LOTUS field demonstration of integrated multi-sensor mine-detection system in Bosnia

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ABSTRACT

In this submission, we report on the successful field demonstration of the LOTUS landmine detection system that took place in August 2002 near the village of Vidovice, in the Northeast of Bosnia and Herzegovina.

Keywords: Humanitarian de-mining, GPR, IR, MD, sensor fusion, system integration, vehicle positioning, protocols

1. INTRODUCTION

LOTUS is a project to develop, integrate and demonstrate the proof-of-concept of a multi-sensor landmine detection system for humanitarian de-mining. The idea is to combine three sensors into a vehicle-mounted system. The system includes a metal detector (MD) array, developed by project partner Förster (Germany), an infrared (IR) camera system from project partner TNO-FEL (The Netherlands) and a ground-penetrating radar (GPR) developed by project partner EMRAD (UK). This project is partly EC-funded as ESPRIT project LOTUS, number 29812. Another partner in the project is DEMIRA, a German mine-clearance NGO. DEMIRA organized the minefield test held in Bosnia.

The aim of the field trial in Bosnia was to give a technology demonstration of all three sensors working together on a vehicle. The idea of using three sensors is to reduce the problems caused by false alarms of individual sensors due to "background clutter". (Hand-held) metal detectors are commonly used in de-mining activities, as most mines have sufficient metal content for today's sensitive metal detectors. Unfortunately, many areas contain vast amounts of other small metal objects. The infrared imaging is the most suitable sensor for detecting objects placed on the surface or buried close to the soil surface. The GPR gives signals from the discontinuity between the soil and a buried mine body. In principle, therefore it is possible to reduce the number of "clutter" signals within the sensor suite and also to detect mines that individual sensors miss. As such, the detection rate of the system as a whole is increased while maintaining or lowering the false-alarm rate at the same time. The way that the data from the different sensors are combined (or "fused") is of critical importance to the performance of such a system. TNO-FEL are responsible for the data fusion and software integration in the LOTUS project and apply sensor-fusion algorithms that have been reported to this symposium before [3,5,7].

2. THE LOTUS SENSOR SUITE

In this chapter the sensor issues are addressed, beginning with the primary mine-detection sensors. The metal detector is the sensor that is most commonly used for mine detection. Its performance has only been challenged by the emergence of minimum-metal mines. To detect these the sensitivity must be increased and then the false-alarm rate may become unsatisfactory. The secondary primary sensor for LOTUS is an IR camera. This was chosen because of the comparatively large number of surface and near surface mines that may be detected by this technology. A radar array was the third sensor. Radar may detect dielectric material specifically the plastic explosive in minimum metal mines. It is also likely to have greater depth penetration than a metal detector. The other key sensor requirement in LOTUS is position. It is essential that the information from the sensors is accurately position referenced so that it may be effectively fused. In LOTUS all the position sensing issues were addressed, but because of the developing mechanical

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deployment issues only the minimum necessary was implemented at each stage. The final issues considered in this chapter relate to sensor fusion. Key decisions were made in the earlier GEODE project and are not reproduced here.

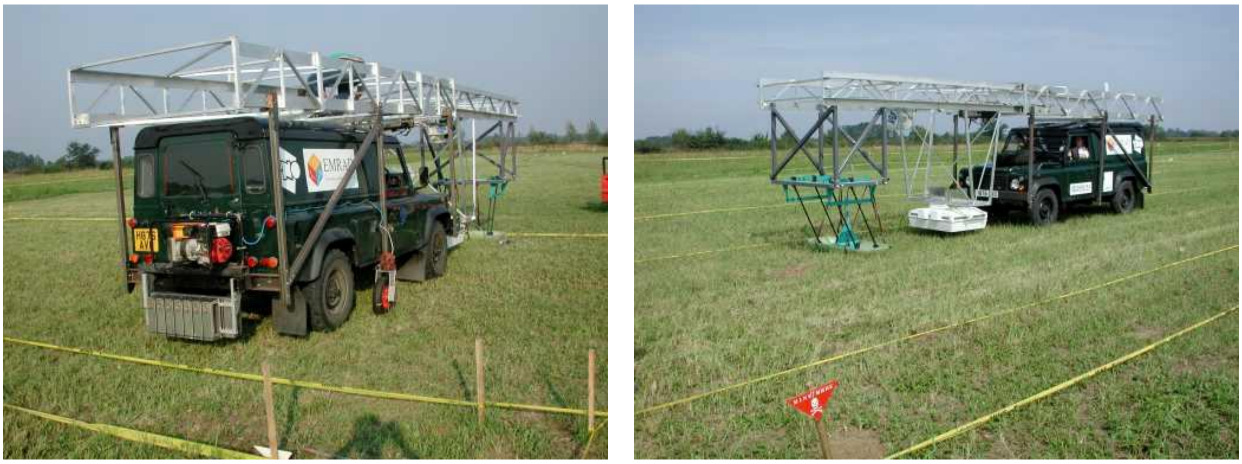

Figure 1: The LOTUS system from different points of views.

