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Lessons Learned from Field Tests in Croatia and Cambodia

This article describes the development and the experiments performed with Gryphon, a new platform for tele-operated landmine detection. With Gryphon, the authors aim at reducing the gap between research and application by introducing partial autonomy in mine-detection operations with a robust platform. Tests have been performed in Croatia and Cambodia.

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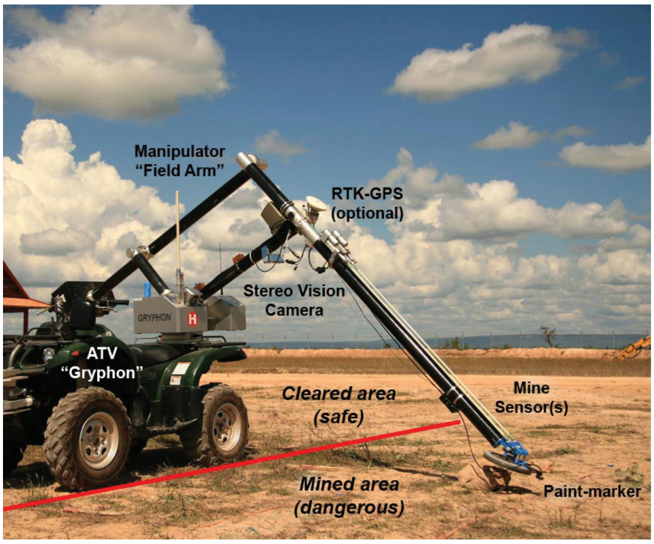
Gryphon is a remote-controlled robot tool with a mobile platform and a robotic manipulator equipped with sensors. The platform moves along the border of the minefield, but always outside of it (called "side-approaching"). There is, therefore, no risk of accidentally triggering a landmine or item of unexploded ordnance. The manipulator can reach inside the minefield and move an array of sensors above the soil. Whenever a possible landmine is detected, the system can mark the spot and move to the next scanning position. Since it never enters the minefield, the system does not require heavy and expensive armoring. In addition, because it is based on a standard vehicle, it can be less expensive than the other armored solutions proposed.

Part of the mine-detection work can be automated; however, the entire operation is always under surveillance of the operator, as is the data-analysis process. The operator performs delicate steps, with remote control, remaining a safe distance from the minefield. This procedure does not exclude the need for armored detonating machines. On the contrary, if the new landmine-detection procedure employed in cooperation with the machines that are already in use, it is believed that the safety —and eventually the speed—of mine clearance can be improved.

In the basic configuration, Gryphon is equipped with mine sensors and can be employed for landmine detection only (Stage II of the tasks performed inside the minefield). With some more research and modifications, it is expected that it could be equipped with other tools, such as rotary cutters and prodders, and be used also for vegetation removal (Stage I) and landmine neutralization (Stage III) by digging the soil and placing explosive charges, thus keeping the human operators away from the minefield at all times.



Gryphon and its subsystems side-approaching a mined area for tests.
ALL GRAPHICS COURTESY OF THE AUTHORS

Subsystems

The platform is based on a commercial all-terrain vehicle. In order to control the ATV remotely, radio-controlled mechanisms have been installed for steering, throttle, braking and gear-changing.[1] The ATV is equipped with a gasoline engine (79cc, 4-stroke) that powers an onboard generator and produces electric energy for all automation mechanisms, as well as for the sensors installed in the manipulator. The platform can operate, therefore, without interruption for one entire day, functioning as a portable source of electricity in the field.

In addition, the ATV can be driven by a pilot. When commuting between the base camp and the minefield, it is preferable to have a pilot driving Gryphon. In this way, no additional vehicles for transporting the machine are required. Once Gryphon reaches the border of the minefield, it can be switched to remote-driving mode.

The manipulator is named Field Arm and was designed in a pantographic configuration, so it is balanced by a counterweight in any posture. Very little energy is required when moving the manipulator or when keeping it still above the minefield because of the balance. Field Arm has been developed with carbon-fiber pipes and aluminum joints, and the actuators are located in its base. Experiments have confirmed that Field Arm consumes much less energy than a conventional manipulator even when the base is inclined[2] as is often the case when operating on rough terrain.

The sensing unit is mounted on the manipulator and may consist of different sensors, as required by the tasks and environment. In the current platforms, the authors are employing a real-time kinematics global positioning system (to acquire the coordinates of objects and mark them in a virtual map), a stereo vision camera (to acquire depth maps from the minefield and generate a three-dimensional model of the terrain prior to scanning it), a MIL-D1 metal detector (*Costruzioni Elettroniche Industriali Automatismi*, Arezzo, Italy) and a ground-penetrating radar unit developed by Tohoku University, Japan.

