HUMANITARIAN DEMINING ROBOT GRYPHON – CURRENT STATUS AND AN OBJECTIVE EVALUATION –

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Abstract- Mechanical systems or robots to assist landmine detection are expected to greatly improve quality of humanitarian demining tasks. These new systems could provide: i) safer operation; ii) advanced methods for automatic target recognition and discrimination; iii) consistent performance with less influence of "human-factors"; iv) better detection performance, i.e., higher probability of detection (POD) and lower false alarm rate (FAR); among others. However, despite many research/development efforts around the world, no practical landmine detection robot has yet achieved maturity for practical use. Nonetheless, the humanitarian demining robot Gryphon, which current status of development is described in detail, is close to meet the requirements for practical use. This paper analyses the results from latest on-site tests underwent by Gryphon in Croatia (2006, 2007) and Cambodia (2006), to make a critical and objective evaluation of its validity, and clarify the points that still require further development in order to realize a practical humanitarian demining robot.

Index terms: All terrain Vehicle (ATV), buggy vehicle, robotic manipulator, metal detector (MD), ground penetrating radar (GPR), global positioning system (GPS), target discrimination.

I. INTRODUCTION

Anti-personnel landmines and explosive remnants of war do not loose their explosive force even long after war or conflicts are over, and even now, they still remain a real threat for many populations around the world. The goal of humanitarian demining is to remove these remnants of war and assure a cleared and safe land that can be used without fears. This differs from the military demining (also called breaching), which basically focus in clearing paths for military purposes.

Current humanitarian demining methods are still slow, costly and dangerous, and depend on many factors such as location, terrain, covering vegetation and locally available resources.

Since the early 1990's, heavy machines such as flails, millers and tillers have been successfully gained acceptance for the mechanization of demining tasks. Machines are used in the mine clearance stage known as mechanized detonation and they can cover wide suspected areas in a short time, decreasing the area that otherwise should be manually scanned by human deminers (area reduction). However, it is important to note that although demining machines can perform very well in many situations, it is not guaranteed that it can destroy all the buried mines. A manual detection using hand-held metal detectors or trained mine detection dogs is performed for posterior quality control and assurance. Moreover, in most countries, the manual demining is still the main or only method for detecting and clearing the minefields.

Additionally, because most mine detectors based on electromagnetic induction technology can not discriminate between landmines and metal fragments, in normal operations 100-1000 false targets (metal fragments) are cleared for every live mine encountered [1]. This causes a large time penalty for the whole demining process. For this reason, alternative sensors that can discriminate mines from other type of inoffensive metal fragments have gained the attention of researchers in recent years (see [12] for a survey). In particular, ground penetrating radars (GPRs) have been identified as a promising complement to the metal detectors (MDs). Where the MD detects buried metallic objects, the GPR detects bigger heterogeneities in the ground. The combination of both in a single sensor, or dual-sensor, allows performing discrimination, and so effectively reducing the number of false alarms.

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

The Tokyo Institute of Technology developed a semi-autonomous mobile robot to assist the mine detection process. Its manipulator is able to automatically scan over a 2 m^2 surface with attached

sensors, record data and present the resulting sensor images to the operator who then can mark suspect spots. Additionally, a novel algorithm based uniquely on the acquired data from an MD has been tested, and shows promising results in extracting more than just the position of buried metallic objects; next to identifying the depth at which a metallic object is buried, it allows also performing discrimination. The developed robot was tested in several field trials on test minefields in Croatia and Cambodia.

II. GRYPHON PROJECT- AN OVERVIEW

During the period of October 2002 to October 2007, the Japan Science and Technology Agency (JST), having received designation from the MEXT (the Ministry of Education Culture, Sports, Science and Technology) has funded research and development in two areas: i) advanced sensing technology; and ii) access-and-control technology, with objective to offer new solutions for the worldwide humanitarian demining problem. Our group in the Tokyo Institute of Technology focused in the latter area, access-and-control technology, and succeeded in the development of a new teleoperated robotic system called “Gryphon” that can effectively and reliably carry and control many mine detection sensors developed by other groups, as well as other commercial sensors.