The complete LOTUS mine-detection system was mounted on a Land Rover. A large aluminum frame on the vehicle roof was used to mount all the sensors for mine detection, interrogating the ground in front of the vehicle. In the front of the vehicle is the Förster metal detector array, which sits in a non-metallic sled that slides along the ground suspended by four swinging arms. Following the metal detector, the infrared camera is mounted, at 2m above the ground. After the IR camera, the GPR antenna is hung from the frame. A tick wheel with shaft encoder is mounted on the side of the vehicle to give a measurement of position. The equipment on the vehicle is controlled by a remote-control (laptop) computer that communicates by wireless LAN with all equipment. The sensor data is transferred over the LAN to the remote-control computer where sensor fusion is performed. Fusion outputs a detection confidence level derived from the combined signal strength and is transmitted back to the vehicle so that its results can be used by the paint marking unit, mounted on the back of the vehicle. The paint-marking unit is used to mark positions at which fusion found a detection and also to mark the lateral limits of the ground covered by the sensors.

The Metal Detector

Figure 2: The MINEX Array with its Ground Adaptation System during Demonstration Trials in Bosnia.

The MD array employed in the LOTUS project is a Förster MINEX 2FD Array. It is a simultaneous two-frequency continuous-wave metal detector. The sensor array has one transmitter and seven receiver coils covering a width of 1.15m. The receiver coils are phase and frequency synchronized. Each receiver channel has a high precision phase

(<0.001°) and amplitude regulation circuit, which is activated for each system frequency (2.4 kHz and 19.2 kHz) 300 times per second. The sensor has a special regulation winding that is coupled with the transmitter coil in order to generate a nominal value for the regulation circuit.

The two-frequency detection system is supported by an advanced real-time filter function, which eliminates uncertain object signals and noise in order to reduce the false-alarm rate of the MINEX 2FD array. An object calculation function defines the object position based on the filtered signals. Filter settings are adjustable and can be set according to scenario requirements. The output of the MD array is real-time data containing the positions and the characteristics of metal detections, like signal strength and size of the detected objects. This data is converted by TNO-FEL processing to produce an area map, containing real-valued, confidence numbers between 0 and 1 indicating the confidence or belief in a mine detection on a certain position, that is used in the subsequent sensor-fusion process.

Key performance features of the MD array are:
1. High sensitivity in detecting small metallic parts such as mine fusing pins.
2. High detection sensitivity for all metals irrespective of conductivity.
3. Suppression of the influence of magnetic soils and salt water.
4. Precision in the localization of the position of small metal objects through use of the multiple differential coil system.

During the LOTUS project, the integrated metal detector array and the deployment mechanism have been developed for field use. All the electronics corresponding to the transmitter, the seven receivers, the digitizer, PC and data logger have also been integrated into the rugged electronics module shown in Figure 2. This is engineered to MIL STD, provides effective environmental protection and has suitable shock mountings for attachment to any all-terrain vehicles.

The Infra-red Detector

The IR detection system consists of a commercial off-the-shelf (COTS) camera, an associated processor board and a PC. The processor board is housed within the PC. The camera specified for LOTUS was the Radiance HS also known as Galileo. The camera is operated using a Matrox Genesis board. This acts as a frame grabber, digitizing the camera output and carrying out the pre-processing based upon the use of DSP. The real-time IR processing method relies on the principle that the mines have a different (apparent) temperature than their surrounding. Furthermore, the method applies local contrast enhancement to make it invariant for the local background intensity and performs false-alarm reduction by selecting blobs on morphological and size attributes by using a priori domain knowledge.

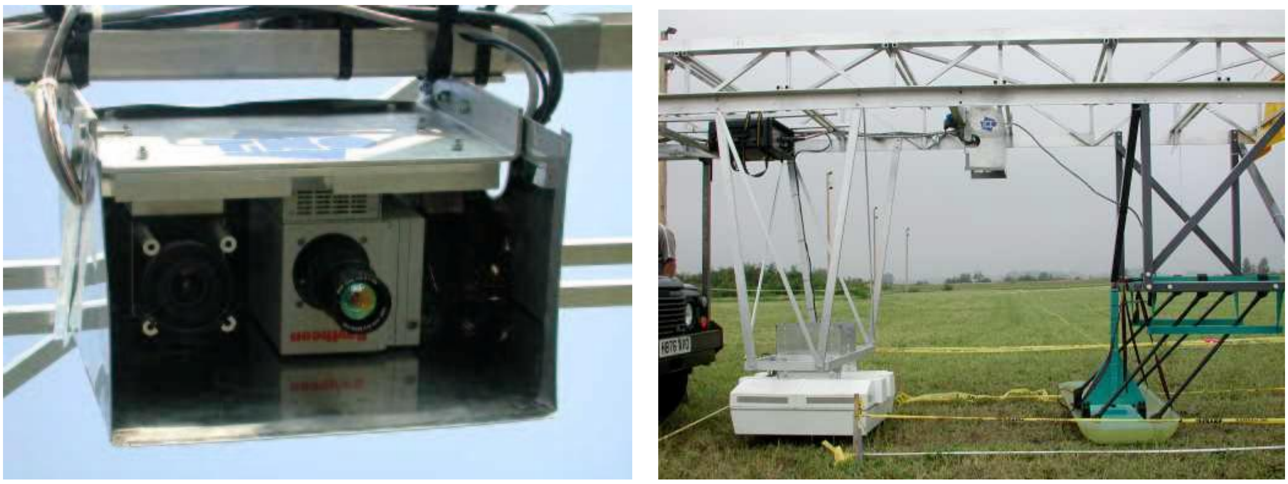

Figure 3: The IR camera looks down between GPR and MD.