For marking possible landmines, there are two different mechanisms. One is based on paint, with a nozzle installed at the tip of the manipulator, and a pump-and-paint cartridge assembled on the base of Field Arm. The other mechanism consists of a dispenser of plastic discs assembled on the main body of the vehicle, and a plastic pad mounted on the tip of the manipulator. When the position of a possible landmine is identified, the manipulator moves automatically to the disc plate dispenser, takes one disc plate and drops it on the desired spot in the minefield.

Physical markers on the minefield to identify the positions of possible landmines are a requirement of the deminers, since they cannot rely only on electronic data; however, for redundancy, all the marked positions are also recorded with coordinates provided by the GPS device.

Simplified SOP

The standard operating procedure described below applies to Stage II (landmine detection).

Position ATV. A typical operation starts with the positioning of the ATV along the border of the minefield (see Figure 2a). The ATV may be driven by a pilot along the minefield, but ideally it should be controlled remotely.

Acquire images. Once the ATV is in place, the stereovision camera will acquire images of the minefield and generate a three-dimensional model of the terrain (see Figure 2b) so that rocks, bumps and ditches can be recognized. At the same time, a scanning path will be generated automatically, taking into account all obstacles present in the three-dimensional model.

Scan area. In the next step, the manipulator will scan the area automatically, following the trajectory on the three-dimensional model of the terrain (see Figure 2c). The operator does not need to control the manipulator. Because of the automatic control, the distance between scanning lines and the scanning speed are always kept constant, contributing to the reliability of the process.[3,4]

Display data. Once the scanning is over (it takes between two and 12 minutes to scan an effective area of 2 square meters [21.5 square feet], depending on the sensors used), the data acquired by the sensor(s) are displayed for the operator in a remote controller (see Figure 2d). It is then up to the operator to decide what signals correspond to possible landmines. To assist this delicate task, several techniques can be employed, such as adjusting the contrast of images or combining data from different sensors in the same image.

Mark mines. When the possible landmines are identified, the operator chooses their positions on the display of the remote controller. Then the manipulator moves automatically to the selected spots to mark them (see Figure 2e), either with paint or with a disc plate. The operator may then move the ATV to the next scanning position and repeat the process.

Experiments in Croatia

The Croatian Mine Action Centre has been employing great efforts to clear its remaining minefields. CROMAC's Center for Testing, Development and Training is testing new technologies,[5] and Gryphon was selected for detailed tests of sensors and locomotion.

Description of the tests. The tests were performed in one of the CROMAC training sites in Benkovac and consisted of eight lanes (16m by 1m) with objects buried at previously undisclosed positions. Each lane was made of different types of soil: uncooperative and heterogeneous, uncooperative and homogeneous, and cooperative and homogeneous.


Figure 2a: Positioning the ATV.

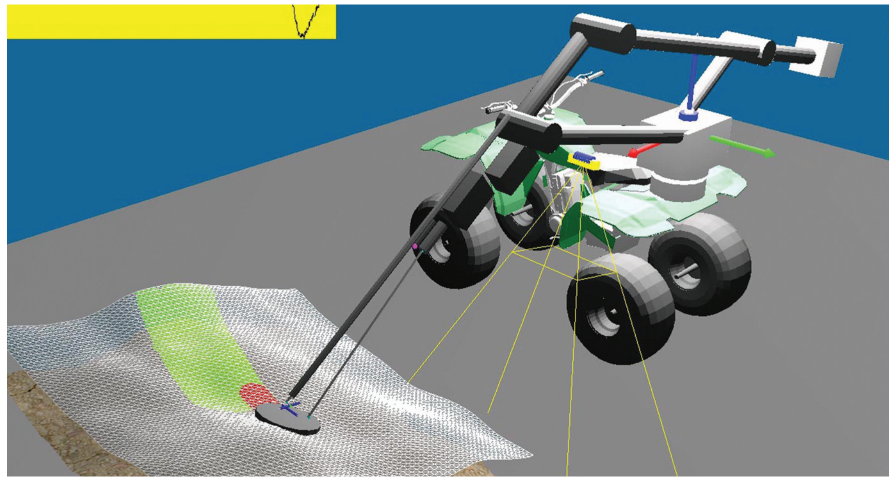


Figure 2b: Generating three-dimensional model of the terrain.

