Multi-sensor cooperative robots for shallow buried explosive threat detection: system architecture, mission strategy, and test field results

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***Abstract*—We describe a new paradigm using cooperating robots and multi-sensor data fusion for surficial and buried plastic and metal-cased landmine detection. The system operates remotely minimizing risk for the operator. With this architecture, it is possible to plan a mission, optimize sensor settings, and visualize the data from a remote computer or handheld device. The sensors were installed on three robotic platforms: microwave radars (Robots #1 and #3), LiDAR (Robot #1 and Robot #3), high-resolution optical camera (Robot #1), and metal detector (Robot #2). The acquisition and processing of multisensor information and application of AI demonstrated effective detection and classification of buried small low metal content landmines (e.g., M-14 and Type-72 mines) and scatterable surface mines like the PFM-1 "butterfly". For continuing safe operation, the system also requires detection of tripwires that are commonly rigged to explosive devices to protect minefields. For this purpose, the first robot uses an optical sensor and an algorithm trained to detect sub-horizontal line segments that could be metal or nylon wires. All robots are equipped with GNSS providing mapping of targets with accuracy better than 10 cm. Based on optimization of sensor power consumption, the operating time for each robot is on the order of hours.**

Keywords—Artificial Neural Network, GPR, GNSS, Holographic Subsurface Radar, LiDAR, Metal Detector, Unexploded Ordnance, UWB, Cooperating Robots.

I. Introduction

The main objective of this project is to fully exploit the most advanced technologies in radars and other sensors, robotics and multi-parametric data processing for demonstrating a safe, cost-effective landmine detection approach. A new and flexible system design is necessary for the challenging problem of demining large areas in different settings (urban, residential, agricultural and cultural/historical).

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The complexity of this problem requires an integration of information that is possible only by using electronic and ICT technology integrated on ground-based robotic platforms.

The large data sets collected by this system will provide a solid base of high-quality images and signatures for the application of artificial intelligence and machine learning, as demonstrated by a test field experiment reported herein.

Our approach consists of a team of three cooperating robots [1], where each robot has specialized sensors for the assigned task:

1) Robot #1: equipped with a ultra-wideband (UWB) radar for detection and positioning [2, 3], LiDAR and a high resolution camera on a steadicam gimbal mount.

2) Robot #2: equipped with a metal detector (MD) mounted on an extended arm with optical and LiDAR cameras

3) Robot #3: equipped with a holographic subsurface radar (HSR) operating at 2 GHz [4] and optical and LiDAR cameras for scanning the soil surface

4) A Graphical User Interface (GUI) for mission planning, sensor tuning, mission monitoring, error handling, fault diagnosis, data archiving, data processing and visualization

5) Real time processing for detection of surface threats (trip wires, scatterable landmines or UXO).

Combining GPR with MD in a handheld device has already been shown to be effective for discriminating mines from clutter [5]. In this project, we have added Artificial intelligence (AI) applied to radar signals to aid in discrimination of mines from clutter and we have used AI applied to optical images for real time detection of surficial threats. The cooperating robots approach has been demonstrated on a test field with buried metal and plastic landmines, clutter objects and surface landmines (PFM-1 and PMA–1) showing that the integrated data can detect all objects, including the very low metal content (LMC) buried M-14 and T-72, as well as the surficial PMA-1 landmines. HSR imaging assists in discrimination of landmines from clutter. The remotely planned and controlled mission allows safe operation.

II. SMART NAVIGATION FOR THE PLANNED MISSION - LARGE DATABASE FROM MULTIPLE SENSORS

The complexity of landmine and UXO detection in post-conflict areas requires acquisition of information on the environment conditions as well as electromagnetic anomalies induced by the presence of shallow buried objects. Acquisition can be done with an unmanned system consisting of three terrestrial robotic platforms with assigned functionality and sensors. All sensor settings can be remotely and dynamically adjusted by a GUI tab named SENSORS. Error handling from each sensor is handled by the manager-agent software operating in real time according to a state-machine design.

Mission planning to cover a specific area is done in another section of the GUI devoted to NAVIGATION. The navigation plan is different for each robot: Robot #1 follows a defined "Greek line" to cover the survey area lane-by-lane During the navigation, optical and LiDAR sensors are used to detect in real time surface threats such as tripwires, UXO or obstacles. Error handling for the communication of these sensors is provided. In case of a detected threat Robot#1 stops before crossing over the threat, maps this position and requires a message from the operator with an update of the mission plan to avoid the threat/obstacle. The position of Robot#1 can be followed in real time on the GUI with a GNSS accuracy better than 10 cm. Again, messaging for positioning failure is implemented to avoid uncontrolled or uncertain navigation and target positioning.

