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Multi-sensor cooperative robots for shallow buried explosive threat detection: radar sensors and optical sensors integrated by system software

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***Abstract*—This project has fully demonstrated a new paradigm using a team of cooperating robots carrying different sensors, with data fusion for detection and discrimination of surficial and buried landmines. The system is operated remotely with negligible risk to the operator. The integration of information collected by three robots has been achieved by software architecture. With this architecture, it is possible to plan the mission path, optimize the sensor settings and visualize the data from a remote terminal (e.g., a tablet or smartphone). The sensors used for the detection of plastic and metal landmines are installed in a configuration of three robots: microwave radar (Robot #1 with a UWB radar and Robot #3 with HSR radar), LiDAR (Robot #1 and Robot #3), high-resolution camera (Robot #1), and metal detector (Robot #2). The acquisition and processing of data from multiple radar sensors displayed improved detection and classification for small plastic-cased low-metal-content landmines (e.g., M-14 and Type 72) using high resolution microwave radar. These are generally difficult to detect with metal detectors alone. In real scenarios like the ongoing war in Ukraine, surface landmines like the PFM-1 ("butterfly"), are often scattered on the surface, and we demonstrated how artificial intelligence can be applied to detect this type of threat. Finally, because of booby traps rigged to protect minefields, demining also requires the detection of tripwires. For this purpose, the first robot in the team can detect trip wires of different types (metal, fiber or plastic) in real time. The robotic platforms are equipped with GNSS providing mapping of targets with accuracy better than 10 cm.**

Keywords—Artificial Neural Network, GPR, GPS, Holographic Subsurface Radar, LIDAR, Metal Detector, Unexploded Ordnance, UWB, Robot swarm.

I. INTRODUCTION

In this paper, we describe a team of cooperating robots equipped with independent complementary sensors. These robots were deployed in a realistic mock minefield to obtain data sets for selected small plastic-cased low-metal-content (LMC) antipersonnel (AP) mine simulants and common clutter. The ground-based sensor system described here has some advantages over unmanned aerial vehicle (UAV or drone) investigations, about which there have been numerous recent studies. These include drone experiments using ground penetrating radar (GPR) and synthetic aperture radar (SAR) [1], [2], [3], [4], [5], [6] with autonomous drone navigation [7]. The advantages of the ground-based system over drones include battery life/working time, the ability to get very close to the ground (so the distance to the mine is on the order of centimeters instead of meters), a lack of jitter in the spatial positioning of the sensor if the ground-based sensor platform is stationary, and the ability of robots to maneuver within areas where drones might get tangled in trees or other overhead obstacles (see, e.g., [8] for an overview). These advantages play a major role for detecting small antipersonnel LMC AP landmines. In this paper, we describe the radar sensors and optical sensors integrated by system software for fusing the data. The objective of this system is to also include optical sensors to complement the GPR technology with optical sensors to scan the ground surface. The detection of buried and surficial unexploded ordnance (UXO) is mandatory for implementing remotely controlled detection systems. The sensors are mounted on three robots [9] which are specialized for collecting information and sharing it in a database.

NATO Science for Peace and Security Programme grant for project G7536, https://www.natospsdeminingrobots.com/

II. IMPULSE GROUND PENETRATING RADAR (GPR)

Robot #1 is designed to have ultrawideband (UWB) GPR for rapid detection of buried plastic or metal objects [10]. As shown on the graph in Fig.1, the GPR has a sub-centimeter accuracy for positioning detected objects. It is also the best method for detecting LMC or entirely plastic objects. Results of tests of the UWB GPR for detection of M-14 and T 72 small diameter plastic-cased LMC landmines show reliable detection of these targets that are barely detectable with a metal detector (MD). After spatial filtering applied to decrease the false alarms, the two plastic landmines are detected at a sequence of three and four consecutive positions of Robot #1, with only one false alarm (single dot on top right). Dimensions of the full survey area were 16 m by 3 m. [11].

