Application of the Industry 4.0 Paradigm to the Design of a UWB Radiolocation System for Humanitarian Demining

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***Abstract*—The modern world is characterized by the pervasive use of computers, sensors, robotics, and Internet connectivity. This represents a new industrial revolution, dubbed Industry 4.0. In this paper, we discuss the application of the Industry 4.0 paradigm to creating a robotic search-and-detection platform intended for humanitarian demining. This is based on the combination and interaction of two microwave radars - including a UWB multi-sensor array, and a holographic imager - as well as 3-D optical cameras, remote navigation, and GPS tracking. The concepts introduced by Industry 4.0 represent an important opportunity for the scientific community to adopt new approaches in the design and use of UWB radar systems, and how data from these systems can be shared, archived, and processed in a decentralized manner accessible to the worldwide community**

Keywords*—Industry 4.0, humanitarian demining, robotic platform, georadar, ultra-wide-band (UWB) radar, holographic radar, computer simulations, landmine, unexploded ordnance (UXO), improvised explosive device (IED), detection

I. Introduction

In their initial manifestations, computers filled entire rooms and were used for (by modern standards) modest calculations. The ability of computers to rapidly perform large and complex calculations quickly became a fixture in the design and simulation of different mechanical, physical, and electrodynamic processes, and in many other technical tasks. Computers have now become not only the means for virtual simulation of processes, but also for producing physical things. For example, *computer numeric control* (CNC) machines are used in the digital fabrication of tools and parts.

In science and engineering, computer simulations with specially-designed software have not only enabled the study of individual physical phenomena using mathematical models (thereby eliminating the need for a significant number of actual experiments), but have the additional ability to create software for the simulation and optimization of physical models involving interactions between different devices (e.g. [1], [2]). These models accurately simulate properties of their real counterparts, and comprehensively include multiple physically-interacting phenomena. In industry, specialized software-controlled robots have come to replace humans for many tasks, even complex ones. Thus, both research and development for new products as well as their actual production have been managed by computers and software. Modern technologies are characterized by the expanding application of computers at all stages of development, replacing existing technologies, and in some cases rendering them entirely obsolete [3].

As part of this, computer-aided design (CAD) programs were written to facilitate simultaneous simulation, design, and analysis for improved product development. These CAD systems are used to create, modify, analyze, and document two- or three-dimensional (2-D or 3-D) digital representations of physical objects as an alternative to antiquated manual blueprints, and product prototypes. CAD is now widely used in computer animation, media special effects [4], and in product and industrial design [5].

High-speed Internet and cloud computing technologies united CAD systems with potentially physically-separated manufacturing facilities, creating adaptable production lines which can produce a huge number of different and unique items quickly and inexpensively. Modification of digital designs is straightforward, and can be done from any location in real time, with the actual production changes implemented almost instantaneously - e.g. by simply sending self-identifying RFID parts with built-in instructions down the production line.

In this production scheme, an important factor is the ability of production lines to manufacture objects at any level of detail or complexity, with no unique specialists or craftspeople required, and with the place of manufacture determined only by the (unimportant) geographical location of the production machines. For example, after delivery and commissioning of a 3-D printer to the International Space Station, it became possible to produce any necessary tools or replacement parts directly on board [6], eliminating the need to launch expensive and time-consuming space delivery missions.

In this paper, we will discuss the application of these approaches, recently dubbed Industry 4.0, to creating a robotic landmine detection platform intended for humanitarian demining, based on multisensory data such as radar, optical, etc. This platform was created with the support

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The platform is intended to exploit, in an open design environment, new electromagnetic and physical-acoustic methods and technologies for landmine detection. This is a high-risk and high-cost task that we believe in the near future can benefit from the Industry 4.0 approach. This paper illustrates the ways in which the Industry 4.0 paradigm has been adopted for this design, and the characteristics of the two radars; UWB ground penetrating radar (GPR) and holographic subsurface radar (HSR) proposed for the buried threat-detection system, along with preliminary results of realistic field tests.

II. What is Industry 4.0?

The Industry 4.0 concept is the latest stage of industrial development. It follows several previous industrial revolutions. In brief, the recognized industrial revolutions:

Industry 1.0. The first industrial revolution (in the late 18^{th} and early 19^{th} centuries) involved the transition from an agrarian economy to industrial production driven by water wheel and steam energy, mechanical devices, and advances in metallurgy.