The IR processing is based upon a number of steps which are shown in Figure 4 with sample data included. The first step involves reducing the resolution of the camera output to that of the other sensors and sensor fusion. At the operating height of the camera it collects 256x256 data points corresponding to a footprint of 1.16m square. Each output pixel of the IR camera corresponds to an area of 4.5mm square compared to the 25mm of the other sensors. The re-sampling involves searching the 25mm square and assigning the highest pixel value found in that search to that grid cell position. The second step is a “blob search”. The image is searched for areas of high contrast and hard limited to identify areas of interest where a target may be present. Essentially the output corresponds to one bit, a zero or a one, defining the perimeter of possible targets. The third step is known as local contrast enhancement and requires the calculation of the local mean intensity and variance for each grid cell. The intensity of each pixel is set according to these values. The fourth step combines the two earlier steps: the output to the fusion process employs the intensity values generated in step 3 in the region of interest defined in step 2.

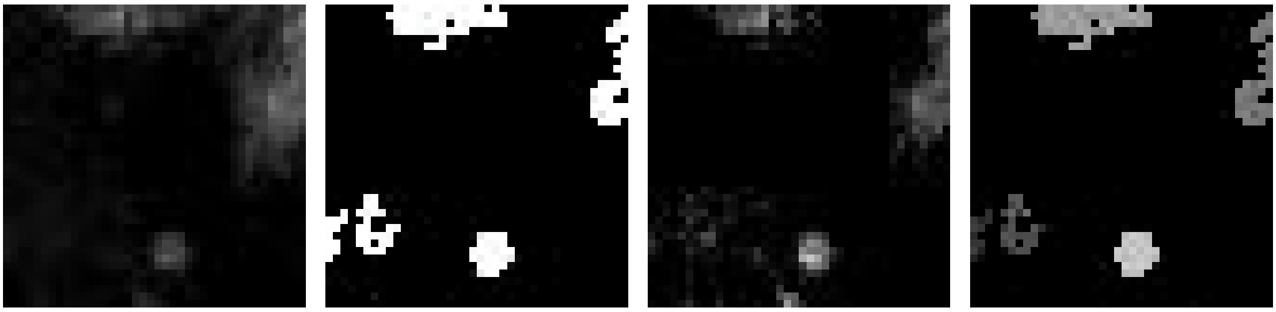

Figure 4: IR processing steps: re-sampling, blob search, local contrast enhancement and final processing output.

The IR processing strategy is appropriate for mine detection. At the re-sampling stage the maximum level signal is employed to ensure that high level signals arising in even very small areas are not ignored. The second step localizes the area of interest reducing the amount of data to be considered. The third and fourth steps ensure that a consistent signal level is generated for such “blob” and supplied to the sensor fusion.

The MINEREC GPR Array

The MINEREC GPR Array was built as part of an earlier Framework 4, EC project and contains many EMRAD proprietary items. The design is based upon the requirement to detect small anti-personnel mines. The electrical properties of soils relevant for GPR operation vary widely with different soil types and water content, but reliable detection is required in all situations. This leads to the requirement to span the area searched by the radar with measurement points and a maximum of a 50mm x 50mm square grid. The finer the grid the better but this has cost implications.

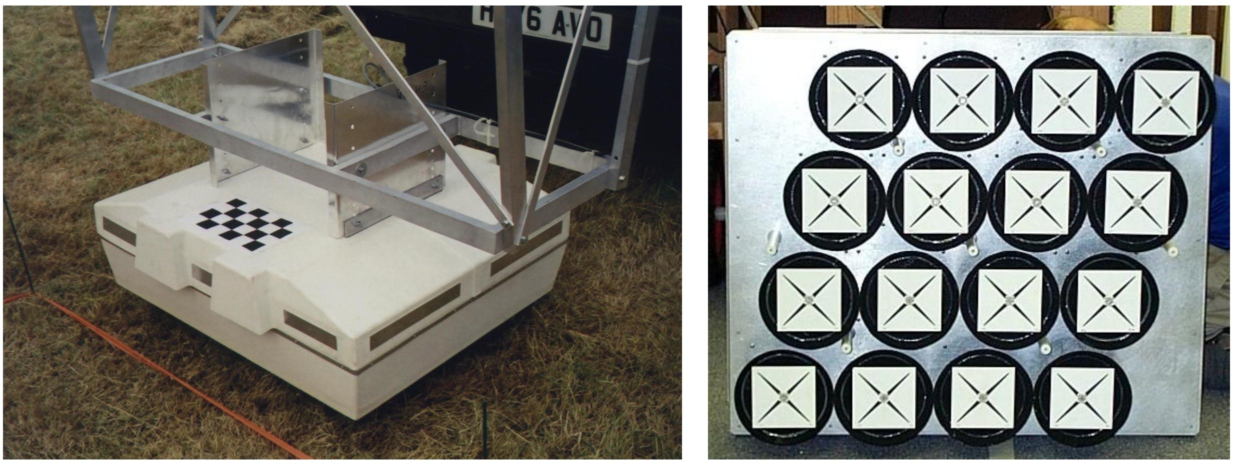

Figure 5: The MINEREC GPR with and without cover.

