Development of Camera System for landmine detection
Results of Phase 2

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## Abbreviations

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<th>Description</th>
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<tbody>
<tr>
<td>AP</td>
<td>Anti-personnel</td>
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<tr>
<td>AR</td>
<td>Area reduction</td>
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<td>AT</td>
<td>Anti-tank</td>
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<td>BW</td>
<td>Black and white</td>
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<tr>
<td>CCD</td>
<td>Charge-coupled device</td>
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<tr>
<td>EO</td>
<td>Electro-optical</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<td>GICHD</td>
<td>Geneva International Centre for Humanitarian De-mining</td>
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<td>HALO</td>
<td>The HALO Trust</td>
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<td>LP</td>
<td>Linear polarisation</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ROC</td>
<td>Receiver-operator characteristics</td>
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<td>TNO</td>
<td>Netherlands Organisation for Applied Scientific Research</td>
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<td>TNO-FEL</td>
<td>TNO Physics and Electronics Laboratory</td>
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1. Introduction

In mine-clearance operations, it is very important to attempt to reduce the suspected area, before close-in detection is started. Area reduction (AR) is the process through which the initial area indicated as contaminated (during a general survey) is reduced to a smaller area. AR consists mainly of collecting more reliable information on the extent of the hazardous area and it is sometimes done as part of the clearance operation.

A recent study performed by the Geneva International Centre for Humanitarian Demining (GICHD) [1], identified 12 tasks, activities and procedures (referred to as capabilities) that provide opportunities for improved equipment and information management systems. Determination of the outer edge of mined areas is one of the capabilities for which very significant benefits are expected from improvements of investment in new and improved equipment, in processes or procedures.

Mechanical methods to reduce the area for mine clearance include rollers and flails. Since better and faster area reduction methods are needed, several research projects are running that exploit airborne techniques; for example, Mineseeker, ARC and SMART projects (last two are EU-sponsored projects). Dogs are sometimes used to determine the boundaries of a minefield.

This document describes an investigation of the use of camera systems to aid in mechanical mine clearance and mine area reduction. The investigation covers different camera recording and image processing techniques for landmine detection. The techniques studied are the processing of monochrome and colour visible-light images and the use of polarisation with these modalities. The investigation is directed towards the deployment of a camera system that will be used on a mechanical area-reduction system. Section 1.2 describes the current procedure of The HALO Trust (HALO) for the reduction of areas that are contaminated with only AP mines. In section 1.2.1 the new anti-tank (AT) mine roller unit is described that has been developed by HALO for areas with AT mines.

Chapter 2 discusses the development of concepts of a camera system and detection algorithms that could be used with the new AT mine roller unit to increase the speed of the area reduction process. Chapter 3 describes the test models that have been used in extensive tests.

In the current phase of the project (see next section for description of all phases), so-called static tests have been performed in a static scenario. For these tests, the camera was mounted on a tripod with a fixed position and not on a moving vehicle. The procedure for these tests is described in chapter 4. Chapter 5 gives the results of the tests and chapter 6 shows our conclusions.
1.1 Project description

This development project consists of six phases.
1. In the first phase preliminary information was gathered that resulted in the scenario description (Appendix A), a first set of requirements (Appendix B), and a test plan for the tests in the second phase (Appendix C).
2. In the second phase concepts were developed and test models were acquired. Tests with a static set up were performed in the summer of 2003 and the results are reported in chapter 5. The feasibility of the concepts has been studied and a full set of requirements will be formulated. At the end of the second phase a proposal for further development will be written.
3. In the third phase, a demonstrator of the camera system for landmine detection will be built. Field tests of the system will be performed in 2004 with a moving vehicle at a Royal Netherlands Army test site in The Netherlands. This phase will conclude with a description of a raw prototype of the camera system.
4. In the engineering phase, tests will be performed in one of the areas in which HALO is active with their AT mine roller.
5. In the prototype phase a final prototype will be developed.
6. In the sixth phase, production of the camera system is foreseen.

1.2 The HALO Trust area reduction procedure

The HALO Trust (HALO) is a non-political, non-religious non-governmental organisation (NGO), registered in Great Britain and in the USA. HALO specialises in the removal of the debris of war. HALO has over 5,500 mine clearers in nine countries, with on-going surveys into new regions. HALO’s operations are grouped under Central Asia, South East Asia, Horn of Africa, Southern Africa and the Caucasus and Balkans.

HALO continually seeks faster and cheaper ways to clear mines, whilst maintaining safe practices and 100% clearance. The most successful area of HALO research and development (R&D) has been in the adaptation of existing agricultural and civil engineering machines for mechanical mine clearance and area reduction.

Front-end loaders are built in numerous forms by many companies world-wide. A feature common to most of them is that they are robust and can be put to work to perform a variety of tasks. They are also simple to operate and maintain. Unlike most purpose-built mine action machinery, commercial vehicles are versatile and can perform tasks beyond mine action alone. After the close of a working day in the minefield, a front-end loader for example can be set to work for the local community building or improving roads, digging water ditches for drinking and agriculture, or digging sanitation trenches. These are tasks that cannot be performed by a 50-ton tiller or heavy flail unit.
HALO uses so-called Pearson rollers [2] mounted on an armoured commercial front-end loader to rapidly reduce areas adjacent to locations within which anti-personnel (AP) landmines are suspected. Area-reduction vehicles designed to drive into suspect areas and define the ‘line’ of laid mines by detonating mines with their wheels or front-mounted Pearson rollers are proving very useful, as they allow a better use of clearance time: de-miners can then be deployed closer to the actual mines.

Rollers typically consist of segmented, weighted plates, each turning separately on a central axle. With the Pearson roller (see Figure 1.1) for example, each individually ‘floating’ disc exerts a ground pressure of 50 kg. The weight of the roller is designed to activate sub-surface AP mines. As the attached vehicle moves forward, the roller contacts the ground. The roller follows uneven ground, bumps and rises with each independently rolling wheel. The roller is capable of withstanding multiple AP mine blasts, but it is not designed to withstand AT mine blasts.
Figure 1.2: Rolling in perpendicular lines from a baseline out to a pre-determined limit of exploitation (LOE) in an area within which AP mines are suspected. Once the roller has established the presence of AP mines, and the approximate pattern of these mines, (manual) clearance assets are deployed.

HALO has approximately ten rollers in service between Abkhazia, Mozambique, Somaliland, Georgia, Kosovo, Cambodia, and Afghanistan. They have been using the rollers since 1998. The rollers are not used as specific clearance devices, but in an area reduction and verification role. The rollers are used in minefields within which the definition of mine location and patterns is not clear. By using the rollers in set patterns as shown in Figure 1.2, large areas of ground are verified for the presence and location of mines by their deliberate detonation. Once the presence of mines has been verified, direct clearance assets can be brought to bear in the smaller area in which mines are actually laid. This inevitably speeds up clearance rates by enabling fast deployment of manual or further mechanical methods directly onto mined areas.

1.2.1 HALO Anti-tank mine roller unit

Since AP mine rollers have proven to be successful within humanitarian mine clearance, HALO has been developing an AT mine roller system. Military AT mine rollers mounted in front of a main battle tank do exist, but have not yet been used in the scenarios described above. HALO has developed an AT mine roller unit to be mounted on a front-end loader as with the AP mine roller, see Figure 1.3.
The roller system is designed to detonate anti-tank mines, but each detonation of an AT mine will incur a down time for repair of the rollers, since some damage is expected on an AT mine detonation, as depicted in Figure 1.4. The frequency of occurrence of such accidents is an important statistic in the decision on deployment of area-reduction vehicles and cost and time efficiency. It is not feasible to build a fully survivable system.

First tests have been performed with the AT mine roller in Somaliland, Africa.

Figure 1.3: Anti-tank mine roller unit.

Figure 1.4: Damaged and broken AT mine roller because of AT mine detonation during tests.
This camera system mounted on top of the mine area reduction vehicle and looking forwards might warn the driver of the vehicle that an AT mine is in front of the vehicle. At that point the driver can decide to stop the vehicle and investigate the situation.
2. Development of concepts

Research performed by TNO-FEL has shown that using polarisation features of light (both IR and visible) improves the detection capabilities of a camera system for landmine detection [3]. In order to minimise the amount of physical AT mine detonations for the AT mine roller of HALO, a camera system has been developed that uses polarisation properties of light to reach a high-detection rate of AT mines, combined with a low false-alarm rate. The camera system will be fitted to the roof of the vehicle and is forward-looking. The goal is to detect as many surface-laid AT mines as possible and to stop the vehicle before the roller detonates the mine. In order to meet the above-mentioned requirements a visible-light camera system is foreseen. A forward-looking camera system mounted on top of the mine area-reduction vehicle can warn the driver of the vehicle that an AT mine is in front of the vehicle. At that point, the driver can decide to stop the vehicle and investigate the situation.

