Design of a robotic platform for landmine detection based on Industry 4.0 paradigm with data sensors integration

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***Abstract*— A new generation of instruments capable of detecting plastic landmines aims to increase operator safety and productivity for humanitarian demining. The complex environmental conditions require the measurements of several physical parameters to enhance the detection of plastic and metal landmines by metal detectors and ground penetrating radars mounted on a robotic platform. The architecture of the multisensor robotic platform, based on the Industry 4.0 paradigm, is described, and an example is provided which describes how to exploit the multiple sensor information with experiments carried out in a test bed with landmine simulants.**

Keywords— industry 4.0, ground penetrating radar, 3D depth camera, Ultrawide Band Radar, Robotic Operating System, sensor data fusion, Landmine detection

I. Introduction

The conditions of post-conflict zones are characterized by the presence of various kinds of hazards. Examples include unexploded ordnance (UXO), plastic or metal landmines, tripwires and, more recently, improvised explosive devices (IEDs) [1]. In the face of the variability of possible threats, one of the main research goals is to ensure field operator safety and to increase the successful detection of minimum-metal landmines produced with plastic cases of various sizes and shapes [2]. Currently, advanced handheld equipment is available to detect subsurface objects via magnetic and electromagnetic discontinuities by combining metal detectors and ultrawideband (UWB) radars [3]. This dual-sensor solution has improved productivity by reducing the time wasted detecting and removing harmless clutter objects (e.g. shrapnel, plastic bottles, cans, etc.) [4], [5]. In this scenario, the exploitation of Industry 4.0 technology for humanitarian demining presents a great opportunity for possible new engineering solutions. This paper describes the architecture of a remotely controlled robotic platform where several sensors are used together to obtain a digital model of the environment. The multi-sensor robotic platform has been designed with two aims: improving operator safety and increasing the productivity of the threat detection procedure by robotic vehicles that can operate for long periods of time without the fatigue that affects the performance of a human operator. This concept is encapsulated in the name "Ugo 1st" (You Go First) that we have given to this novel vehicle (see Figure 1).

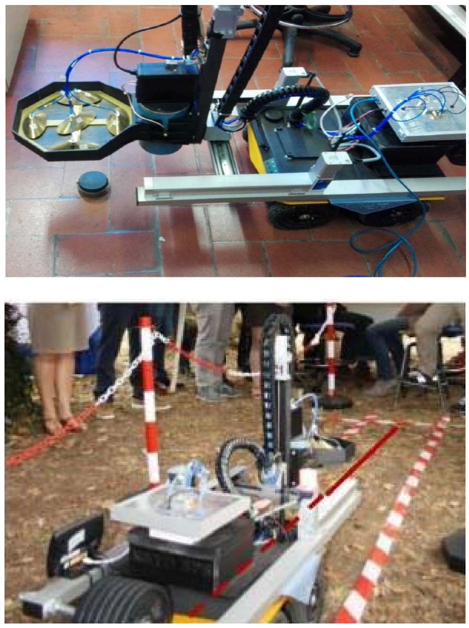

Figure 1 – (Top) Robotic platform in laboratory and a small (11 cm diameter) PMN-4 plastic landmine, (Bottom) demonstration in a field.

The built prototype integrates many sensors, the most relevant of which are a UWB pulsed radar for detection [6], [7], a Holographic Subsurface Radar (HSR) for classification by imaging [8], and a PMD depth camera for soil surface analysis. The information from these three main sensors is complemented by other sensors, such as an accelerometer, thermometer, gyroscope, etc. Data from the main sensors are correlated in space and time to achieve early detection of buried ordnance while keeping the sapper operator at a safe distance. The integration of complementary data from different types of sensors into a single robotic platform (Figure 2) enables the automatic position identification of possible targets with a low false alarm rate.