It is undesirable to require the radar antenna to be mechanically scanned. The search grid requirement then demands that antenna elements are spaced across the width of the swathe to be searched at a spacing of 50mm. The antenna elements are physically larger than this spacing and this naturally leads to MINEREC antenna geometry shown in

Figure 5. The figure indicates four rows of four antenna elements with successive rows that are offset by 50mm. As the array is moved forward, the sixteen radar antennas scan along sixteen paths each separated by 50mm to search the swath 0.75m wide.

The data generated by the MINEREC array is subject to significant processing before an output is obtained in the form of a “confidence” map that is used as input to the fusion process. The first step in the processing is to remove the effects of antenna breakthrough and reflections from the ground. For the real-time software used in LOTUS a moving average is subtracted from the signal to remove these effects. The second step generates a smoothed local energy map. The conversion to a confidence value requires the calibration of the system. In LOTUS this was done by scanning a “clean” area of ground approximately 3m x 1m with one mine present of the type sought.

The positioning System

In a system such as LOTUS there are many requirements for position information. This arises because there are three different sensors and a marking system each moving over a different path or searching a different swathe. The sensor outputs must be combined for sensor fusion and the marker system. It is also essential in an operational system to be able to record the co-ordinates of the track thoroughly searched and of any targets for inclusion in a Geographical Information System (GIS) for later reference.

All the primary sensors require triggers to initiate the next measurement when they have attained the required grid position. The metal detector requires fifty triggers per meter and the radar forty. At the maximum forward speed of 0.5m/s employed in the Bosnian trial the rate required is not compatible with complicated sensors like Differential Global Position Sensing (DGPS) systems. With their slow repetition rate of around 2 Hz, these precision position sensors cannot generate the trigger information for the sensors in LOTUS. MD and GPR require trigger rates of up to 50 Hz and 20 Hz respectively. The solution adopted was to use a measurement wheel with an optical shaft encoder. The encoder produced one thousand pulses per revolution and was able to resolve millimeter increments. A simple digital electronics box was provided to multiplex the pulse stream from the wheel sensor, and count the appropriate number of increments to initiate the various start measurement signals required by the different sensors.

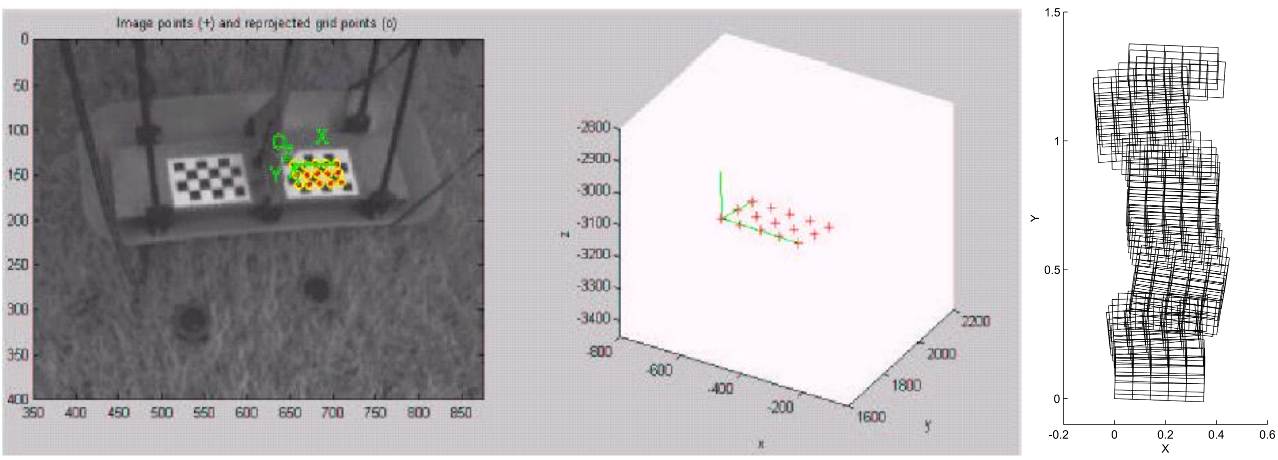

Figure 6: On the left: detection of pattern intersections on the MD and an estimated 3D reconstruction of the pattern (and as such sensor) orientation and position. On the right: reconstructed MD trajectory.

