilities and on board manipulators or technological tools. Mobile robot’s integrated structure permits to realize complex motion on not determined environments or over vertical and slope nonregular in the space (fig. 1, 2).

![Fig. 1 Multilink mobile robot structure for the motion in the space.](image1)

Multiplatform robot structure with vacuum grippers satisfy the motion over the surfaces disposed under arbitrary angles between them (fig. 3,4). One of the platform can rotates relatively other.

![Fig. 2 Multilink mobile robot transportation from the wall to the ceiling.](image2)

![Fig. 3 Surrouting of the angle equal 90° by means of two platform robot.](image3)
Integrated robot’s assistance very important in many extreme situations such as fire-fighting, decontamination of the surfaces, explosive search. Such robots can be equipped with special technological detectors or tools (fig. 5,6).

The control sensory systems of such robots have adaptation possibilities [7,8] or some elements of artificial intelligent behavior, permitted to produce decising making, change the motion trajectory planning processes or produce some maneuver [9,10]. Progress in mechatronic approaches lead up to design multilink or multiplatform mobile robots which assistance helps significantly man-operators working in extreme conditions.

Experience in advanced application show’s that fire prevention conditions and decontamination of the surface in the nuclear power stations are efficacious areas for demonstration effective assistance by means of robots.

Man-operators may to control situations and robot actions. From other sides robots itself have to interfere in extreme conditions spontaneously to produce technological operations near by real dangerous conditions.

3. FIRE – FIGHTING ROBOTIC ACTIVITIES.

Last year fire – fighting robotic activities was growing. Previous basic R&D provided in the Institute for Problems in Mechanics in cooperation with VNIIPo (Federal Institute for Fire Prevention) was realized on the production fire-fighting robots.

The design, development and testing of fire-fighting robots produced in the new Mechanical Engineering center of fire-fighting equipment “FR” (Petrozavodsk city).

The modular design of Fire-Fighting robots were studied and developed in Mechanical Engineering Center.

The various modifications of fire-fighting robots are produced and applied depends on fire solved tasks. Robots are applied in modular design and some examples are delivered on the Fig. 7-9.

Total number of fire-fighting robots is 14. It is possible to have many additional variations. Examples of robot applications on industrial objects (fig. 9).

4. APPLICATION OF ROBOT “MPK-25” FOR REMOVAL RADIOACTIVE DAMAGE IN ARZAMAS –16

At the 17-the May of 1997 in Russian Scientific Research Institute of Experimental Physics (RSRIEP) during one of experiments took place radiation damage. Special expedition equipped by mobile robots came from Moscow for removal of this damage. The reason of this accident was a destroying of experimental installation. As a result of this trouble conditions for beginning spontaneous nuclear reaction (SNR) formed (Fig. 10). Executive RSRIEP had got a lethal radiation dose.

There were five containers with radioactive materials in this room. To prevent radioactive materials from SNR it should be removed from the room.
Problem that expedition have been done:
removal five containers from the room;
exportation some parts of breaking installation.

Was organized complex group from specialists of
MSTU, RSRIEP, EMERCOM and FSS for doing this
problem.
Some mobile robots were provided in Arzamas-16 for
removal damage. Robots were brought from the
Moscow:
MF-4 produced by firm “Telerob” (Germany)
belonged to RSRIEP. Function of MF-4 to remove
radiation damage (Fig. 11);
MPK-25 produced by MSTU (Russia) and
belonged to this organization (Fig. 12);
HOBO and RASCAL produced by firm
“Kentree” (Ireland), belonged to FSS (Fig. 13).

The function of three last robots is to struggle
against terrorism actions by founding and breaking of
explosive devices. These robots have no special
radiation protection at control system.

In Arzamas-16 all mobile robots were used in
research building and its rooms. For fulfilment problem
put to robots were determined such steps:
• evacuation containers with radioactive materials by
MRK-25;
• monitoring on a hook of electric telpher vacuum
capture by MF-4;
• extracting a top of critical assemblage of fissile
materials and discontinuation of SNR.

That operation had been done damage should be
disposed.
MF-4 worked with air free clutch and it was bracken. In
addition, top of critical assemblage had not moved away
from a place from the first. The plan of work was
changed.
Necessity of additional operation became. These was
such operation:
• preparation for evacuation of breaking MF-4, by
robot MRK-25;
• preparation works for moving away the top part of
critical assemblage of fissile material with the help of
MRK-25;
• moving away a top of “assemblage” when all these
operations executed the damage stopped.

Few versions of technologies were offered to stop
this damage. Various types of device were produced for
this purposes. These devices had been mounted on
robots. All operations were trained with these devices in
identical room before would be done in real obstacle.
Especially operations for moving up a top of
“assemblage” had been done with the help of these
devices (Fig. 14).

Because robot MRK-25 successfully executed
operations the later was used in a role of “fireman” (Fig.
15). Two fire – hose barrels were installed on
manipulator for smother fire by carbonic acid gas.
Operations of evacuation robot MRK-25 by robot
HOBO also were trained in safe side.
When robot MRK-25 worked in a room robot HOBO
was equipped as a “firemen” in safe side and stayed at
another enter to the room (Fig. 16).