Acceptance of such a system depends on the detection and false-alarm rate of the system. HALO has stated that a very low false-alarm rate (less than 3 alarms per 100 m forward movement) combined with a moderate detection rate would be a valuable system. The following list presents some possible camera system concepts and the assumptions they have on the camera image modality:

- Black and white (BW), visible light, video camera;
- Colour, visible light, video camera;
- BW, visible light, video camera with polarisation;
- Colour, visible light, video camera with polarisation.

All mine-detection camera systems are based on assumptions regarding the appearance of landmines for image processing and landmine detection (see Table 2.1).

Table 2.1: Different camera systems and corresponding assumptions.

<table>
<thead>
<tr>
<th>Camera system</th>
<th>Assumptions on modality</th>
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<tbody>
<tr>
<td>BW, visible light, video camera</td>
<td>Landmines have intensity values that are different from local surroundings.</td>
</tr>
<tr>
<td>Colour, visible light, video camera</td>
<td>Landmines have distinctive colours or have a colour contrast with the background.</td>
</tr>
<tr>
<td>BW, visible light, video camera with polarisation</td>
<td>Landmines have a smooth (artificial) surface and / or have intensity values that are different from local surroundings</td>
</tr>
<tr>
<td>Colour, visible light, video camera with polarisation</td>
<td>Landmines have a smooth (artificial) surface and / or have distinctive colours or have a colour contrast with the background.</td>
</tr>
</tbody>
</table>

The above-mentioned camera concepts of a visible-light camera with or without polarisation have different mine-detection capabilities. In addition to the conventional way of detecting mines using image intensity [4] and colour features,
an additional way is created by the use of polarisers. Polarisation can add significantly to the system's robustness and its detection performance [3], especially in the case of detecting artificial objects within a natural background. However, the performance of polarisation features depends more on the operating conditions than on the colour or intensity features, which are more invariant to those features. For example, the position of the sun (both azimuth and elevation), viewing angle with respect to the sun position, and weather conditions (daylight, clouds) have an impact on the use of polarisation. The extensive tests (see chapter 4 for a description) conducted have given some insights into the application of polarisation system and its effect on the system characteristics.

2.1 Camera system concept

Contrary to the IR polarisation set-up developed by TNO-FEL [3], the visible-light camera of the system is intended to have no moving parts; it has fixed polarisers. An optical prism assembly, mounted behind the camera lens, will be used to separate an image into three equal components. Each image is captured with a charge-coupled device (CCD). A polarisation filter with a different orientation is mounted in front of each CCD element. Using this configuration the polarisation state (expressed by the Stokes components $I$, $Q$ and $U$) of each pixel in the image can be measured in one snapshot, which is important when the camera is mounted on a vehicle moving over rough terrain.

For the tests described in chapter 4, however, a different polarisation set-up was used because the visible-light camera with fixed polarisers was not available at the time of the tests. For these tests a polarisation set-up with one visible-light camera and a rotating polariser in front of the lens was used. This set-up is comparable to that developed by TNO-FEL for IR polarisation measurements [3].

2.2 Landmine-detection concept

The above-mentioned camera concept of a visible-light camera with fixed polarisers opens the way to extended mine-detection capabilities based on cameras. The proposed mine-detection concept combines features and cues from different image-processing techniques:

- **Colour and intensity analysis**: Detection is based on object colour or intensity contrast with the surrounding background. The contrast threshold is defined by local image statistics (mean and standard deviation) of the image.

- **Edge detection and grouping**: Straight or partly circular edges are extracted because they can indicate artificial objects. The subsequent step groups edges into hypothetical artificial objects.
• **Polarisation analysis:** Objects are detected based on their polarisation contrast with the surrounding background.

Each image-processing technique results in a set of possible object detections with computed colour, edge or polarisation features for which additional features (e.g., morphological) can be calculated. The resulting set of objects is put into a pattern-recognition classifier that performs the final mine detection based on all computed features and previously learned examples. In order to ensure robustness of this classifier it is important that the image-processing techniques deliver invariant features. Scale invariance [5] can be found with proper camera calibration, and colour invariance [6] is obtained by choosing the correct normalised colour space. Furthermore, invariant morphological features exist, but invariant polarisation features are still a research issue.

Depending on the type of camera system, the following detection methods can be applied:
- Threshold on intensity [4];
- Threshold on polarisation [3];
- Threshold on colour [7];
- Application of colour histograms [8];
- Template matching and image correlation;
- Shape recognition (edge-based Hough transform) [9];
- Data fusion [3].

These detection methods are described in the following paragraphs.

### 2.2.1 Threshold on intensity

The assumption that landmines have intensity values that are different from local surroundings can be exploited using a BW, visible-light camera. As mines can be brighter or darker than the background, the intensity contrast can be a so-called positive or negative contrast with the background.

The (normalised) positive intensity contrast image is defined as:

\[ I_{pos}(x) = \frac{I(x) - \min(I)}{\max(I) - \min(I)}. \]  

The (normalised) negative intensity contrast image is defined as:

\[ I_{neg}(x) = 1 - \frac{I(x) - \min(I)}{\max(I) - \min(I)}. \]  

On both contrast images a threshold can be applied to obtain an image with binary values indicating the detection of landmines. The applied threshold is a parameter of the detection method, and its choice of value depends on the scenario of application and required performance.
The positive intensity contrast detections are defined as:

\[ D_{\text{pos}}(x) = \{ I_{\text{pos}}(x) \} \]  \hspace{1cm} (2.3)

The negative intensity contrast detections are defined as:

\[ D_{\text{neg}}(x) = \{ I_{\text{neg}}(x) \} \]  \hspace{1cm} (2.4)

where the threshold operator is defined as:

\[ \{ f(x) \}_b = \begin{cases} 1 : f(x) \geq t \\ 0 : f(x) < t \end{cases} \]  \hspace{1cm} (2.5)

### 2.2.2 Threshold on polarisation

Landmines that have a smooth artificial surface (and/or have intensity values that are different from local surroundings) can be detected using a monochrome, visible-light video camera with polarisation.

The Stokes vector is a mathematical representation of polarisation. Using this representation, optical elements can be described as matrix operators on these vectors. The Stokes vector is constructed by measuring the intensity of four different polarisation states:

- \( I_0 \) measures all states equally through an isotropic filter,
- \( I_h \) measures the intensity through a horizontal linear polariser,
- \( I_{45} \) measures the intensity through a linear polariser oriented at 45°,
- \( I_L \) measures the intensity through a polariser which is opaque for left circular polarisation.

Using these measured intensities, the Stokes parameters \( I, Q, U, V \) are defined as:

\[
\begin{align*}
I &= 2I_0 \\
Q &= 2I_h - 2I_0 \\
U &= 2I_{45} - 2I_0 \\
V &= 2I_L - 2I_0
\end{align*}
\]  \hspace{1cm} (2.6)

Often different representations are used for the polarisation:

\[
LP = \sqrt{Q^2 + U^2}
\]

\[
DoLP = \frac{LP}{I}
\]  \hspace{1cm} (2.7)

\[
\Psi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)
\]
with \( LP \) the amount of linear polarisation, \( DoLP \) the degree of linear polarisation and \( \Psi \) the angle of polarisation (orientation of the polarisation ellipse).

The polarisation detections are defined as:

\[
D_{\text{pol}}(x) = \{f(I, Q, U)(x)\},
\]

(2.8)

where \( f(I, Q, U)(x) \) is a function that projects the Stokes Vector to a scalar. For example:

\[
f(I, Q, U) = \sqrt{Q^2 + U^2}
\]

(2.9)

is the function that calculates the linear polarisation \( LP \).

### 2.2.3 Threshold on colour

The assumption that landmines have distinctive colours or have a colour contrast with the background can be exploited using a colour, visible-light video camera. In order to do this, the colour space and the colour contrast metric must be defined. The common choice is to use an RGB colour space and Euclidean distance metric. Furthermore a global or local estimate of the background colour is necessary.

This defines the colour contrast between foreground image \( f(x) \) and background image \( b(x) \) per pixel as follows:

\[
C(f, b)(x) = d(f(x), b(x))
\]

(2.10)

where \( d(x, y) \) is a Euclidean distance measure defined as:

\[
d(x, y) = \sqrt{(x_{\text{red}} - y_{\text{red}})^2 + (x_{\text{green}} - y_{\text{green}})^2 + (x_{\text{blue}} - y_{\text{blue}})^2}
\]

(2.11)

The colour contrast detections are defined as:

\[
D_c(x) = \{C(x)\}_l
\]

(2.12)

### 2.2.4 Colour Histograms

Given a discrete colour space, a colour histogram counts how much of each colour occurs in the image. Colour histograms are invariant to translation, rotation about an axis perpendicular to the image and change only slowly with rotations about other axes, occlusion, and change of distance to the object. On the other hand, histograms for different objects can differ markedly. Therefore, the colour histogram is an excellent representation to use for identifying objects.