The other issue that should be addressed in an operational system is the movement of the sensors and marker system relative to each other on the vehicle. The LOTUS system was assumed to operate on flat level terrain and this was therefore not perceived as an immediate issue. As the work progressed and areas of unevenness were encountered on the test trials this began to emerge as a more important issue. The MD’s mounting mechanism as show in Figure 2 was particularly demanding as without other instrumentation the vertical and lateral movements could not be readily accommodated into the fusion. This decreased the overall certainty of detection.

As part of the investigation of position sensing requirements the LOTUS platform was fitted with a pair of stereovision cameras from TNO-FEL during the third data collection. These were mounted facing down alongside the IR camera to view the MD and GPR. Both these sensors were fitted with chessboard patterns to aid the analysis of the data, see Figure 6. Progression of the vehicle position on the ground can be tracked by concatenating successive ego-motion estimations [2]. If the vehicle motion is combined with the relative position and orientation of the MD its position on the ground can be computed. Figure 6 shows the tracked MD on the ground for about two seconds. The figure clearly shows how the observations of the MD should be distributed over the grid areas for sensor fusion in landmine detection.

Sensor Fusion

A key element of the LOTUS system is the treatment of the set of sensors as one integrated sensor suite making the essential decision upon the presence or absence of a target that may be a mine. This requires that the output from all the sensors is employed in one decision making process, typically termed sensor fusion. There are many ways in which this could be implemented and extensive literature upon the subject. Many of the important decisions regarding the use of fusion in LOTUS were made in the earlier project GEODE in which TNO investigated a number of different techniques for sensor fusion [4]. This included techniques known as:

- Best sensor
- Naïve Bayes
- Dempster-Schafer
- Rules
- Fuzzy probabilities
- Voting

It is not easy to compare the merits and the limitations of these approaches. Some need an extensive history of events to teach the system before they may be effective while others may be implemented with little background information. Earlier studies indicated that some techniques are not particularly appropriate for a project like LOTUS because the total volume of available data is unlikely to be of any great statistical significance. For LOTUS it was established that the Naïve Bayes approach is likely to be the most appropriate. Best sensor simply using the output of what appears to be the most appropriate sensor at any time and may provide a basis for simple comparison.

3. SYSTEM INTEGRATION

The integration of the LOTUS system was a demanding task. A number of different systems with potentially disparate requirements were being brought together for the first time to produce a new type of mine-detection system. All aspects of the system had to be considered, this included their mechanical requirements, their siting demands, their operating characteristics, software communication issues, power requirements, EMC characteristics and environmental issues for field use. Any one of these issues can prevent the successful field operation of this prototype demonstration system. The communications protocol defines software integration. major hardware integration took place at Emrad's premises, associated with the second and third data collections. Both integration trajectories are discussed in the next sections.

Software Integration

The communication protocol forms the base for all software integration and is based on the common TCP/IP protocol. The protocol defines the interface of all communication between sensors, fusion, UI, marking and positioning unit. The protocol has flexibility, readability (for debugging purposes), and extensive error handling. Making almost all communication in ASCII text ensures readability of the protocol. This simplifies debugging protocol software enormously. Opening a telnet connection to the sensor and typing in your commands can simply perform testing of the sensor. Furthermore, during operation all communication can be sent to a terminal window to monitor and check progress of operations.

Error handling is provided in an HTTP-style: each request is answered with a report that includes a three-digit number that indicates the status of the subsystem (ok, warning, error). An additional report field can be used to specify warnings and errors further. As such, error and warning codes are no longer coded into the protocol. The sensor only indicates the severity of the status in the three digits; its additional specification has no meaning for the fusion or UI and is ignored.

Because of above-mentioned points, the communication protocol could easily be tested. Integration of all computer software items like fusion, GUI and sensor-processing units could therefore be reached before any physical hardware integration of all sensor and processing units. Because of the extensive testing of protocol software of partners over the internet, software integration and initial testing went smoothly. This saved a great deal of time when the systems elements come physically together, as the genuine real-time and full system issues needed to be addressed.

Hardware Integration

Figure 7 shows the integration steps made within the LOTUS project from sensor integration trial via the 2nd and 3rd data collection to the Bosnia demonstration. The actual data collections took place at Gibraltar Barracks, Minley Manor. This is the home of the UK Army unit responsible for humanitarian de-mining. An area of the playing fields adjacent to the rugby pitch and the police dog training area was hired for the duration of this activity.

Figure 7: From left to right, top to bottom: sensor integration trial, 2nd data collection, 3rd data collection, and Bosnian field trial.

Hardware integration at the Bosnia demonstration was complete. The following list details the integration steps taken at the different trials and data collections:

- sensor integration trial (January 2002): integration of GPR and IR on sensor platform, real-time testing of communication protocol and tick-wheel position unit.
- 2nd data collection (March 2002): integration of GPR, MD and IR on sensor platform, real-time testing of graphical user interface and position alignment of sensor data for fusion, data collection.
- 3rd data collection (July 2002): final integration of GPR, MD and IR on new sensor platform on Land Rover, final testing of graphical user interface and position alignment of sensor data for fusion, data collection.
- Bosnia demonstration (August 2002).