I can say that practically all operations were done by
MPK-25.
Level of radiation of all robots was measured after
removal of damage.
Main features of robot’s application in Arzamas-16:
• exploration of working place by photo, video;
• visual examination of environment by periscope;
• additional equipment with TV cameras to help in
operator’s work;
• training of all operations before execution in
identical building;
producing and installation of protection on control system of mobile robots;
• training an order of moving robots in a room.

Some features elimination of damage with robots describes in details.
Exploration place of robot’s work allowed to change tracks of moving got to know environment and etc.

Reliable control of robot required continuous information from the working place obtained by TV cameras. TV cameras installed at robots were not enough for this purpose. Therefore, additional TV cameras were installed. Unfortunately, radiation-resistant TV cameras were not enough for successful work.
Ordinary TV cameras which were stayed near the door of the room were disabled after fifteen minutes of work. TV cameras of robots HOBO, RASCAL and MF-4 were used in addition to other for help operators to work. The first TV cameras were connected to periscope, but the second TV camera was mounted on rotary device in the nearest room. This camera allowed viewing interior of the lab and corridor between two rooms. Executives of expeditions controlled these TV cameras.

4.1 MANUFACTURING PROTECTION FOR ROBOTS

Function of robot HOBO and MPK-25 is struggle against terrorist actions. These robots had no radiation protection of control system and TV cameras. We have made protection for these systems before operation in situ. Executive of RSRIEP brought necessary materials for protection of TV cameras and control system. Then protections of these systems were done (Fig. 17, 18, 19). For protection were used such materials: granules of polyethylene and plates of cadmium-plated polypropylene. Experience of production such protection was successful. [8, 11-13]

Some “white points” appeared on monitor of control unit after eight minutes of working of MPK-25 in the room where «assemblage» was installed. But their quantity and brightness were constant during the time of the work.

4.2. TRAINING OPERATIONS

All operations were trained at identical building in details. Various methods of execution of operations were trained. For example were few versions of moving away of container. There were such versions:
• clutching container by manipulator, lifting and removal by air;
• clutching container by manipulator, lifting and installation on upper surface of robot body;
• threading hook handle of container attaching through short line to a body of MRF-25 and moving container on place of storage.
The weight of container was more than 25 kg.

4.3. REMOVAL OF ACCIDENT.

Some operations which wire done by robot show on Fig. 20, 21
The main task was to remove containers and to decrease a time of robot staying in the room in radiation zone. This task needed moving of robot with minimum quantity of bends.

Aside from nose, stem and upper plate of robot body were most protected parts of robots. TV camera had additional protection with peak so that radiation did not hit in camera’s lens. In that way TV cameras had been fixed in order to two of them were directed in zone of robot move and work, and one were directed back for moving reverse. Robot moved on at maximum velocity in radiation zone. Operator tried to move robot without sharp turning.
Time of execution some operations was measured. Time of fulfillment evacuation of container also was measured. For evacuation of five containers was necessary 11 minutes 47 seconds. For clutching evacuee robot MF-4 by our one was necessary only 13 minutes 53 seconds. For mounting vacuum clutch to electric telpher and a moving table, magnetic clutch was necessary 14 minutes 30 seconds.
4.4 INFLUENCE OF RADIATION ON ROBOT MRK-25 AND DEACTIVATION OF MOBILE ROBOTS.

On robots were mounted some radiotracers so called “tablet” in certain places. “Tablets” was mounted on robot MRK-25 at points 15 and 16 (Fig. 22).

Fig. 22. “Tablets” on robot MRK-25

After finishing evacuation of containers “tablets” were taken away and measured. Also mobile robots passed through dosimetric control which had been done with hand device. Robot MPK-25 was washed by light alkaline solution after dosimetric control.

5. APPLICATION OF ROBOT MRK-25 FOR REMOVAL OF RADIOACTIVE ACCIDENT IN CHECHNYA

In Chechnya near a road Grozny-Argun had been lost some radioactive sources as a result of careless handling with protection container. It had happened in a difficult region. For compliment request of Chechnya Government, Emercom of Russia sent expedition equipped by robot MRK-25 for removal of this damage. Robot worked at rugged terrain covered with snow. It was too difficult to decide this problem in such conditions. Sources of gamma radiation with cap city exposition dose near 200 R/h were laid in ground at 15 meters of freeway.

Expedition consisted of expert from Emercom of Russia, Moscow Scientific – Production Association “Radon” and MSTU removed this radiation accident [8].

Expedition were needed to solve such problems:
- determine a places of radioactive sources;
- get out radioactive sources;
- load in special container radioactive sources
- close container special cork.

It was difficult work because radioactive sources had been in frozen ground covered with snow. It was dangerous to use electric hammer because radioactive sources could be fractured, so that parts of them got into a ground. This ground was necessary to remove and buried. It was decided to heat ground with the help of device putted on it. Device consisted from heater with infrared lamp (Fig. 23). After heating ground should become soft and got by special plug- which installed on setting of manipulator (Fig. 24). Each batch of ground saw with TV cameras and checked up with dosimeter.