Figure 2c: Automatic scanning.

Each lane had a 1 square meter calibration box, where the positions of the landmines were known. Among the buried objects were PMA-1 and PMA-2 mines[6] (all landmines were previously deactivated for safety reasons), metallic fragments of various shapes and light ammunition shells.

During these tests, one Gryphon unit was employed, with a metal detector and GPR set as the sensor payload (see Figure 3). In addition, at that time the GPS and other marking systems had not been implemented yet, so every time a possible landmine was identified in the data from the sensors, it was necessary

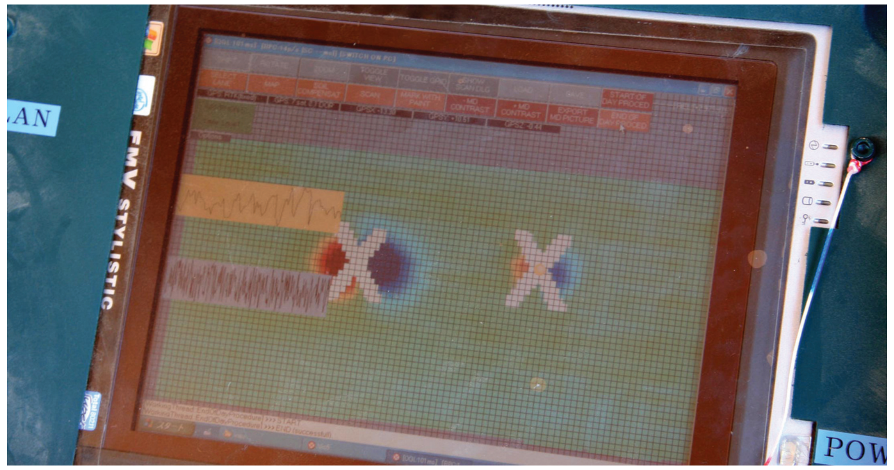


Figure 2d: Visual analysis of data.

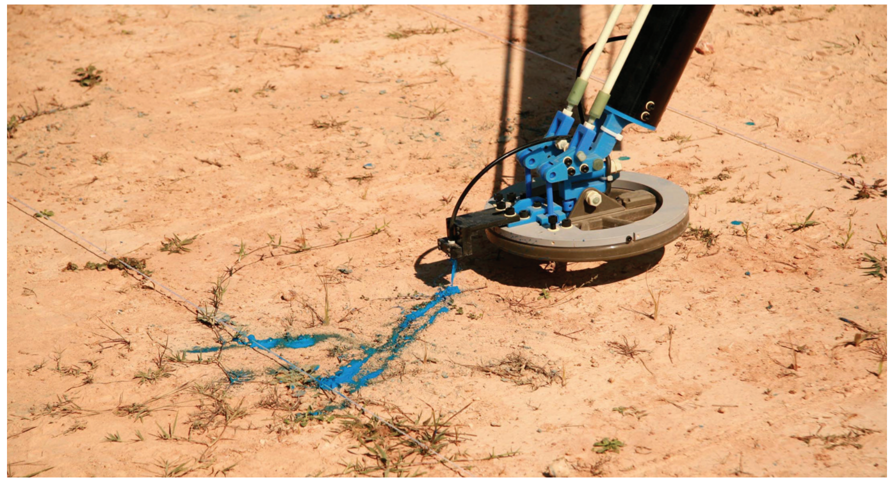


Figure 2e: Marking buried objects.


Figure 3: Gryphon undergoing tests in Benkovac, Croatia.

to measure its coordinates and then manually place a disc plate on the test lane. The operation of Gryphon and the analysis of the data acquired with the sensors were performed by members of our team, with limited interaction with local deminers. However, operating in conditions close to those of a real minefield provided the authors with feedback and insights that are often missed when developing machines in the controlled environment of a laboratory or factory.

Results. During the tests, each team was asked to employ the data from the GPR to determine if the metallic target detected by the metal detector was a landmine, a metallic fragment or just noise. The official results of the tests were compiled based on these instructions. The operators, therefore, were supposed to mark any positive signal from the MD as a metallic fragment if the GPR did not show clearly the shape of a landmine. If the target actually was a landmine, the final result would be considered a false negative (i.e., a missed landmine), even though the MD identified the presence of a metallic object.

Ground-penetrating radar is a new technology that is still undergoing adjustments and improvements. To bring Gryphon closer to real minefield conditions where only MDs are employed as sensors, the authors have made a new evaluation of the results, considering only the data from the MD assembled on the manipulator of Gryphon.