4. THE BOSNIAN FIELD TRIAL

The Bosnian field trial provided the focus for the conclusion of the LOTUS phase in the development of a vehicle-based mine detection capability. The trial was undertaken for a number of reasons including:

1. providing an effective benchmark of the technological progress achieved by the project,
2. to provide a demonstration of that technology to interested parties who were invited to visit the trial,
3. to examine the suitability of the achieved and required development in realizing a product that could operate in the modes defined by the LOTUS Scenario Definition.
4. to provide an effective interchange of views between the technology based development team and active de-miners.

In order to effectively address these issues it was essential that the trial was carried out in a mine-infected area. It was also necessary that it was supported by a team of experienced de-miners who had a clear view of their role and of the assistance that a vehicle-based detection system could provide them.

Figure 8: The town of Vidovice.

The trial took place on farmland next to the village of Vidovice, near the town of Orašje. This location is in the Northeast of Bosnia and Herzegovina, close to the border with Croatia (the Sava river) and not far from the border with Yugoslavia (Serbia). The area was the scene of very heavy fighting in the war and there are still many reminders of this. There are many destroyed houses in the area, and most of the others have walls peppered with bullet holes. There is however clearly a lot of reconstruction going on in the area, with many new houses being built.

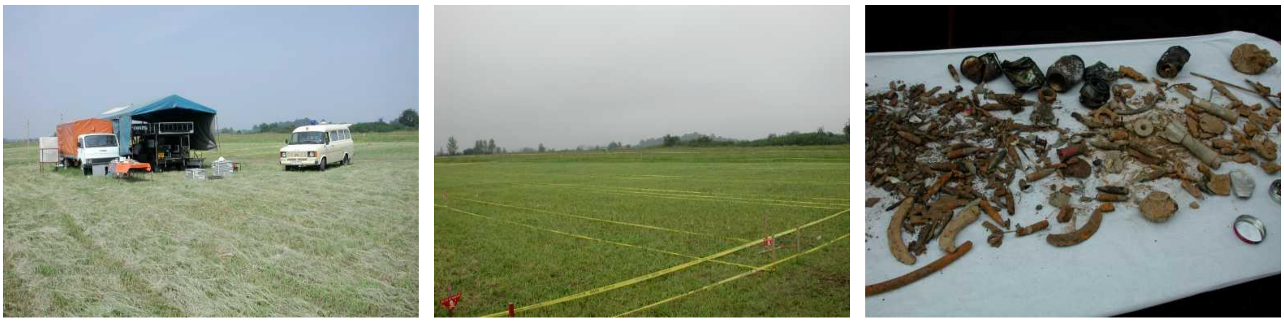

Figure 9: The trial site and removed metallic debris.

The LOTUS trial site was within a suspected mined area of flat farmland, but it had been cleared by DEMIRA for reasons of safety for all participating project members (no clearance, no trial). The area surrounding the trial field was uncleared land. The soil of the test field appeared to be fairly heavy clay, on which the grass had been cut short. When the field was cleared, a large amount of metallic debris was removed. A lot of this debris was from ordnance fired in the war - there were many large-calibre bullets for example. Despite the removal of this metal, it was conceded that there probably remained some metallic clutter that would be give metal-detector signals.

Figure 10: A surface laid PMA-3, PMA-2 and No 4 mine.

The focus of the trial was upon the five 50m long test lanes that were carefully prepared by DEMIRA. The choice of targets and layout was designed by DEMIRA to being representative of Bosnian mine-detection issues and problems. In general, the first three lanes numbers one to three were laid to reflect current field issues and lanes 4 and 5 were laid with a view to establishing the limitations of the LOTUS system. In lanes 4 and 5 targets were buried at depths of up to 200mm which is deeper than required but was thought could be required if the area had been extensively flailed.