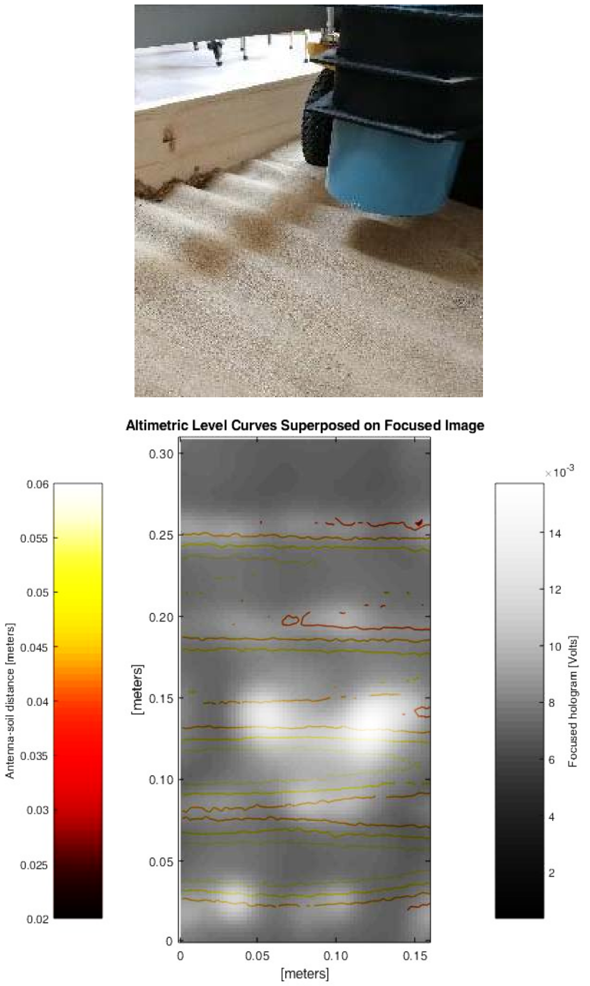

Figure 2 - Test bed with undulated surface sand and buried PMN-4 landmine simulant (top) Superposition of soil level curves obtained by PMD depth camera and the amplitude data from the holographic radar (bottom). The contour levels allow us to distinguish the undulations of the surface from the buried mine in the greyscale image.

The HSR, all the control and acquisition electronics, and the quasi-real-time remote processing algorithms were designed and tested as part of NATO project G5014, funded by NATO's Science for Peace and Security Programme. Before illustrating the system's architecture, it is important to understand the new operational procedure called Demining 4.0. During the operation, the GPR first performs UWB GPR sounding of soil under the "1Tx+4Rx" antenna system [9], which is mounted in front of the robotic platform. The GPR provides radar data showing the presence or absence of a shallow buried object within a lane of detection and all 3D Cartesian coordinates of this object. The UWB GPR is capable of detecting both metal and plastic-cased objects. Results from the sounding can be shown in real time on the sapper's computer monitor in the form of B-scans, and these scans can be processed using automated detection algorithms [10]. After the alarm signal is generated by the firmware of the GPR or by the decision of the sapper, the GPR returns coordinates of the subsurface object with respect to the reference system connecting to the GPR antenna system to the robotic system. The robotic system then uses these data to place the antenna of the holographic radar just over the detected object with a suitable distance from the ground (typically about 10 cm). The overall procedure is depicted in Figure 3, where we show the use of remote terminals for applying processing for feature extraction and classification of the images produced by the holographic radar.

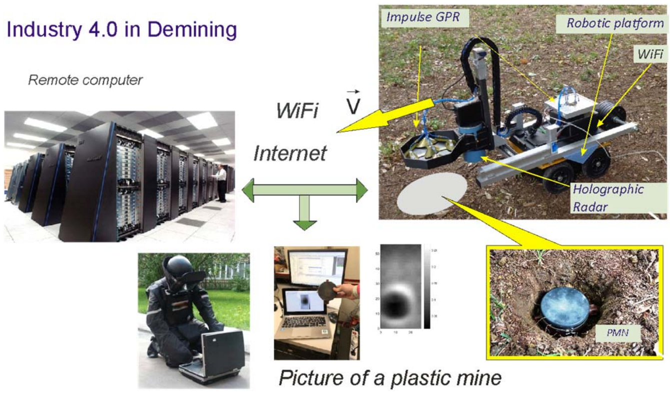

Figure 3 – The picture shows the main concept of Industry 4.0 paradigm applied to innovate the demining procedure.

The data are stored in real-time on a remote server where big data archives are realized. It is also important to emphasize that to obtain a digital model of the experiment, it is necessary that all data are spatially and temporally correlated. For example, large temperature variations or bumping of the robot on uneven soil can be recorded by temperature sensors and an accelerometer and later correlated to interpret radar signatures.

II. System Architecture

The system architecture is designed specifically for the multisensory robotic platform and is one of the key points for developing a usable instrument in the field. The main blocks of the system are shown in Figure 4.

