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Multi-optical mine detection system (MOMS)

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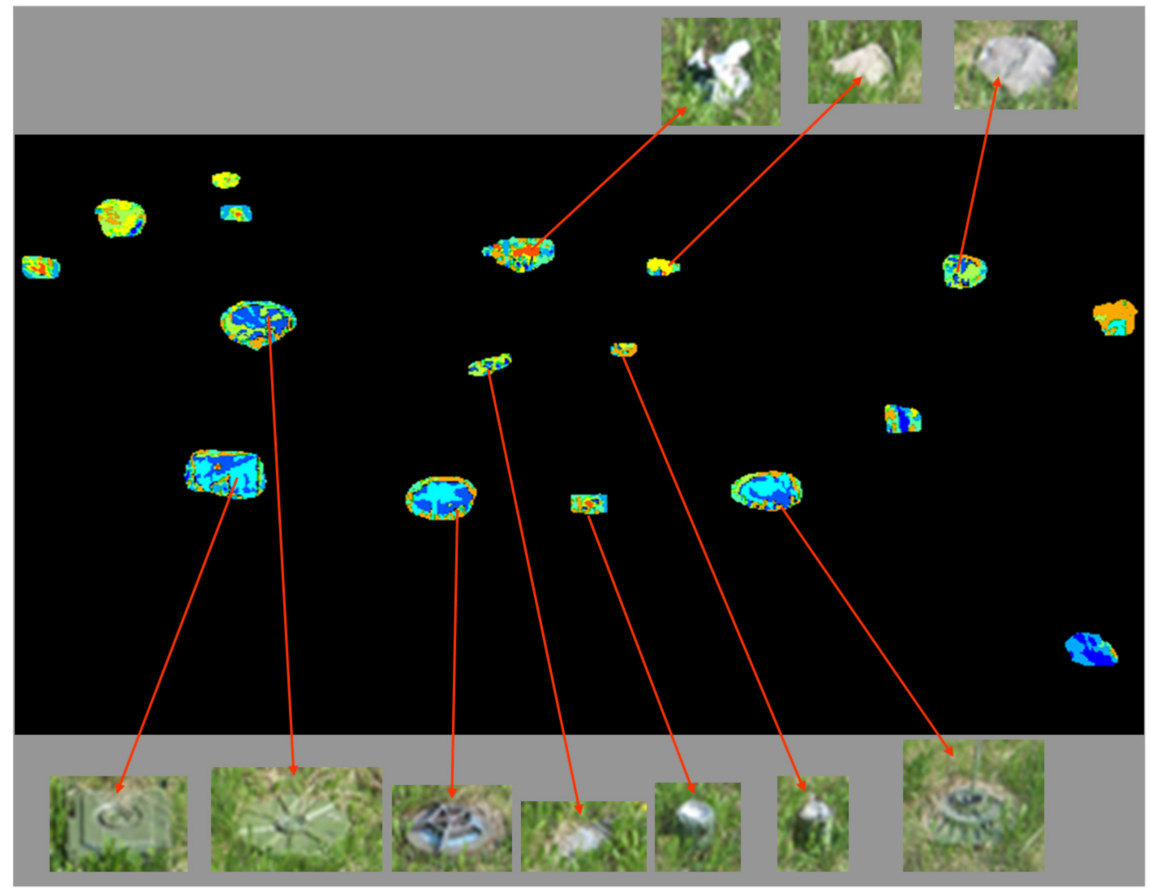

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Multi-optical mine detection system (MOMS)

Final report

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Sammanfattning

Det övergripande målet för MOMS har varit att ge kunskap och kompetens för snabb detektion av ytlagda minor. Fokus för MOMS-projektet var värdering av koncept; att analysera och beskriva möjligheter och brister med olika sensorkombinationer och koncept. Ett antal sensorkoncept med aktiva och passiva EO-sensorer har beskrivits.

Den spatiella upplösningen hos en sensor måste medge flera pixlar på målet. Även för att analysera spektrala likheter mellan objekt måste upplösningen vara så bra att tillräckligt med data finns för att få bra statistik för varje objekt. Detektion av minor i vegetation är oftast enklare om sensorn tittar rakt ned. I ett flygburet sensorpaket måste hög upplösning kombineras med snabb avsökningsförmåga. I ett optimalt system ingår troligen en kombination av flygfarkost (UAV) och markfordon.

Bland de metoder för signalbehandling som studerats framstår anomalidetektion som en nyckelkomponent i ett systemkoncept. Dessutom kan denna teknik troligen användas för detektion av andra objekt, t.ex. IED.

Fusion mellan sensordata från olika sensortyper har visats vara framgångsrikt och ett sätt att minska antalet falsklarm vid detektion. För klassificering tror vi att det behövs en operatör. Automatisk måligenkänning är ett stöd men det slutliga beslutet eller verifieringen av en mina eller IED måste göras av en människa.

De flesta sensorer, metoder och tekniker för signalbehandling som har använts i MOMS är också relevanta för IED-problemet. I rapporten ges en översikt över nuvarande teknologi och utvecklingstrender.

Nyckelord: mindetektion, elektrooptiska sensorer, hyperspektrala sensorer, laserradar, signalbehandling, datafusion

Summary

The overall objective for MOMS was to provide knowledge and competence for fast detection of mines, especially surface laid mines. The focus of the MOMS project was assessment of concepts; to analyze and describe the possibilities and shortcomings of various sensor combinations and concepts. A number of sensor concepts for active and passive EO sensing have been described. ,

The spatial resolution of the sensor must allow for having several pixels on the target. Also for evaluating spectral similarities between objects, the resolution must be good so that there are enough data for computing sufficient statistics for each object. Detection of mines in vegetation is mostly easier when the sensor looks down. Airborne sensor suites should combine high resolution with large surface coverage rate. The optimum system will most probably be a combination of airborne (UAV) and ground vehicle sensors in cooperation.

Among the signal processing techniques considered, anomaly detection emerges as a key component in a system concept. In addition, this technique can potentially be used for detection of other objects, e.g. IED’s.

Sensor data fusion has been shown to be successful and a way to decrease the number of false alarms for detection. For classification we believe that an operator is needed. Automatic target recognition is a support but the final decision/verification of a mine or IED threat should be done by a human.

Most of the sensors, methods and signal processing techniques used in MOMS also have high relevance for the IED problem. In the report an overview of current technology and development trends is given.

Keywords: mine detection, electro-optical sensors, hyperspectral imaging, laser radar, signal processing, data fusion,

Contents

List of abbreviations

AHP	Analytic Hierarchy Process
ALMDS	Airborne Laser Mine Detection System
APD	Avalanche photo diode
ARV	Armed Robotic Vehicle
ASTAMIDS	Airborne Stand-off Mine Detection System; renamed to Airborne Surveillance, Target Acquisition and Minefield Detection System
CFAR	constant false-alarm rate
C-IED	Counter-IED
CMT	Cadmium-Mercury-Telluride
COBRA	Coastal Battlefield Reconnaissance and Analysis
DARPA	The Defense Advanced Research Projects Agency
DGA	Direction générale de l'armement (France)
EMF	Electro-motive force
EO	Electro-optic
FCS	Forward Combat System
FFI	Forsvarets forskningsinstitutt (Norway)
FM	Försvarsmakten (The Swedish Armed Forces)
FMV	The Swedish defence material administration
FOI	Totalförsvarets forskningsinstitut (The Swedish Research Agency)
FPA	Focal plane array
GPR	Ground-penetrating radar
GSTAMIDS	Ground Stand-off Mine Detection System
HYPOLAC	Hyperspectral Polarimetric Active and Passive Imaging
IED	Improvised explosive device
IR	Infrared
LIBS	Laser-induced breakdown spectroscopy
LWIR	Long-wave infrared
MOMS	Multi-optical mine detection system
MRR	modulated retro-reflector
MSS	The Swedish armed forces Land warfare centre (*Markstrids-skolan*)
MULE	Multifunction Utility/Logistics Equipment
MWIR	Medium-wave infrared
NIR	Near-infrared
NLJD	Nin-linear junction detector

NTNU	The Norwegian University of Science and Technology
PCA	Principal component analysis
RAMICS	Rapid Airborne Mine Clearance System
ROAR	Rapid Overt Airborne Reconnaissance
RONS	Remote Ordnance Neutralization System
RTO	Research and Technology Organisation
RVS	Raytheon Vision Systems
SAR	Synthetic aperture radar
SCI	System Concepts and Integration
SPAD	Single photon avalanche diode
SVA	Support vector machine
SWEDEC	The Swedish EOD and Demining Centre
SWIR	Short-wave infrared
TIC	Toxic industrial chemicals
TRT	Thales Research and Technology
UAV	Unmanned aerial vehicle
UGV	Unmanned ground vehicle
UV	Ultraviolet
UXO	Unexploded ordnance
VNIR	Visual and near-infrared

0 Executive summary

This report is a summary of progress the in the project Multi-optical mine detection system (MOMS), performed on commission for the Swedish Armed Forces. Here, we have collected the results from tests and concept studies conducted in the course of the project.

The overall objective for MOMS is to provide knowledge and competence for fast detection of mines, especially surface laid mines, and thereby increase the FM[a] manoeuvrability in international as well as national operations. The most important scenario was decided to be the Swedish Armed Forces' international capacity/ability to check roads. The focus of the MOMS project was assessment of concepts; to analyze and describe the possibilities and shortcomings of various sensor combinations and concepts.

Several major field trials have been conducted at SWEDEC[b]. A mine scenario (the "grass square") was also arranged outside the laboratory at FOI. The purpose was to monitor seasonal variations in vegetation, as well as weather and light conditions.

A workshop with invited end-users was held with the purpose to present some initial concept ideas and to get a more comprehensive view on system requirements. The MOMS project has also been supported by a reference group, with participation from FMV[c], FM Headquarters, SWEDEC, and MSS[d].

A number of sensor concepts for active and passive electro-optical (EO) sensing have been proposed, including performance and estimated size, weight and power. Based on an initial literature survey, the phenomena below were chosen as candidates for an evaluation:

- Spatial properties (2-D or 3-D geometry; i.e. shape, size)
- Spectral properties (incl. angular and spectral dependence of reflectivity and emissivity)
- Thermal inertia (earlier called temperature or temporal analysis. This does not include long-term changes in e.g. reflectivity)
- Polarisation ("passive" as well as "active", i.e. with illumination)
- Fluorescence (not experimentally evaluated in MOMS)
- Material composition (spectroscopic methods, e.g. LIBS[e], laser wave mixing) (not experimentally evaluated in MOMS)

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[a] The Swedish Armed Forces
[b] The Swedish EOD and Demining Centre, Eksjö
[c] The Swedish Defence Material Administration
[d] The Swedish Armed Forces Land warfare centre
[e] Laser-induced breakdown spectroscopy

According to recent literature the SWIR[a] wavelength region appears to be a potentially effective means for detecting the disturbed soil associated with buried mines. Both passive sensor systems (benefiting from solar illumination) and active laser systems can be used in combination with thermal sensing. Buried mines have however not been the focus for the MOMS project.

The spatial resolution of the sensor must allow for having several pixels on the target. For a relatively large object, e.g. an anti-tank (AT) mine, the pixels should correspond to a resolution on the target of maybe about 2-3 cm, to enable the removal of small, irrelevant objects. Also for evaluating spectral similarities between objects, the resolution must be good so that there are enough data for computing sufficient statistics for each object.

Among the signal processing techniques considered, anomaly detection emerges as a key component in a system concept. This method detects objects that are different from what is expected (the background) and thus gives a first indication of possible mines. In addition, this technique can potentially be used for detection of other objects, e.g. IED's[b].

Fusion on the lowest level (pixel or signal level) requires very accurate data registration, i.e., transformation into a common coordinate system. Fusion on the decision-level, on the other hand, will cope considerably better with a less accurate registration.