For executing of these works were produced and installed protection from the lead. It was installed to protect control unit of mobile robot MRK-25. In addition, special for this work were produced special plug-in rubber and also post for additional TV camera on rotary device and heater with infrared lamp (Fig. 25). Robot was equipped by dosimeter for measuring level of radiation.

Also was manufactured sledge on which were installed containers for loader founded radioactive sources to it. Sledges by long hawser were pulled up to a place of work with the help of truck and stayed there during execution of all operations. All technology consisting from operations: heating, loading, removing etc was trained at similar conditions in place near Moscow.

The work of expedition for removal radioactive accident in Chechnya lasted only seven hours since arrival to the place of work.

6. CONCLUSION

Robot assistance was discussed in the cases of applications for fire- fighting, decontamination and humanitarian demining. Processes for removal damages by means of robots attended by complex group of experts from various organizations without what to get successful work was extremely difficult and practically was not possible.

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MODEL-BASED SOIL PARAMETER IDENTIFICATION FOR WHEEL-TERRAIN INTERACTION DYNAMICS
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Abstract— Terrestrial robots used for environmental surveillance, risky interventions and humanitarian de-mining have to operate in unstructured outdoor environments. The interaction dynamics between the wheels of such robots and the outdoor environment play a crucial role in traversability prediction, traction control, and performance optimization. From wheel-terrain interaction dynamics, it is seen that wheel slip and soil parameters play a vital role in determining vehicle drive forces. Thus, knowing the soil parameters of the terrain on which a vehicle is moving is beneficial for controlling the vehicle. In this paper we develop an algorithm for identifying soil parameters for wheel-terrain interaction dynamics. This paper presents a method to identify the set of soil parameters required to predict drawbar pull and wheel drive torque from measurements of slip, sinkage, and drawbar pull for a wheeled vehicle traversing unknown terrain. The soil parameters identified are internal friction angle, shear deformation modulus, and lumped pressure-sinkage coefficient. A 2-stage iterative Newton Raphson (NR) method is used for soil parameter identification. Simulation results show successful identification of a complete set of soil parameters with relatively fast speeds. The algorithms are also tested using experimental data obtained from a specially designed test rig where wheel slip can be accurately controlled and measured. Test results show that the algorithm can identify the soil parameters accurately and robustly with relatively fast speeds. The identified soil parameters are then used to predict the vehicle driving forces at various slip values and correlated to experimental measurements. The drawbar pull and wheel drive torque predicted from the identified soil parameters are shown to be in good agreement with their measured values. It is shown that the drawbar pull and wheel drive torque can be effectively predicted and used to for vehicle performance optimization. The algorithms presented in this paper can be used to develop traction control algorithms for off-road robots operating in rough terrain.

INTRODUCTION
Wheeled vehicles traversing rough unknown terrain has many potential applications, including defence, agriculture, mining, and space exploration. Most wheeled vehicles still operate under driver supervision while carrying out tasks. Knowledge of the terrain characteristics helps the driver to have a better control of the vehicle.

From wheel-terrain interaction dynamics, it is seen that soil parameters play a vital role in determining vehicle drawbar pull which can, in turn, be utilized for developing traversability prediction criteria and traction control algorithms.

Research on wheel-terrain and track-terrain interactions has progressed since Bekker started pioneering this area [1-3]. Iagnemma and Dubowsky focused on the characteristics of a rigid wheel in deformable terrain for planetary rover applications [4, 5]. In [6], soil parameter identification for a tracked vehicle traversing unknown terrain is presented. Soil parameter estimation for a wheeled vehicle traversing deformable terrain was first carried out by Iagnemma and Dubowsky [5]. A Linear Least Square estimator was employed as an on-line identification method to identify two key soil parameters, cohesion (c) and internal friction angle (\( \phi \)), using on-board rover sensors.

In this paper, for the first time, a method for identifying all five soil parameters is proposed for wheel-terrain interactions. The method is an extension from [7] where only three soil parameters were identified.

The Composite Simpson's Rule (CSR) is used to approximate the integrals of the original wheel-terrain interaction model, as they cannot be integrated analytically. By doing this, the speed of the algorithm increases by a factor of 9. The Generalised Newton Raphson (GNR) method is applied to the modified non-linear wheel-terrain interaction model for soil parameter identification. This method has been shown to identify unknown parameters with high accuracy and rapid convergence [6, 8].

The experimental data from the wheel-terrain interaction test rig are used to validate the proposed algorithm. The results show that the identified soil parameters can be used to predict \( DP \) over the entire slip range with good accuracy. The range of initial estimates of each parameter that give converged solutions is proposed. The predicted \( DP \) can be used for vehicle performance optimization, traversability prediction, traction control, and trajectory planning.

