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 larger 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, 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 poloxymethylene, 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.

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.

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 probing 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.

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.

**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.

Gryphon operates by scanning a 1 meter wide lane, 2 square meters at each ATV position. The approach direction is always from the cleared side, the vehicle staying in safe zone. MD and GPR sensing is performed simultaneously and recorded data is presented as a series of images, which can be evaluated separately by the operator.
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.

Fig. 9. Gryphon dual-sensor system, composed by an MD-Gryphon and an array GPR-Gryphon.

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.

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.

<table>
<thead>
<tr>
<th>Lane</th>
<th>Probability of detection (POD)</th>
<th>False alarm rate (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
11 shows comparative results obtained on each soil type.

![Graph](image1.png)

**a) Lanes 1 and 2 (Obrovac 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.

![Graph](image2.png)

**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.**

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).

![Graph](image3.png)

**Fig. 13. Metallic targets tested for the discrimination algorithm.**

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.

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