As shown in Figure 1, Gryphon is based on a commercially available All Terrain Vehicle (ATV) to which a custom long-reach robotic manipulator carrying a mine detector is mounted. The robotic manipulator is automatically controlled to scan the terrain, without intervention of a human operator. This is achieved by acquiring three-dimensional topographical information of the area to be scanned, by using a stereo vision camera. The recorded mine detector data is then presented to the operator who, after careful inspection and evaluation, can indicate suspect spots that will be marked directly onto the minefield with an onboard paint- or plate-marking system. Additionally an optional RTK-GPS localization system records the location of the acquired data and marked spots, within a few centimeter precision.

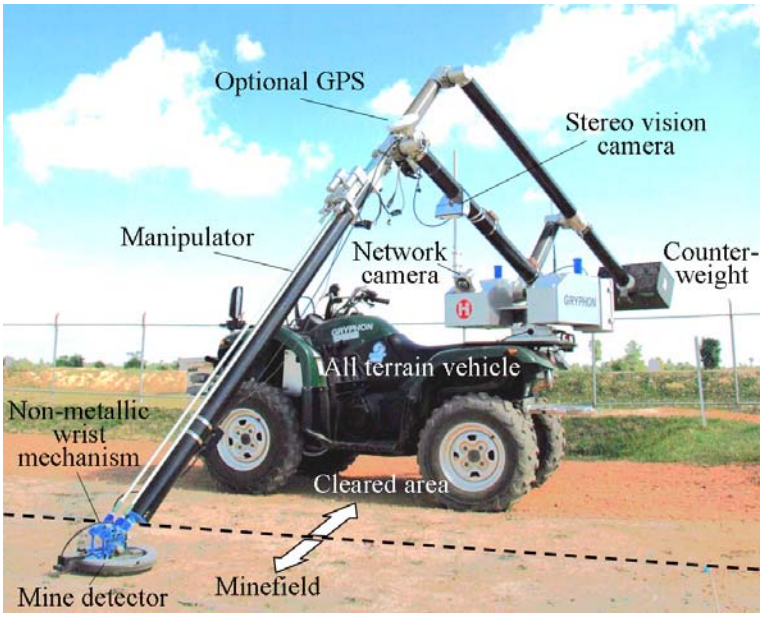


Figure 1: Overview of the Gryphon system.

Safety of the system: Gryphon always operates along the minefield borderline from the already cleared and safe side of the minefield. During the scanning motion, the mine detector is positioned over the dangerous area by the manipulator, keeping a close distance to the ground but without ever touching it. This operation method assures maximum safety for the total system. Additionally, most operation steps are fully automated and Gryphon can be operated and monitored from a safe distance through a control box.

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

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

- *The Mobile Platform*

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

- *The Manipulator*

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

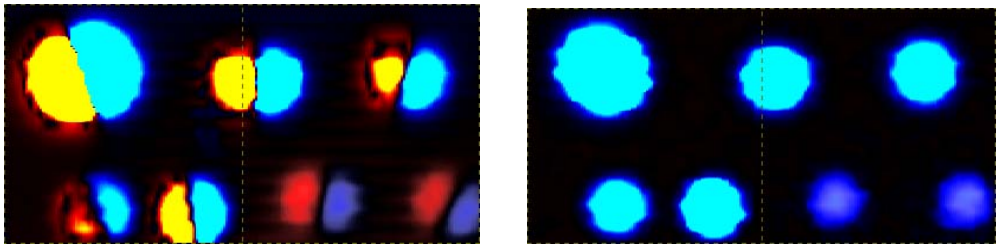
An alternative 3 degrees of freedom wrist mechanism can also be attached to the manipulator and is meant to be used when carrying heavier mine detectors (capacity of about 10 Kg).