Detection of mines in vegetation is mostly easier when the sensor looks down, than when looking horizontally, as the occlusion is usually lower for that aspect. This favours an elevated sensor platform, or even better, an airborne platform. From a signal processing perspective, it is desirable that the sensors are mounted close to each other, preferably with common optics and/or detector array, so that the registration can be as accurate as possible.

Airborne sensor suites should combine high resolution with large surface coverage rate. Active/passive high resolution mapping and surveillance functions for targets in general are included in the airborne platform. The optimum system will most probably be a combination of airborne (UAV[c]) and ground vehicle sensors in cooperation via an operator in the ground vehicle.

For classification we believe that an operator is needed. Automatic target recognition is a support but the final decision/verification of a mine or IED threat should be done by a human.

Most of the sensors, methods and processing techniques used in MOMS also have high relevance for the IED problem. However, the IED threat also contains

[a] Short wave infrared
[b] Improvised explosive devices
[c] Unmanned aerial vehicle

buried and hidden explosives, person and vehicle borne bombs etc. which requires other sensors and methods as well. Some of these, which should be investigated in a future C-IED[a] project, include:

- High resolution and well stabilized active/passive EO systems suitable for change detection.
- High resolution well stabilized active/passive EO systems suitable for track detection and for detection of humans, recognition and tracking to investigate intent well before and during IED preparation.
- Persistent surveillance sensors (e.g. radar, EO, acoustic sensors, ground sensors, signal intelligence)
- Remote explosive detection techniques, in combination with cueing sensors to detect and point out specific objects or regions to be investigated.
- Radar systems (ground penetrating, including SAR[b]) and laser Doppler techniques for detection of buried and hidden objects.

[a] Counter-IED
[b] Synthetic aperture radar

1 Introduction

This report is a summary of progress the in the project Multi-optical mine detection system (MOMS), performed on commission for the Swedish Armed Forces. Here, we have collected the results from tests and concept studies conducted in the course of the project. The method of work is presented in Section 1.3 including some external contacts described in Section 1.4. In Section 2 the phenomenologies that have been studied are presented and the choice of sensors and platforms is discussed. The system concepts are further discussed in Section 3. A short overview of the international technology development is given in Section 4. In Section 5, the results are discussed and some recommendations are given. A compilation of publications is given in Section 6.

1.1 Background

In a study called FramFoT [1] conducted by FM[a], FMV[b] and FOI, the ongoing and the planned research within ammunitions and mine clearance activities was analyzed. The aim was to propose a new direction for future R&D in this field. As a result, a new research project based on electro-optical (EO) sensors, the Multi-Optical Mine detection System (MOMS[c]), was proposed.

A project proposal was presented in early 2005 [2, 3] and the MOMS project was formally launched at FOI in March 2005.

1.1.1 Scenario

In June 2005 a readjustment of the priorities of the scenarios was decided by FM [4]. The new priority order for the scenarios is:

1. Increase the Swedish Armed Forces' international capacity/ability to check roads
2. Mine detection for battalion's offensive against recently landed airborne enemy
3. Contribute to development of mine detection within humanitarian mine clearance (Describe the possibilities in this scenario)
4. Mine detection in order to open roads and paths for own forces
5. Mine detection for battalion crossing watercourses

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[a] The Swedish Armed Forces
[b] The Swedish Defence Material Administration
[c] In Swedish: *Multioptisk minspaning.*

1.2 Objectives

The overall objective for MOMS is to provide knowledge and competence for fast detection of mines, especially surface laid mines, and thereby increase the FM manoeuvrability in international as well as national operations.

MOMS will give answers to the question: How should an optical mine detection system be designed, based on laser and EO/IR sensors, in order to detect land mines and UXO[a] in accordance with the scenarios defined by FM.

1.3 Method of work

The tactical land mine detection problem is very difficult and complex, as illustrated by the lack of operational systems with rapid surface coverage in the international arena. The MOMS project was formed to build a deeper knowledge of the phenomena and potential sensor technology to use in a future system demonstrator. The MOMS mission was not to build this system but to deliver the specification and guidelines for such a system. With the decision not to initiate the demonstrator phase, the focus of the MOMS project was limited to an assessment of concepts; to analyze and describe the possibilities and shortcomings of various sensor combinations and concepts. The work at different system levels and at different levels of detail in MOMS is illustrated by the triangle in Figure 1, beginning at the phenomenology level at the base and with increasing complexity to the top.

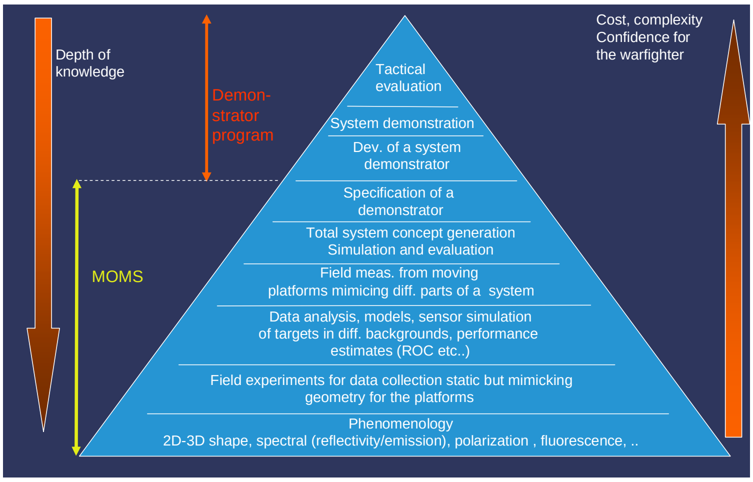

Figure 1. The work process in the MOMS project. The demonstrator program, intended to follow the MOMS project, was not launched.

[a] Unexploded ordnance

1.3.1 Sensors

In the project a large number of sensors have been used to collect data. For the large field trials, the sensors presented in Table 1 were used. In addition, data has also been collected with a gated viewing system, an active polarimetric hyper-spectral sensor, and a high-resolution 3-D laser radar.

Table 1. The sensors that were used in the field trials, and the corresponding wavelength coverage.

Sensor	Waveband	Name	Wavelength [μm]
Digital camera	VIS	Nikon D200	Visual
Hyperspectral camera	VNIR	Imspec	0.396-0.961 (240 bands)
Multispectral camera	VNIR	Redlake	0.525-0.575; 0.64-0.69; 0.77-0.83
3-D laser radar	SWIR	Optech ILRIS-3D	1.54
Multispectral camera	SWIR/MWIR	Multimir	1.5-1.8; 2.1-2.5; 3.5-4.0; 4.5-5.2
Thermal camera	LWIR	Thermacam SC3000	8-9

1.3.2 Experimental activities

Several major field trials have been conducted (May 2005, October 2007, April and August 2008) [5, 6, 7] at the "Sensor track" (Sensorbanan) belonging to (SWEDEC[a]). A large number of mines were provided by SWEDEC and arranged in three scenarios: dirt road, meadow, and forest (sprigs) [8]. Measurements were made with five EO sensors arranged on a turn-table mounted on a telescopic boom at a height of 15 m, see Figure 2.

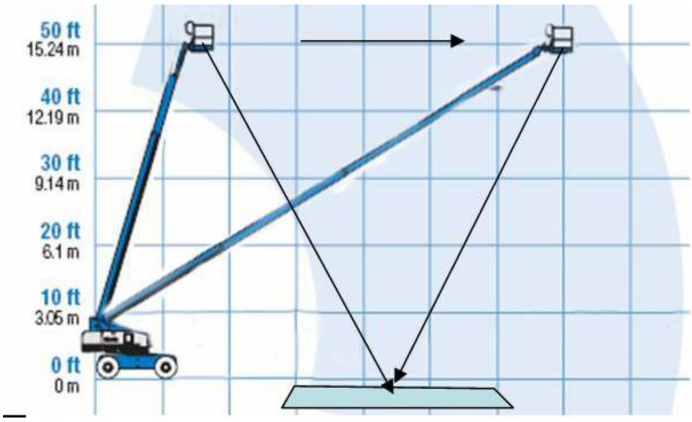

Figure 2. Simulation of an airborne platform, with the sensor head looking towards the same centre point on the ground from different angles.

[a] The Swedish EOD and Demining Centre, Eksjö

A mine scenario (the “grass square”) was arranged outside the laboratory at FOI. The purpose was to monitor seasonal variations in vegetation, as well as weather and light conditions. In order to get high accuracy data suitable for data fusion, the sensors were mounted on a rigid tripod in the roof-top lab at FOI, see Figure 3 [9]. The same sensor suite was used as in the field trials at SWEDEC.

Figure 3. The sensors mounted on a tripod, looking through at the grass test area outside the roof-top lab at FOI.

1.3.3 Assessment and evaluation

Assessment and evaluation, at different levels and stages of the project, has been done; involving experience from supporting projects, literature surveys, international contacts, and a more structured approach using AHP[a] [10]. The software for AHP was Expert Choice, including visualisation of how the choice of parameters affects the assessment result.

1.3.4 Activities

A large number of conference papers have been published, see Section 6.2. The participation in conferences and information collected on visits at other laboratories has contributed to the choice of sensors and concept development. Furthermore, the participation in the C-IED study group (Section 1.4.1) has brought extensive insight to the IED problem into the project.

A workshop for assessment of phenomenologies was held in 2006, with support from FOI Defence analysis. The purpose of the workshop was to give directions for the choice of phenomenologies, sensors, and future data collections and to aid

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[a] Analytic Hierarchy Process

in the identification of knowledge gaps. Results from the workshop have been reported previously [11, 12].

In April 2008 a workshop with invited end-users was held. The purpose was to present some initial concept ideas and to get a more comprehensive view on system requirements.

The MOMS project has also been supported by a reference group, with participation from FMV, FM Headquarters, SWEDEC, and MSS[a].

1.4 External contacts

1.4.1 National

Active participation in the study group *"IED-hot mot våra förband och vår verksamhet"*[b], conducted by SWEDEC, has given a deep understanding of the IED threat. Experience and knowledge about sensors and detection technologies that has been acquired in the MOMS project has been transferred into the study.

1.4.2 International contacts

The MOMS project has been connected with several international activities and collaborations, bilateral as well as multilateral. Participation in two task groups under the NATO RTO[c] SCI[d] panel has been rewarding. Furthermore, collaborative experimental activities have been conducted together with FFI[e] and NTNU[f], Norway, and Thales (TRT)[g], France. This is further described below.

1.4.2.1 NATO RTO SCI-193

The objective of the Task Group SCI-193 "Detection and neutralisation of route threats" is to investigate the physical and operational potential and limitations of techniques for stand-off detection and neutralisation of route threats, such as landmines and IED's [13]. Detection techniques to be considered include infrared, electro-optical and radar systems, and other emerging technologies. The sensor technologies should be complemented with the appropriate signal and data

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[a] The Swedish Armed Forces Land warfare centre
[b] "IED threat against our troops and our activities"; a part of the study "Force Protection ", MARK 071001S
[c] NATO Research and Technology Organisation
[d] System Concepts and Integration
[e] Totalforsvarets forskningsinstitutt, Norway
[f] The Norwegian University of Science and Technology, Trondheim, Norway
[g] Thales Research and Technology, Palaiseau, France.

processing techniques. Neutralisation techniques will be matched to the detection techniques and the threat.

A pilot test was conducted at Fort A.P. Hill, VA, USA in October 2008. The primary purpose of the test was to get an idea of the applicability of the participating detection systems and to generate lessons learned to be used in subsequent tests; hence this test was not intended to generate detailed quantitative results. The contribution from FOI to the pilot test was data collection with the hyperspectral imager Imspec [14], see Figure 4.