### 2.2.5 Template Matching and Image Correlation

The image correlation uses normalised grey-scale correlation to solve vision problems such as alignment. Normalised grey-scale correlation is widely used in
industry for pattern matching applications. The technique provides quick
techniques to find horizontal, vertical, and angular displacement of most images.
The main function of pattern matching is to search for occurrences of a pattern in
an image. Pattern matching is performed on 8-bit grey-scale unsigned buffers.

The image-correlation operation can be seen as a form of convolution, for which
the pattern-matching model is analogous to the convolution. In fact, ordinary (un-
normalised) correlation is exactly the same as convolution:

$$ r = \sum_{i=1}^{N} I_i M_i $$  \hspace{1cm} (2.13)

In other words, for each result, the N pixels of the model are multiplied by the N
underlying image pixels, and these products are summed. Note that the model does
not need to be rectangular because it can contain ‘don’t care’ pixels that are
completely ignored during the calculation. When the correlation function is
evaluated at every pixel in the target image, the locations for which the result is
largest are those at which the surrounding image is most similar to the model. The
search algorithm must then locate these peaks in the correlation result, and return
their positions.

Unfortunately, with ordinary correlation, the result increases if the image gets
brighter. In fact, the function reaches a maximum when the image is uniformly
white, even though at this point it no longer looks like the model. The solution is to
use a more complex, normalised version of the correlation function (the subscripts
have been removed for clarity, but the summation is still over the N model pixels
that are not ‘don’t cares’):

$$ r = \frac{N \sum I M - (\sum I)(\sum M)}{\sqrt{[N \sum I^2 - (\sum I)^2][N \sum M^2 - (\sum M)^2]}} $$  \hspace{1cm} (2.14)

With this expression, the result is unaffected by linear changes (constant gain and
offset) in the image or model pixel values. The result reaches its maximum value of
1 where the image and model match exactly, gives 0 where the model and image
are uncorrelated, and is negative where the similarity is less than might be expected
by chance. In our case, we are not interested in negative values, so that results are
clipped to 0. Finally, the result is converted to a percentage, where 100% represents
a perfect match.

2.2.6 Shape Recognition
The assumption that landmines have distinctive shapes can be exploited using an
image-processing method that can recognise shapes. Common shapes of landmines
are square and disc-like structures.
2.2.7 Data Fusion

Data fusion is not a landmine-detection technique on its own but it makes an intelligent combination of other detection techniques that achieves better performance. Popular fusion methods are Bayesian approaches, applications of Dempster-Shafer theory, fuzzy logic, rules and voting techniques.

2.3 Landmine-detection implementation

For the tests of chapter 4 we have made a first partial implementation of the mine-detection concepts described in the previous paragraphs. Not all of the concepts showed the expected performance. For example, when detecting mines by colour features, using colour histograms [8], colour proved not to be a very discriminative feature for this application. This is probably due to the fact that colour histograms only grab the global colour information of the object without taking into account the spatial distribution of colour (as mines typically have a uniform colour). As such, the surrounding background clutter can have a similar colour histogram to the mine, although its spatial colour distribution might be different. In addition to colour features we have looked at edge detection and grouping, and using morphological features based on a modified Hough transformation on intensity and polarisation [9]. This technique proved to work reasonably well, but only on a subset of the mines. However, it requires camera calibration and is computationally expensive, which limits its real-time implementation.

Therefore, for these tests we have implemented the threshold on intensity and polarisation, and a blob analysis on size as final implementation.

2.3.1 Threshold on intensity

The assumption that landmines have intensity values that are different from local surroundings can be exploited using intensity contrast. As mines can be brighter or darker than the background, the intensity contrast can be so-called positive or negative contrast with the background. The positive and negative contrast are defined in section 2.2.1.

2.3.2 Threshold on polarisation

Landmines that have a smooth artificial surface (and / or have intensity values that are different from local surroundings) can be detected by polarisation. The amount of linear polarisation is, in the implementation for the tests, taken as the polarisation feature. The amount of linear polarisation is defined as:

\[ LP = \sqrt{Q^2 + U^2} \]  

(2.15)

with \( Q \) and \( U \) being the Stokes components that are determined for each pixel. The normalised polarisation contrast image is defined as:
\[ LP(x) = \frac{LP(x) - \min(LP)}{\max(LP) - \min(LP)} \quad (2.16) \]

The polarisation detections are defined as:
\[ D_{LP}(x) = \{ LP(x) \}_i \quad (2.17) \]

### 2.3.3 Combination of intensity and polarisation

For implementation for the tests, we have combined intensity and polarisation in the following way:
\[ F(x) = \left\{ I_{pos}(x) \right\}_{t_1} \lor \left\{ I_{neg}(x) \cdot LP(x) \right\}_{t_3} \quad (2.18) \]

The blobs in the resulting binary image \( F(x) \) are extracted by means of a connected-component algorithm. Blobs are groups of connected pixels that represent possible landmine detections. Blobs with a size smaller than threshold \( t_3 \) are removed from image \( F(x) \). As such, the complete detection procedure has three parameters: thresholds \( t_1 \), \( t_2 \), and \( t_3 \).

The reason for this combination is as follows: The combination takes a disjunction of the positive intensity and polarization contrast to use either positive intensity or polarisation, whichever has more contrast at the appropriate moment. The conjunction between the negative intensity contrast and the polarisation is applied for reasons of false-alarm reduction. Furthermore, it is assumed that intensity and polarisation are complementary features. This assumption has been validated from the results of the tests, see section 5.2.
3. Test models

This chapter describes the camera hardware and the detection and performance evaluation software that has been used for the feasibility tests. These feasibility tests have been performed using a static setup, looking at a static scene and two different test models have been used.

3.1 Camera hardware

The measurement set-up consisted of one visible-light camera system, mounted on a tripod. The visible-light camera has a frame rate of 25Hz and the images of the visible light are grabbed from the analogue video output of the camera using a Matrox Orion II frame grabber. Two different visible-light cameras have been used: a 3CCD Hitachi colour camera and a black-and-white Sony camera. A rotating polarisation filter (Polaroid sheet) was mounted in front of the camera lens (Zoom lens 12.5-75mm). The filter was rotating at a constant speed. A trigger pulse from the rotation set-up started the acquisition of the frame grabber in the computer. Since the camera was running at a fixed frame rate, the time between the frames and thus the rotation of the polarisation filter between the different frames is fixed.

A complete sequence consists of 56 images for the visible light. The sequences contain at least one full rotation of the filter, which had a rotation time of just over 2 seconds.

Figure 3.1: The two cameras used for the measurements, mounted in the polarisation setup. The left image shows the Sony BW camera and the right image the Hitachi 3CCD colour camera. The zoom lens and the motor that rotates the polarisation filter are visible.
Table 3.1: Camera parameters

<table>
<thead>
<tr>
<th></th>
<th>BW camera</th>
<th>RGB camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Sony CCD Video Camera Module N50</td>
<td>Hitachi HV-C20 3CCD</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>768 x 572 (video)</td>
<td>768 x 572 (video)</td>
</tr>
<tr>
<td>Lens</td>
<td>Zoom lens 12.5-75mm</td>
<td>Zoom lens 12.5-75mm</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>8 bits</td>
<td>8 bits</td>
</tr>
<tr>
<td>Output</td>
<td>Analogue video</td>
<td>Analogue video</td>
</tr>
<tr>
<td>Field of view</td>
<td>±3 x 9 m</td>
<td>±3 x 9 m</td>
</tr>
<tr>
<td>Frame rate</td>
<td>25 fps (video)</td>
<td>25 fps (video)</td>
</tr>
<tr>
<td>Interlaced</td>
<td>Yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

3.2 Detection software

The algorithms used for the tests are those described in section 2.3: the intensity and polarisation contrast are combined into a single combination function. As mentioned above, the complete detection procedure has three parameters: thresholds $t_1$, $t_2$, and $t_3$ and these three parameters were varied for the tests to obtain the receiver-operator characteristics (ROC) curves.

3.3 Performance evaluation tools

The performance of the camera system was evaluated using the ROC curve. In an ROC curve the detection rate is plotted against the false-alarm rate for adjustable optimisation parameters. Each working point on the ROC corresponds with a set of values for the thresholds $t_1$, $t_2$, and $t_3$. The detection rate is defined as the fraction of detected landmines.

The corresponding number of false alarms per unit area is calculated using the following method: The camera system will be fitted on top of a vehicle that moves forward, and we count multiple false alarms that are on the same horizontal line of the measurement area as one false alarm. This is because the vehicle must stop only once if one or more false alarms are detected on the same horizontal line in front of the vehicle.

In order to evaluate the performance of the results of the tests a Matlab tool was developed to construct the ground-truth of the recorded sequences. Figure 3.2 shows the graphical user interface for the tool. In the left window of the tool a visualisation of the recorded polarisation sequence is shown. Within that window we can mark the region of interest by drawing a boundary box, which appears as a shaded grey area on the right. Detections and/or false alarms outside that box are not taken into account for the results of that sequence. The ground-truth mine positions can be entered by placing a circular or rectangular object on the mines on
the left. The size of the mine can be altered and the ground-truth mines appear in white on the right.