Gryphon performed two scans for each type of soil (namely, cooperative homogeneous in Lane 1, uncooperative homogeneous in Lane 3, and uncooperative heterogeneous in Lane 7). Table 1 (next page) presents the results of the tests after the new evaluation by the authors, plotted against the best-performance set by two human deminers working with standard handheld MD. As one can see, the Gryphon-mounted MD performed better than the standard in Lane 1. In Lanes 3 and 7, however, the performance of Gryphon was inferior to the standard. In addition, Gryphon presented a higher rate of false positives per square meter in Lanes 1 and 3 than the standard values.

Note that neither handheld nor Gryphon methods achieved a 100-percent detection ratio. This is normal for a test setup, where a relative comparison of the results of the tests with many different sensors is necessary.

The performance of any sensor should not be degraded by integrating it into Gryphon. In the worst-case scenario, the sensors assembled on Gryphon should perform as well as the standard handheld sensor. This was true only in Lane 1. Among the reasons for an apparent decrease in the performance of the Gryphon-mounted MD, there may be problems in the calibration of the MD, in the analysis of the data and in the positioning/marking on the terrain. The latter was especially repetitive, time-consuming and prone to errors. The authors strongly believe that the performance of the MD assembled on Gryphon was not decreased and that the results in Lanes 3 and 7 inferior to the standard are due mostly to the reasons mentioned above. Later experiment results from tests in Cambodia (2006, presented next) and a different set of tests in Croatia (2007) demonstrate that, in fact, Gryphon can achieve better results than hand-held scanning. Official results of the CROMAC test should be available in 2008.

Figure 4: Gryphon in the CMAC test field in Siem Reap, Cambodia.

In spite of the problems, the local deminers praised some of the features of Gryphon. One of them was the visualization of MD data on a display. Instead of identifying buried metal only by sound from the MD, with Gryphon it is possible to store the data from the MD and then display it as a color graphic. Because the motion of the manipulator is kept at a constant speed with regular intervals between the scanning lines, the visual interpretation of data can be considered to be reliable, something that would be very difficult to achieve with a handheld MD.

The automatic three-dimensional terrain model generation capability with the stereovision camera performed as expected and allowed Gryphon to scan irregular soil, keeping the sensor head always a constant distance from the ground. This feature is an important one, since some landmines with low metal contents may be missed if the MD is too far from the soil.

The most important lessons learned during those experiments were:

- Automatic positioning and marking systems should be integrated to reduce the operating time while scanning a minefield.
- Analyzing and displaying data should be done in a faster and more intuitive way, since one cannot afford to work on a desk inside a room in a minefield.
- The most basic and repetitive tasks, such as acquiring images for the three-dimension terrain model and copying sensor data from Gryphon to the portable control unit, should be automated, so that the operator can focus his or her attention on the supervision of the system.

Experiments in Cambodia

The Cambodian Mine Action Centre has been working to remove landmines remaining from conflicts 30 years ago in what, at first sight, may seem to be an overwhelming task. According to a senior manager of CMAC, approximately 75 percent of the country remains to be cleared of landmines in a verifiable way. CMAC has been focusing its efforts on high-priority areas such as roads, villages, water reservoirs and fields suitable for agriculture. The consequences of these efforts can be seen in villages flourishing again, schools being rebuilt and infrastructure being slowly, but steadily, restored.

Description of the tests. The tests were performed in the training facilities of CMAC close to Siem Reap (see Figure 4), and consisted of seven lanes (25m by 1m). The buried objects consisted of anti-personnel landmines (Type 69, Type 72, MN79, PMN, PMN-2), anti-tank mines (TM-46),[6] UXO (60-mm and 82-mm mortars), metal fragments and wood blocks, all in undisclosed positions. In front of each lane, there was a calibration box of 6m by 1m, where the positions of the landmines were known. The lanes were composed of clay, sand and laterite soils (the latter with a high iron composition), in both dry and wet conditions.

During the tests, two versions of Gryphon were employed: one with an MD and paint marker, and another one equipped with MD, GPR and a disc plate marker. Both vehicles were also equipped with the real-time kinetics GPS.

Local deminers operated the system and the authors were prohibited from entering the test lanes. Only access to the calibration boxes was granted, where the deminers were instructed in the operation of the system for approximately two weeks. After the initial period of training, the local deminers were able to operate both vehicles without any support from the authors and solved some simple problems that happened during the operation. The analysis of acquired data from MD and GPR was also performed by the deminers in the field.