Other sensors that were used in the Pilot test were a polarization camera (wavelength) two non-linear junction detector (NLJD) devices (RE975 NLJF from Richmond EEI Ltd., and NR 900 EK "Eagle" from STT Group) and a wire detector (Guartel). Also demonstrated were an interrogation arm to be used in manipulating suspected IED's and mines, and a ground penetrating radar (GPR) VISOR from NIITEK[a] [15].

Figure 4. During participation in the NATO SCI-193 pilot test at Fort A.P. Hill, the hyperspectral imager Imspec was mounted on an elevated platform (left) on a cherry picker (right).

1.4.2.2 NATO RTO SCI-233

The objective of the Task Group SCI-233 "Route Clearance Concepts" is to analyze concepts and investigate the integration of technologies and systems for mounted and dismounted route clearance in land operations [16].

[a] NIITEK, Non-Intrusive Inspection Technology, Inc., USA

Route clearance consists of a number of different tasks, such as detection, identification, marking and neutralisation. Since it is obvious that route clearance can not be achieved by using one single technology or system, the investigation will address integration aspects of suitable individual techniques and systems, necessary to conduct the different tasks that can be distinguished in route clearance operations. Moreover, the Task Group will also identify the appropriate platforms, both land-based and airborne, manned and unmanned, that are suitable to deploy the mentioned techniques and systems. Other important aspects that will be addressed by the TG are the role of the operator(s) and required support for the operator(s).

1.4.2.3 Norway

A joint experiment to collect hyperspectral signatures on mines was carried out together with FFI [17]. In the experiment, a hyperspectral imager (Imspec) for VNIR[a] was used together with two hyperspectral imagers in the VNIR and SWIR bands, manufactured by Norsk Elektrooptikk.

A polarimetric investigation of samples of landmines has been performed at NTNU. The result was presented in a joint conference paper [18].

1.4.2.4 France DGA

In a previous Eurofinder program RTP 8.13 *HYPOLAC*[b], a sensor system for active spectro-polarimetric imaging was developed by France and Norway [19]. Combining multi-spectral and polarimetric imaging techniques improves the detection of man-made targets [20, 21]. Under a project agreement with DGA[c], a preliminary test with the Hypolac system was carried out at TRT in Palaiseau.

[a] Visual and near-infrared
[b] Hyperspectral Polarimetric Active and Passive Imaging
[c] Direction générale de l'armement, France

2 An overview of project results

2.1 Phenomenologies

In conflicts less than war, most mines are buried or hidden; therefore the probability of surface laid mines is low. In war, time and area access does not always allow for buried mines and the probability of surface laid mines is much higher. A system addressing surface laid mines can still be of high priority. If the mine is buried, the probability of exposing the mine surface is zero and therefore not available for detection based on surface properties. There can still be indirect thermal, reflectivity and other effects that can be detected by optical sensors, both active and passive. The surface disturbance caused through the burial of an object alters the grain size, surface roughness, and possibly composition of the soil. According to recent literature [22], the SWIR wavelength region appears to be a potentially effective means for detecting the disturbance associated with buried mines. Diurnal thermal variations based on thermal transport may be used to indicate the presence of buried mines even without visible disturbance on the surface [23-26]. Both passive (using solar illumination) and active laser systems can be used in combination with thermal sensing. Buried mines have however not been the focus for the MOMS project.

The size of the mine surface area that is exposed to the line-of-sight depends strongly on the landscape. If the mine is placed in vegetation substantially higher than the mine, the exposed area will be small and very dependent on the viewing angle. In this type of terrain, the mine will not be observed at slant viewing angles and a nadir looking sensor system is needed. Even for nadir looking systems, a distribution of exposed areas will be observed. With only a fraction of the mine surface being exposed to the sensor system, there is a high probability that the surface is not illuminated by direct sunshine. A diffuse illumination will penetrate better and in fact improve on the detection probability. Active illumination is another way of improving performance in shadows.

Most mines exhibit some kind of *spectral feature*. Often the paint is not well adapted to the background outside the visible spectral region and also less than perfect within the visible spectral region when observed in high spectral resolution. This makes multi-spectral or hyperspectral feature extraction very promising. In anomaly detection, any deviation from a general background is used for detection. False alarms therefore exhibit spectral features that deviate from the background and most often also from other mine-like objects. These differences are frequently not known in advance but will be part of an operator supported learning process. The goal of this process is to decrease the false alarm rate to a level not saturating an operator based classification process. The classification is mainly based on cued high resolution sensors. Other special features for detection are the *depolarization and shape*. Both these features are suitable for laser sensing. The spectral, shape and polarization features have been the main interest in the MOMS program. The spectral feature is utilized both for detection and classification, polarization primarily for detection and the shape for classification and/or verification.

Other techniques of interest mainly for verification include spectroscopic methods such as *fluorescence, Raman spectroscopy and laser-induced break-down spectroscopy (LIBS).* We have only made performance estimates of these techniques based mainly on literature information. LIBS is the laser technique with the best classification results so far [27], and may be developed into a field-deployable device that could be utilized as a confirmatory sensor in landmine detection.

Stand-off Raman spectroscopy for explosives detection has been demonstrated at FOI and elsewhere [28, 29]. This method has not been further investigated in the MOMS project.

Another feature which was explored a few years ago and now seems to have regained interest is *the remote vibration* sensing of mainly buried mines using Doppler laser techniques to sense the vibration induced from exciting the ground with either pulse laser energy or seismic or acoustic energy. The main drawback with the techniques has been the very slow coverage obtained with a single or few laser beams.

2.2 Sensors

Information theoretic measures like entropy and mutual information are useful when configuring the sensor and detector system. Different configurations can be compared regarding how much information they convey about the presence or absence of targets in the scene. In many cases it is possible to estimate how much information the sensor data convey about the scene. [30]

In order to be able to extract the relevant information about potential targets in the scene, the sensor must have a sufficiently good spatial resolution. The spatial resolution of the sensor must allow for having several pixels on the target. For a relatively large object, e.g. an AT mine, the pixels should correspond to a resolution on the target of maybe about 2-3 cm, to enable the removal of small, irrelevant objects. Also for evaluating spectral similarities between objects, the resolution must be good so that there are enough data for computing sufficient statistics for each object. [31]

For mine *recognition* based on spatial properties, the sensor resolution on the target should be significantly better than 2 cm, probably around 5 mm or below. Even at that resolution, it may be difficult to distinguish (small) objects from each other.

As a rule of thumb, the performance for various resolution on the target (pixel footprint) can be described as:

- *low resolution* (>10 cm) is likely to result in relatively poor performance, as the expected number of "clean" mine pixels will be quite small, thus making it difficult to match spectral signatures and to estimate object size
- *medium resolution* (5-10 cm) gives the ability to detect anomalies and possibly to detect suspicious-looking pixels through matching of spectral signatures
- *high resolution* (2-3 cm) enables us to clean up the detections, define objects and to detect mine-like objects
- *very high resolution* (<0.5 cm) is probably needed to be able to distinguish between different mines based on their spatial appearance.

A system for detection of small ground objects, like land mines, would benefit from including an active imaging sensor, preferably operating at several wavelengths or a broader range of wavelengths. In addition to providing night-time capabilities, such a system would also probably result in reduced problems caused by uneven and unpredictable illumination of the scene (e.g. shadows), which would be very favourable from a signal processing point of view.

The anomaly detection and the supervised approaches can be updated under a mission, to adapt to the current conditions in the area of interest. At the first trials in a new environment there is likely to be a higher level of false detections. Through an extra training phase, supervised by a skilled operator, the algorithms can be tuned to the new environment and the false alarm rate can be lowered while retaining the mine detection rate.

High spatial resolution data, both two-dimensional and three-dimensional, can be used for target recognition. In order to reduce the amount of data that has to be processed, multi- and/or hyperspectral sensors are used for cueing [30].

2.2.1 Passive EO sensors

In hyperspectral imaging, the spectral information in each pixel element, representing a scene element, is used in the analysis. This spectral information is a unique signature characterizing the material (see the green curve in Figure 5). The signature is spectrally modified (pink curve in Figure 5) by the solar illumination (yellow curve in Figure 5) which is transmitted through the atmosphere, where it is absorbed and scattered due to the presence of gas and aerosols. The spectral features of the object can still be obtained and used as a fingerprint.

More than 80% of the solar illumination is in the visible spectral region. In the near infrared, the illumination is only 20% of the total irradiance and at longer wavelengths it is still less. Reflected signatures can be obtained between 0.4 and

2.5 µm during daytime. Object discriminating capability is supported over this spectral region.

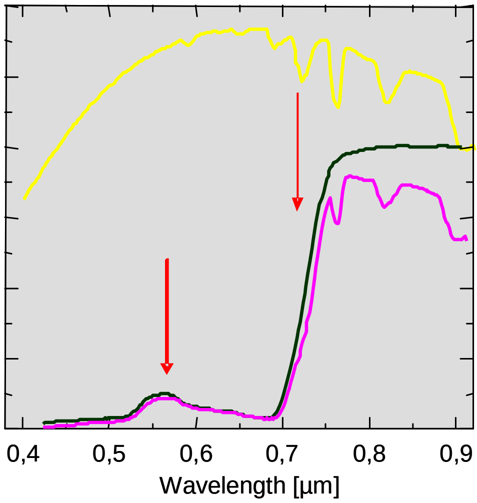

Figure 5. The solar illumination transmitted through the atmosphere [yellow] is reflected by a green object [green]. The resulting spectrum is modified by the spectral properties of the illumination [pink]. The spectral features of the object can still be obtained and used as a fingerprint.

In the spectral region from 3 to 12 µm, the thermal emission from the object is used for discrimination. In its most basic form, the signal is representing the temperature of the object and this information together with diurnal variation, is used for discrimination. The spectral content or the emissivity variation with wavelength can also be obtained by separating the temperature from emissivity due to the wavelength dependency. These sensors have so far been quite expensive. A new generation of hyperspectral sensors based on interferometric technique is now being developed with a potential of much lower cost.

We have demonstrated the gain brought by hyperspectral imaging in the visible and near infrared domains. Estimated performance and general conclusions are given in Table 2.

In the thermal infrared, hyperspectral imagery of mines has not been obtained in the MOMS project. However, results from other applications such as detection and classification of military targets are encouraging. This spectral region is the only one available during the night. A sensor that exploits the spectral content and not only temperature variations will offer improved detection and recognition capability. Even if detection is improved by using the spectral signatures, angular resolution plays an important role. A single pixel target can be detected only if its spectrum is significantly different from the surrounding pixels. If the target is too small compared to a single pixel, the spectral difference will also be minute. Some conclusions on tactical scenarios evaluated for detection and recognition purposes are presented by spectral domain in Table 3.

Table 2. Capabilities of hyperspectral sensors in the VNIR domain.

Specific uses	**Comments**
Anomaly detection Signature based detection	Detection of all open and semi-hide mines Detection of open (90%), semi-hide (70%) and deep-hide (40%) targets
Decamouflage	Detection of camouflaged mine (spectral signature needs to be known), not the case with natural camouflage
Decoy discrimination	Limited discrimination of decoy from mine
Civilian objects discrimi-nation	Civilian objects are detected (>90%). They can still hide real mines.