On Robot#1 a UWB GPR is also continuously active to provide detection of buried objects (metal, plastic or other materials) and provide their positions on a shared table of detected targets (see the video with the navigation on the listed positions of targets and accuracy estimation recorded in Ukraine:

https://drive.google.com/file/d/1Cl45EFxv3Ksr4OxqgSn8qyCJPt4V9D6f/view?usp=drive_link

At the end of its Greek line mission, Robot #1 returns to the safe parking area.

Then Robot#2 with an MD starts the Greek line mission covering the same area, possibly with modification based on information provided by Robot #1. The MD coil is at present mounted on a sweeping arm. The audio tone is recorded and provides information on the presence of metal targets. This information is useful to map the positions of objects found in the shared list of positions. The processed sound signals can produce a "heatmap" of the scanned area for further visualization. Robot #2 returns to the parking position at the end of its mission.

Finally, Robot #3 starts navigation, but only to the target positions previously recorded by Robots #1 and #2 and archived in the shared list. On each position the HSR scans a 30 cm by 30 cm area around it, collecting amplitude and phase information using a programmable electronic unit. All samples are acquired and stored in a shared database for further processing and visualization. The scanned area is also inspected by a LiDAR and an optical camera and the data is archived and shared for data fusion with HSR and MD information. Again, error handling from the electronic unit, mechanical scanner and optical/LiDAR sensors is implemented.

Robot#3 returns to the parking position at the end of the mission when all the listed positions have been scanned and the microwave, LiDAR and optical images archived.

The final section of the GUI is ANALYSIS and provides options for data processing and visualization. Acquired data can be processed independently from each remote unit connected to the system and the results visualized in quasi-real-time. The integrated information allows optimization of probability of detection versus probability of false alarm in creating the final list of mapped targets to be addressed by deminers.

Fig. 1 shows the present architecture used in the test field demonstration. The evolution of the technology and the use on real fields may require a different configuration of the robotic platforms and sensors, but we have designed the architecture so that such changes can be done with minimal intervention on the hardware.

Because of the invasion in Ukraine and interruption of the work of the Ukrainian team, the first robot now has only the tripwire detection and an optical detection system rather than GPR. However, the GPR performance has been independently demonstrated in Ukraine as described later in this report.

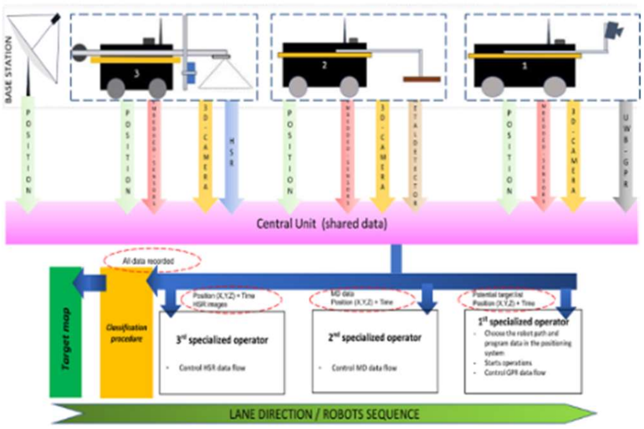

Fig. 1. Architecture of the robot team for landmine detection

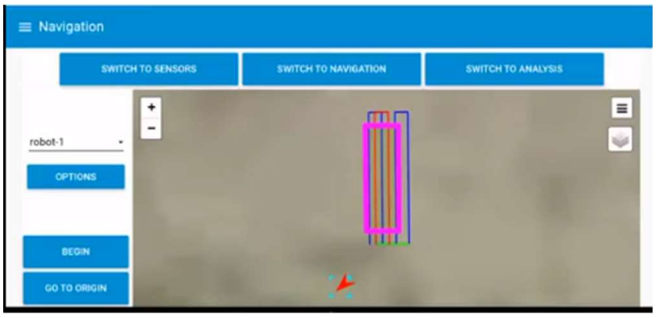

Fig. 2. Screenshot of the GUI navigation interface

III. TEST FIELD RESULTS

The design of the test field with buried landmines and clutter objects, as well as surficial objects, is described in Fig. 3 where for each target the position and depth were defined. The test field is replicated in each country (Italy, Ukraine, USA), obviously with different soils.

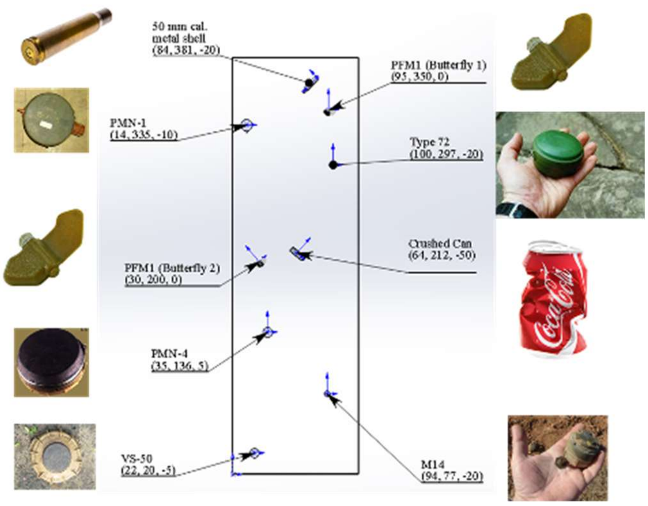

Fig. 3. Test field design with LMC and high-metal antipersonnel landmines and clutter objects.