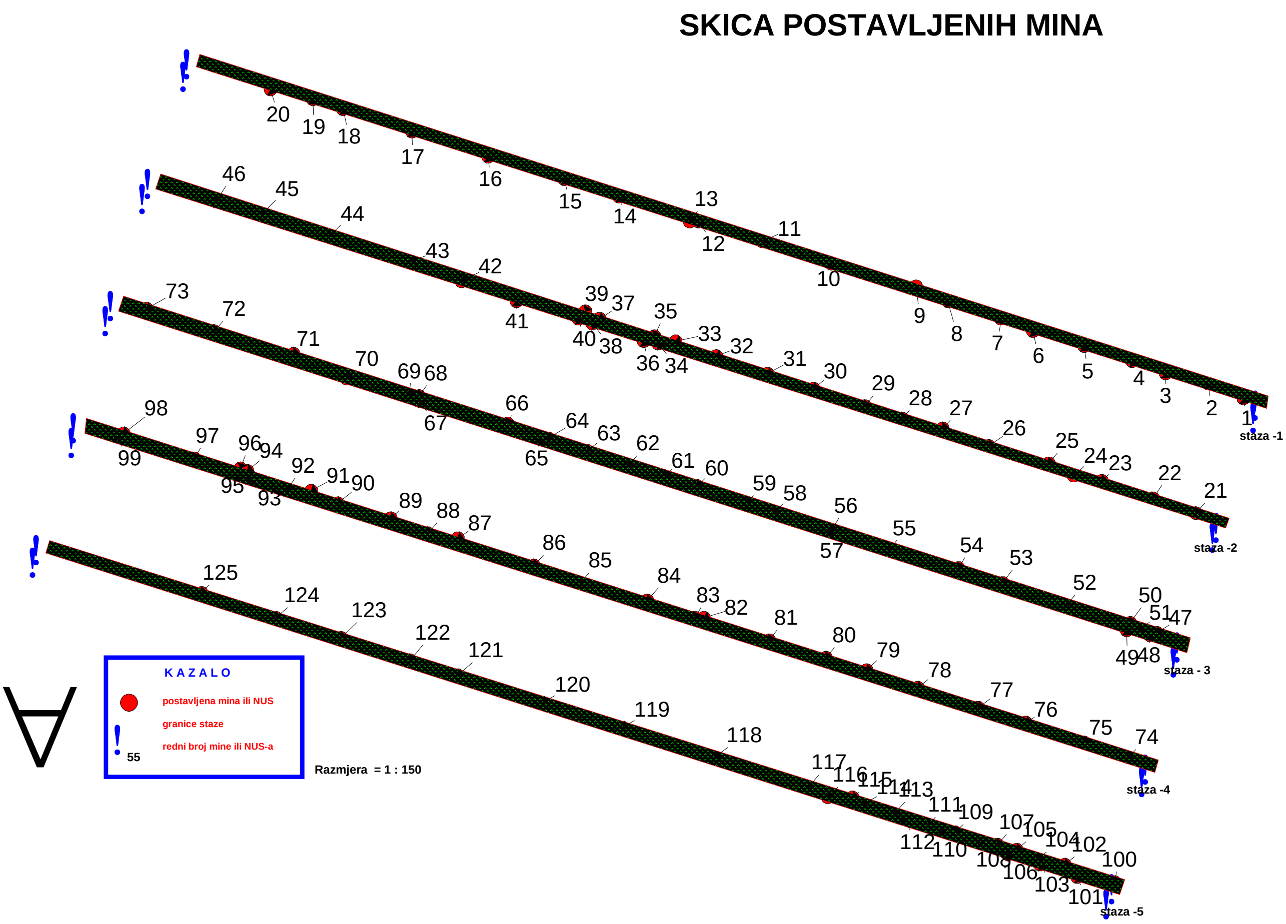

Figure 11: Layout of the five test lanes.

The major detection problem in Bosnia is from minimum metal mines. Generally the mine types of concern employ plastic explosive in a plastic housing and the only metal present is the metal firing pin forming part of the fuse. Mines of this type were readily available in Bosnia, are a major concern and were therefore widely used in the test lanes. All the mines used in the trial employed live explosive. Plastic explosive in isolation is extremely stable and did not present any threat to the personnel or equipment upon the trial. It was, however, imperative that all the mines used in the trial were made safe by the removal of the fuse. Commonly in minimum metal mines the only metal present is the firing pin within the fuse. To compensate for that, a carefully selected surrogate piece of metal was included in the target, which matches the MD signal of the fuse.

Table 1: Ground truth description of the five demonstration lanes at LOTUS site in Bosnia.

Lane	Number of AP mines and type	AT	UXO / remnants	Burial depth
1	11 (PMA 2 & 3, No 4, PROM)	2	7	Mostly surface laid without cover
2	21 (PMA 2 & 3, No 4, MRUD)		5	Mostly surface laid without cover
3	11 (PMA 1A, 2 & 3, PROM, PMR 3)	1	15	Mostly shallow buried
4	14 (PMA 2 & 3, PMR 3)		12	All buried from 6 to 21cm to top
5	19 (PMA 2 & 3)	6	1	All buried from 1 to 17 cm to top

The layout of the mine lanes is shown in Figure 11. In some cases, targets were laid in small clusters, in other cases they were laid in isolation. Generally the patterns were specified to reflect the situations that DEMIRA had encountered in the locality. In the five mine lanes one hundred and twenty five targets were laid, approximately one every 2m. Table 1 gives a statistic of employed mine type and burial depth. The width of the test lanes in which targets were buried was restricted to 50cm. The sensors search width was a minimum of 75cm, but a margin was allowed for driving inaccuracies.

5. THE BOSNIAN FIELD TRIAL RESULTS

The objective of the LOTUS system is to detect and mark mines in real-time. The most important set of results obtained with the system is thus those obtained in Bosnia on the ground. Subsequently, it is straightforward to generate much details concerning the behavior of the dynamic range of the system most of which is only of relevance to the developers and of little value to de-miners. The on-line real-time results for the system are therefore the most important.