- *The Stereo Vision Camera*

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

- *The Mine Detector*

Currently, the default configuration of the mine detector is based on commercial hand-held MDs. Two types are available and have been thoroughly tested: the CEIA MIL-D1 and the Minelab F3. Both are statically operating MDs, they however differ from their generated signals and how their respective image interpretation should be performed. Figure 2 shows the sensor images of two scan passes performed with Gryphon equipped successively with the two MD types over the same 2 m^2 area. One can see that the output of the MIL-D1 (double-coil configuration) has a typical 2-lobe pattern centered over the metallic objects, while the single-coil type F3 produces a simple circle. Still, both are easy and intuitive to interpret even for novice operator/deminer who should identify the landmine/metal fragment.



(a) CEIA MIL-D1 (b) Minelab F3

Figure 2: Illustration of imaging of metal detector's sensor data for targets at different depths

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

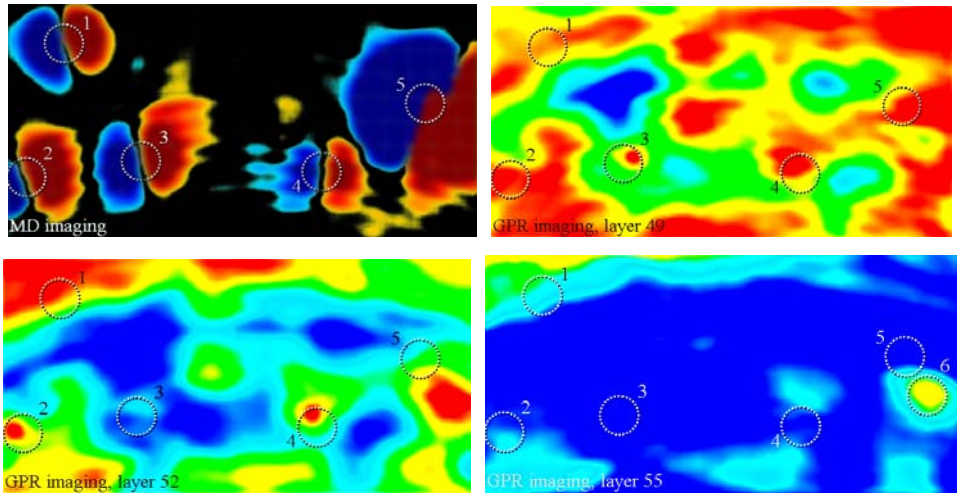


Figure 3: MD and corresponding GPR imaging of a 2 m^2 scan. Buried targets are: 1: PMA-2 at 5 cm depth, 2-4: PMA-1A at 12.5 cm depth, 5: metallic fragment at 5 cm depth and 6: bigger stone at 10 cm depth.

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

- *The Marking Systems*

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



Figure 4: Paint marker and marking plate dispenser.

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

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

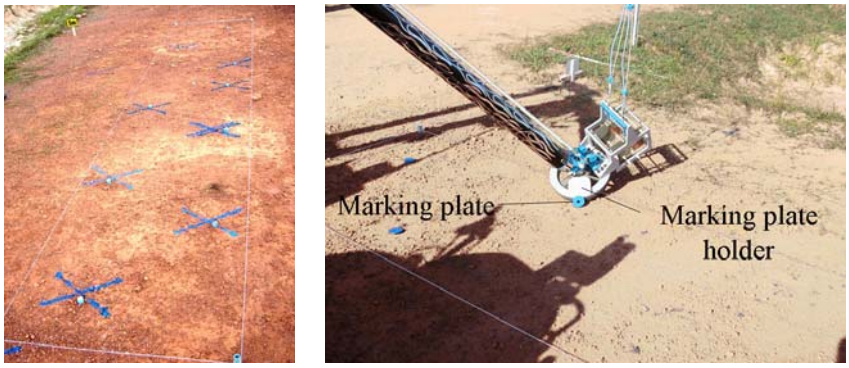


Figure 5. Paint-marked spots and marking plate dropping.

- *The control Box*

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



Figure. 6. Control box.