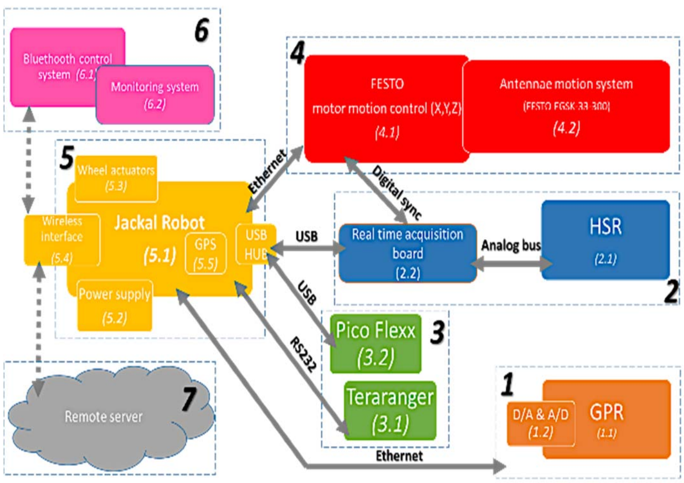

Figure 4 – Electronic system architecture for the robotic platform.

Table 1 lists the main blocks, and the sub-components are described in Figure 4.

Table 1. List of system components.

1	GPR
	1.1 Antenna system GPR (5 antennas: 1 TX, 4 RX) for detection.
	1.2 Signal decoder and A/D
2	Radar holographic HSR
	2.1 Antenna system HSR for holographic imaging
	2.2 Real time acquisition board
3	Sensors of position/distance/visualization
	3.1 TOF Scanner laser of distance (Teraranger®)
	3.2 PMD Camera-Scanner 3D (PicoFlexx®)
4.	Dedicated interface for XYZ motor system (FESTO®)
	4.1 Proprietary electronic controller with external COM interface
	4.2 Three axis moving system FESTO EGSK-33-300
5.	Jackal unmanned ground vehicle
	5.1 On-board standard computer (with ROS OS)
	5.2 Power management unit/Power meter
	5.3 Wheels actuators
	5.4 Wi-Fi interface
	5.5 GPS
6.	Wireless remote controls
	6.1 Remote control system (joystick)
	6.2 Control and monitoring data
7.	Remote server
	7.1 Server remote for control system and postprocessing data

The software integration of the different sensors required us to adopt a platform to develop drivers and cabling with a standard protocol. Most of the commercial sensors used were supported by drivers for the Robotic Operating System (ROS) installed on the motherboard of the commercial robotic platform. The maneuvering of the robot was done by a standard Bluetooth remote control available from Clearpath®, the manufacturer of the Jackal robot,. The interface software was developed for use on any remote terminal (e.g., laptop PC, tablet, cell phone) that can connect to the platform by Wi-Fi and a web-based interface. This solution allows multiple end users to supervise the experiment in real time from any location and requires just a single field operator maneuvering the robot to avoid obstacles. We also provide a diagram of the main communication flow during the acquisition, depicted in Figure 5.

It is worth pointing out that the system has been successfully tested for possible interference between the communication systems (Wi-Fi, Bluetooth) and the two radar (UWB GPR and HSR).

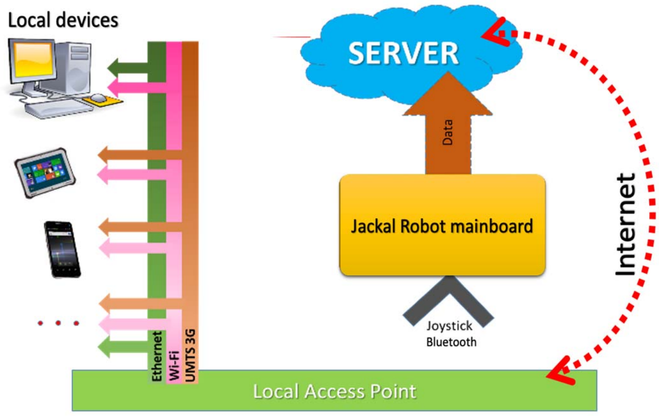

Figure 5 – Diagram of communication flows between robotic platform and remote server, remote terminal and Joystick control for remote driving.

III. IMPLEMENTED METHOD

The detection and imaging have been implemented by devising two microwave (≈ 2 GHz) radars: a 1 TX + 4 RX UWB pulsed Ground Penetrating Radar (GPR) and a Holographic Subsurface Radar (HSR) combined with a 3D scanner based on Photonic Mixed Devices (PMD) technology. The detection procedure is represented in Figure 6 and can be entirely controlled with a control panel accessible on the web.