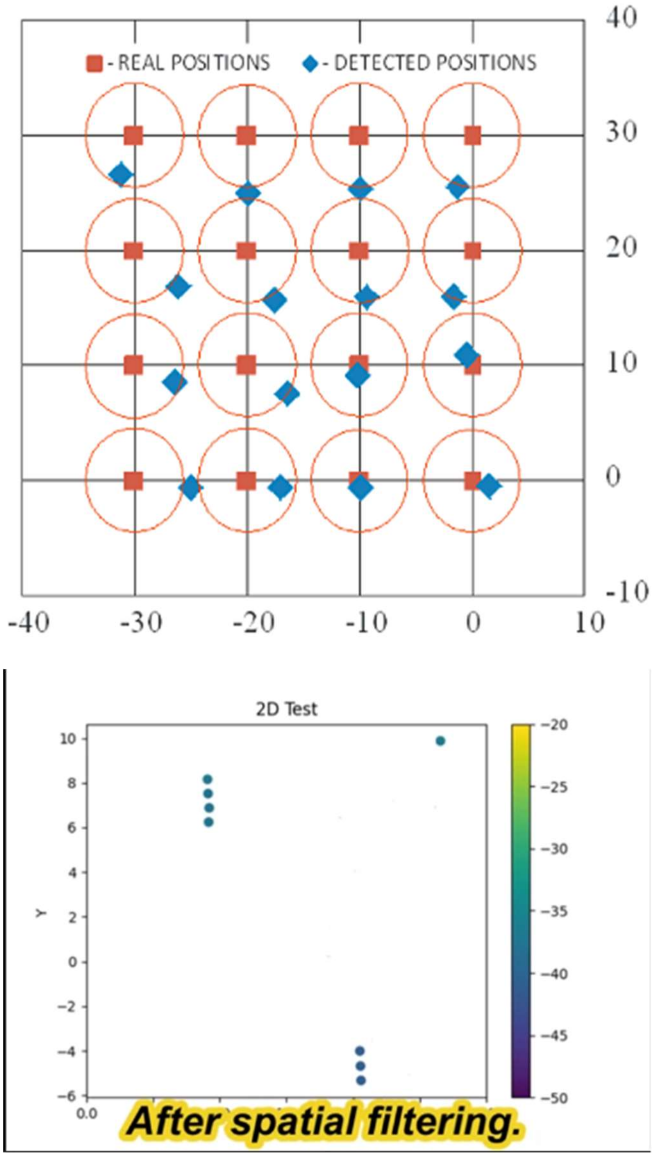

Fig. 1. (Top) Results of tests of the impulse GPR for shallow buried targets (both plastic and metal). The units on both the axes are cm. (Bottom) Real-time detection and positioning of two LMC AP landmines. The figure shows a 1 m by 1m sample of the 16 m by 3 m testbed.

III. REAL-TIME TRIPWIRE DETECTION

Robot #1 uses a camera to detect a tripwire in the field. With this technology being part of the first robot, the subsequent robots can avoid the tripwire. We also already have a request for tripwire detection spin-off technology. We have gotten a request from the Armed Forces of Ukraine and the State Emergency Services to help modify our algorithm so that people on the front lines can use GoPro cameras mounted on their helmets to detect tripwires.

An example of the results obtained from the field is the detection of three different tripwires (a metal wire painted green, a fishing line, and a colored military-grade metal wire) at the focus distance of about 50 cm with 3 frames per second. Fig. 2 shows the real-time detection of a military-grade green tripwire in a field: the red line overlay of the live video camera indicates the successful detection. In the background behind the laptop PC display you can see the Robot#1 in the tripwire test field at F&M, Baker Campus.

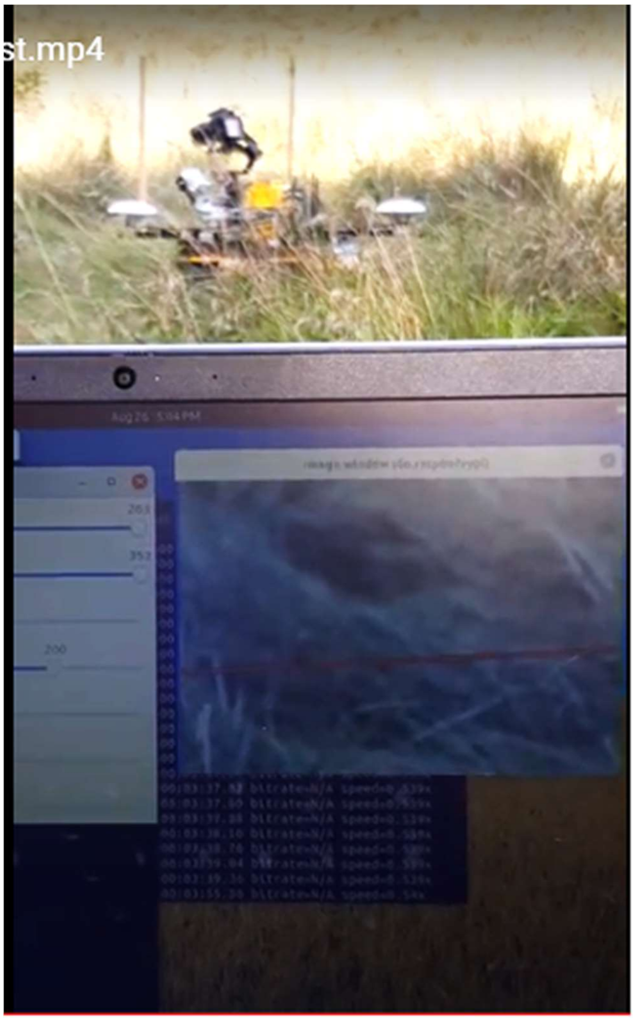

Fig. 2. Screenshot of the real-time tripwire detection by a remotely connected terminal to Robot #1. (See also the video: https://drive.google.com/file/d/1UeMUwQBvmkozCH3wP0WTPo5HZ6-E8p8j/view?usp=drive_link). Note in the background image the Robot #1 is operating in the field with high grass.