- *Operation Procedure*

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

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

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

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

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

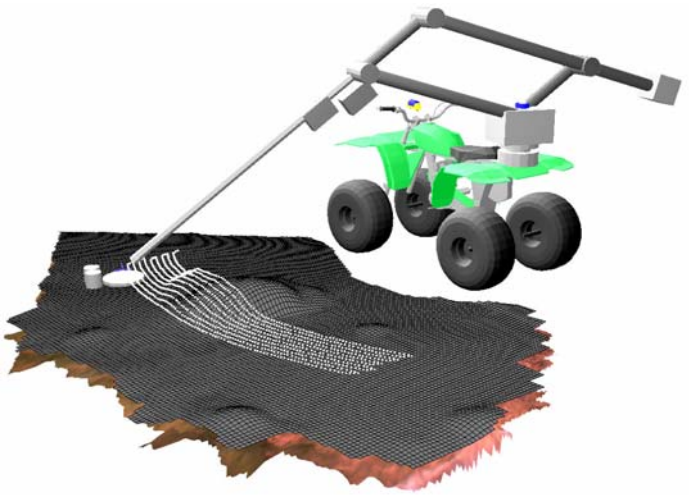


Figure. 7. Control software display image with model of terrain.

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

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

III. FIELD TRIALS

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

i. *Kagawa, Shikoku, Japan, Jan. 2005* [13]
ii. *Benkovac, Croatia, Feb. 2006* [14]
iii. *Siem Reap, Cambodia, Nov.-Jan. 2006-2007* [15]
iv. *Benkovac, Croatia, October 2007* [16]

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

A. The Test Site

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

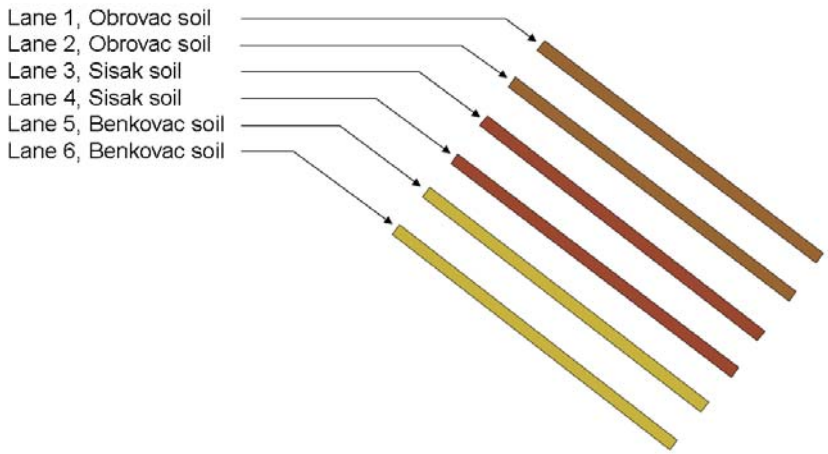


Figure 8. Layout of the test site as acquired by the RTK-GPS.

B. The mine detector

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

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



Figure 9: Gryphon dual-sensor system, composed by metal detector and GPR
(left) MD-Gryphon, (right) GPR-Gryphon

C. Evaluation and Results

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

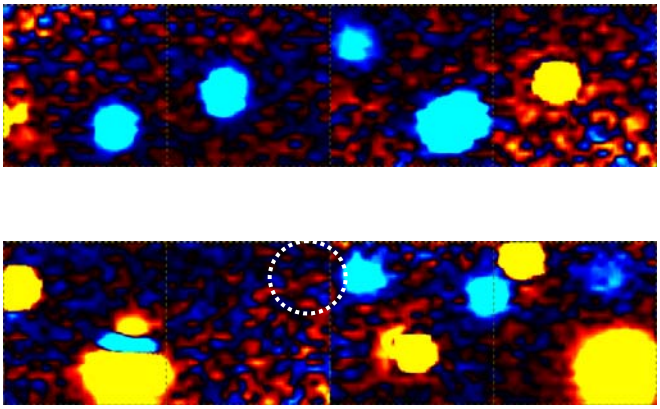


Figure 10. MD images as recorded with the F3-MD-Gryphon. Based on RTK-GPS coordinates, images are automatically appended with the right position/orientation. The adjusted contrast reveals deeply buried objects (indicated with the circle), but at the same time, noise levels also increase.