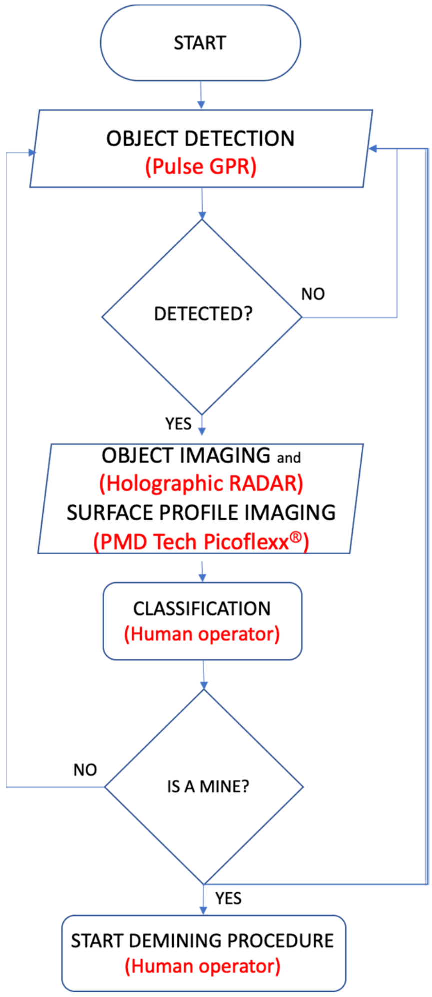

Figure 6 – Diagram of detection procedure.

The GPR, placed on the front side, is used for the early, inline detection of shallow targets during robot motion. After the human operator starts driving robot on the lane, the radar-grams are visible in real-time on the web-based control panel. An alarm is raised by a human who interprets radar-grams received from the robotic platform and stops the robot motion with a button on the same web-based robot control panel. With another button on the screen, the same operator activates the scan with the HSR and the 3D acquisition of the soil of the scanned area with the PMD Picofleex® scanner. The holographic radar is mounted on a XYZ movement system that can perform a rectangular scanning of the suspected target area. The 3D soil data are processed to create a 2D (contour level) representation of the height of the soil relative to the scanning plane. The images of the soil level and the holographic radar are superposed through a data-fusion process. This improves the capability of the person in charge of the interpretation to discriminate between mines and clutter since they are using the imagery presented at the end of the scanning procedure. The contour levels superimposed on the radar image allow identification of the effects of a depression in the ground or the presence of a foreign relief body, such as a root, which would not otherwise have been easily discriminated from buried objects. During the robot motion a streaming video is also available on the web control interface by the optical sensor output of the PMD Picoflexx scanner. This information is essential to alert the field operator for the presence of large relief changes in the terrain or obstacles that could block the robot, as well as more subtle and dangerous features, such as tripwires, that are hard to detect even with the human eye. In a companion paper presented at this conference, a high-resolution optical sensor and an algorithm strategy is presented but not yet integrated in the system for tripwire early detection. When the specialized operator decides that a landmine has been detected, the robotic system can resume the detection process because its weight is not large enough to trigger the mine. The point where the mine is located is marked with the coordinates identified by the system for the subsequent demining operation by qualified personnel.

IV. RESULTS

The strength of the proposed approach lies in combining the information obtained by the multiple sensors which have been calibrated to have the same spatial reference. An example is provided by the combination of the soil profile information obtained in real time by the 3D depth camera and the holographic image generated at the end of the mechanical scan with the HSR antenna. The position of the area to be scanned is determined by an alarm generated by the signal processing of the UWB radar that stops the robot over the target. In the experiment shown in Figure 2, an undulated surface of a sandbox was created in the laboratory. A plastic landmine simulant (PMN4 type) was buried under this sandy soil, and the corresponding holographic image should have shown a circular plastic case. Due to the interference of the probing field with the undulated surface, the holographic image shows a horizontal contrast pattern. Without any other digital information of the environment, the pattern could be misinterpreted as being from a buried elongated object. By correlating the 3D map with the holographic imaging, the origin of this horizontal pattern becomes clearer, and the contrast of the buried plastic mine can be correctly interpreted as the only buried object in the image (Figure 2 bottom). Moreover, remote access to all sensor data and images enables additional processing to improve the interpretation of the contrast image. For example, the height of the antenna aperture from the soil varies owing to the irregular soil surface. This parameter affects the HSR antenna propagation that changes with target depth. A correction scheme based on aperture deconvolution [10] has been proposed which uses the distance measured by optoelectronic sensors. The resulting images of two different targets (a metal tin and a plastic mine simulant) are shown in Figure 7. The amplitude and phase images for each target clearly show the circular shape of each object as well as accurate size scales for each object (due to calibration of the sensors).