All the results presented were recorded during the demonstration day. During that day data from all five lanes was analyzed in real-time during the demonstration runs and recorded for subsequent off-line processing. No hardware or software failure occurred. The ground truth of all five lanes was measured by DEMIRA in GPS co-ordinates and converted manually by TNO-FEL to two-dimensional sensor-fusion grid co-ordinates. The overall weather conditions for the demonstration and measurements were good: warm, sunny with some occasional clouds.

Table 2: The Detection Results achieved in the Real-time Demonstration on the Bosnian Mine Lanes.

lane	Detection result (all objects)	detection result (metal objects)
1	95%	100%
2	100%	100%
3	96%	100%
4	93%	93%
5	69%	69%

During the demonstration day some different sensor-fusion algorithms and settings were implemented and tested. The choice of algorithm was made after suggestions of the EC reviewer Dr Vernon Joynt, taking into account the number of available marking colors. The ultimate, demonstration sensor-fusion algorithm can be described as follows:

- mark all MD signals with one colour (yellow);
- mark all MD signals with significant support from at least one other sensor (IR, GPR) with another, second colour (white).

Examination and evaluation of all sensor-fusion detection results took place by visual inspection of the marking results by a number of attending people (including the EC reviewer). Inspection was relatively easy because all objects placed by DEMIRA were either directly visible or identified with a small flag with an identification number at the same horizontal position, 1m away. Furthermore, DEMIRA personnel aided in this evaluation by describing their targets in detail. After collection and re-checking of some of the results, by re-processing of data the real-time detection performance of the system achieved is presented in Table 2.

The detection results apply to all classes of object without distinction including anti-personnel mines, anti-tank mines, UXO and remnants of objects, see also Table 1. The number of false alarms was negligible. This arose for two reasons. Each of the sensors was operated at their calibrated operating points, severely limiting the number of sensor-generated false alarms. The second reason was that DEMIRA had cleared the land of metal detritus to meet the insurance requirements of the trial.

6. CONCLUSIONS AND RECOMMENDATIONS

At the completion of such a high profile trial as LOTUS it is important to draw effective conclusions about the state of development of the detection system. It should be understood that the conclusions made are indicative of performance because the statistical base of this trial is small with only 125 targets. Nevertheless important comments may be made. Firstly, there should be no ambiguity that it is the on-line results that are appropriate to de-mining, the condition where all the sensors are individually operated to give the best detection rate with minimum false alarms. In Bosnia, the false-alarm rate for real-time results was negligible. It is then important to examine the detection results.

In Lane 1 there are twenty targets, eighteen of which include metal. The MD detected all the targets with a metal content but the other sensors did not confirm one of the non-metal objects. The two plastic objects were a large AT mine and a plastic hand grenade support case. Both the GPR and the IR detected the AT mine. The object not detected, the hand grenade case was not of interest, it was empty, otherwise it would have generated a GPR response. In Lane 1 all the targets of interest were detected but the one non-metal target not of interest was rejected by the ensemble of sensors.

In Lane 2 only metal objects were present. The MD detected them all and the other sensors confirmed the detections. All the targets are relevant to a de-miner and all were detected.

In Lane 3 all the targets that contained metal were detected by the MD, a number of coins were present, and one of these was not confirmed as a detection by the other sensors. This shows that the sensor suite has the ability to discard responses such as this from a MD as not of interest. It achieved this in one case, but it is likely that the number of such instances could be increased by a more detailed review of settings and thresholds. The MD needs to be able to detect the small signal from an AP mine firing pin, which is comparable to that from a coin. If the GPR indicates that the metal fragment is alone, such as a coin, the target should be rejected. Alternatively, if the small response from the MD is accompanied by a signal from a large volume in the GPR, the explosive of an AP mine, the response is of interest.

In Lanes 4 and 5 there is a fall off in the real-time detection rate that is identical for both the MD and all objects. From the off-line results it became clear that the GPR is achieving deeper ground penetration than the MD. In the real-time sensor-fusion strategy adopted, the GPR may only confirm the results of the metal detector. If the MD does not detect the target in the first place the GPR can not confirm its presence. The fall off in detection rate in Lanes 4 and 5 reflects that the trial was well designed to assess the depth penetration of the sensor suite. Targets in Lane 4 and 5 are laid progressively deeper than in lower numbered lanes. In Lane 5, there is a large proportion of minimum metal anti-personnel mines. If it is assumed that it is this target that is not detected by the MD at depth then the detection rates in Lanes 4 and 5 would indicate that the metal detector may reliably detect down to a depth of 8 to 9 cm. In Lane 4 two targets were not detected. There were two buried at 9cm and one at 10cm. In Lane 5 eight targets were missed. There were two buried at 8cm, two at 9cm, two at 10cm and one each at 13cm and 17cm.

The conclusion from the real-time operation is that the sensor suite may be used to detect minimum metal AP mines down to a depth of 8cm, with no false alarms caused by the system. False alarms caused by fragments in the ground may be present but not system-generated false alarms. This limitation is a direct reflection of the limitations of the metal detector. At a greater depth the GPR takes over as the most important sensor and the strategy for combining sensor outputs may need to be different as also put forward in our publication on depth fusion [5].

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