I. GOVERNING MODEL
The analytical model of a wheeled vehicle interacting with an unknown deformable terrain is presented in this section, Fig. 1. For simplicity, the wheel is assumed to be rigid. From Fig. 1, for constant vehicle forward velocity, considering the force balance in the horizontal direction...
In (3), (4), and (5), \( k_c, k_s, \) and \( n \) are the pressure-sinkage coefficients of the soil. These parameters have been derived for terramechanic applications and they characterize normal pressure from a vehicle with sinkage in the soil. \( c \) and \( \phi \) are the soil cohesion, and internal friction angle, respectively. These two parameters characterize the strength of a soil when exposed to axial and shearing loads. \( K \) is the shear deformation modulus of the soil and characterizes displacement behavior of the soil under shearing forces from a driven wheel.

All four integral terms of the \( DP \) model, (2), cannot be integrated analytically. The Composite Simpson’s Rule (CSR) is applied to find an approximation to these integrals in order to facilitate the implementation of the identification algorithm and increase the identification speed.

For the integral \( \int_a^b f(x)dx \), suppose that the interval \( [a, b] \) is subdivided into \( 2m \) subintervals of equal width \( h = \frac{b-a}{2m} \), by using the equally spaced sample points \( x_k = x_0 + kh \) for \( k = 0, 1, 2, ..., 2m \). The Composite Simpson’s Rule for \( 2m \) subintervals is given by:

\[
E(f, h) = \frac{h}{3} \left( f(a) + f(b) + 2 \sum_{k=1}^{m-1} f(x_{2k}) + 4 \sum_{k=0}^{m-1} f(x_{2k+1}) \right).
\]

The drawbar pull (\( DP \)) based on the Composite Simpson’s Rule (CSR) approximation and the \( DP \) based on numerical integration are shown in Fig. 2. It is observed from this figure that the CSR gives a very accurate approximation of the \( DP \) model with an rms error = 0.22 \%. In deriving the \( DP \) curves in Fig. 2, it is found that while the numerical integration takes 0.045 s, the CSR approximated model takes only 0.005 s. Therefore, this new approximate \( DP \) model is more suitable for soil parameter identification in real-time.
The pressure-sinkage coefficient, \( k_c/b + k_b \), is a constant, for constant \( b \) values. Since in current applications the wheel tread \( b \) of a vehicle is constant, a lumped pressure-sinkage coefficient, \( S = k_c/b + k_b \), is used in (2) and will be treated as a single soil parameter.

II. SOIL PARAMETER IDENTIFICATION BASED ON THE GENERALIZED NEWTON RAPHSON (GNR) METHOD

The proposed soil parameter identification algorithm for wheeled vehicles traversing unknown terrain is based on the Generalized Newton Raphson (GNR) method. This method is well suited for real-time parameter identification since it has been shown to identify unknown parameters with high accuracy and rapid convergence [8].

The concept of the GNR method is based on the Newton Raphson (NR) method. The NR method works by iteratively modifying an initial estimate and, after a number of iterations, arrives at a converged solution. Commonly, the iterative process is halted when the error between the identified value and the current value falls below a predefined threshold. The main difference between the GNR and the NR methods is that the NR method employs the same number of equations as the number of unknowns whereas the GNR method uses more equations than the number of unknowns.

The GNR method has the same advantages as those of the NR method, namely its ability to identify unknown individual parameters, its robustness to noise and its fast speed of convergence. In addition, the robustness of the GNR method is even better than that of the NR method [8] because it considers more equations than the number of unknowns. However, it is noted that if the initial estimate is selected at a point where the derivative of the function is relatively small, the convergence speed may be slow [9].

![Fig. 3. Diagram showing implementation of the GNR method for soil parameter identification](image-url)

The GNR method is implemented to identify the soil parameters for vehicle wheel-terrain interaction dynamics, Fig. 3. Here, vector \( p \) comprises five parameters, the cohesion \( (c) \), the internal friction angle \( (\phi) \), the shear deformation modulus \( (K) \), the lumped pressure-sinkage coefficient \( (S) \), and the pressure-sinkage exponential \( (n) \). The vector \( x \) consists of three measured signals, drawbar pull \( (DP) \), sinkage \( (z) \), and wheel slip \( (i) \). The Composite Simpson’s Rule modified wheel-terrain interaction model of (2), and the measurement vector \( x \) are used to identify the unknown soil parameters. To find \( p \), \( q \) independent equations are required \((q \geq 5)\). These equations are generated by evaluating the function \( f \) at \( q \) different time samples \((t_1, t_2, \ldots , t_q)\). This results in \( q \) nonlinear equations expressed in matrix form as:

\[
\begin{bmatrix}
\frac{\partial f_1}{\partial c} & \frac{\partial f_1}{\partial \phi} & \frac{\partial f_1}{\partial K} & \frac{\partial f_1}{\partial S} & \frac{\partial f_1}{\partial n} \\
\frac{\partial f_2}{\partial c} & \frac{\partial f_2}{\partial \phi} & \frac{\partial f_2}{\partial K} & \frac{\partial f_2}{\partial S} & \frac{\partial f_2}{\partial n} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\frac{\partial f_q}{\partial c} & \frac{\partial f_q}{\partial \phi} & \frac{\partial f_q}{\partial K} & \frac{\partial f_q}{\partial S} & \frac{\partial f_q}{\partial n}
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
\vdots \\
0 \\
\end{bmatrix}
\]

where, \( p = [c, \phi, K, S, n]^T \), and \( x = [DP, z, i]^T \).