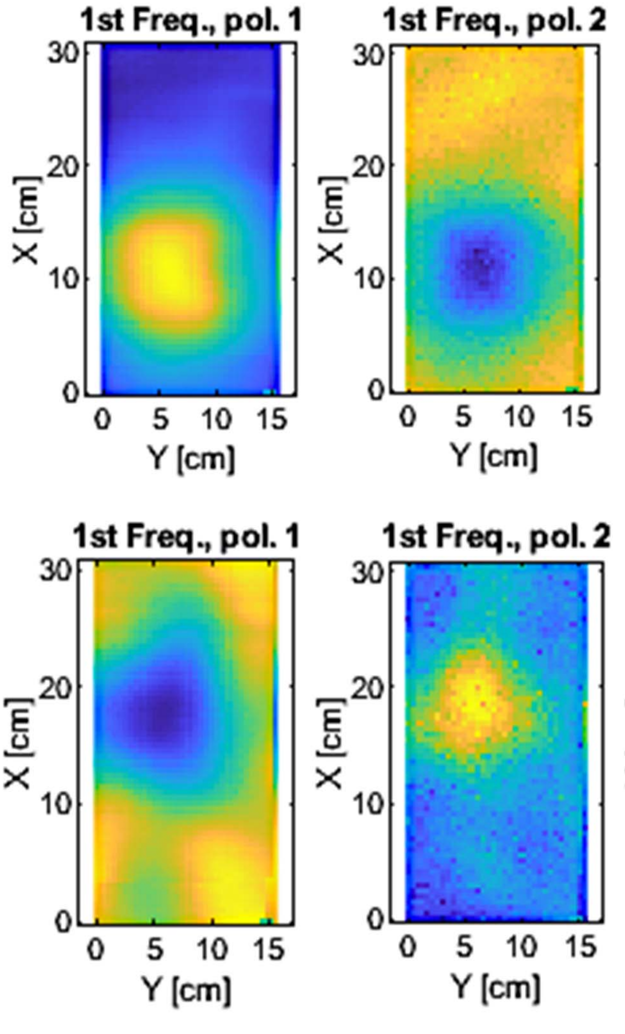

Figure 7 – Microwave holograms: magnitude and phase of a metal tin with 10 cm diameter and 3.5 cm depth (top), and of a PMN1 mine simulant buried in garden soil at an 8 cm depth for four months, acquired in winter with wet terrain (bottom).

V. CONCLUSIONS

In this paper we have reported on the design of a new integrated robotic platform which is part of a new paradigm for humanitarian demining we are developing called Demining 4.0. This robotic platform includes different sensor, communication, and scanning systems controlled by the Robotic Operating System (ROS). The adoption of Industry 4.0 concepts and technologies allows for the easy replication of the robotic platform as well as improvement and modification of its design by different specialized teams stationed in spatially separated locations around the world. One example is the use of CAD and 3D printing for the radar antenna holder and holder for the 3D depth camera. The web-based software architecture is a key advantage during field operation because the sensor data can be accessed in real time, and detection procedures can be supervised by experts remotely connected to the robotic platform. In the near future, the data will be collected in a remote repository to form a data archive for each survey. The data from various sources (including the robotic platform, which conveys the vehicle trajectory and acceleration, the forward-looking video camera, the GPS, the metal detector, and the ground penetrating radar) will be fused together to create a digital model of the experiments. This will aid in the interpretation of the main sensor data from the metal detector and GPR to determine a correct target identification and to lower the false alarm rate which is detrimental to productivity and efficiency. Finally, the accurate system positioning of the HSR antenna and the measurement of the actual air gap from the soil relief mitigate the influence of the soil response on the microwave holographic imaging. We report on examples of measurements of buried targets in natural wet soil where the measured shape and dimensions are well-matched with the actual features of these objects.

A vehicle having obstacle prevention capability and trajectory planning features is already under consideration. The system will be designed for automatic detection, imaging, and recognition (within defined operational specifications) of landmines.

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