IV. REAL-TIME AI SURFACE THREAT DETECTION

Using an iPad/iPhone with AI real-time detection (Yolo) and LIDAR, Robot #3 can detect surficial objects. A model for training an artificial neural network (ANN) is developed based on a large database of videos acquired at UNIFI and F&M, under different light and weather conditions. The dataset is labeled using CVAT software. The detected object is localized virtually on the screen as the identification is made. Fig.3 is an example of real-time detection and positioning for targets PFM-1 “Butterfly” and PMA-2 “starfish” [12].

Fig. 3.. Surface threat detection using AI. (See also the video: https://drive.google.com/file/d/1eZaCW97h4hpwm2b-fdL7MBNVrcfdxQpJ/view?usp=drive_link)

V. METAL DETECTOR SCANNING SYSTEM

A Fisher Model M-101 MD was used to record a signal (voltage as read from the MD audio jack by a Fluke digital multimeter) as a function of lateral position from the object center for several height offsets from the surface of the object. The vertical offsets used were 0, 5, 10, 15, and 20 cm. Fig. 4 shows a comparison of the “heat maps” obtained by scanning two plastic-cased landmines: the PMN-4 and Type 72. It is evident from the figure how difficult the detection of the small Type 72 mine is with this MD even under ideal conditions.

VI. HOLOGRAPHIC SUBSURFACE RADAR IMAGING AND LIDAR DEPTH IMAGE FUSION

In this section, we report the results from two test runs with the holographic subsurface radar (HSR) antenna at distances of 5 cm and 3 cm from the target, respectively, with a frequency range from 1.95 GHz to 2.05 GHz [13], [14]. The graphs shown Fig. 5 and Fig. 6 are the best-obtained holograph inversion results. We look for contrast between amplitude and/or phase values to identify an object by its shape and dimensions. The images collected in a database are used to train various ANNs for more robust detection and classification in different scenarios [15]. Both inverted (3D) and original holograms (2D) are used to train two-class and fine-grained classification ANNs [16]. The microwave images are of the buried targets in the test field we have designed for this project, which also contains a crushed aluminum can and a 25 mm shell casing representing metallic clutter.

Geometrical and dimensional features are retrieved from these images in order to discriminate mines from both natural and anthropogenic clutter. One can observe that both M-14 and Type 72 landmines are discriminated by distinctive features in the imaging.

The approach of HSR + Optical + LiDAR images is operational but not yet fully validated in the system. Data can be visualized and scaled by a GUI and an example of a surface VS-50 landmine is reported. We can observe that the LiDAR provides surface profile variation of an object or the soil, both types of information are useful to improve the interpretation of the HSR image.

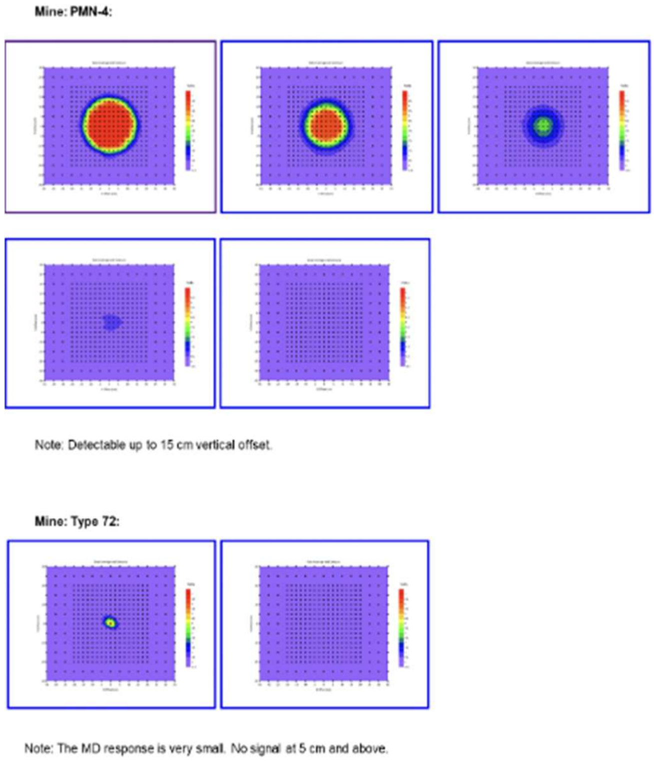

Fig.4. High-spatial-resolution laboratory measurements taken with a MD of two different AP landmines: a small plastic LMC Type 72 mine and a PMN-4 mine.