Let \( p_0 = [c, \phi, K, S, n]^T \) be an initial estimate of the unknown parameters. Applying the GNR method to (7) yields:

\[
K = \begin{bmatrix}
c \\
\phi \\
K \\
S \\
n
\end{bmatrix}
- J^{-1} \begin{bmatrix}
f_1(c, \phi, K, S, n, DP, z, i) \\
f_2(c, \phi, K, S, n, DP, z, i) \\
\vdots \\
f_q(c, \phi, K, S, n, DP, z, i)
\end{bmatrix},
\]

where, \( J^{-1} \) is the pseudo inverse of \( J \) since \( J \) is not a square matrix.

\[
J = \begin{bmatrix}
\frac{\partial f_1}{\partial c} & \frac{\partial f_1}{\partial \phi} & \frac{\partial f_1}{\partial K} & \frac{\partial f_1}{\partial S} & \frac{\partial f_1}{\partial n} \\
\frac{\partial f_2}{\partial c} & \frac{\partial f_2}{\partial \phi} & \frac{\partial f_2}{\partial K} & \frac{\partial f_2}{\partial S} & \frac{\partial f_2}{\partial n} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\frac{\partial f_q}{\partial c} & \frac{\partial f_q}{\partial \phi} & \frac{\partial f_q}{\partial K} & \frac{\partial f_q}{\partial S} & \frac{\partial f_q}{\partial n}
\end{bmatrix}
\]

III. TEST RIG AND EXPERIMENTATION PROCEDURE

The wheel-terrain interaction test rig used in this study is shown in Figs. 4 and 5. This test rig is developed to test the algorithm proposed in Section III in a controlled environment allowing us to acquire all needed parameters in a simple and straightforward manner, and to test the feasibility and effectiveness of the soil parameter identification algorithm. In particular, it is difficult to measure slip parameters on a real vehicle manoeuvring through terrain. Based on current developments in slip estimation [10] - [14], we assume slip to be measurable online enabling the implementation of the proposed soil parameter identification process. With this test rig, the wheel slip, \( i \), the wheel sinkage, \( z \), and the drawbar pull, \( DP \), can be measured very accurately. This allows the soil parameter identification algorithm to be validated in an effective way.
In practice, the signals needed for soil parameter identification in real wheeled vehicles can be acquired as follows. To measure the drawbar pull ($DP$) of the vehicle, a single-axis force sensor can be installed between the wheel and the vehicle suspension to measure the resultant force in the vehicle heading direction. The vehicle sinkage ($z$) can be acquired by measuring the gap between axle of driven wheel and ground. Ultrasonic sensors (facing downwards) attached to the vehicle suspension system can be employed for this purpose.

Slip is estimated by employing a sliding-mode observer whose inputs are wheel angular speeds and vehicle heading speed [11]. The wheel angular speeds can be measured by using shaft encoders on the vehicle wheels. The vehicle heading speed can be obtained using several techniques such as Differential Global Positioning System (DGPS) [12], Inertial Navigation System (INS) [13], and Optical Flow [14].

The test rig consists of a driven wheel mounted on a horizontal driven carriage. The wheel is not vertically constrained and can move freely in the vertical direction. The wheel assembly is connected to the carriage assembly using 2 shafts. During experimentation, two motors - one driving the wheel and another driving the carriage - are operated simultaneously at different speeds to generate wheel slip. By varying the differential speeds between the wheel and the carriage motors, various controlled wheel slips can be generated. The test rig is equipped with various sensors to acquire all the measured signals needed for soil parameter identification. Two optical encoders are used to measure the angular speeds of the wheel motor and chain motor. The wheel slip can then be calculated using (9).

\[
i = 1 - \frac{r_c \omega_c}{r_w \omega_w}, \tag{9}
\]

where, $i$ is the wheel slip, $r_w$ is the wheel radius, $r_c$ is the chain sprocket gear radius, $\omega_w$ is the wheel angular velocity, $\omega_c$ is the chain sprocket gear angular velocity.

A Gamma ATI 6-Axis force/torque (F/T) transducer mounted between the wheel assembly and the horizontal carriage is used to acquire the drawbar pull, $DP$. The sinkage ($z$) of the wheel is measured by a potentiometer. The wheel used in the experiment is 0.1 m in width and 0.2 m in diameter. The test rig is fixed to a 1 m x 1 m x 0.5 m frame. The experimental soil is contained in a 0.3 m x 0.85 m x 0.1 m soil box. Experiments were performed on two types of soils - Garside 60 soil, and Garside iron sand. These soils were purchased from the Garside Sands Company, UK.

### IV. EXPERIMENTAL RESULTS

In this section, the soil parameter identification results are presented based on experimental data taken from the test rig described in Section IV. From all the measured data obtained from experiments, the entire sets of measured $DP$, $z$, and $i$ are used for soil parameter identification based on the algorithm developed in Section III. There are 20 and 17 sets of data for Garside 60 soil and Garside iron sand respectively, acquired from wheel-terrain interaction test rig. The measured data for both soils were curve-fitted to a polynomial spline before being used as inputs to the algorithm. Tables I and II show the identification results for all 5 soil parameters for Garside 60 soil and Garside iron sand, respectively.