Table 3. Conclusions on tactical scenarios evaluated for detection and recognition purposes by spectral domain

	Daylight based sensor (Visible to SWIR)	**Night based sensor (LWIR)**
Detection	⇨ Encouraging for **automatic** detection of open and semi-hide mines in several types of environment and also for decamouflage ⇨ Limitation for decamouflage concerns targets camouflaged with natural vegetation or hidden under other objects	⇨ Encouraging for **automatic** detection of open and semi-hide mines in several types of environment. ⇨ Limitation for presence of water (dew or rain) on the target which decreases the spectral contrast ⇨ Limitation for decamouflage concerns targets camouflaged with natural vegetation or hidden under other objects.
Recognition	⇨ Very encouraging; the methods used shows that it is possible to discriminate military objects from civilian ones ⇨ Main operational constraint: Requires *a priori* knowledge on spectral signature. This points out the importance of military **intelligence** to access this information.	Not yet evaluated

At this stage, though we have not been able to compare quantitatively our results with corresponding broadband images, we conclude that:

- Anomaly detection using hyper-spectral imagery is a very powerful tool to automatically highlight an area of interest in an image. Results also indi-

cate interest for a combined high resolution broad band and hyper-spectral sensor. Furthermore, different situations have been encountered where the mine signal is not detected on broad band images but it is detected with hyper-spectral imagery. The identified situations are:
  - The spatial target background contrast on broad band image is too weak.
  - The shape of the target could not be used: too small or semi-hide.
- When the mine shape is visible, processing with spatial image processing is adequate, the signature based detection is very efficient for decamouflage and decoy discrimination and civilian / military object discrimination.
- The spatial resolution of the hyper-spectral sensor, at a centimetre scale, seems sufficient for the tested scenarios.

Hyperspectral sensors collect data in many contiguous spectral bands, often of the order of several hundred. Spectral information improves on the discrimination capability with respect to background clutter and also supports signature based detection and classification. [30, 32]

Multispectral sensor systems could potentially produce useful capabilities by careful selection of the spectral bands with respect to both target and clutter characteristics. The advantage with multispectral systems stems from larger coverage capability and also the possibility to incorporate micro-polarisers directly on the focal plane array. In the long wave thermal infrared spectral region, filters could be selected to emphasize variations in emissivity together with the polarimetric characteristics. This has applications in e.g. disturbed soil detection.[33]

Hyperspectral sensor systems have proven very effective in automatic target detection, especially in the visible and near infrared spectral region. For night operations, illumination is needed with a broad-band source. An example of this is shown in Figure 6 [30, 34]. The performance of such systems compares quite favourably with the daylight systems due to reduced shadowing effects but they do have substantially increased power requirements.

There is a fundamental difference in polarisation exploitation of passive sensor data compared to active sensor data. Passive polarimetric imagery is of greatest interest in the thermal infrared and for object surfaces being monitored close to Brewster angle. For this angle, the degree of polarisation will be larger than for natural background. [35-38]

Figure 6. An example of multi-spectral imaging with white light illumination using a flash-light. Note that the spectral bands of the sensor not were optimized for the purpose and further improvement can therefore be expected. Left: Multispectral image in the visible and near infrared spectral region. Middle: The image shows the PCA[a] components 3, 2 and 1 as RGB of the left image. Detection using the PCA component 3 is exhibiting very low false alarm rate. From [34]

2.2.2 Laser radar

Laser radar (ladar) is an important sensor for mine detection and classification. It is used in all major airborne mine detections system in the US as an illumination source, for detecting, classifying, marking and designating targets. High power lasers are used for clearing of metal mines and unexploded ordnance (UXO).

A review of laser sensing techniques and systems, including performance estimates of potential systems suitable for MOMS has been published [39]. The laser sensor has the following important properties with respect to mine detection:

- It measures reflectivity, polarization and shape irrespective of daylight conditions and is even better during nigh time.
- It provides a high range resolution enables some penetration capability through vegetation and to use shape and shadows for detection and classification.
- It can detect sea mines (underwater objects also from an airborne platform).
- It can excite specific spectral features for classification (Raman spectroscopy, fluorescence, LIBS spectroscopy).
- It can be used also for detection of buries mines utilizing vibration (Doppler) and/or small changes in surface reflectivity.

The importance of a high range resolution for the detection of mines in vegetation is clear from scaling down the vehicle in vegetation problem [40] to the surface mine in vegetation scenario. We have simulated the waveforms at much higher band-widths and shorter pulses using data on mines in vegetation from the 3-D laser scanner [41].The required performance, in terms of range resolution, could not be found in commercially available ladar systems. This motivated an

[a] Principal component analysis

in-house effort to develop a high performance 3-D ladar (HiPer). With a pulse deconvolution method the range resolution can be improved [42].

A field test with the purpose of evaluating the potential of 3-D ladar combined with change detection for detection of IED was conducted at SWEDEC [43]. A mobile scanning laser radar from Infoterra Ltd[a] was used to make two recordings along a road section, first without targets and a second run with IED's placed in the scenario.

Change detection was done by calculating some simple features, e.g., point density in a smaller volume (cube) and nearest-neighbour distance. The results were promising, but it can be noted that bushes and tree branches (in particular the outer parts) can result in non-negligible "change score", caused by wind movement of the branches, and the laser beam hitting different parts of the vegetation in the two recording instances. Further development of the method could include filtering of (local) shape and automatic size estimation of detected (suspicious) objects.

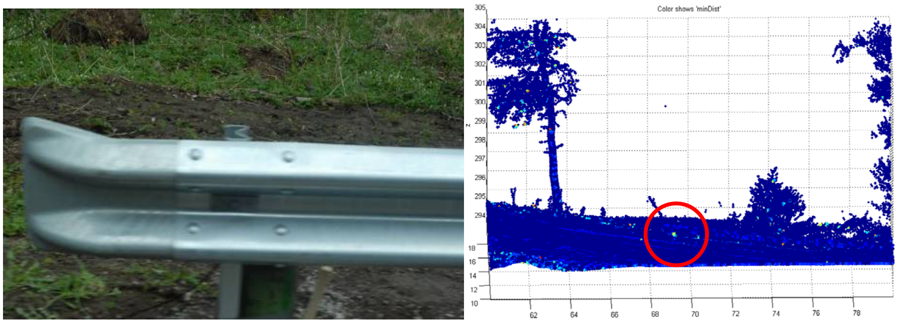

Figure 7. Left: An IED (artillery shell) is placed behind the crash barrier. Right: Change detection reveals an object that was not present on an earlier occasion.

2.3 Signal processing

A signal processing framework has been developed for detection and recognition of surface-laid mines. The goal has been to design a framework that could help an operator detect and recognize potential threats (mines). Figure 8 shows a simplified schematic diagram of the main stages involved in the data processing. For simplicity, the graph emphasizes the conceptual signal processing layout and hence dependencies on other information than sensor data have been excluded from the diagram. Examples of such information are *a priori* information about expected target size and estimated target density, target model libraries, etc. that are still necessary for the signal processing. [31]

[a] Infoterra Ltd., Leicester, UK.

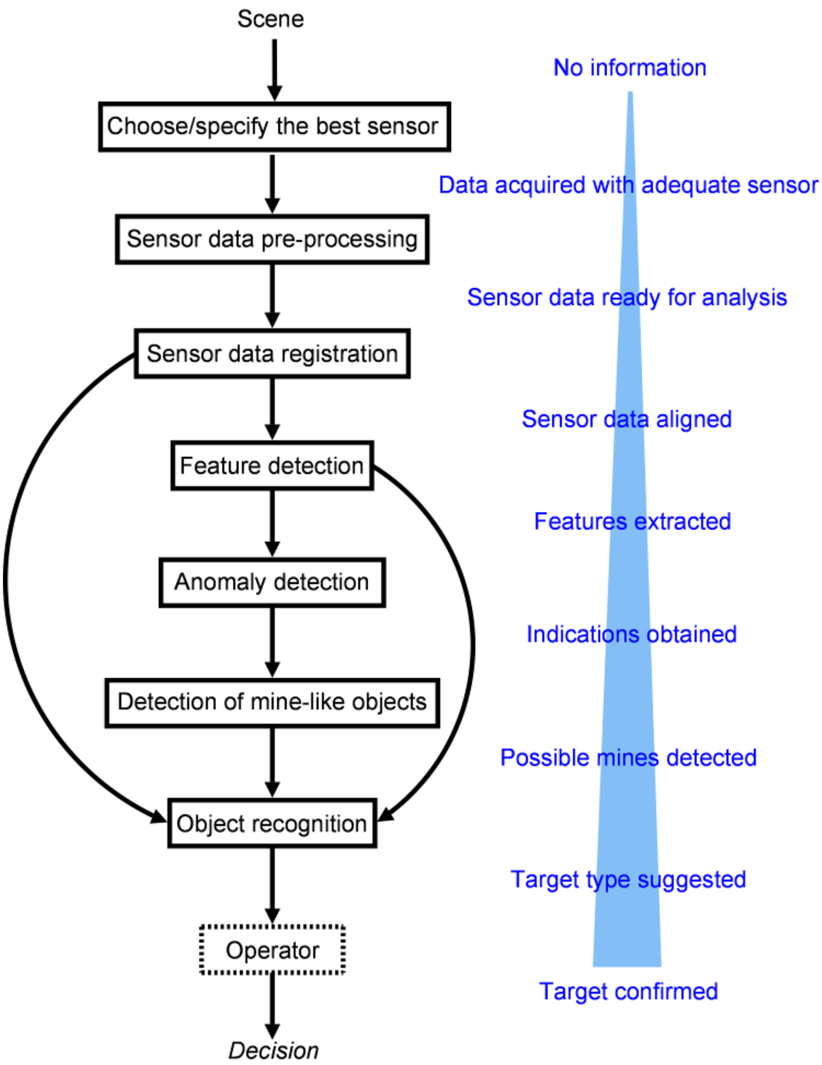

Figure 8. Description of the mine detection and recognition process developed in MOMS. (From [31]).

Among the signal processing techniques considered, anomaly detection emerges as a key component in a system concept. This method detects objects that are different from what is expected (the background) and thus gives a first indication of possible mines. In addition, this technique can potentially be used for detection of other objects, e.g. IED's.

Fusion on the lowest level (pixel or signal level) requires very accurate data registration, i.e., transformation into a common coordinate system. Such accuracy is difficult to obtain with a distributed sensor system (e.g. airborne and ground-based sensors), at least for small targets (AP mines). In fact, pixel correspondence between sensor images will probably require a common detector array or arrays situated very close to each other. Fusion on the decision-level, on the other hand, will cope considerably better with a less accurate registration, as the different sensor data streams are processed individually and only the final outputs are combined.

3-D information can be used in combination with reflectivity to improve anomaly detection. We have used a method based on Gaussian mixture estimation for anomaly detection and segmentation [44]. Classification can be improved by fusion of laser intensity and hyperspectral information, as shown in Figure 9.

The overall probability of actually detecting mines in a real scene is strongly influenced by *occlusion* effects. We found that many objects often escaped detection due to the fact that they were heavily occluded (by grass, sprigs, leaves, etc.). Occlusion effects are usually lowest for a nadir-looking system. The level of occlusion can also be lower by collecting data from multiple views but this, on the other hand, demands very accurate registration.

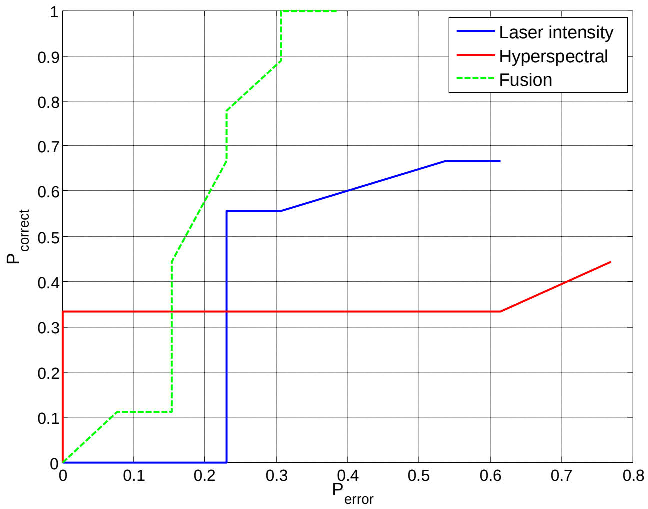

Figure 9. The graph shows some results obtained with SVM[a]-based classification for *recognition* of land-mine type. The classifier was trained on a sub-set of mine objects in one scene and tested with objects in another, yet similar scene acquired six hours later (different light conditions). Fusion of data from the two sensors improves the performance. From [31].