Figure 3.2: Performance evaluation tool to make ground-truth of measurement areas.

Figure 3.3 shows a screen dump of a performance evaluation tool that shows an ROC curve. ROC curves can be loaded and displayed. By selecting specific hours, directions, day, mine types, and parameter settings we can assess the performance under different conditions and with different parameter settings.

Figure 3.3: Performance evaluation tool that displays an ROC curve.
4. Procedure for Static Tests

This chapter describes the test procedure, including preparation of the test fields, selection of the test mines and pre-processing of the measured data before detection evaluation. In the test plan (appendix C) several factors are mentioned that are expected to influence the detection performance. These factors have been taken into account when setting up and performing the static tests.

Factors that are expected to influence the detection results are:

- Light conditions (elevation and relative azimuth of the sun)
- Distance between camera and mine (number of pixels on mine)
- Mine type
- Condition of mine surface
- Burial depth (fraction of mine body visible for camera)
- Vegetation
- Orientation of top surface of mine (horizontal or tilted)

4.1 Test fields

In order to perform measurements with different relative sun positions, four test fields were constructed, each in a different direction relative to the camera, which was placed in a central position. Three of the four fields had a stony background; the field in the west direction had a grass background.

![Figure 4.1: Two examples of the four measurement areas (facing North, South, East and West). The example on the left is the West measurement area that has grass as background. The other measurement areas have stones as background clutter as shown in the example on the right.](image)

During data collection, the camera made recordings of the different measurement areas with the camera being rotated on the tripod to view the different areas. From the camera viewpoint, the four areas faced the North, South, East, and West directions. The distance between the camera and the far end of the test fields was chosen to be identical to the maximum distance required in the HALO application.
4.2 Test mines

The most important test mines for the tests are the Belgium PRB-M3 and Pakistani P2, since these AT mines appear most frequently in Somaliland, in which HALO is currently active and where they will use the new AT roller system. Since these mines were not available during the tests, replicas were constructed.

The mines were placed in a rectangular area with a width of 3 m and a length of 6 m, ranging from 8 to 13 m from the camera. 18 objects (3x6) were placed on a square grid with a minimum distance of 1 m between the objects. Table 4.1 shows the layout of the measurement areas. Each measurement area contains three samples of four mine types and six false alarms (stones).

Table 4.1: Lay-out of all four measurement areas.

<table>
<thead>
<tr>
<th>distance to camera</th>
<th>column 1</th>
<th>column 2</th>
<th>column 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>row 1</td>
<td>13 m PRBM-3</td>
<td>TM62P-3</td>
<td>PRBM-3</td>
</tr>
<tr>
<td>row 2</td>
<td>12 m TM62P-3</td>
<td>P2</td>
<td>TM62P-3</td>
</tr>
<tr>
<td>row 3</td>
<td>11 m P2</td>
<td>PRBM-3</td>
<td>P2</td>
</tr>
<tr>
<td>row 4</td>
<td>10 m false alarm</td>
<td>false alarm</td>
<td>false alarm</td>
</tr>
<tr>
<td>row 5</td>
<td>09 m PMN</td>
<td>false alarm</td>
<td>PMN</td>
</tr>
<tr>
<td>row 6</td>
<td>08 m false alarm</td>
<td>PMN</td>
<td>false alarm</td>
</tr>
</tbody>
</table>

Quite often only the cap of the mine was visible and not the whole mine body. In the test field only the TM62P-3 mines were surface laid. From the P2 and PRBM-3 only replicas of the detonators were placed. Extra dummy (PMN) mines were used since these mines have roughly the same diameter as the detonator of the PRBM-3. These PMNs were surface laid.

Specular reflectivity and thus polarization contrast depends on the smoothness of the mine surface. Measurements were performed with clean mine surfaces and with mine surfaces with some sand on them.

During most measurements, the mines were placed horizontally. However, some measurements were performed with tilted mines, with tilt angles in different directions relative to the camera.

4.3 Measurement procedure

Every 30 minutes during data gathering recordings were taken of each field. The time difference between the recordings of the four fields is less than 1 minute. Most recordings took place between sunrise and sunset. Only a few recordings were taken during the twilight period.
4.4 Pre-processing of data

The detection algorithms as described in section 3.2 use Stokes images as input. The recorded data consists of image sequences with different orientations of the rotating polarisation filter for the different images in the sequence. Several pre-processing steps are needed to convert the raw data to calibrated Stokes images.

1. Determination of rotation frequency of polarisation filter.
2. Correction for intrinsic polarisation of camera.
3. Determination of offset angle of filter.
4. Determination of three Stokes parameters for each pixel.

4.4.1 Determination of rotation frequency and offset

The measured intensity $I_p$ (a function of the angle $\varphi$, where $\varphi$ is the angle between the principal axis of the polarisation filter and the horizon) is given by:

$$I_p(\varphi) = \frac{1}{2} [I + Q \cos(2\varphi) + U \sin(2\varphi)]$$

(4.1)

where $\varphi=0$ represents the situation where all horizontal polarised light waves pass the linear polariser. The angle $\varphi(n)$ as a function of the frame number $n$ is given by the following formula:

$$\varphi(n) = \varphi_0 + n \times d\varphi$$

(4.2)

where $\varphi_0$ represents the angle of the polarisation filter at the trigger position when the recording starts with frame 0, and $d\varphi$ is the rotation of the filter during the time between subsequent frames (0.04 s). This rotation is assumed to be constant during the recording of one sequence, but is known to vary during the day. Using equation (4.1) and the assumption that $d\varphi$ is about $\frac{2\pi}{56}$, the exact value of $d\varphi$ can be estimated using a fit procedure. The value of $d\varphi$ varies from sequence to sequence since the rotation speed is not constant.

4.4.2 Correction for intrinsic polarisation of the cameras

Both cameras we used show intrinsic polarisation. This means that when the incoming light is unpolarised, a certain degree of polarisation is still measured. Figure 4.2 shows an example for the three colour channels of the RGB camera. This intrinsic polarisation is assumed to originate from the prisms that are used to split the three colour channels in a 3 CCD camera.
To correct for this effect measurements were taken from a piece of diffuse reflectance material (from Labsphere Inc.), perpendicular to the surface. Two parameters, the amplitude and the phase of the intrinsic polarisation were determined. Figure 4.2 shows that these values are different for the three colour channels.

The intrinsic polarisation effect is much smaller for the BW camera used.

### Offset angle determination

In order to determine $\phi_0$, the offset in the angle, measurements were taken from a horizontal piece of glass, under a grazing angle. In this measurement setup the only Stokes component with a finite value is the $Q$ component of equation (4.1), while $U$ is assumed to be 0.

### Determination of Stokes components

When the intensity is measured for a full rotation of the polariser then the Stokes-Müller polarisation parameters $\tilde{I}, \tilde{Q}, \tilde{U}$ can be estimated by:

$$\tilde{I} = \frac{1}{N} \sum_{i=1}^{N} I_\phi(\phi_i)$$

(4.3)

$$\tilde{Q} = \frac{2}{N} \sum_{i=1}^{N} I_\phi(\phi_i) \cos(2\phi_i)$$

(4.4)

$$\tilde{U} = \frac{2}{N} \sum_{i=1}^{N} I_\phi(\phi_i) \sin(2\phi_i)$$

(4.5)

where $N$ is the number of frames that fit in a full rotation, $i$ the frame number and $\phi_i = \frac{i\phi}{N}$ the angle of the linear polariser.
5. Test results

This chapter presents detection results on recordings made during August and September 2003 on the test field described in the previous chapter. Table 5.1 lists the datasets recorded during the tests. The recordings were made with two different cameras: black and white (BW) and colour (RGB). Details on these cameras can be found in chapter 3. In order to test system performance on a more difficult scenario, recordings in September 2003 also include datasets with mines that were dirty or tilted with respect to the ground surface.

Table 5.1: Recorded datasets: for each dataset the recording hours, the type of camera, as well as the orientation and mine surface are given.