Industry 2.0. The second industrial revolution (in the second half of the 19^{th} century and the beginning of the 20^{th} century) saw the widespread implementation of electric power, mass production on assembly lines, and the division of labor – all providing tremendously increased productivity.

Industry 3.0. The third industrial revolution (since roughly the 1970s) involved the integration of electronics and information systems into production, providing intensive automation and application of robotic (rather than human) manipulation in production processes.

In the closing decades of the 20^{th} century, the invention and production of electronic devices (such as transistors, and later - integrated circuits) allowed more complete automation of individual machines, supplementing or replacing human operators. This period also spanned the full development of software systems for the control of electronic equipment.

Industry 4.0. In the 21^{st} century, Industry 4.0 connects the “Internet of Things” or IoT [7] with production technologies to allow systems to share information, analyze it, and use it to guide actions.

Industry 4.0 has four principles [8].

- *Interaction*: the ability of machines, devices, sensors and people to connect and interact with each other via the IoT or the Internet of People (IoP).
- *Information transparency*: The ability of information systems to create a virtual copy of the physical world by enhancing digital production plant models with sensor data. This requires the aggregation of raw sensor data to higher-value context information.
- *Technical assistance*:
  a. The ability of digital assistance systems to support humans by integrating and visualizing information comprehensibly – for making informed decisions and solving urgent problems on short notice.
  b. The ability of cyber-physical systems to physically support humans by conducting a range of tasks that might be, for example, unsafe for their human co-workers. This is, of course, directly connected to our task of humanitarian demining.
- *Decentralized decisions*: The ability of cyber-physical systems to make decisions on their own, and to perform their tasks as autonomously. Only in the case of exceptions (anomalous interference or conflicting goals) are tasks delegated to a human level.

Thus, Industry 4.0 is a new way to develop manufacturing technologies based on automation and the rapid exchange of data. It includes cyber-physical systems, the IoT, and cloud and cognitive computing [8]. Currently, Industry 4.0 is the topic of many scientific conferences (e.g. [9]) which are held all over the world, and address both general organizational issues and individual tasks. In fact, every scientific conference (including UWBUSIS) is in one way or another a stage in the advancement of Industry 4.0 technology.

III. Project G5014 - “Holographic and Impulse Subsurface Radar for Landmine and IED Detection”

We have designed a robotic humanitarian demining platform with a system architecture that extensively uses robotic systems, sensor integration, and wireless data communication and control. The following diagram (Fig. 1) is a schematic of the architecture we have implemented for this platform, with the numbered component systems as follows:

1. Impulse GPR

1.1 GPR antennas (5 total); 1 transmitter (Tx) and 4 receivers (Rx)

Impulse Subsurface Radar for Rapid Landmine and IED Detection

1.2 Signal decoder and A/D converter

2. Holographic Subsurface Radar (HSR)

2.1 HSR antenna system

Holographic Subsurface Radar for Landmine and IED Detection

2.2 Real-time acquisition board

3. Sensors of position/distance/visualization

3.1 Time-of-flight (TOF) laser rangefinder (TeraRanger)

3.2 3-D camera/scanner (PMD Pico Flexx)