[a] Support vector machine

2.4 Platforms

As mentioned previously, detection of mines in vegetation is mostly easier when the sensor looks down, than when looking horizontally, as the occlusion is usually lower for that aspect. This favours an elevated sensor platform, or even better, an airborne platform.

From a signal processing perspective, it is desirable that the sensors are mounted close to each other, preferably with common optics and/or detector array, so that the registration can be as accurate as possible.

3 System concepts

In a previous report we have discussed system concepts in more detail [45]. A concept of a UAV interacting and followed by a ground vehicle is probably the best choice with respect to the requirements on relatively high coverage speed, proper downlooking angles and minimization of the risk for manned platforms. An alternative to the UAV might be a manned helicopter, but the flight altitude has to be very low and the limited flight speed results in vulnerability from hand guns and other short range weapons.

The original requirement in MOMS for the surface coverage rate was based on a 200 m wide swath interrogated at a speed of 50 km/h, which translates into a coverage rate of 2780 m^2/s. This turned out to be a *very* demanding requirement, concerning both available sensors and lasers and the small ground pixel size needed (cm-class); we recommend reducing this requirement. As a comparison the corresponding figures for the US UAV-borne ASTAMIDS[a] system [46] is a 70 m swath width at 100 m altitude and a speed of 70 knots. This translates to a coverage rate of 2450 m^2/s.

3.1 Sensor suites

The detailed cooperation between sensors in terms of search and classification functionalities and the exact role of the operator has to be investigated further. High resolution 3-D data together with passive EO-data can determine subsequent impact on emitted thermal and reflective signatures. Active illumination has promises for polarization and multispectral feature extraction together with shape and some look through capability. The ladar sensors, especially high resolution FPA's[b], are not as developed as their passive counterparts. Passive sensors have a great capability concerning ground resolution, spectral resolution for example but are more limited in concerning the need for daylight (VNIR), 3-D shape, vegetation penetration, ambient light and polarization than active sensors.

<u>Change detection</u> is a mode which may the only realistic detection mode for unknown targets like IED's. 3-D mapping is very suitable for change detection and may also be done with passive cameras at high spatial resolution. This technique has been used in photogrammetry for a long time but it has been shown that it is now possible to do the calculations, with carefully designed image processing algorithms, in e.g. a PC in real time [47]. High resolution mapping will also help in other ways for example guide the ground vehicle in the terrain.

[a] Airborne Surveillance, Target Acquisition and Minefield Detection System (formerly known as the Airborne Standoff Minefield Detection System)
[b] Focal plane arrays

A number of sensor concepts for active and passive EO sensing have been proposed, including performance and estimated size, weight and power. Based on an initial literature survey, the phenomena below were chosen as candidates for an evaluation:

- Spatial properties (2-D or 3-D geometry; i.e. shape, size)
- Spectral properties (incl. angular and spectral dependence of reflectivity and emissivity)
- Thermal inertia (earlier called temperature or temporal analysis. This does not include long-term changes in e.g. reflectivity)
- Polarisation ("passive" as well as "active", i.e. with illumination)
- Fluorescence (not experimentally evaluated in MOMS)
- Material composition (spectroscopic methods, e.g. LIBS, laser wave mixing) (not experimentally evaluated in MOMS)

Lasers used for illumination and imaging in the airborne platform may also be used for marking the region of interest for the ground vehicle, Figure 10. By modulating the laser beam, information about the illuminated object can be transferred to the ground vehicle.

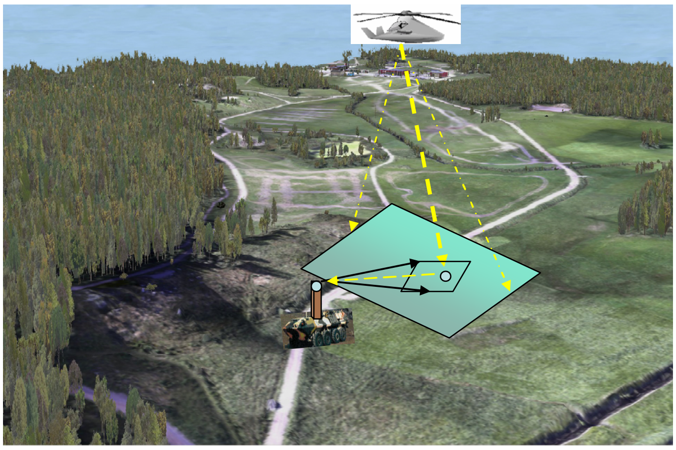

Figure 10. Laser marking regions of interest or detected objects from the airborne to the ground platform. Modulating the illuminating laser beam may be used to send specific information (position, type of object etc.)

The sensor in the ground vehicle can automatically direct its high resolution or verification sensor at the pointed object, thus minimizing the time span between airborne detections and land vehicle sensing and verification. The laser point may also be target for sending a bullet or high power laser beam to neutralize the threat. There has to be free line of sight between the vehicle sensors and the laser illuminated point. This is not always the case in which the laser beam may guide the ground vehicle towards the position by pointing just ahead of the vehicle.

3.2 Sensor packages and platforms

In a combination of airborne and ground platforms a both large and narrow swath can be obtained, where the airborne sensor platform can lead the way for the ground vehicle by avoiding mine areas, linking down terrain and surveillance information about the enemy including danger sectors etc. Active/passive high resolution mapping and surveillance functions for targets in general are included in the airborne platform. Laser designation capability, laser marking or other targeting systems are an option to further increase usefulness of the system. If the UAV marks potential targets for the ground vehicle, e.g. by illuminating with a pencil laser beam, the ground vehicle may slow down and automatically use its sensors for verifying the target. [45]

3.2.1 Airborne sensor packages (A)

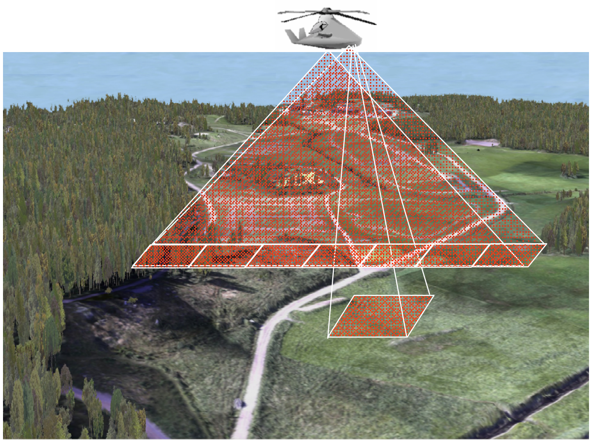

Figure 11. An airborne sensor should ideally cover a 200 m swath and also have multiple look and locking to a region of interest capability.

Airborne sensor suites should combine high resolution with large surface coverage rate, up to several 1000 m^2/s if possible. Special limitations are size, weight, and power and stabilization. The state-of-the-art in line-of-sight stabilization for gimbals is in the order of 10-20 µrad, which corresponds to about 0.2-0.4 cm from 200 m altitude. The stabilization performance is essential for data fusion and also for change detection.

We have studied three alternative sensor suites, with different capability and maturity expressed as TRL[a] [48], for an airborne platform; this is illustrated in Figure 12.

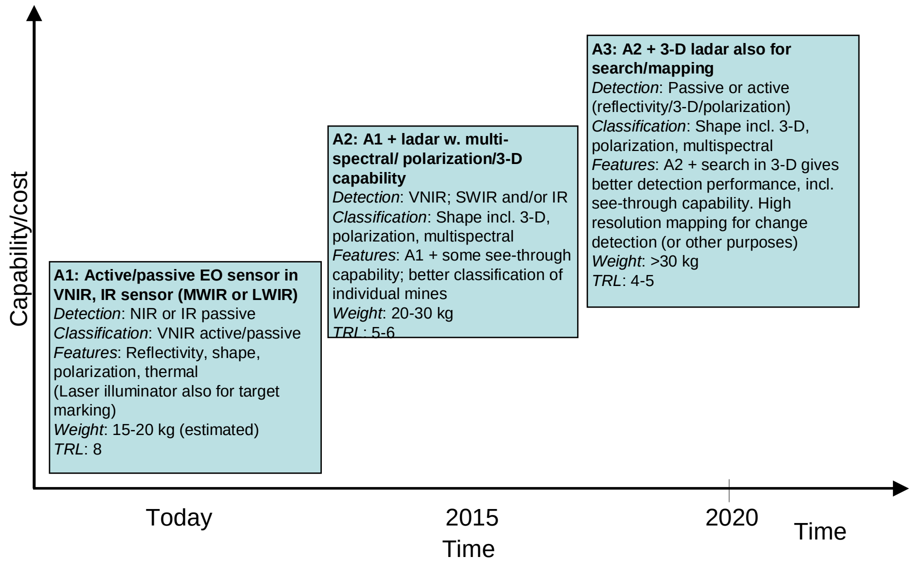

Figure 12. The capability and maturity of some potential sensor packages (A1-A3) for the airborne platform with increasing capability. The TRL refer to those present today.

The **sensor suite A1** consists of active/passive EO sensor in the VNIR region plus an IR sensor (MWIR or LWIR). A thermal sensor in the MWIR or LWIR may be seen as an option for the sensor package. They are interesting especially if the time for operation can be chosen with regard to the optimum thermal contrast conditions.

In the **sensor suite A2** we add a laser sensor with 3-D and polarization capability for increased detection and recognition using shape recognition. The high resolution 3-D ladar is used for verification of a mine/minelike object detected by the passive or active multi/hyperspectral sensors, including polarization.[b]

Note that verification of a single or few mines by the airborne system may provide useful tactical information in that the route may be avoided or a ground vehicle sent in for clearance.

The **sensor suite A3** is similar to A2 but the ladar is given a search capacity also for the high resolution 3-D imaging mode. The advantage would be increased

[a] Technology readiness level

[b] This technique is also proposed in the US mine detection system ASTAMIDS.

detection performance due to shape, absolute size and look through vegetation capability. The range data will allow real time ground tracking and range slicing to look just above the surface in a range interval not more then the mine height. In dense vegetation it will be advantageous to have a multiple look capability to ensure enough pixels on the mine. The multiple look has the cost of reduced coverage rate.

3.2.2 Sensor suites for the ground vehicle (G)

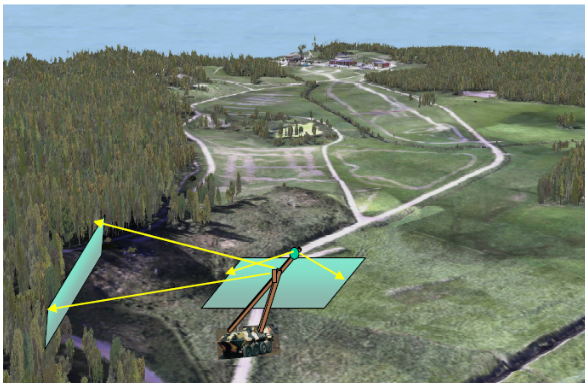

Figure 13. Potential search areas for a ground vehicle looking for land mines including side hitting ones.

The **sensor suite G** for a ground vehicle system could in principle be similar to the airborne sensor suite, but with higher resolution and maybe with some additional sensors. Radar is a possible additional sensor enhancing the “see-through” capability. Verification and search sensors with longer dwell times, such as LIBS or Raman lidar – or a laser vibrometer for detection of buried mines – are also of interest on a ground vehicle.