<table>
<thead>
<tr>
<th>Date</th>
<th>Hours</th>
<th>Camera</th>
<th>Mine Orientation</th>
<th>Mine Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-08-04</td>
<td>14:00 - 15:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-08-05</td>
<td>09:00 - 15:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-08-06</td>
<td>07:00 - 08:00</td>
<td>RGB</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-08-06</td>
<td>09:00 - 23:00</td>
<td>RGB</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-08-07</td>
<td>00:00 - 13:00</td>
<td>RGB</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-08-07</td>
<td>14:00 - 15:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-08-12</td>
<td>15:00 - 23:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-08-13</td>
<td>00:00 - 23:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-08-14</td>
<td>00:00 - 15:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-09-11</td>
<td>10:00 - 15:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-09-12</td>
<td>08:00 - 09:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-09-12</td>
<td>13:00 - 13:00</td>
<td>BW</td>
<td>horizontal</td>
<td>clean</td>
</tr>
<tr>
<td>2003-09-12</td>
<td>14:00 - 15:00</td>
<td>BW</td>
<td>horizontal</td>
<td>dirty</td>
</tr>
<tr>
<td>2003-09-15</td>
<td>09:00 - 15:00</td>
<td>BW</td>
<td>horizontal</td>
<td>dirty</td>
</tr>
<tr>
<td>2003-09-16</td>
<td>09:00 - 15:00</td>
<td>BW</td>
<td>horizontal</td>
<td>dirty</td>
</tr>
<tr>
<td>2003-09-17</td>
<td>13:00 - 15:00</td>
<td>RGB</td>
<td>horizontal</td>
<td>dirty</td>
</tr>
<tr>
<td>2003-09-22</td>
<td>08:00 - 15:00</td>
<td>BW</td>
<td>tilted away from</td>
<td>clean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>the camera</td>
<td></td>
</tr>
<tr>
<td>2003-09-25</td>
<td>09:00 - 15:00</td>
<td>BW</td>
<td>tilted towards</td>
<td>clean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>the camera</td>
<td></td>
</tr>
<tr>
<td>2003-09-26</td>
<td>09:00 - 15:00</td>
<td>BW</td>
<td>tilted toward the</td>
<td>clean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>left</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 lists for the same datasets the weather conditions during the recording hours. Furthermore, Figure 5.1 shows the sun elevation at TNO-FEL (recording site) and Somaliland (target application area) at 5 August, and 1 and 26 September.
**Table 5.2:** Recorded datasets: for each dataset weather conditions of that day are given.

<table>
<thead>
<tr>
<th>Date</th>
<th>Hours</th>
<th>Weather conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-08-04</td>
<td>14:00-15:00</td>
<td>Perfect clear sky</td>
</tr>
<tr>
<td>2003-08-05</td>
<td>09:00-15:00</td>
<td>Perfect clear sky</td>
</tr>
<tr>
<td>2003-08-06</td>
<td>07:00-08:00</td>
<td>Low light level</td>
</tr>
<tr>
<td>2003-08-06</td>
<td>09:00-23:00</td>
<td>09.15-11.30 clear sky</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.30-13.15 clouds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.15-15.00 clear sky</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.00-19.00 clouds</td>
</tr>
<tr>
<td>2003-08-07</td>
<td>00:00-13:00</td>
<td>Perfect clear sky</td>
</tr>
<tr>
<td>2003-08-07</td>
<td>14:00-15:00</td>
<td>Perfect clear sky</td>
</tr>
<tr>
<td>2003-08-12</td>
<td>15:00-23:00</td>
<td>15.00-16.30 clear sky</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16.30-17.45 clouds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.45-21.00 clear sky</td>
</tr>
<tr>
<td>2003-08-13</td>
<td>00:00-23:00</td>
<td>Cloudy</td>
</tr>
<tr>
<td>2003-08-14</td>
<td>00:00-15:00</td>
<td>Lots of clouds</td>
</tr>
<tr>
<td>2003-09-11</td>
<td>10:00-15:00</td>
<td>Lots of clouds</td>
</tr>
<tr>
<td>2003-09-12</td>
<td>08:00-09:00</td>
<td>Dark, complete overcast</td>
</tr>
<tr>
<td>2003-09-12</td>
<td>13:00-13:00</td>
<td>Cloudy</td>
</tr>
<tr>
<td>2003-09-12</td>
<td>14:00-15:00</td>
<td>Cloudy</td>
</tr>
<tr>
<td>2003-09-15</td>
<td>09:00-1500</td>
<td>Light clouds</td>
</tr>
<tr>
<td>2003-09-16</td>
<td>09:00-15:00</td>
<td>Light clouds</td>
</tr>
<tr>
<td>2003-09-17</td>
<td>13:00-15:00</td>
<td>Clear sky</td>
</tr>
<tr>
<td>2003-09-22</td>
<td>08:00-15:00</td>
<td>9.30-11.15 clear sky</td>
</tr>
<tr>
<td>2003-09-25</td>
<td>09:00-15:00</td>
<td>Clear sky</td>
</tr>
<tr>
<td>2003-09-26</td>
<td>09:00-15:00</td>
<td>9.45-11.30 clear sky</td>
</tr>
</tbody>
</table>
Figure 5.1: Sun elevation at TNO-FEL and Somaliland on 5 August, and 1 and 26 September.

5.1 Examples

In the following paragraphs the detection results for different example datasets are presented. The examples are given to show the advantage of using polarisation and to assess the influence of several factors (as mentioned in the test plan) to the detection performance as well as to validate the landmine-detection concepts. These factors of influence were taken into account while setting up and performing the tests. Factors that were expected to influence the detection results are:

- Light conditions
- Mine type
- Condition of mine surface
- Burial depth
- Vegetation
- Orientation of top surface of the mine.

Each paragraph assesses one or more of these items.
5.2 Polarisation versus intensity

In this paragraph we look at the detection results for dataset 2003-08-07 using only intensity or polarisation features. Dataset 2003-08-07 was recorded under ideal recording conditions: completely clear sky during the whole day, see Figure 5.2. Figure 5.3 shows the ROC of the system for dataset 2003-08-07 using only positive intensity contrast. The next figure (Figure 5.4) shows the ROC of the system for dataset 2003-08-07 using only linear polarisation. Figure 5.5 shows the ROC of the system using the combination of positive intensity contrast and linear polarisation, as detailed in section 2.3.3.

![Figure 5.2: Dataset 2003-08-07 was recorded under ideal recording conditions: completely clear sky during the whole day.](image1)

![Figure 5.3: Dataset 2003-08-07: ROC using only intensity feature.](image2)
Figure 5.4: Dataset 2003-08-07: ROC using only polarisation feature.

Figure 5.5: Dataset 2003-08-07: ROC combination of intensity and polarisation.

From Figure 5.3 and Figure 5.4 we may conclude that polarisation is the most important feature for detection. Although detection based on intensity only has very low performance, the combination of polarisation and intensity features results in a better ROC (Figure 5.5). This implies that intensity and polarisation are complementary features and justifies their combination, as discussed in section 2.3.3.
5.3  Negative intensity contrast and system robustness

In this paragraph we look at the detection results for dataset 2003-08-04. With this dataset we can assess the use of negative intensity contrast and system robustness. These topics are discussed in the next two paragraphs.

Figure 5.6: Dataset 2003-08-04 was recorded under ideal recording conditions: completely clear sky during recording hours.

5.3.1  Negative intensity contrast

Figure 5.7 shows the detection rate versus the time of measurement for the four viewing directions. The results for the North viewing direction in the left figure can be explained from Figure 5.8.

Figure 5.7: Dataset 2003-08-04: Detection rate vs. time of measurement for the four viewing directions. A false-alarm rate of 3% was chosen. The results for all mine types except P-2 mine type are shown. On the left the results are with normal processing, on the right with an adaptation of the detection algorithm to favour negative intensity contrast. The straight dashed lines in both figures are the detection result for the whole sequence (instead of the result of one hour).
On the right side of Figure 5.8 the amount of linear polarisation is shown and it is clear that the polarisation contrast is negative for almost all mines. The same applies to the contrast for the monochrome intensity on the left. For this case the normal detection algorithm was adapted to favour negative intensity contrast and the results are shown on the right of Figure 5.7. In this case the results improve significantly for the North viewing direction. The current implementation of the combination of intensity and polarisation (see section 2.3.3) does not take into account negative intensity contrast as a separate feature. Given the above results, it would be worthwhile to enhance system robustness to different situations by including negative intensity contrast.

Figure 5.8: Visible-light intensity and polarisation images of measurement 2003-08-04, North, 14:00 hours.

5.3.2 System robustness
When we compare the straight dashed lines in both graphs of Figure 5.7, which represent the detection result for the whole sequence, with the detection result per hour, we can assess the robustness of this system. If the whole sequence results do not deviate much from the results per hour, both have more or less the same optimal settings (for example, North and East on the left of Figure 5.7). When results do differ, for example West on the left and North on the right of Figure 5.7, settings may vary significantly per hour and one optimal setting for all hours cannot be found that matches the per hour results. We can conclude that the results for North direction can be improved using negative intensity contrast but it has consequences for the South viewing direction.

5.4 Influence of the position of the sun relative to the camera

In this paragraph we look at the detection results for dataset 2003-08-05. With the detection results of this dataset we assess the influence of the relative position of the sun on the performance of the system. Dataset 2003-08-05 was recorded under ideal recording conditions: completely clear sky during the whole day, see Figure 5.9.
Figure 5.9: Dataset 2003-08-05 was recorded under ideal recording conditions: completely clear sky during the whole day.

Figure 5.10 (left graph) shows the detection results when the detection rate was plotted against the viewing direction of the camera and the local time. Figure 5.10 (right graph) shows the detection results when the detection rate was plotted against the mine type and the local time. For both figures the system false-alarm rate was set to 3%.