The greatest change in the Gryphon system between the tests in Croatia and Cambodia was perhaps in the user interface. In order to make it easy to operate for local deminers (many of whom had no previous experience using a computer), the interface was greatly simplified with fewer buttons and switches, and an intuitive graphic interface based on colors was added.

The automatic marking system contributed even further to reducing the errors in marking the objects. Even though the paint marker required cleaning at the end of each day to

	Standard hand-held MD			Gryphon-mounted MD		
	Detection Ratio	False Positives	False Negatives	Detection Ratio	False Positives	False Negatives
Lane 1	79.8%	0.19 per m^2	20.2%	86.9%	1.56 per m^2	13.0%
Lane 3	92.9%	0.63 per m^2	7.1%	83.0%	2 per m^2	16.6%
Lane 7	75.0%	1.8 per m^2	25%	65.5%	1.81 per m^2	34.5%

Table 1: Results of scanning tests in Croatia.

Figure 5: Portable control unit improved and adapted for use by deminers in Cambodia.

	Hand-held MD (standard)			Gryphon-mounted MD		
	Detection Ratio	False Positives	False Negatives	Detection Ratio	False Positives	False Negatives
Lane1	98.0%	0.62 per m^2	2.0%	98.0%	0.52 per m^2	2.0%
Lane 2	72.0%	0.8 per m^2	14.0%	90.0%	0.78 per m^2	10.0%
Lane 3	92.0%	0.24 per m^2	8.0%	92.0%	0.30 per m^2	8.0%
Lane 5	84.0%	0.44 per m^2	8.0%	88.0%	0.78 per m^2	12.0%
Lane 6	96.0%	0.4 per m^2	4.0%	96.0%	0.96 per m^2	4.0%
Lane 7	52.8%	0.56 per m^2	44.5%	52.8%	0.50 per m^2	47.2%

Table 2: Data for each lane of the test site for Gryphon equipped with MD. Data from lane 4 were not available at the time of publication.

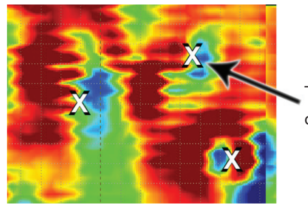


Figure 6: Example of a landmine identified by Gryphon but undetected by the standard handheld MD.

prevent the dried paint from clogging the nozzle, it performed slightly better than the plastic marker. Sand and dust that accumulated on the marker pad sometimes prevented the plastic markers from sliding smoothly from the manipulator to the ground.

Results. The tests assessed target location and accuracy, proximity between landmines (resolution), and effects from radio frequencies. These tests basically evaluate the sensors attached to the tip of the manipulator of Gryphon. In order to prove that mounting the sensors on Gryphon does not affect their performance, the detection ratio of Gryphon should be at least similar to a standard detection ratio. In the case of Cambodia, this standard reference was set with experienced deminers scanning the test lanes with a handheld MD (Minelab F1A4).

The standard evaluation procedure in Cambodia considers an area around the buried target where the detection point must be placed. The targets should be marked before their actual position or exactly where they are buried, but not after. This assumption is made in order to ensure the safety of the deminer who will prod and dig the soil to uncover the target before he continues to scan the remaining area. All the results of the experiments were analyzed according to this evaluation procedure.

This evaluation procedure does not necessarily apply to vehicle-mounted sensors. In the case of Gryphon, detecting targets does not interfere in its progress along the lane. Therefore, the standard halo area around the landmine[7] was employed, and the data were re-evaluated by the authors. These data are presented in Table 2 (referring only to MDs), along with the standard values set by handheld MDs.

The detection ratio obtained with Gryphon matched those of the standard, meaning that there is no degradation in the detection capability. In fact, in two lanes Gryphon achieved a higher detection ratio than the standard. This improvement might be credited to the fact that Gryphon keeps the scanning speed and distance between scanning lines always constant. With a handheld MD, there may be small variations in the scanning speed and pitch induced by the operator. In addition, the visual analysis of data may contribute to locating targets that were not found by the handheld MD. Figure 6 shows, as an example, one landmine that was not detected by the standard MD, but that was located with the graphical analysis of Gryphon by greatly increasing the contrast of the obtained image.

The targets missed by Gryphon were also missed by the standard MD, which means they were buried in positions that were too deep or too difficult to detect by a conventional MD.