The sensor package should be placed in an elevated position to have a capability of looking down or sideways. The single mine detection performance must be much higher than for the airborne system and the sensor should be able to detect a mine at a range of 20-40 m in order to minimize the damage risk. High range resolution imaging and optics detection based on retroflection enhances the performance against side hitting mines. Disturbed soil can be detected by both passive and active sensors.

A small UGV (forerunner) may be an interesting sensor platform. The sensor suite **g** on the small vehicle may be a subset of the one mounted on the larger vehicle. Potential sensors may be passive EO and ladar for retro-reflection detection and 3-D imaging. The sensor position will be more advantageous (allow better viewing angle) for detecting side hitting mines in the terrain next to the road. The forerunner can be tele-operated through radio/free space optics or cable or have some autonomous functionality. The small vehicle can have a mechanical mine neutralization capability for AP mines. For AT mines the high energy laser may serve as neutralizer, as it also can from the optics at the end of the beam. With the combination **(G+g)** of a ground vehicle and a UAV, the small robust vehicle can take more risks and also act as a decoy for mine triggering. The concept is outlined in Figure 14.

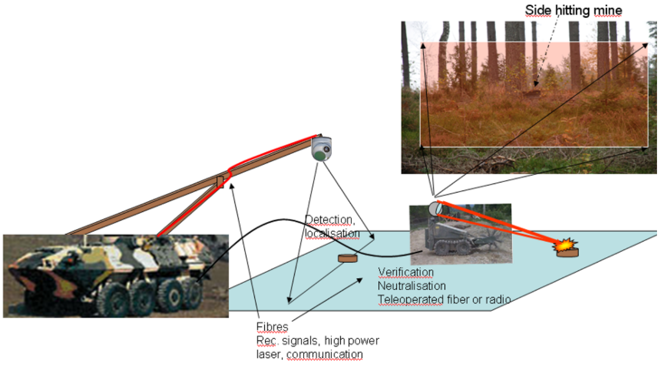

Figure 14. Advanced concept with a main vehicle with elevated sensor and a small robust unmanned vehicle for combined sensing and mine neutralization. The inserted image on the small vehicle is the US UGV called RCSS [49].

The concept with **airborne and ground vehicles** in cooperation means that a combined large and narrow swath can be obtained, where the airborne sensor platform transmit terrain and surveillance information to the ground vehicle, hence enabling it to avoid mined areas. An airborne laser can mark potential mines or IED's for the following ground vehicle, which can automatically direct its sensors towards these positions for verification and clearance. Change detection is another capability which may be essential for the airborne platform.

The communication between the UAV and the ground vehicle should allow data transfer rates at Mbit/s or more. Optical communication especially the techniques based on MRR[a] [50, 51] could be attractive if large data volumes (up to many Gb/s) have to be sent from the UAV to the ground vehicle in with low probability of intercept and jamming and without introducing frequency allocation problems. The light (<100 g) modulated retro-reflector – the size of a large coin –with small power consumption is ideal for use on a UAV.

[a] Modulated retro-reflector

3.3 Platforms

The optimum system will most probably be a combination of airborne (UAV) and ground vehicle sensors in cooperation via an operator in the ground vehicle. A flexible solution would be to permit the UAV to start and land from the vehicle. Examples of UAV's which have interesting properties for the MOMS task are Skeldar from Saab Aerosystems [52] and APID 55 from CybAero [53], see Figure 15. Both are small helicopters with 4-6 hours endurance and 30-50 kg payload, depending on the fuel weight. They may land on small platforms like ground vehicles and small ships. Although more technically demanding, a helicopter is believed to be the most appropriate airborne platform due to the flexibility in search speed and the hovering capability.

A tactical issue of importance is the vulnerability, especially for the UAV. The threat from handguns will in many scenarios force the altitude to be at least 200-300 m. There is a trade-off between coverage rate, ground pixel resolution and altitude.

Figure 15: Swedish UAV systems of potential interest for airborne mine detection. Left: Skeldar V-150 from Saab Aerosystems, right: APID 55 from CybAero.

A ground vehicle should carry elevated sensors in a telescope mast. It would be desirable if the sensor could change positions in height and in the driving direction to be able to look down as close to nadir as possible. The sensor should work both in a driving and non driving mode but at different sensor positions. In particularly dangerous environments a small UGV might be used for object verification and possibly to assist in clearing found mines and IED's. The UGV is teleoperated and may also be fully autonomous. The main vehicle could also act as a control station for the UAV/UGV and also have a sensor system control. The data from the airborne sensors and the mast mounted sensor may support the path planning of the UGV which will only have close range sensors.

3.4 Performance

Our experience with the passive and active sensors tested so far is that the detection of a single mine is hard to achieve with realistic performance figures. From experiments we conclude that the false alarm probability P_{fa} can be as high as 2-5/m^2 during daytime with a high clutter in the IR region. On the other hand, if we define the task to detect a mine field (defined as detecting *k* out of *m* mines) the detection and false alarm performance can become much more realistic. This is discussed in more detail in [45].

For classification we believe that an operator is needed. Automatic target recognition is a support but the final decision/verification of a mine or IED threat should be done by a human. The classification should be done by a high resolution cued sensor, active or passive or in combination. For a hyperspectral system, a realistic coverage rate is 200 m^2/s at a ground resolution of 2.5×2.5 cm^2. An upper limit for an operator could be to handle a rate of one detection every third second. This is one detection per 75 m^2. With a constant false alarm rate (CFAR), the detection capability of low contrast targets will improve after a training period. Multi-spectral systems might achieve improved coverage rate but subsequent increase in false alarm rate has to be mitigated. Laser sensors have a good capability for classification using geometry and absolute size estimation. It is important to relate the performance (for example measured in detection probability under a specified false alarm rate) to the coverage speed as illustrated in Figure 16 [54].

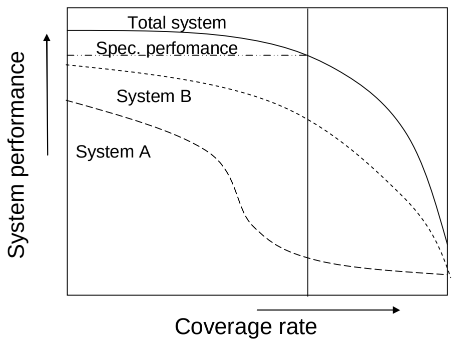

Figure 16. Schematic illustration of performance vs coverage rate.

Most tested approaches can meet real-time or near real-time demands. The spatial resolution of the sensor must allow for having several pixels on the target. For detection the pixels should correspond to a resolution on the target of maybe about 2-3 cm, to enable the removal of small, irrelevant objects. For mine recognition based on spatial properties, the sensor resolution on the target should be significantly better than 2 cm, probably around 5 mm or below. Even at that resolution, it may be difficult to determine object type. In Table 4 some system capabilities and platform alternatives are summarized. These are discussed in more detail in [45].

Table 4. Outline for a system specification.

Capability/parameter	**Potential goal**	**Comments**
Probability of detection (P_d)		
- Mine field	>0.95 (0.75-0.95)	Very important; what is *detection* of a mine field? X out of totally Y mines? This has to be specified.
- Single mine	> 0.5	Is linked to the mine field definition and coverage speed. The figure is only relevant for a ground vehicle application and a coverage rate much lower and not more than a few 100 m^2/s. than for airborne systems.
False alarm (P_{fa})		
- Mine field	< 0.1/km^2 (0.5)	Very important; what is false alarm of a mine field detection? >Z false mines detected per km^2 given there are no mines in the area.
- Single mine	<0.01/$m^{2)}$	Is linked to the mine field definition and coverage speed. The figure is only relevant for a ground vehicle application.
Surface coverage	200 m swath width @ 50 km/h	This gives 2778 m^2/s. This figure is very high and the P_d/P_{fa} performance has to be linked to the coverage speed so that an optimum choice between speed and performance can be made.
Platforms		
- Airborne vehicle (A)	UAV	Due to the risk with manned platforms and to fulfil the swath and surface coverage rate for down looking angles.
- Ground vehicle (G)	Armoured vehicle with a beam to allow the sensor to look down/side and sensor to be in front of the vehicle	Manned or unmanned vehicle. An operator has to be involved either in the sensor ground vehicle or in case of this being un-manned in a second vehicle. The ground vehicle verifies that a road is safe for trans-port down to the single surface mine. More narrow swath than for the airborne sensor.
- Small unmanned ground vehicle, forerunner (g)	Manned ground vehicle + small forerunner (un-manned)	Small forerunner implies narrow swath and limited sensor altitude. Small forerunner can take more risks, verifying detections, look sideways and securing the movement of the larger ground vehicle.

3.5 Limitations

In MOMS we have concentrated on surface laid mines; the problem of buried mines has to be separately investigated to conclude which sensors are suitable for that task. Although a slow method, and maybe not useful for the MOMS task, we have shown in previous work that a temporal analysis of diurnal measurements can be used to detect buried and overgrown mines [23-26]. From literature [22] we conclude that both passive IR and active and passive SWIR have a potential to detect disturbed soil, but the system may have to be complemented with radar and or other techniques such as laser Doppler sensor for sensing buried objects at least for the ground vehicle sensor suite. Snow, heavy rain and very dense vegetation for mines laid out a long time ago offer obvious limitations for the present optical sensors.

A verification sensor such as LIBS or Raman spectroscopy for stand-off detection of material composition is also something which will add value to the system.

The airborne system may not be able to fly as high as would be recommended form a vulnerability point of view (>300 m). The altitude will more probably have to be around 100 m or lower to guarantee a high spatial resolution on the ground for recognition.

The detailed cooperation between sensors in terms of search and classification functionalities and the exact role of the operator has to be investigated further. The sensor data can support adaptive algorithms. High resolution 3-D data together with passive EO-data can determine subsequent impact on emitted thermal and reflective signatures. Active illumination has promises for polarization and multispectral feature extraction together with shape and some look through capability. The ladar sensors, especially high resolution FPA's, are not as mature as their passive counterparts.

Change detection has been investigated with a high resolution vehicle borne ladar. Due to our experience so far the change detection seems to be rather difficult at least for an airborne system.

4 Technology

4.1 International development of mine detection concepts

There are a number of experimental airborne systems using EO systems for land mine detection; some examples are ASTAMIDS and ROAR[a] in the US. The ASTAMIDS, shown in Figure 17, is going into production (prototypes tested during 2009). The future for ROAR is not known at present time.

For sea mines the US helicopter-borne ALMDS[b] is operational. RAMICS[c] provides a rapid response clearance capability against near-surface and surface (floating) moored mines and its hardware has an 80 percent hardware commonality with ALMDS [55]. After detection and localization with the help of a gated imaging ladar a supercavitating projectile destroys the mine. Like ALMDS, the system is designed to operate from an MH-60S helicopter. The RAMICS is about to be operational. The main sensor in the Cobra program is ROAR, an advanced active lidar system for UAV airborne littoral mine, minefield, and obstacle detection and localization.

All major US airborne mine detection systems (e.g. ALMDS, ASTAMIDS, COBRA[d], and RAMICS) use manned or unmanned helicopters. In the Army system the Fire Scout – an unmanned helicopter developed by Northrop Grumman – is used, see Figure 18.

High resolution 3-D imaging is used in airborne mine detection systems for underwater and land mine detection. The US system ROAR is one example [56]. The ROAR has a combined active/passive EO sensor with high 3-D imaging and spectral capability.

The US program FCS[e] will also have a ground vehicle concept for mine detection, classification and neutralization along a 4-m wide corridor at speeds up to 15 km/h, called GSTAMIDS[f] [57]. Two of the vehicles are unmanned of the type MULE[g].