Marked spots were then scanned and evaluated by the GPR-Gryphon operator. The lack of clear

signal in the GPR images would allow discriminating targets. Once the entire lane was scanned and evaluated, a *total station* would acquire marked spots. This allowed evaluating the performance of the Gryphon dual-sensor system by matching Gryphon-identified target coordinates with the real target coordinates. At the same time overall performance of the dual-sensor Gryphon system doesn't say much about the effect of automation; when looking at MD results only, is Gryphon able to attain the same performance than the handheld version in terms of probability of detection or false alarm rate?

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

TABLE I

PROBABILITY OF DETECTION AND FALSE ALARM RATE FOR MD-GRYPHON

	Probability of detection (POD)	**False alarm rate [m^{-2}] (FAR)**
Lane 1	76%	0.11
Lane 2	86%	0.07
Lane 3	93%	0.04
Lane 4	86%	0.04
Lane 5	93%	0.07
Lane 6	90%	0.04

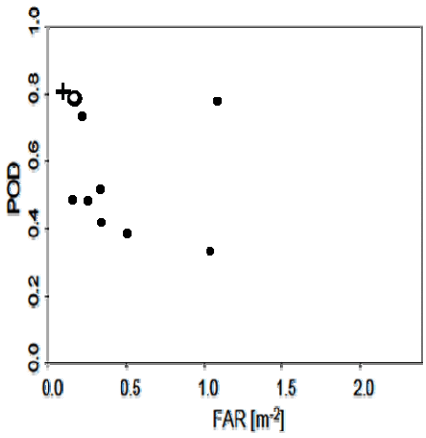
Above results were obtained by using an F3 as sensor payload on Gryphon. The MIL-D1 was also tested on lane 5 (POD of 45% and FAR of $0.21/m^2$). This performance discrepancy between the F3 and MIL-D1 doesn't necessarily tell anything about each MD's overall performance and could be linked directly to the soil type on that lane (some MDs perform better or worse depending on the soil type).

Worth noting, details about the number of targets, type or their burial depth or position were not

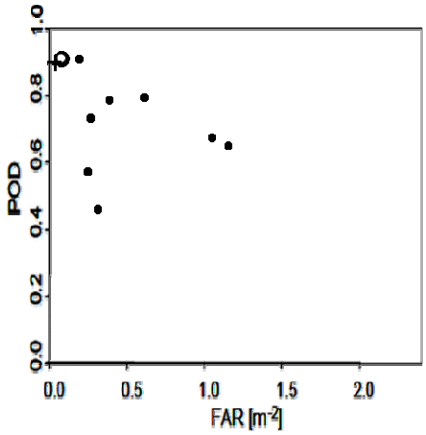
disclosed to the testees at the time of the tests.

The performance of any MD should not be degraded by integrating it into Gryphon. In the worst-case scenario, the MD attached to Gryphon should perform as well as its standard hand-held version. Unfortunately at the time the Gryphon machines carried out the trials, no hand-held MDs were tested so that a direct comparison is not possible. However, the ITEP project of Systematic Test and Evaluation of Metal Detectors (STEMD), carried out in September-October 2006 on the same test site, produced a report [17] comparing several hand-held MDs. Targets in all 6 lanes have remained the whole time in the ground so that a comparison with the MD-Gryphon becomes possible. Figure 11 shows comparative results obtained on each soil type.

a) Lanes 1 and 2 (Obrovac soil)



b) Lanes 3 and 4 (Sisak soil)



c) Lanes 5 and 6 (Bencovac soil)