The identification algorithms were run on an Intel Pentium(R) 4 processor with a 2.80 GHz CPU and 1.00 GByte of RAM.

<p>| TABLE I | IDENTIFICATION RESULTS FOR 5 SOIL PARAMETERS FOR GARSIDE 60 SOIL |</p>
<table>
<thead>
<tr>
<th>Soil Parameters</th>
<th>Actual Values</th>
<th>Identified Value</th>
<th>Relative Error (%)</th>
</tr>
</thead>
</table>
$K$ varies from 0.01 m (firm sand) to 0.025 m (loose sand) for sand-like soils [3]. The parameter $K$ of both experimental soils falls within this range, as they are sands with varying degrees of compaction (firmness). The traditional method of measuring $K$ is by using torsional annular shear tests or transitional rigid track shear tests [15]. In this study, since $K$ is very difficult to measure and requires complex measuring devices, its value is assumed to be between 0.01 m and 0.025 m [3]. Values of $c$ and $\phi$ of both soils were obtained by a standard shear box test [16].

### TABLE II
IDENTIFICATION RESULTS FOR 5 SOIL PARAMETERS FOR GARSIDE IRON SAND

<table>
<thead>
<tr>
<th>Soil Parameters</th>
<th>Actual Values</th>
<th>Identified Value</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$ (Pa)</td>
<td>3000</td>
<td>2624.48</td>
<td>12.52</td>
</tr>
<tr>
<td>$\phi$ (degree)</td>
<td>33</td>
<td>35.53</td>
<td>7.67</td>
</tr>
<tr>
<td>$K$ (m)</td>
<td>0.01 – 0.025</td>
<td>0.01112</td>
<td>In range</td>
</tr>
<tr>
<td>$S$ (N/m$^{n+2}$)</td>
<td>4365332.41</td>
<td>4365812.37</td>
<td>0.01</td>
</tr>
<tr>
<td>$n$</td>
<td>1.27</td>
<td>1.26</td>
<td>0.79</td>
</tr>
<tr>
<td>Elapsed time (s)</td>
<td></td>
<td>0.516 (after 12 iterations)</td>
<td>5.50</td>
</tr>
<tr>
<td>DP prediction error (% rms)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table II (using test rig data for Garside iron sand), the identification accuracies are relatively high with identification errors less than 12.52 % for all 5 parameters. For parameter $K$, ‘In range’ shown in percentage error column means that the identified $K$ is within range of the actual $K$ (0.01 m - 0.025 m). From Table I (for Garside 60 soil), the identification errors are quite high for parameters $S$ and $n$ (54.72 % and 25.35 %, respectively); however, they can be used to predict the drawbar pull with good accuracy (7.25 % rms error), Fig. 7 and Table I.

‘N/A’ shown in percentage error column (Table I) means that error for $c$ cannot be computed since its actual value is equal to 0. However, its identified value is considered close to its actual value (the practical range of $c$ for real-world soils is 0 Pa $\leq c \leq 68500$ Pa [3]).

Figures 6 (a) and (b) are used to explain the possible reason for high identification errors of $S$ and $n$. As illustrated in these figures, with a given set of values for $c, \phi$, and $K$ ($c = 1000$ Pa, $\phi = 34$ degree, and $K = 0.015$ m), using different sets of values for $S$ and $n$ gives similar DP plots. When compared to the DP calculated using $S = 50000$ N/m$^{n+2}$ and $n = 0.64$, the rms error of the DP calculated using $S = 50000$ N/m$^{n+2}$ and $n = 0.2$ is 0.84 % (Fig. 6 (a)), while that of the DP calculated using $S = 880000$ N/m$^{n+2}$ and $n = 1.2$ is 1.15 % (Fig. 6 (b)). It can, therefore, be concluded that a slight deviation of DP inputs to the algorithm would yield different set of results for $S$ and $n$. In reality, due to the random nature of the measurement noise, the measured DP will result in inaccuracies of identified pressure-sinkage parameters, $S$ and $n$.

The identification times are 0.516 s and 0.344 s for Garside iron sand and Garside 60 soil, respectively. The execution time can be further reduced if the code is optimized. In this paper, the code is created using Matlab 6.5 running in command mode; the execution time can be significantly reduced, if an optimized code is executed. Therefore, the proposed algorithm has promising potential for on-line soil parameter identification for off-road wheeled vehicles.

![Fig. 6. Plot of DP using $c = 1000$ Pa, $\phi = 34$ degree, $K = 0.015$ m with different pairs of $S$ and $n$](image)

![Fig. 7. Comparison between the experimental DP and that predicted from the identified ‘$c, \phi, K, S, n$’ for Garside 60 soil](image)
The identification results from Tables I and II are used to predict the DP and compared with the experimental DP from the test rig. Figs. 7 and 8. From these figures, the rms errors are 7.25 % and 5.50 % for Garside 60 soil and Garside iron sand, respectively. This shows relatively good prediction accuracy of DP over the entire slip range using the identified soil parameters.