Table 1 shows the results of buried object detection with the different sensors mounted on the three robotic platforms. The final column shows the overall results once the detection information from the individual sensors is combined. We can see that none of the sensors is fully capable of detecting and classifying targets with low false alarm rate.

TABLE I. TEST FIELD RESULTS

Target	***Mapped position X[mm],Y[mm]***	***Robot #1: GPR***	***Robot #2: MD - Detected position X[mm],Y[mm]***	***Robot #3: HSR (h=5cm)***	***Overall Detection by System***
1. –VS-50	***220, 200***	***Detected***	***220, 200***	***Detected***	***Detected***
2. M14	***940, 770***	***Detected***	***Not detected***	***Uncertain***	***Detected***
3. PMN-4	***350, 1360***	***Detected***	***380, 1370***	***Detected***	***Detected***
4. PMN-1	***140, 3350***	***Detected***	***140, 3300***	***Detected***	***Detected***
5. Type 72		***Detected***	***Not detected***	***Uncertain***	***Detected***
6. Crushed Can		***Detected***	***630, 2080***	***Uncertain***	***Detected***
7. 50 mm Metal Shell	***840, 3810***	***Detected***	***760, 3800***	***Detected***	***Detected***

Fig. 4 shows Robot #1 and Robot #3 operating on the test field at Franklin and Marshall College (Lancaster, PA USA) for tripwire detection and surface object detection using AI. The detection and positioning of the T-72 and M-14 small LMC landmines using UWB GPR in the test field in Ukraine is shown in Fig. 5.

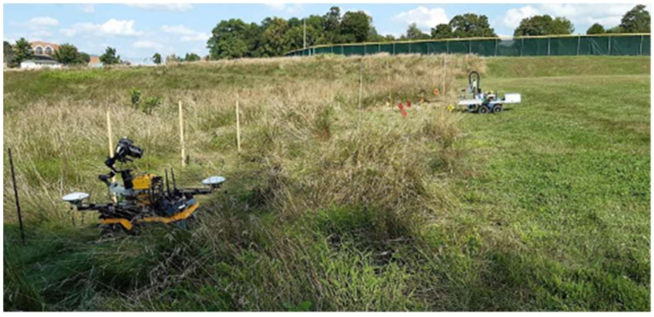

Fig. 4. Mission simulation in the test field at Franklin and Marshall College (Lancaster, PA).

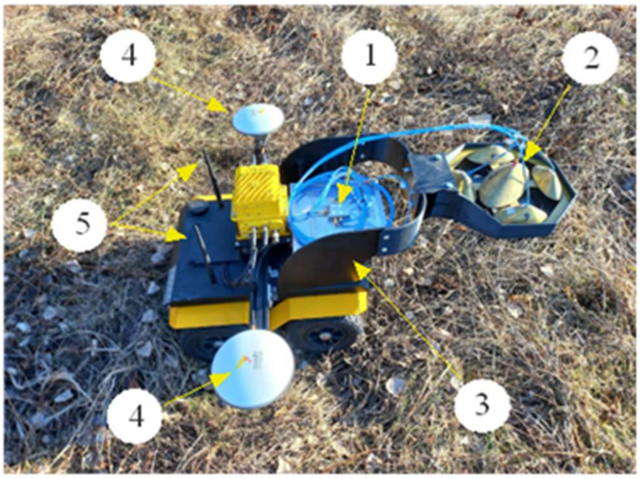

Fig. 5. The main parts of the GPR robot are the GPR hardware unit (1); antenna system (2); Jackal robotic platform (3); GPS antennas (4); WiFi antennas (5).

IV. DISCUSSION AND CONCLUSIONS

In brief the main accomplishments of the research project on the cooperating robotic team architecture are:

- Robotic platform architectural design.
- Real time GPR processing for alarm generation (object detection and position).
- Development of Holographic Subsurface Radar with a 3D printed compact antenna for generating layered focused images and integration with 3D optoelectronic scanner data for buried object classification interpretation.
- Construction of a test field with landmine simulants and clutter
- Acquisition and integration of data from all sensors run on the test field
- Final assessment of the added value of using a robotic platform with two radars (UWB GPR and HSR) integrated with optical sensors for landmine detection.

- By sensor fusion, all targets were detected (Table 1), despite the result that in several cases the individual sensors alone could detect the object or detection was uncertain.

- Microwave plus optical and LiDAR imaging was shown to be capable of discriminating between targets and clutter.

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