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[a] Rapid Overt Airborne Reconnaissance
[b] Airborne Laser Mine Detection System
[c] Rapid Airborne Mine Clearance System
[d] Coastal Battlefield Reconnaissance and Analysis
[e] Future Combat System
[f] Ground Stand-off Mine Detection System
[g] Multifunction Utility/Logistics Equipment

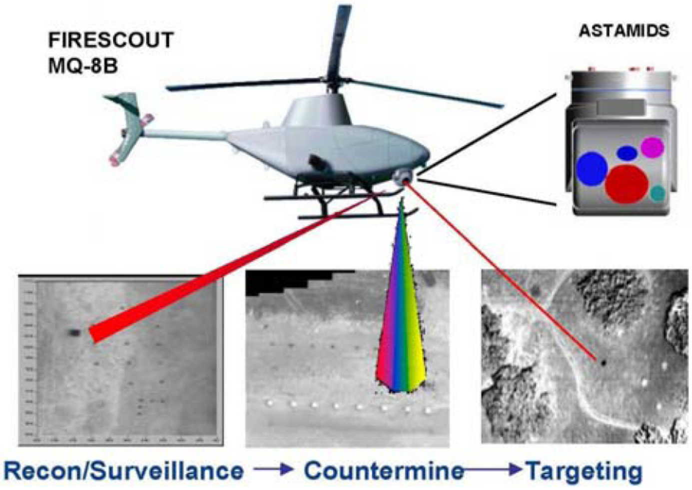

Figure 17. ASTAMIDS developed by Northrop Grumman and others. It combines multi-spectral imaging with laser illumination in order to give night and day capability. Low rate production is scheduled to 2009. From [58].

Figure 18: The Northrop Grumman Fire Scout unmanned helicopter carrying the ASTAMID's sensor package for land mine detection. It includes a multispectral EO/IR sensor, a laser illuminator and a laser designator.

Small UGV's can function as forerunners for verifying and manipulating mines and IED's. Figure 19 shows examples of some unmanned ground vehicles for mine detection and manipulation such as the ARV[a] with a mast mounted (16 ft high) EO system developed in the US FCS program, and RONS[b] for remote neutralization of explosives.

[a] Armed Robotic Vehicle
[b] Remote Ordnance Neutralization System

Figure 19. Left: Example of a mast mounted (16 ft high) EO system for ARV in the US FCS program. Right: The RONS with a manipulator arm for remote ordnance neutralization.

4.2 Trends and technology development

There are a number of sensor gimbals for airborne platforms available on the market, ranging from small to large, see Figure 20. The DST Colibri Duo weighs only 1.7 kg [59], while the total weight of the ASTAMIDS gimbal is 34 kg.

Figure 20. Two examples of sensor gimbals. Left: DST Colibri DUO gimbal with IR and TV cameras and a laser range finder, weight 1.7 kg. Right: ASTAMIDS gimbal employing an integrated, EO infrared/multi-spectral imaging payload, including an illuminating laser and a laser rangefinder/designator. The sensors can detect obstacles, combat vehicles, and other targets, including those under camouflage.

The technology development for optical sensors is rapid. New multispectral arrays with large pixel numbers are in development. For example large arrays based on avalanche photo diodes (APD arrays) will have gain (high sensitivity) and can be used for a wide wavelength region for both passive and high resolution laser imaging. Detectors support high resolution 3-D and spectral imaging including single photon avalanche diode (SPAD) arrays [60, 61], the flash imaging 3-D receiver used in ROAR [56] and the new InGaAs [62] and CMT APD arrays [63]. InGaAs and the new CMT arrays can even compete with intensifier technology concerning low light performance.

Raytheon Vision Systems (RVS) has for example obtained the initial performance data on a 1280×1024 format short wave infrared (SWIR) sensor. The integration of the conflicting design requirements of extremely low noise with high dynamic range allows recognition of low contrast targets, without saturation from bright sources within the same frame of information. This enables operation in urban environments at low levels of ambient illumination, and simultaneously with bright sources that saturate conventional sensors.

A promising approach for buried mine detection uses acoustic waves to induce mechanical vibrations in both plastic and metal mines. The vibration field above these mines can then be measured remotely with a laser Doppler vibrometer [64]. FOI has investigated the vibration method for buried mine detection in the past [65]. However, the main drawback with the technique has been the very slow coverage rate obtained with a single or a few laser beams. The dwell time is about 0.2 s/pixel; for a ground resolution of, say, 5 cm the time to scan a 5 m wide line takes 20 s, resulting in an area coverage rate of only 0.75 m^2/min. Raytheon has recently received a $19 million contract from DARPA[a] to demonstrate a 600 simultaneous pixel system, increasing the area coverage rate to 450 m^2/min.

Extreme vibration sensitivity from diffuse surfaces has recently been demonstrated by Wang et al. [66] using photo electro-motive force (Photo-EMF), see Figure 21. They demonstrated detection of displacement down to 2 pm from a diffuse vibrating surface. The Photo-EMF photo detectors can be considered as 2-D structures of photo induced p-n junctions optimized for detection of fast displacements of spatially non-uniform light intensity patterns and interference patterns in particular.

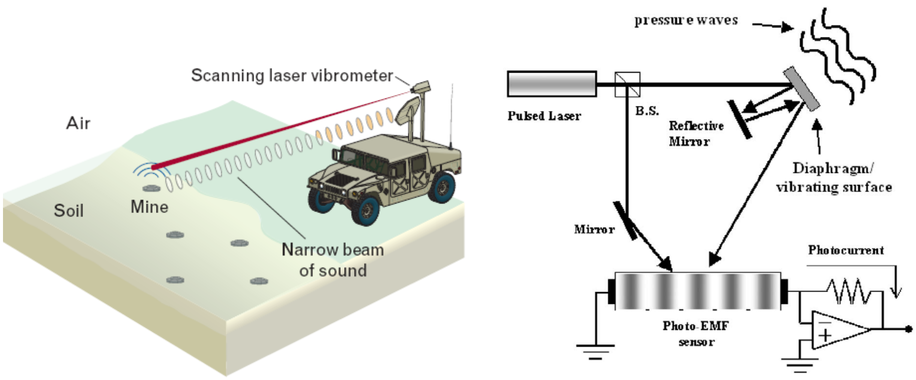

Figure 21. Left: The principle of buried mine detection using acoustic excitation and laser vibration sensing [64]. Right: The high-sensitivity laser vibrometer using the Photo-EMF sensor [66].

[a] The Defense Advanced Research Projects Agency

Several methods based on laser spectroscopy are being investigated for verification of mines and explosives as well as other chemicals. The three techniques that have received the most interest and development are LIBS, fluorescence, and Raman spectroscopy. Also infrared absorption methods are of interest in this application.

Recent developments in broadband and man-portable LIBS provide the capability for real-time detection at very high sensitivity of all elements in any target material because all chemical elements emit in the 200-940 nm spectral region. This technological advance offers a potential for the development of a rugged and reliable man-portable or robot-deployable sensor that would be capable of both *in situ* point probing and chemical sensing for landmine detection. It can also be developed for stand-off ranges up to some tens of meters. An ideal landmine detector would detect and identify both the exterior casing and the contained explosive charge. LIBS has demonstrated such a dual capability, with unique broadband spectra successfully acquired under laboratory conditions for explosive materials and both metal and plastic anti-personnel and anti-tank landmines. [27]

LIBS have also been investigated for explosives on surfaces. A review of the literature demonstrates that the capability of LIBS in the discrimination of chemical warfare simulants, explosives, and biological warfare simulants has made progress over the past five years [67]

Fluorescence detection of surface contamination has mostly focused on biological materials and toxic industrial chemicals. Little work has been done on the standoff detection of explosives or chemical agents using fluorescence spectroscopy. Much work is needed to characterize their fluorescence signatures [67].

The applicability of UV Raman for short-range stand-off detection of surface contamination has been demonstrated at FOI [68] and elsewhere. While technological challenges remain, the underlying phenomenology has been proven in field and laboratory trials. The current application is limited to the detection of chemical agents and TIC's[a], but laboratory results point toward its applicability to explosive and possibly biological contamination detection. The high levels of biological material in the ambient background, however, make the latter highly problematic, especially for outdoor detection on natural surfaces [67].

Infrared absorption using laser based photo acoustic techniques also show some promise and for remote detection of explosives and chemical warfare agents. Recently Patel et al. [69] demonstrated remote explosive detection at 150 m range.

[a] Toxic industrial chemicals

5 Discussion

The MOMS project has been of great value for investigating a number of sensors and technologies for detecting surface laid mines, both in laboratory and field-like conditions. A lot of data have been collected and processed to form a base for performance estimates. Processing techniques have been developed which can be implemented for real-time applications. The environmental influence on surface laid mine detection has also been investigated in detail for the environments we could create in Sweden. A valuable data repository on optical mine signatures have been obtained. Furthermore, a good insight in present and future technology development has been obtained.

General experience suggests that no single detection architecture is able to meet the performance needed under all operating conditions. The sensor suit and the specific algorithm will depend on environmental and operational conditions. The system knowledge is predominantly data driven, i.e. the database and algorithm performance is based on mine and minefield infrared and multi/hyperspectral imagery data collection and information on terrain, weather, time of day and pixel resolution. This type of information is extremely important and determines the detection performance. Knowledge based architectures can therefore bring improved decision support.

However, since then start of the project, the interest from the Armed Forces has shifted towards detection of IED’s. These are much more complex to define from a sensor feature perspective and the performance is more difficult to optimize as IED’s occur in such a great variety. Most of the sensors, methods and processing techniques used in MOMS also have high relevance for the IED problem. However, the IED threat also contains buried and hidden explosives, person and vehicle borne bombs etc. which requires other sensors and methods as well. Some of these, which should be investigated in a future C-IED project, include:

- High resolution and well stabilized active/passive EO systems suitable for change detection.
- High resolution well stabilized active/passive EO systems suitable for track detection (trip wires, optical sensors (video cameras), disturbed soil) and for detection of humans, recognition and tracking to investigate intent well before and during IED preparation.
- Persistent surveillance sensors (e.g. radar, EO, acoustic sensors, ground sensors, signal intelligence)
- Remote explosive detection techniques, in combination with cueing sensors to detect and point out specific objects or regions to be investigated.
- Radar systems (ground penetrating, including SAR) and laser Doppler techniques for detection of buried and hidden objects.

The original requirement in MOMS for the surface coverage rate was based on a 200 m wide swatch at a speed of 50 km/h which translates into a speed of 2780 m^2/s. This turned out to be a very high demand concerning both available sensors and lasers and the small ground pixel size needed (cm-class) and we recommend reducing this requirement. As a comparison the corresponding figures for the US UAV-borne ASTAMIDS[a] [70] system is a 70 m swath at 100 m altitude and a speed of 70 knots. This translates to 2450 m^2/s.

5.1 Recommendations

Also Swedish forces are encountering hostile IED's of increasing complexity in design. Detection of IED's is therefore a complex issue dealing with not only detection of explosives but also of persistent surveillance and detection of violations of expectations.

Maybe still more important is to locate, identify and track the terrorist and his/her activities. Besides conventional surveillance, initiatives critical to intelligence and the operations are tagging, tracking and locating using special sensor systems.

In future projects related to mine and IED detection (for example the Swedish route clearance program and the research activities on IED's) the following recommendations are made:

- Preserve and maintain the data repository collected for the different target and backgrounds.
- Data obtained from simulated airborne sensors should be combined with those from a ground vehicle to better evaluate a total system performance. Perform selected new testing.
- Test developed and new algorithms with regard to modern processing hardware and real-time aspects.
- Develop a system oriented modelling and simulation tool to evaluate different sensors, sensor combinations and total system performance.
- Investigate which sensors from the MOMS program that has high relevance for the IED problem.
- Perform more IED oriented testing with these selected types of sensors and with new sensors (e.g. radar, stand-off explosives detection, Doppler laser)
- Perform sensor tests for disturbed soil detection and stable high resolution sensors for change detection.