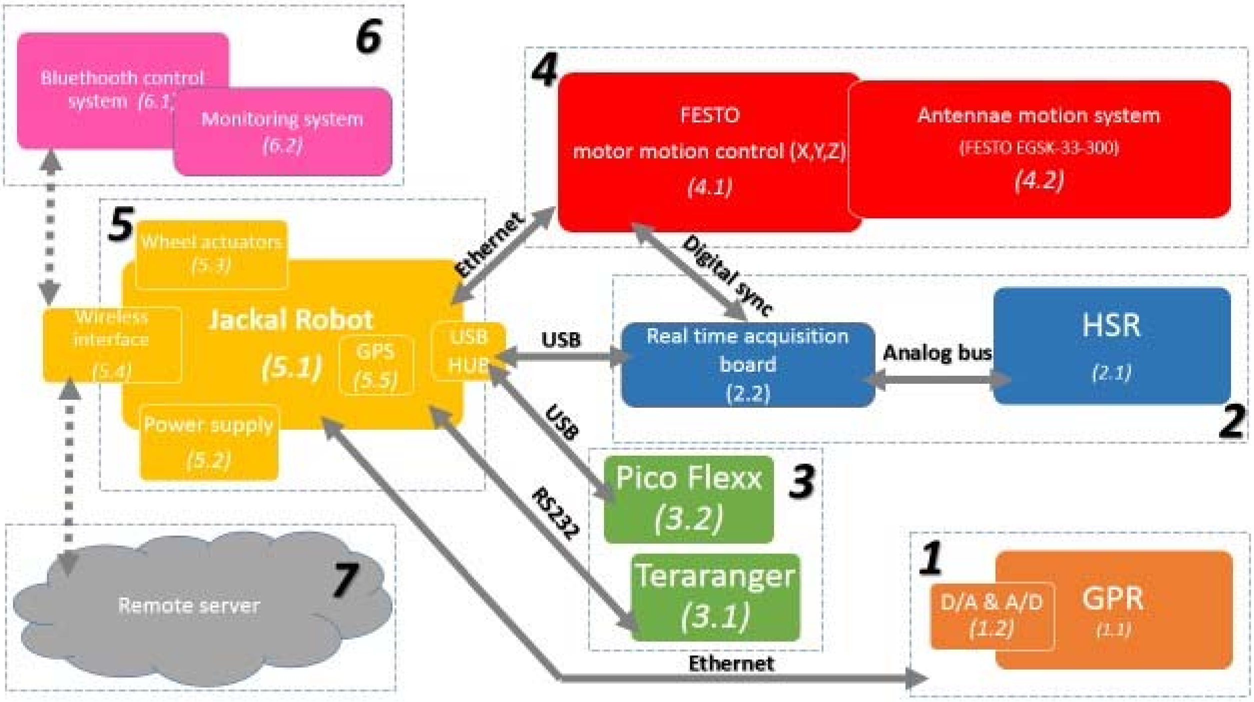

Fig. 1. Schematic of the architecture of the robotic platform

4. Dedicated interface 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 unit/power reserve meter

5.3 Wheel actuators

5.4 WiFi interface

5.5 GPS

6. Wireless remote controls

6.1 Remote control system (joystick)

6.2 Control and monitoring data

7. Remote Server for control system and postprocessing of sensor and navigational data

The architecture relies upon sensors and upon information and communication technologies (ICT) that are the pillars of Industry 4.0. The robotic platform is a Jackal from Clearpath Robotics (Canada) using open-source for research purposes. The Jackal is built for the Robot Operating System (ROS) software.

A. Industry 4.0 in the Design of the Robotic Platform

Based on our mission to build a device for a specific conflict zone, we measured the electrical and morphological characteristics of in-situ local soils during expeditions in the intended deployment zone; eastern Ukraine's Donbass region [10, 11]. These soil characteristics became the basis for the design of various systems on the robotic platform. Electromagnetic characteristics of the soils were used for computer simulation of subsurface radar probing - propagation, scattering, and reflection in realistic soil models – which defined the frequency and temporal characteristics of the holographic and impulse radar signals. Electronic files with digital models of the antenna systems and their accompanying structural elements were transmitted via the Internet to distant production sites, where they were used to produce the physical antenna elements.

Data on the structure of the soil, its surface profile, and its mechanical properties and variability became the basis for selecting the carrier platform, and were used in computer simulations of the platform behavior (stability, vibration, potential nose-in or hang-up failure, etc.) expected during field operations. The simulation results also allowed us to formulate the criteria (limitations) imposed for the overall weight (about 40 kg) of the built-in equipment and its distribution on the carrier platform. Note that these computer simulations obviated the need to conduct field experiments and testing in the dangerous Donetsk conflict zone in eastern Ukraine. The capability and reliability of the robotic platform to operate in any post conflict terrain is an important requirement for a final product, however we can verify for a specific area the conditions where the robot motion can be done without failure [12], and thus ensure a drastic improvement in the landmine detection capability.

Modern electronic components, including printed circuit boards (PCBs) of electronic devices, are typically designed using CAD programs. Instructions and specifications for the manufacture of PCBs are transferred in the form of special files to production facilities where the boards are manufactured, or electronic devices are completely assembled in accordance with these specifications.

Recently, 3-D printing technologies have become widely available. Their use facilitates precision fabrication of most of the structural elements, mountings, and fasteners used in our robotic platform. Using this technology, we manufactured an electronically-controlled articulated arm manipulator (Fig. 2) which will be used to deploy a sensorized prodder for discriminating compliant buried mines from (e.g.) stones [13]. This arm design was an adaption of a shared 3-D model available on the web. This tool can be remotely maneuvered and can hold different type of sensors selected by the operator for explosive and buried threat detection or marking.