Figure 5.10: Dataset 2003-08-05, on the left: detection rate vs. time of measurement for the four viewing directions (P2 mine type is included in the results). On the right: detection rate vs. time of measurement for the four mine types. A false-alarm rate of 3% was chosen.

Figure 5.11 shows the detection rate versus the time of measurement for the four mine types. A false-alarm rate of 3% was chosen. The straight dashed lines in the graph are the detection result for the whole sequence (instead of the result of one hour) per mine type.
Figure 5.11: Dataset 2003-08-05: Detection rate vs. time of measurement for the four mine types. A false-alarm rate of 3% was chosen. The straight dashed lines in the figure are the detection result for the whole sequence (instead of the result of one hour per mine type).

From Figure 5.10 and Figure 5.11, we may conclude that detection results per mine type do not differ much, except for the P2 mine for which there is a very low performance. This can be explained by the fact that the P2 mine has no flat top surface whereas the other mines have, and, as such, cannot be detected very well by polarisation.

Furthermore, Figure 5.11 clearly shows the dependency between the recording hour and the detection rate. For all mines (except the P-2 mine type, which cannot be detected well using polarisation) the detection graph shows similar behaviour. At 9:00 to 10:00 hours we have top performance, at 12:00 hours the graph shows a local minimum and after 12:00 hours there is increased performance again, with the exception of 15:00 hours. This indicates that there is a relationship between the relative position of the sun and the detection results, given that the recording conditions were ideal. This is discussed in more detail in the following paragraphs.
Figure 5.12: Dataset 2003-08-05: Detection rate vs. time of measurement for the four viewing directions. A false-alarm rate of 3% was chosen. The results for all mine types with the exclusion of the P-2 mine type are shown. The straight dashed lines in both figures are the detection result for the whole sequence (instead of the result of one hour).

From Figure 5.12 we may conclude that three out of four viewing directions perform better than 50% detection with a false-alarm rate of 3% when we look at the detection results for the whole sequence (straight dashed lines). However, looking at the results per hour, there are some significant variations with the whole sequence results. This indicates that different parameter settings are used for different hours and which do not closely match the global settings for the whole sequence. One possibility is that the polarisation results differ per recording hour, as discussed in detail below.

The following figures show for the viewing directions the influence of the time of day and, because of that, the relative position of the sun, on possible detection results with polarisation. From these images and the above results we may conclude that a viewing direction directly towards the sun results in the highest polarisation contrast of the mines. When the viewing direction is along with the sun, the polarisation contrast of the mines is lowest.

When we look in detail we see that for West the polarisation contrast of the mines differs per hour. At 9:00 hours there is some minimal polarisation contrast. As the background clutter does not polarise at this time, the detection rate is very high (see
Figure 5.12) and the performance is probably limited only by camera noise. At 12:00 hours we still see some polarisation contrast (especially at the edges of the objects) but also far more background clutter, which explains the detection results from 11:00 to 13:00 hours (in this case performance is clutter-limited). At 15:00 hours we see that clutter has increased further but the polarisation contrast has increased far more resulting again in high-detection rates. Furthermore, some shadows can be identified in the left (intensity) and right (polarisation) image; the large TM-62P-3 on the left is slightly affected by that in the polarisation image.

Figure 5.13: Visible-light intensity and polarisation images of measurement 2003-08-05, West: 9:00, 12:00, and 15:00 hours.
When we look at the East viewing direction, the polarisation contrast also differs per hour. At 9:00 hours there is reasonably good polarisation contrast. As the background clutter does not polarise at this time, the detection rate is very high (see Figure 5.12) and the performance is probably camera-noise limited. At 15:00 hours we see that clutter has increased further but the polarisation contrast has become negative (see section 5.3). When we compare the West viewing direction with the East we see that the polarisation behaviour of East is an inversion of the behaviour of West. West has good polarisation contrast at the end of the day whereas East has good polarisation contrast at the beginning of the day. This indicates that there is a direct relationship between relative position of the sun and polarisation contrast.

![Image of East: 9:00, and 15:00 hours.](image)

Finally, when we look at the South viewing direction polarisation contrast again differs per hour. At 9:00 hours there is medium polarisation contrast. As the background clutter does not polarise much at this time, the detection rate is high (see Figure 5.12). At 12:00 hours we see that both polarisation contrast and clutter have increased somewhat but the difference between mines and background clutter polarisation remains sufficient to allow high detection rates. At 15:00 we can see that the mine polarisation contrast falls below the clutter, and the detection rate deteriorates for this recording hour (see Figure 5.12). When we compare the South viewing direction with the East and West directions we see that the polarisation behaviour of South is a 90 degrees rotated behaviour of East or West. South has good polarisation contrast at the middle of the day whereas East and West have
good polarisation contrast at the beginning and end of the day, respectively. Again, this indicates that there is a strong relationship between the relative position of the sun and polarisation contrast.

Figure 5.15: Visible-light intensity and polarisation images of measurement 2003-08-05, South: 9:00, 12:00, and 15:00 hours.

5.5 Influence of clouds

In this paragraph we look at the detection results for dataset 2003-08-13. With the detection results of this dataset we assess the influence of cloudy weather on the
performance of the system. Dataset 2003-08-13 was recorded under the recording conditions as shown in Figure 5.16.

![Graph showing shortwave and longwave irradiance](image_url)

**Figure 5.16**: Dataset 2003-08-13 was recorded under cloudy weather conditions.

Figure 5.17 presents the detection results of dataset 2003-08-13 for the four mine types. With the exception of the P-2 mine the detection results are good. Furthermore, the variation in the results is only significant in the morning and at the beginning of the evening. When we compare the results with the results for the four mine types of dataset 2003-08-05 (recorded under a completely clear sky) we can see that there is no drop in performance during the middle of the day.
Figure 5.17: Dataset 2003-08-13: detection rate vs. time of measurement for the mine types. A false-alarm rate of 3% was chosen.

Figure 5.18 presents the detection results of dataset 2003-08-13 for the four viewing directions. For all viewing directions the results are above the required 50% detection rate. Note that these results include the P-2 mine, which explains the differences between Figure 5.17 and Figure 5.18. Furthermore, the variation in the results is only significant in the morning and at the beginning of the evening, with the exception of the East direction. When we compare these results with the results for the four viewing directions of dataset 2003-08-05 (recorded under a completely clear sky) we can see that there is far less variation between the four viewing directions. This probably stems from the fact that in that case specular polarisation is the main component, and for this cloudy weather condition it is polarisation from non-uniform lighting. Under shadow conditions, for example in the neighbourhood of trees, the same kind of effects are expected.
Figure 5.18: Dataset 2003-08-13: detection rate vs. time of measurement for the four viewing directions. A false-alarm rate of 3% was chosen.

5.6 Clean mine surfaces compared with dirty surfaces

In this paragraph we look at the detection results for dataset 2003-09-15. For the measurements of this dataset, the mines in the left and right columns of the four measurement areas were covered sparsely with some dirt. The mines in the inner column remained the same, as a reference point. Figure 5.19 presents the detection results for dirty and clean mines for the four viewing directions (dataset 2003-09-15).
Figure 5.19: Dataset 2003-09-15: detection rate vs. time of measurement for the four viewing directions. A false-alarm rate of 3% was chosen. The results for clean mines are shown on the left. The results for the dirty mines are shown on the right (note that the axes scales differ).

From Figure 5.19 we may conclude that detection results deteriorate for dirty mines when compared with the clean mines of the same dataset. Another dataset also clearly shows this behaviour. Figure 5.20 shows the results for dataset 2003-09-12. For this dataset all mines were clean until 13:00 hours. After 13:00 hours two-thirds of the mines were made dirty in the same way as the previous dataset. In the results we see that after 13:00 hours the detection results drop significantly.

Figure 5.20: Dataset 2003-09-12: detection rate vs. time of measurement for the four viewing directions. A false-alarm rate of 3% was chosen. The results for clean mines are shown on the left. The results of the dirty (after 13:00 hours) mines are shown on the right (note that the axes scales differ and the P2 mines are excluded).

Note that between 9:00 and 13:00 hours no measurements were taken because of heavy rain during that period (see Figure 5.21). However, this does not completely explain the fall in performance for the dirty mines after 13:00 hours because most of the performance was maintained for the clean mines.
5.7 Horizontal mine surfaces compared with tilted mine surfaces

This paragraph describes the results of tests performed using the camera system on tilted mines. The tests were conducted to assess the influence of the mine orientation on polarisation results when compared with mines that are not tilted in the same scenario. The tests were divided into three parts:

- Mines tilted away from the camera (dataset 2003-09-22);
- Mines tilted towards the camera (dataset 2003-09-25);
- Mines tilted to the side (dataset 2003-09-26).