[a] Airborne Surveillance, Target Acquisition and Minefield Detection System

6 Publications

A large number of documents (reports, memos, conference papers and journal papers) have been published. A list is given below.

6.1 Reports

1. **MOMS multi optical mine detection system – initial report**
   Sjökvist Stefan, Abrahamson Staffan, Andersson Pierre, Chevalier Tomas, Forssell Göran, Grönvall Christina, Larsson Håkan, Letalick Dietmar, Linderhed Anna, Menning Dennis, Nyberg Sten, Renhorn Ingmar, Severin Mattias, Steinvall Ove, Uppsäll Magnus, Tolt Gustav, Linköping, FOI, 2005, 210 p., (FOI-R--1721--SE).

2. **Influence of laser radar sensor parameters on range measurement and shape fitting uncertainties**
   Grönwall Christina, Steinvall Ove, Gustafsson Fredrik, Chevalier Tomas, Linköping, Dep. of Electrical Engineering, LiU, 22 p., LITH-ISY-R-2745, (FOI-S--2343--SE).

3. **Approaches to object/background segmentation and object dimension estimation**
   Grönwall Christina, Gustafsson Fredrik, Linköping, Dep. of Electrical Engineering, LiU, 2006, 25 p., LITH-ISY-R-2746, (FOI-S--2344--SE).

4. **MOMS – Analysis and evaluation of experimental data**
   Letalick Dietmar, Chevalier Tomas, Larsson Håkan, Nelsson Claes, Nyberg Sten, Steinvall Ove, Sjökvist Stefan, Tolt Gustav, Linköping, FOI, 2006, 32 p., (FOI-R--2012--SE).

5. **Modelling of Imaging Spectral Sensors**
   Renhorn Ingmar, Linköping, FOI, 2006, 31 p., (FOI-R--2118--SE).

6. **MOMS - Progress report 2006**
   Letalick Dietmar, Andersson Pierre, Chevalier Tomas, Grönwall Christina, Linderhed Anna, Larsson Håkan, Menning Dennis, Nelsson Claes, Nilsson Pär, Nyberg Sten, Sjökvist Stefan, Steinvall Ove, Tolt Gustav, Uppsäll Magnus, Linköping, FOI, 2006, 71 p., (FOI-R--2147--SE).

7. **MOMS Planeringsdokument 2006**
   Sjökvist Stefan, Letalick Dietmar, Uppsäll Magnus, Linköping, FOI, 2006, 31 p., (FOI-D--0248--SE). (In Swedish.)

8. **Laser systems and technology for surface mine detection and classification – A literature update and performance discussion**
   Steinvall Ove, Linköping, FOI, 2007, 120 p., (FOI-R--2269--SE).

9. **MOMS – Data collection and evaluation. A status report**
Letalick Dietmar, Grönwall Christina, Hallberg Tomas, Larsson Håkan, Renhorn Ingmar, and Tolt Gustav, Linköping, FOI, 2007, 39 p., (FOI-R--2328--SE).

10. **A sensor fusion method for detection of surface laid land mines**
Westberg Daniel, Linköping, Dep. of Electrical Engineering, LiU, 2007, LiTH-ISY-EX--07/4021--SE.

11. **MOMS (Multi-optical mine detection system): Progress report 2007**
Letalick Dietmar, Larsson Håkan, Linderhed Anna, Renhorn Ingmar, Steinvall Ove, Linköping, FOI, 2007, 28 p., (FOI-R--2368--SE).

12. **Characterization of the polarimetric Imspec**
Nelsson Claes, Linköping, FOI, 2007, (Internal report FOI-D--0284--SE).

13. **SensorComb, a Matlab toolbox for combining sensors. Development status**
Björklund Svante, Linköping, FOI, 2007, (Internal report FOI-D--0293--SE). (in Swedish).

14. **Measurement Report from MOMS field trial in Eksjö 2007**
Håkan Larsson, Pär Nilsson, Dietmar Letalick, Roland Nilsson, Thomas Svensson, Linköping, FOI 2007, 24 p., (Internal report FOI-D--0297--SE).

15. **MOMS: Visit to the US. Discussions on mine detection in April 2007**
Letalick Dietmar and Steinvall Ove, Linköping, FOI, 2007, (Internal report FOI-DH--0038--SE).

16. **A sensor fusion method for detection of surface laid land mines**
Westberg Daniel, Tolt Gustav, Grönwall Christina, Linköping, FOI, 2008, 72 p., (FOI-R--2488--SE).

17. **Mine detection and classification using optical sensors – Initial results**
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18. **MOMS – System concept ideas**
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20. **MOMS (Multi-optical mine detection system) -- Progress report 2008**
Letalick Dietmar, Björklund Svante, Larsson Håkan, Steinvall Ove, Tolt Gustav, Linköping, FOI, 2008, 24 p., (FOI-R--2622--SE).

21. **Measurement report from MOMS field trial in Eksjö April 2008**
Larsson Håkan, Karlsson Kjell, Lindell Roland, Letalick Dietmar, Nilsson Pär, Svensson Thomas, Linköping, FOI, 2008, 19 p., (Internal report FOI-D--0314--SE).

22. **Mätrapport Gräsrutan 2008. Mätning mot minor inom projektet MOMS**
Larsson Håkan, Lindell Roland, Nilsson Pär, Svensson Thomas, Linköping, FOI, 2008, 28 p., (Internal report FOI-D--0315--SE). (In Swedish).

23. **Measurement report from MOMS field trial in Eksjö October 2008**
Larsson Håkan, Karlsson Kjell, Lindell Roland, Letalick Dietmar, Nilsson Pär, Svensson Thomas, Linköping, FOI, 2008, 22 p., (Internal report FOI-D--0324--SE).

24. **Reserapport: Army Advanced Concept Workshop on Disturbed Soil Characterization & Exploitation. Atlanta, Georgia, USA. 15-17 januari 2008**
Menning Dennis, Stockholm, FOI, 2008, 4 p., (FOI Memo 2328). (In Swedish).

25. **MOMS – Föredragning i FoT-gruppen SoS**
Letalick Dietmar, Linköping, FOI, 2008, 26 p., (FOI Memo 2584). (In Swedish).

26. **Detection and recognition of surface-laid mines**
Tolt Gustav, Esteki Hadi, Lauberts Andris, Grönwall Christina, Wadströmer Niclas, Linköping, FOI, 2009, 77 p., (FOI-R--2777--SE).

27. **Redovisning av milstolpe kvartal 4, 2009, för projekt Multioptisk min-spaning – MOMS, FoT nummer 04:09**
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28. **Cocalibration of Sensors with Mutual Information 2009**
Björklund Svante, Jörgen Ahlberg, Linköping, FOI, 2009 (Internal report FOI-D--0352--SE). (In Swedish).

29. **MOMS: Results from experimental activities 2009**
Letalick Dietmar Håkan Larsson, Magnus Elmqvist, Tomas Hallberg, Linköping, FOI, 2009 (Internal report FOI-D--0355--SE)

6.2 Conference papers

1. **Temporal analysis for land mine detection**
   Linderhed Anna, Sjökvist Stefan, Nyberg Sten, Uppsäll Magnus, Grönwall Christina, Andersson Pierre, Letalick Dietmar, Proc. of 4th International symposium on image and signal processing and analysis, pp. 389-394, 2005, (FOI-S--1889--SE).

2. **Land mine detection by IR temporal analysis: detection method**
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3. **Land mine detection by IR temporal analysis: Physical numerical modeling**
   Sjökvist Stefan, Linderhed Anna, Nyberg Sten, Uppsäll Magnus, Loyd Dan, Proc. SPIE vol. 5794, *Detection and remediation technologies for mines and minelike targets X*, 2005, pp. 30-41, (FOI-S--1890--SE).

4. **3-D imaging of partly concealed targets by laser radar**
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   Steinvall Ove, Chevalier Tomas, Larsson Håkan, Proc. of SPIE Vol. 6214, *Laser radar technology and applications XI*, p. 85-102, 2006, (FOI-S--2231--SE).

6. **Multi-optical mine detection: results from a field trial**
   Letalick Dietmar, Tolt Gustav, Sjökvist Stefan, Nyberg Sten, Grönwall Christina, Andersson Pierre, Linderhed Anna, Forssell Göran, Larsson Håkan, Uppsäll Magnus, Proc. of SPIE Vol. 6217, *Detection and remediation technologies for mines and minelike targets XI*, paper 0D1-15, 2006, (FOI-S--2303--SE).

7. **MOMS - A multi optical approach for land mine detection**
   Sjökvist Stefan, Uppsäll Magnus, and Letalick Dietmar, Proc. of SPIE Vol. 6217, *Detection and remediation technologies for mines and minelike targets XI*, paper 0J1-11, 2006, (FOI-S--2304--SE).

8. **MOMS – Multi Optical Mine Detection System: Project overview**
   Linderhed Anna, Sjökvist Stefan, Steinvall Ove, Letalick Dietmar, Tolt Gustav, Chevalier Tomas, Nyberg Sten, Larsson Håkan, Uppsäll Magnus, Menning Dennis, Proc. of SPIE Vol. 6395, *Electro-Optical and Infrared Systems: Technology and Applications III*, paper 6395-03, 2006, (FOI-S--2383--SE).

9. **Electro-Optic Detection of Land Mines and UXO**
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10. **Statistical approaches to mine detection using optical sensors**
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11. **Assessments of phenomenologies for multi-optical mine detection**
Letalick Dietmar, Sjökvist Stefan, Uppsäll Magnus, Menning Dennis, Andersson Pierre, and Grönwall Christina, Proc. of SPIE Vol. 6553, *Detection and Remediation Technologies for Mines and Minelike Targets XII*, paper 65530X, 2007, (FOI-S--2566--SE).

12. **Waveform analysis of lidar data for targets in cluttered environments**
Tolt Gustav, Larsson Håkan, Proc. of SPIE Vol. 6739, *Electro-Optical Remote Sensing, Detection, and Photonic Technologies and their Applications*, paper 67390A, 2007, (FOI-S--2671--SE).

13. **The use of Optech ILRIS-3D in the research work at the Swedish Defence Research Agency (FOI)**
Larsson Håkan, Andersson Pierre, Chevalier Tomas, Grönwall Christina, Gustafsson Frank, Letalick Dietmar, Steinvall Ove, Tolt Gustav, 2007 ILRIS Global User Meeting, pp. 1-12, (FOI-S--2678--SE).

14. **A sensor fusion method for detection of surface laid mines**
Tolt Gustav, Westberg Daniel, Grönwall Christina, Swedish symposium on Image Analysis 2008, 4 p., (FOI-S--2811--SE).

15. **An information theoretic model of target discrimination using hyper-spectral and multisensor data**
Wadströmer Niclas, Renhorn Ingmar, Proc. SPIE Vol. 6940, *Infrared technology and applications XXXIV*, 12 p., (FOI-S--2858--SE).

16. **System concepts for optical detection of surface laid mines**
Steinvall Ove, Renhorn Ingmar, Letalick Dietmar, Proc. SPIE Vol. 7114, *Electro-Optical Remote Sensing, Photonic Technologies, and Applications II*, 14 p., (FOI-S--2952--SE).

17. **Discriminating land mines from natural backgrounds by using depolarization information**
(Invited Paper), Stabo-Eeg Frantz, Lindgren Mikael, Letalick Dietmar, Steinvall Ove, Proc. SPIE Vol. 7114, *Electro-Optical Remote Sensing, Photonic Technologies, and Applications II*, 10 p., (FOI-S--2951--SE).

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   Grönwall Christina, Steinvall Ove, Gustafsson Fredrik, Chevalier Tomas, Optical Engineering, Vol. 46, No. 10 (October 2007), (FOI-S--2663--SE).

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