Next, a robustness test is carried out to examine whether the proposed algorithm will result in converged solutions when different initial conditions \((p_0)\) are used. Table III gives the ranges of initial conditions that allow successful convergence. It is noted that values in brackets in this table are the practical range of parameters for real-world soils [3].

### TABLE III

<table>
<thead>
<tr>
<th>SOILS</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0 (0))</td>
<td>(68500 (68500))</td>
</tr>
<tr>
<td></td>
<td>(6 (6))</td>
<td>(40.1 (40.1))</td>
</tr>
<tr>
<td></td>
<td>(0.006 (0.006))</td>
<td>(0.014 (0.05))</td>
</tr>
<tr>
<td></td>
<td>(140000 (43720))</td>
<td>(6321000 (6321000))</td>
</tr>
<tr>
<td></td>
<td>(0.15 (0.11))</td>
<td>(1.6 (1.6))</td>
</tr>
</tbody>
</table>

The algorithm shows good robustness to initial \(c\) and \(\phi\) since any value chosen from their practical range results in converged solutions. However, for the other three parameters, it is recommended that initial \(K\) be chosen towards its practical lower bound \((0.006 \leq K \leq 0.014)\), initial \(S\) be chosen towards its practical upper bound \((140000 \leq S \leq 6321000)\) and initial \(n\) be chosen towards its practical upper bound \((0.15 \leq n \leq 1.6)\).

To sum up, by measuring DP and \(z\) samples at 5 or more slip values, soil parameters can be identified and used to predict the vehicle DP over the entire range of slips. These identified soil parameters can also be sent to following vehicles to improve their navigation on terrains ahead. Hence, accurate DP prediction of a wheeled vehicle over a particular terrain can be achieved. Consequently, based on accurate prediction of vehicle DP, the proposed algorithm can potentially be advantageous for traversability prediction and traction control for off-road wheeled vehicles.

V. CONCLUSIONS AND FUTURE WORK

This paper investigates soil parameter identification for wheeled vehicles traversing unknown terrain based on a wheel-terrain interaction dynamic model and sensor feedback (drawbar pull, wheel slip, and wheel sinkage). The paper presents a new real-time approach for identifying all the unknown soil parameters required for drawbar pull prediction based on the Generalized Newton Raphson (GNR) method. This is the first time a technique for identifying all the unknown soil parameters for wheeled vehicles is proposed. The experimental data from the wheel-terrain interaction test rig are used to validate the feasibility and effectiveness of the approach. The results show that, despite high identification errors for some parameters, the identified soil parameters can be used to predict the drawbar pull with good accuracy. The range of initial estimates for each parameter that give converged solutions is also proposed. With terrain parameters identified by the proposed algorithm, the vehicle drawbar pull for off-road wheeled vehicles can be predicted for all driving conditions and can subsequently be used for traversability prediction, traction control, and trajectory tracking. The identified terrain parameters can also be forwarded to vehicles following behind to improve their navigation on that terrain. The technique can be applied to any wheeled vehicle with rigid wheels or deformable wheels with relatively high inflation pressure. Future work will focus on the outdoor testing with a real wheeled vehicle or wheeled mobile robot.

REFERENCES


Robotized Combine for cleaning mine fields

Author: Marin Grudev Midilev, Translator: Georgi Slavov Slavov

Summary — This presentation gives concise information about the options for cleaning mine fields through the Robotized Combines. The expose contains the organizational structure and the principle of operation of the Robotized Combines. The initial details are given for design and construction, as well as other applications of technologies.

I. INTRODUCTION

This expose is based on the acquired personal knowledge in engineering activity—about land mines and anti-tank mines and setting land fields, as well as the practical training, held by me from 1979 to 1992. The expose is a version of a project element (logical solution of organizational structure and principle of operation) Robotized Complex for ecological production of fruits and vegetables for fresh consumption on open areas.

Technological offer OB 0106:
http://www.bit.or.at/ik/ec-bbshow8.php?ref1=OB-0106&vQuelle=ecaustria.at&cc

Analogue are the Robotized Combines of complex types are combines as principle of operation and organizational structure for: production of prick-in plants, gathering crops of melons and watermelons etc, with certain construction modifications, limitations and additions, relevant to the specific use.

II. PROCEDURE

A. Review Stage

The mine fields are created basically before battle activities in the past. They have been set for the purpose of destruction of the living force of the enemy, as disposed from the site point of view on accessible areas—mainly plane and fertile areas. To create the mine fields motorized or infantry units have been used, by means of step method.

The depth (width) of the mine field is up to 120 m, the length of the mine field depends on the participants to create it, the shape is always rectangular, the type of land field depends on the types of mines, disposed there.

Creating the mine field is accompanied by drawing up a scheme. The scheme of the mine field gives the basic characteristics of the field, the diagram of mine location and the type of mines. Most of the mine fields are created with mines, which were in arms with the Bulgarian National Army up to 1989 and in the Warsaw Treaty. The manuals, methodology and handbooks used in Bulgarian National Army have relations with the forthcoming clearing of mine fields.