5.7.1 Results for mines tilted away from camera

In this paragraph we look at the detection results for dataset 2003-09-22. For the measurements of this dataset, the mines in the left and right column of the four measurement areas were tilted from the camera away at an angle of 10 degrees (see Table 4.1). The mines in the inner column remained the same as a reference point. Figure 5.22 presents the detection results for tilted and non-tilted mines for the four viewing directions (dataset 2003-09-22).
Figure 5.22: Dataset 2003-09-22: detection rate vs. time of measurement for the four viewing directions. A false-alarm rate of 3% was chosen. The results for tilted mines are shown on the left. The results for the non-tilted mines are shown on the right.

From Figure 5.22 we may conclude that detection results deteriorate for tilted mines when compared with the non-tilted mines of the same dataset.

5.7.2 Results for mines tilted towards the camera

In this paragraph we look at the detection results for dataset 2003-09-25. For the measurements of this dataset, the mines in the left and right column of the four measurement areas were tilted towards the camera at an angle of 10 degrees. The mines in the inner column remained the same as a reference point. Figure 5.23 presents the detection results for tilted and non-tilted mines for the four viewing directions (dataset 2003-09-25).

Figure 5.23: Dataset 2003-09-25: detection rate vs. time of measurement for the four viewing directions. A false-alarm rate of 3% was chosen. The results for tilted mines are shown on the left. The results for the non-tilted mines are shown on the right (note different scale of detection axis).

From Figure 5.23 we may conclude that detection results for tilted mines only deteriorated for the North viewing direction when compared with the non-tilted mines of the same dataset. The other viewing directions showed improved performance. The East viewing direction performs poorly for tilted and non-tilted mines because of shadows in the morning imagery and background clutter in the
recordings later on the day (see Figure 5.24 below). This is explained in section 5.4.

![Figure 5.24](image)

As well as reduced performance, shadows cast on the measurement area cause variation in detection performance per hour as can be seen for the South viewing direction in the graph of Figure 5.23. Figure 5.25 shows the visible-light intensity and polarisation images of the South viewing direction at 15:00 hours. The shadows and fragmented light fall can clearly be seen. This probably explains the bad performance of South at 14:00 and 15:00 hours when compared with the other hours of the day.

![Figure 5.25](image)

5.7.3 Results for mines tilted along the viewing direction

In this paragraph we look at the detection results for dataset 2003-09-26. For the measurements of this dataset, the mines in the left and right column of the four measurement areas were tilted towards the right at an angle of 10 degrees. The mines in the inner column remained the same as a reference point. Figure 5.26 presents the detection results for tilted and non-tilted mines for the four viewing directions (dataset 2003-09-26).
Figure 5.26: Dataset 2003-09-26: Detection rate vs. time of measurement for the four viewing directions. A false-alarm rate of 3% was chosen. The results for tilted mines are shown on the left. The results for the non-tilted mines are shown on the right (note different scale of detection axis).

From Figure 5.26 we may conclude that detection results deteriorate for tilted mines when compared with the non-tilted mines of the same dataset.

5.8 Influence of vegetation

In this paragraph we look at the influence of vegetation on the detection results. Some of the recordings made at the end of September 2003 contain some vegetation that was not present when the measurement field was prepared 2 months earlier. A nice example of this is shown in Figure 5.27. In this figure we see the imagery of the dataset of 2003-09-26, South viewing direction, 12:00 hours. In the polarisation image in the middle of the figure we see a large amount of clutter in the middle of the left side of the image. This clutter is caused by some weed that is in close up in the picture on the right. The clutter is significantly more than the background clutter.

Figure 5.27: Dataset 2003-09-26, south viewing direction, 12:00 hours. From left to right: visible-light intensity image, polarisation image, and close-up in colour of vegetation causing polarisation false-alarms in the 1st column between rows 4 and 5 (see Table 4.1).
5.9 Influence of limited dynamic range

In this paragraph we give some examples that show that the choice of a manual camera iris has implications on the system performance. Because the dynamic range of both the BW and RGB camera (as used with the tests) is only 8 bits, an adjustment of the camera iris is necessary when the recording conditions change, to prevent low exposure or saturation. This adjustment can be done automatically (auto gain) or by hand. The first option has the benefit that it always and quickly adapts to the light conditions. Disadvantages are that the selected gain setting is not recorded and quick variations in auto gain make consistent sequence recordings with a rotating filter impossible. In order to use the rotating filter set-up for the static tests we need a consistent sequence recording with a manually adjusted camera iris. This has the disadvantage that for some recordings there is underexposure or saturation because manual adjustment is not as quick as auto gain. Examples of this are given in Figure 5.28 and Figure 5.29.

Figure 5.28: Overexposure due to manual camera iris setting (dataset 2003-08-14, East, 15:00 hours).

Figure 5.29: Underexposure due to manual camera iris setting (dataset 2003-08-14, East, 10:00 hours).
5.10  **Comparison with test plan and discussion**

When we compare the test results with the test plan (see Appendix C) we may conclude that it is in principle possible to detect surface-laid and partly buried AT mines with a polarised visible-light system. The expected false-alarm rate is 3%. The current detection software can have a real-time implementation.

Factors that are of influence on the detection results are:

**Light conditions (elevation and relative azimuth of the sun)**
Light conditions are of influence to the detection results. For detection based on polarisation features it is beneficial to have a viewing direction towards the sun. For other viewing directions it is more difficult to draw unequivocal conclusions from the test results. The tests were recorded with camera using a manual iris. Adjustments were made manually during the recordings to adjust to light conditions; these adjustments may affect the results. Furthermore, the presence of shadows in the imagery has influenced the results for some of the recorded sequences.

**Distance between camera and mine (number of pixels on mine)**
The distance between the camera and the mine may influence the detection results but we cannot draw this conclusion from the static tests we have conducted.

**Mine type**
The type of mine influences the detection results. Detection results do not differ much except for the P2 mine for which there is a very low performance. This can be explained by the fact that the P2 mine has no flat top surface, and as such, cannot be detected very well using polarisation unless a large portion of the mine is visible.

**Condition of mine surface**
The condition of the mine surface influences the detection results. When mines are dirty or partly covered, detection results deteriorate in comparison to clean mines.

**Burial depth (fraction of mine body that is visible for camera)**
The burial depth and the fraction of the mine body that is visible for the camera influences the detection results. When mines are dirty or partly covered, detection results deteriorate when compared with clean mines. However, whether the part of the mine that is visible has a smooth, flat surface is also important. For example, the fraction of the mine body of the P2 mine type that is visible in the tests is not smooth, and as such, the results with polarisation are not good when compared with the other mine types that have a smooth surface (P2, PMN, and TM62-P3).
Vegetation
The vegetation and in general the background clutter of the mines influences the detection results. From the static tests we may conclude that background clutter polarises differently than the mines.

Orientation of top surface of the mine (horizontal or not)
The orientation of the top surface of the mine influences the detection results. The detection results depend on the tilt direction of the mines.
6. Conclusions

In this report we have described the development of a camera system for detection of AT mines. This system uses polarisation features of visible light and will be used to increase the speed of area reduction with AT mine rollers. This camera system could also be used in other scenarios, for example, roadside inspection for mines and unexploded ordnance. Before reaching any conclusions on camera systems and landmine-detection methods there are some important caveats to identify beforehand:

- The performance of a landmine-detection system based on a camera system depends heavily on the scenario and surroundings in which the system is applied. For example, a landmine-detection system that performs well in a Western-European country may fail when applied in an African area near to the equator, even after extensive calibration of the system.

- The only sensible way to evaluate the robustness and performance of a landmine-detection system is to test the system under a wide range of circumstances and application areas. Therefore, the conducted experiments in this report provide an insufficient basis on which to draw general conclusions, they only give an indication of expected performance.

Notwithstanding the above statements, we can draw the following conclusions given the results of the conducted experiments:

- Combination of intensity and polarisation gives the best performance of the system.

- Performance depends on viewing direction, relative to the position of the sun. Looking towards the sun (i.e., when the sun is in a sector of ± 45° when looking in the forward motion direction) seems to be the best viewing direction. This is illustrated by the results for some of the datasets from the West viewing direction. Note that for the West viewing direction the background clutter is far less (grass field) when compared with the other directions, which have debris as background clutter.

- The East viewing direction performs less well because of the position of the sun relative to the viewing direction during most measuring hours.

- It would be beneficial to include the negative intensity contrast feature in another way than currently implemented (see dataset 2003-08-04 in section 5.3.1).

- Performance depends on the time of day and shows large variations, which may be partly due to weather conditions, shadows and a fixed camera iris. A camera with a larger dynamic range could solve part of these variations.

- Performance depends on the type of mine: detection results do not differ much for the mines used in the test, with the exception of the P2 mine for which there is a very low performance. This can be explained by the fact that the P2 mine has no flat top surface, and as such, cannot be detected very well using polarisation.
• Detection of tilted mines proves to be more difficult, except for mines tilted towards the camera.
• Use of global colour information provides no significant extra information. Most of the used landmines have similar colours to the background, which makes colour alone not a very discriminative feature. However, when we extend the colour histogram approach in such a way that colour and also the spatial distribution of colour is taken into account, colour histograms may provide additional information for the detection of mines (mines have in general a uniform colour). Furthermore, when the scenario of application is different (for example, deployment of the system in a sandy environment), global colour statistics may benefit to the performance of the system as in this case mines and background have different colours.