Lane 7 was composed of three different sections of dry sand, dry clay and dry laterite. In addition, the targets consisted of Type 72 anti-personnel mines and TM 46 anti-tank mines,[6] buried close to each other. This layout was devised to test the limitations of the sensing devices. In fact, the MD data often showed only one target when an anti-tank mine was buried beside anti-personnel mine. Therefore, the detection ratio in Lane 7 was considerably lower than in all other lanes. Even then, the results obtained with Gryphon match the standard.

These results are closely tied to the type of mine sensor used. Obviously, they are also affected by the capability of Gryphon to move the sensor close to the ground at a constant speed, with uniform spacing between the scan lines. The other features of Gryphon (safety of operation, simplicity of operation, visualization of scanned data and comfort to the user) were evaluated with feedback from the local deminers.

It is clear, therefore, that the weakest points of Gryphon were in its relatively complex assembly, insufficient documents and manuals for operation and maintenance, and the readability of the portable display against the strong sunlight in Cambodia. Equipment that requires maintenance by local deminers has been placed in easily reachable places. Additionally, the authors are working to improve the technical documentation of Gryphon, including a video showing the standard operating procedures that can be used in training. Finally, the display of the portable control unit must be covered by a portable shade (which can be folded inside the control unit) and placed, whenever possible, against the sunlight.

Comfort to the operator, safety, and ease of understanding the graphic interface and audio tones were ranked highly by the deminers. The controls and the operation sequence still can be improved to meet the SOPs of CMAC. The feedback from the local deminers about the vehicle-mounted approach is very encouraging and suggests that if Gryphon is employed in combination with other sensors, it may reach a detection ratio higher than the standard.

Future Works

From the reevaluation of 2006 field tests in Croatia and Cambodia, it can be concluded that the performance of landmine detection with Gryphon has reached a satisfactory level. Vegetation removal (see Figure 7) has been studied to some extent, but there is still some research required before its implementation. With the use of rotary tools connected to the end-effecter of Field Arm, it would be possible to cut vegetation prior to performing landmine detection, while keeping the operators away from the minefield.

Another task that would benefit from the use of a remote-operated tool is landmine neutralization. To perform landmine neutralization with Gryphon, prodders and other digging tools could be attached to the end effecter of Field Arm. Additionally, placing explosive charges for the detonation of landmines on the spot could be achieved with another tool connected to the end-effecter of Field Arm. For this purpose, a common interface between the various tools must be designed and implemented, so that the same platform (Gryphon and Field Arm) can be employed for all demining stages of the works performed inside a minefield.

System Operation		Ergonomics		Others	
Assembly	2.0	Comfort	4.0	Manuals/Documents	2
Operation	3.0	Audio Tones	3.0	Safety	4
Understand Alerts	4.0	Readability of display	2.3		
Graphics Interface	4.7	Controls	3.3		
Change batteries	5.0				

Table 3: Evaluation of vehicle-mounted system Gryphon by Khmer deminers (from 1 to 5, with 1 being the lowest and 5 the highest evaluation).

Figure 7: Vegetation removal and landmine detection performed in a minefield in Cambodia.

Conclusions

The Gryphon system for remote landmine detection has seen steady progress in recent years, mainly due to the field experiments performed in Japan and other countries. By testing the machines in close-to-real-world conditions and operating them with local deminers, it is possible to learn much about their requirements, not only in terms of environmental resistance (extreme temperatures, rain, sand, etc.) but also with respect to operational procedures and human-machine interface. Any system or tool developed in laboratories of factories to assist humanitarian landmine clearance should be tested in the field as soon as possible, ideally in the presence of deminers, so that they can be adjusted to the local conditions and needs.

It is important to note that Gryphon is a mobile platform for remote operation in minefields. The results of tests described in this paper and the rate of landmine identification are linked directly to the types of sensors employed. The authors designed this system so that it can easily be adapted to operate with different kinds of sensors, according to the minefield conditions and requirements.

Furthermore, the experiments in Croatia and Cambodia proved that the vibration generated by the gasoline engine of Gryphon, the compliance of the suspension of the vehicle and the motion of Field Arm do not negatively affect the performance of the sensors used. There were also no interferences with the electronics of the sensors employed. Instead, with the controlled motion of Field Arm, it was possible to acquire data in a regular density, something that is very difficult to achieve by moving the sensors manually. It is this regular pattern that allowed the visual analysis of data on a screen, greatly enhancing the evaluation process.

The Gryphon system performed as expected in Croatia and Cambodia. Although there are still details to be improved, the authors are testing other sensing technologies and hope to deploy the system in minefields for landmine detection in the near future. ✣

See Endnotes, page 114

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