Review of initial data

Types of mines, armed in Bulgarian National Army:

1. Anti-tank mines:

   TM-46

2. Land mines:

   A. / PMH

   B. / POM 2M (POMZ-2) and POMZ-2M
3. Sample scheme of mine field setting:

Sample scheme of mine depletion:

A. / POM-2M

B. / Land mine – scheme

C. / OMZ – 4

D. / Anti-tank mine with non-extraction element

4. Mine-seeker device MT 66-1

The types of mine, armed in the member-state of NATO, have the same applications in the review of initial data for creating a Robotized Combine for clearing mine fields, but due to the requirement for conciseness of the expose, they will be omitted.

B. Final Stage

The existence of mine fields causes not one or two innocent human casualties; the same refers to the standard methods of mine-sweeping by manual method. Their disposition on fertile soils causes the non-use of the areas. The mine-sweeping of mine fields by the method of explosion causes excessive waste of energy, and pollution of environment.

The sequence and principle of operation in mine-sweeping by manual method is reciprocal to the creation of mine fields after discovering the mine by means of auxiliary devices, metal detectors, mine detectors, explosion detectors and other auxiliary means and localization of mine, as well as the type of mine.

The sequence of actions is:

1. For land mines and anti-tank mines, with activating the detonator on pull:
   A. Remove the cover (camouflage) soil layer, if any;
   B. Disconnect the strained wire;
   C. Deactivate the detonator by setting a safety lock-pin;
   D. Dismount the detonator from the mine body;
   E. Dig out the mine;
   F. Bring out the mine body from the field.

2. For anti-tank and land mines, with activating the detonator mainly on pressure and with or without non-extraction element:
   A. Remove the cover (camouflage) soil layer;
   B. Deactivate the detonator by setting a safety lock-pin;
   C. Dismount the detonator from the mine body;
   D. Dig out the mine;
   E. In case of a non-extraction element – second detonator, activated on pull, then the steps on pull are executed before bringing out the mine body of the mine field.

The final possible option for mine-sweeping of mine fields and separate mines, by duplicating the activities by manual methods is the use of androids – e.g. ASIMO of Honda. The known to me existing robots for mine-sweeping of mine fields and separate mines can perform only part of
the activities in mine-sweeping. It is obligatory to have a robot control operator. 
For Robotized cleaning of mine-fields I suggest to design a Robotized Combine:

The organizational structure and principle of operation of the Robotized Combines are analogue to a production line with the following main features:
1. The manipulated elements are immovable, only the manipulating units are moved.
2. The power and control units are out of the manipulation area and are temporary immovable.
3. The principle of movement in a new zone for manipulation is by waking (step broken movement) in a straight line or by determined axis.
4. Others

On the grounds of construction activity by using ready made elements, the variety of Robotized Combines is wide.

C. Appearance/ Figures

Prototype by description of the site – plane with small uneven zones and null slope angle, depth of mine field 120 m.:
1. A rail, comprising of equal modules, as the first module contains the metal detectors and explosive detectors. The rail in unfold appearance (all modules assembled) is 120 m or 60 m long.
2. Major (main) Module of the Robotized Combine. The power elements are located in it, the control of the Robotized Combine, the operator, observing the process etc.
3. Operational (executive) module. It comprises mounted gantry robot, performing the above described activities of deactivation of the mine types.
4. And performing the actions in storage of deactivated mines in armoured containers for transportation to the next purpose.

The elements for execution of actions in mine sweeping, united in a common module – called operative (minesweeper) body.
5. Storage robot – transfers the armored containers. The module moves by ‘walking’.
6. Transport module – transports the armored containers from the Main module to the Operation module and vice versa and moves the containers from and to the Main module and to and from the Operation module.
7. Transport automobile with robotized loading and unloading activity of the armored containers.

D. Electronic Image Files (Optional)

Robotized Combine

Gantry robot

Operation module

E. Copyright Form

Know How
http://projects.despark.com/043-MarinMidilev/

III. VERSION WITH ADDITIONAL OPTIONS

The versions for creating the Robotized Combines for cleaning mine-fields are based mainly on the characteristic features of the terrain – slope angle and can be designed for movement on plane land site with slope angle of about 30 degrees. The existing real possibility that the Operation (mine-sweeping) body executes activities on mine-sweeping out of board is about 50% of the length of the horizontal crossed module of the gantry robot.

IV. UNITS

All the required elements/ units - pneumatic pincers, vacuum-driven handlers, pneumatic modules for linear movement and electro-mechanic modules of linear movement are real and are manufactured by not one or two multinational companies.

V. TASK FOR FURTHER OPERATION. CONCLUSION

The stages of the future work in creating the working prototypes of a Robotized Combine for cleaning land-mines are:
1. Finding or creating the necessary normal working conditions – financial funds, place and time.
2. Forming the engineering team.
3. Clearing up the tasks.
4. Providing necessary technologies and technical products for creating the experimental prototype.
5. Experiments with the prototype.
6. Alterations and supplements to the prototype on the base of achieved results in the tests during experiments.

REFERENCES