6.1 Feasibility

In this paragraph we discuss the feasibility of a camera system with real-time processing for detection of AT mines. The feasibility assessment includes the following four items:
• Detection performance;
• Real-time implementation;
• Operator aspects;
• Costs.

Based on the static tests results a camera system using polarisation features for detection of AT mines seems feasible. There are, however, some caveats that need attention. One issue is the robustness of polarisation against environmental factors. Some of these issues need to be resolved by clear instruction on operation of the system, e.g., only work in daylight, drive towards the sun, etc. Other issues need to be addressed by improvement of the current detection algorithm; for example, better combination of intensity and polarisation, use of negative contrast, etc.

Furthermore, a real-time implementation of the current detection software is feasible. The current detection algorithm is relatively easy to implement in a real-time system and does not need dedicated hardware to process the imagery.

In addition to technical feasibility it is also important to assess the feasibility of the camera system for the operator. The system is designed to be operated by non-technical personnel with no extensive education. In other words, the system should need limited input from the operator: it should have a power on/off button and possibly a sensitivity knob to control the number of false alarms. The system will come with a guidance that explains the manner of operation and will detail operation rules (working hours, etc.). It is foreseen that the camera system will need a calibration procedure to start with when a new site is entered or when the conditions differ from the previous operations. After calibration the system can be
operational according to guidance rule. The system will give an audible alarm when it detects a land mine. After the alarm the operator can inspect the situation, and with an affirmative detection roll back to the next lane (see Figure 1.2). This procedure seems feasible for the operator. It does not require any technical skills other than execution of the guidance rule on system calibration and system operation. Note that when on a site a landmine is detected in a certain lane, the sensitivity setting of the system can be increased by the operator. The higher probability of false alarms may be acceptable when working in a small region within which the presence of at least one mine has been proven.
7. References


8. Signature

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Author
Appendix A  Scenario Description for the use of a camera system

HALO uses mine rollers for area reduction and area verification [1, 2].

When the roller goes over a mine, the mine detonates and the operator stops the vehicle and knows the position of the first mine. Detonation of an AP mine does not damage the roller system. However when an anti-tank (AT) mine detonates, the rollers must be reassembled, which costs time and money. Eventually damage occurs to the vehicle which must also be repaired. The following table shows the material costs and repair time for different components of the roller system:

Table A.1:  Material costs and repair time for different components of the roller system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Number of this item in system</th>
<th>Cost (US Dollar)</th>
<th>Replacement time</th>
<th>Expected chance of occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roller shaft</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 mm front disc</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>900 mm rear disc</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear Bolts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HALO could integrate a polarised visible-light camera system with their new anti-tank mine roller unit, as shown in Figure A.1.

The polarised visible-light camera system will give an audible warning to the operator when a surface-laid mine is detected. The operator will stop the vehicle before the roller hits the mine. After the vehicle is stopped the operator can inspect the area that caused the warning and decide whether it was a mine or a false alarm.
A.1 References

1. Technical Note 09.50 /01 Guide to mechanical mine clearance / ground preparation using commercial tractors and front loaders. Technical Notes for Mine Action (TNMA) can be found on the following website: http://www.mineactionstandards.org/tnma_list.htm

Figure A.1: New anti-tank mine roller unit of HALO.
Appendix B  Raw Set of requirements

The role in which HALO could integrate the use of the polarised visible-light camera system has been discussed by Phil Straw (HALO) and Wim de Jong (TNO-FEL) on 27 November 2002. Such a camera system could be fitted to one of their new anti-tank mine roller units. The scenario description describes where and how the camera system could be used. Following on the discussion Phil Straw of HALO defined the following criteria that the camera system would need to meet to work successfully:

B.1  HALO criteria

1. Simple to install onto the vehicle. Fitting of the camera and processing unit will be performed in the country of operation (Africa). HALO has extensive workshop facilities in all areas of operation; however the vehicle cannot be brought to the Netherlands for fitment. Main components should be pre-assembled prior to shipping to allow simple plug-together assembly, and should be accompanied with a set of clear and concise assembly instructions.

2. Operation of the camera should be as simple as possible as non-technical personnel will operate it. If the system is too difficult for the operator to use and understand, then it is likely that he will not use it. Simple operation must also include a simple to understand readout, be it visual or audio.

3. Maintenance of the system should be possible within its country of operation. The easiest way to achieve this is to have the system built with exchangeable components. This would make repair simpler and also allow the return/exchange of lightweight parts that could be air-freighted back the Netherlands for repair. HALO has trained radio and detector technicians in all countries of operation.

4. The unit must be robust and able to withstand temperatures of 45°C. External components will also need to be dust and water-resistant.

5. Signal processing is required in real time. A delay of not more than one second for the processing of the signal should be allowed. The camera will be mounted on a moving platform operating at a minimum speed of 2 m/sec\(^1\) over rough terrain and may require a gimbal frame.

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\(^1\) When a lower speed is necessary for good operation of the camera system, special precautions must be taken to keep the speed of vehicle at this low value.

\(^2\) Otherwise the operators will most probably drive too fast.
Appendix C  Test plan for the tests with a static camera.

To be tested:
In principle it is possible, using a polarised visible-light system, to detect surface-laid and partly buried AT mines in light vegetation at a maximum distance of 13 m from a camera that is mounted on a static platform. What is the false alarm rate and how fast is the image processing?

Factors that are expected to influence the detection results are:
- Light conditions (elevation and relative azimuth of the sun)
- Distance between camera and mine (number of pixels on mine)
- Mine type
- Condition of mine surface
- Burial depth (fraction of mine body that is visible for camera)
- Vegetation
- Orientation of top surface of the mine (horizontal or not).

The first tests will be performed with a rotating polarization filter in front of a visible-light camera. This camera has fewer pixels than the 3-CCD Duncan camera. A lens will be chosen to achieve the same IFOV namely 0.47 mrad. The camera will be mounted on a static platform at a height of 4 m.

Light conditions

The position of the sun relative to the position of the camera is not known in advance and the influence of the sun must be determined. This will be performed in a measurement set up with a camera that can rotate to look at different directions relative to the position of the sun. Mines will be placed at four different positions, approx. North, East, South and West of the camera system. Measurements will be performed on a clear sunny day. Measurements will start shortly after sunrise and will last till noon. Every 15 minutes a measurement is taken from each of the four positions.

Distance between the camera and the mines

The mines will be placed in a rectangular area with a width of 3 m and a length of 6 m ranging from 8 to 13 m from the camera. 18 objects (3x6) can be placed on a square grid with a minimum distance of 1 m between the objects. For calibration the distance of three to four objects towards the camera must be determined before the tests start.
Mine type

Emphasis lies on the Belgium PRB-M3 and Pakistani P2, since these mines are those to be detected in Somaliland, where HALO is currently active. Phil Straw will provide us with the detonator caps of these mines, since transportation of the whole mine casing is difficult. Some TM62-P dummies will also be tested.

Condition of mine surface

Specular reflectivity and thus polarisation contrast depends on the smoothness of the mine surface. It has not yet been decided whether and how the mine surfaces will be treated. For mines with an iron casing rust will influence the surface smoothness.

Burial depth

Quite often only the cap of the mine is visible and not the whole mine body. Extra PMN dummy mines will be used since these mines have roughly the same diameter as the detonator of the PRB-M3. These PMNs will be surface-laid. Some TNO test mines will also be placed on the surface.

Table C.1: Test-lane layout.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Object</th>
<th>Object</th>
<th>Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>13m</td>
<td>PRB</td>
<td>TM62</td>
<td>PRB</td>
</tr>
<tr>
<td>12m</td>
<td>TM62</td>
<td>P2</td>
<td>TM62</td>
</tr>
<tr>
<td>11m</td>
<td>P2</td>
<td>PRB</td>
<td>P2</td>
</tr>
<tr>
<td>10m</td>
<td>Stone</td>
<td>Stone</td>
<td>Stone</td>
</tr>
<tr>
<td>9m</td>
<td>PMN</td>
<td>Stone</td>
<td>PMN</td>
</tr>
<tr>
<td>8m</td>
<td>Stone</td>
<td>PMN</td>
<td>Stone</td>
</tr>
</tbody>
</table>

Vegetation and background

The area used will be the ‘beveiligingsproefterrein’ (security test area) near the HOM2000 test lanes. Four boxes in this area will be filled with objects. Two of them (South and West) will have existing grass vegetation, with some extra stones. In the other two boxes the grass will be removed and stones will be put on the surface.
Mine orientation

For the first experiment, the mines will be placed horizontally. Alternatives are mines at an angle of 10 degrees maximum.

Processing

The acquired images will be processed and the detection rate will be determined for all parameters that are mentioned above.