Fig. 5. (Left) picture of the AP landmine; (Centre) Amplitude image of HSR at antenna height h=3 cm and (Right) at h=5 cm.

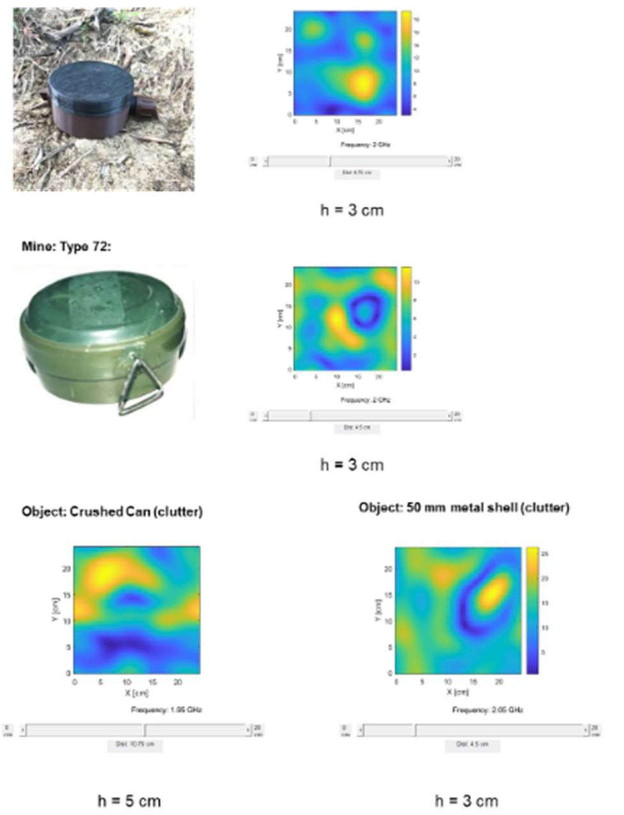

Fig. 6. (Left) picture of the AP landmine; (Right) Amplitude image of the microwave radar hologram at antenna height h=3cm. Bottom line: the amplitude image of the hologram of two clutter objects: a crashed can and a 50 mm caliber bullet.

As shown in Fig. 7, the optical image is correlated with the other two when a surface feature is found in the HSR and LiDAR images. In this case, the HSR imaging is well-correlated and interpreted as the response of a VS-50 AP landmine deployed on the ground surface (not buried).

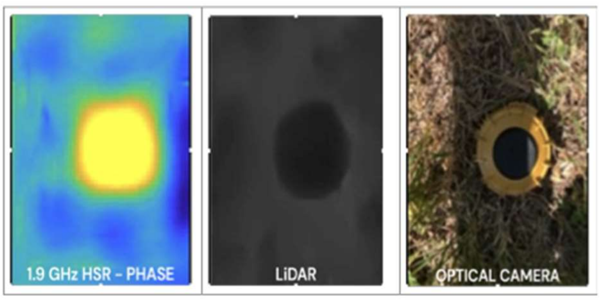

Fig. 7. Correlation of images obtained with Robot #3 carrying a HSR, a LIDAR, and an Optical Camera.

VII. CONCLUSIONS

The paper has provided a first evaluation of the multisensory system for landmine detection and some of the the main accomplishments of the project are discussed below:

● The optimization of MD and GPR operating parameters is still needed for best ROC performance in discriminating explosive devices from clutter, besides the preliminary test in relevant experimental field have been obtained.

● The real time GPR processing for triggering an alarm and associated to the position obtained by the GNSS real time kinematic module is useful to map all subsurface object. It is still difficult to discriminate the detection of a buried landmine from a clutter object. Beside this limitation, even the most difficult low metal content M14 and Type 72 landmines have been detected.

● The design and test of the real time tripwire detection system is completed. The proof of concept is demonstrated but the high resolution optical camera installed on robot #1 is too expensive and not rugged to operate in harsh environment. A work in progress is the replacement with an outdoor camera with lower resolution, lower power consumption.

● The development of Holographic Subsurface Radar with a 3D printed compact antenna and integration with 3D optoelectronic scanner data for buried object classification interpretation has been validated and demonstrated successfully to enhance the interpretation of HSR microwave images that can be misinterpreted for the classification when a surface object is present..

● 3D Radar imaging processing and 3D optoelectronic scanner data fusion by using a large database.

● AI for real time surface threats detection and positioning become has been successfully applied with a model executed in a remote server. The perspective of this work is the execution on board of the robot by installing the model on a high performance computer board.

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