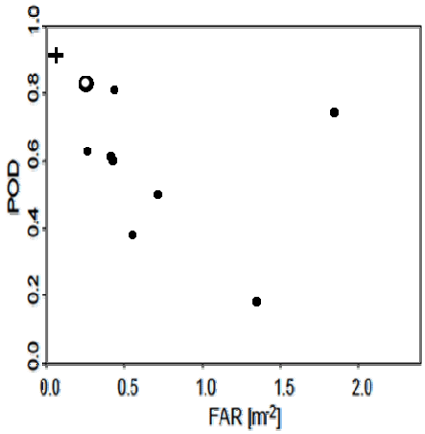


Figure 11. FAR vs POD diagrams for lanes 1-6. "+" indicates performance of Gryphon equipped with an F3, "O" indicates performance of a hand-held F3, and "●" indicate performances of other hand-held MDs tested during the STEMD trial 2006.

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

IV. MD-BASED LANDMINE DISCRIMINATION

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

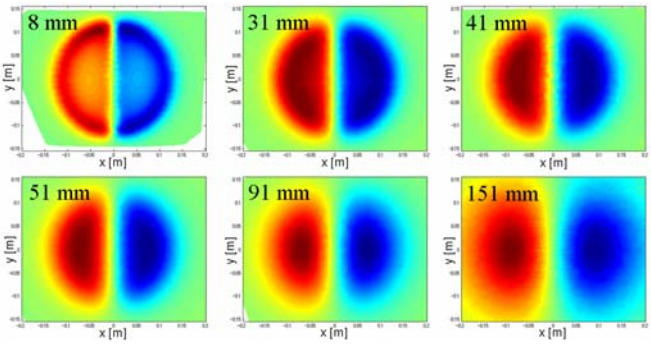


Figure 12. Cut through sensitivity profile of a PMA-2 landmine simulant at various depths. Each image at a given depth has been normalized for better visualization.

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



Figure 13. Metallic targets tested for the discrimination algorithm.

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

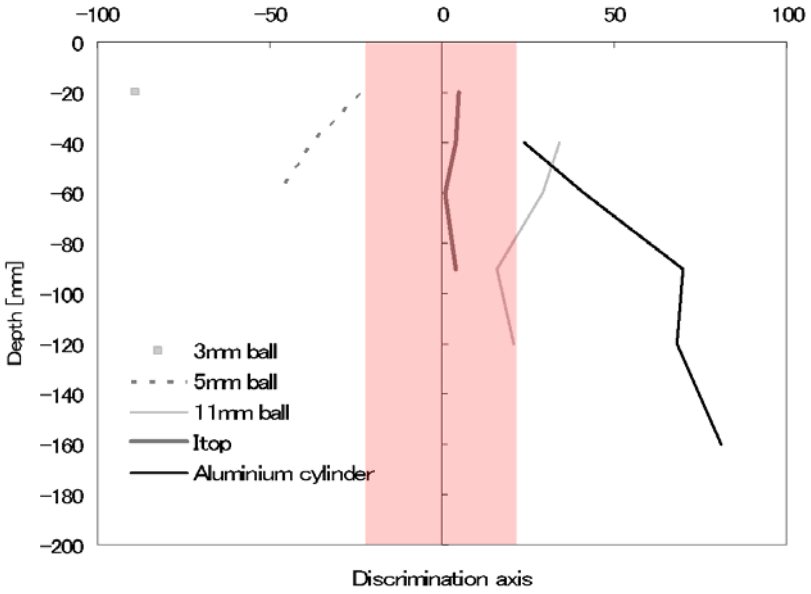


Figure 14. Discrimination experiment result for in-sand buried targets.
The shaded area indicates that the target has higher similarities with the searched object (e.g. itop), and should therefore be handled like a landmine (not discriminated).

V. CONCLUSIONS

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

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

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

The effectiveness of Gryphon as an access-and-control vehicle is already confirmed, and advanced

sensing methods can be integrated to the overall system. It also meets most of the overall requirements and procedures for building a practical system as suggested in [18], so the authors believe that the continuation of the development efforts will produce a practical system in a near future.

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