Fig. 2. (Left) Articulated robotic arm. (Right) End effector to be used for manipulating a sensorized prodder

The mechanical adaption necessary to install the modular GPR and HSR radars was also designed and realized with CAD and a 3-D printer. We developed a digital mechanical model of the robot (Fig. 3) and used the model to simulate vibrational behavior and perform movement failure analysis.

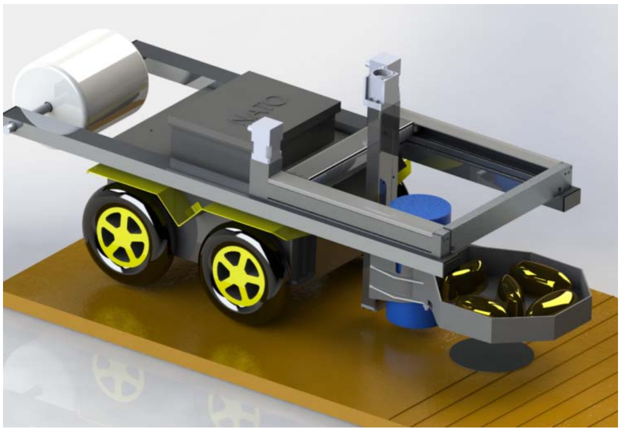

Fig. 3. Mechanical model of the robotic platform. The flat octagonal case suspended below the ends of the two extended horizontal bars contains the payload of the impulse radar. the blue vertical cylinder between the impulse radar and the robotic platform is the holographic radar in a defined x-y-z position. The x-y-z scanner provided by FESTO is not included in this analysis.

In addition, it became possible to manufacture hulls, fasteners, and other specially-designed parts on-demand and directly on-site during the assembly and testing of the system. For example, the GPR case (Fig. 4), which was designed in Italy for the “1Tx+4Rx” antenna system [10] (which in turn was designed and built by the Ukrainian team), was easily manufactured in Ukraine using the digital model sent from Italy over the Internet.

B. *Industry 4.0 in the Use of the Robotic Platform*

A mine-detecting radar instrument that is built and deployed following Industry 4.0 principles is no longer just a device that simply detects a buried object and provides an alarm as the operator moves through the minefield (like, for example, a simple metal detector). An Industry 4.0 device can be part of an integrated system that is geographically distributed (perhaps even in different countries and on different continents) and which consists of a set of instruments for collecting, transmitting, archiving, and analyzing geo-referenced data. In the future, this will probably also form the basis for making automated decisions.

Fig. 4. 1Tx+4Rx antenna system for the impulse GPR is shown in the octagonal 3-D printed case.

The principles of Industry 4.0 for humanitarian demining pre-suppose the use of robotic platforms that carry a whole set of sensors, operating with different physical principles to ensure detection and identification of a wide range of subsurface objects with differing materials and construction. These different physical characteristics that can be associated with objects with similar morphology make it possible to discriminate the type of the subsurface object with a higher confidence, reducing the time and expense to “neutralize” harmless trash. This is particularly important in a conflict zone there can be a huge variety and number of objects buried under the surface, of which many (most) are not mines and are clutter objects detected as false positives by the mine searching system. In recent history, false positives may comprise over 90% of detections [14], but this can be greatly reduced using radar technologies [15].

The multiple sensors can discriminate mines from clutter [16], but analyzing large sets of data from a whole array of sensors consumes computing resources and time. To reduce the computing time and simplify the analysis, it is possible to exploit powerful computing tools that are not located in the necessarily-limited mobile robotic field system. Here, high-speed Internet and WiFi connections provide the solution. The data gathered by the robotic platform can be sent to a remote server for nearly-instantaneous processing, integration, and perhaps artificial intelligence interpretation. The operator of the robotic platform receives the results of the analysis to make a final decision on the presence and type of target that lies beneath the ground.

In our system (Fig. 5), the robotic platform is controlled remotely by means of commands transmitted via WiFi so that the operator can be a sapper in a safe area, not in the minefield. The operator could even be a specialist in a distant office of the mine-clearing service. In fact, in a recent trial [report in preparation], the robotic platform in Firenze detected a buried hammer in a test bed; while under the control of an operator with a tablet in Switzerland; with the data monitored in real time by personnel with laptops in Ukraine. The raw holographic data were elaborated into images in near-real-time in USA, and uploaded back to the device in Firenze.

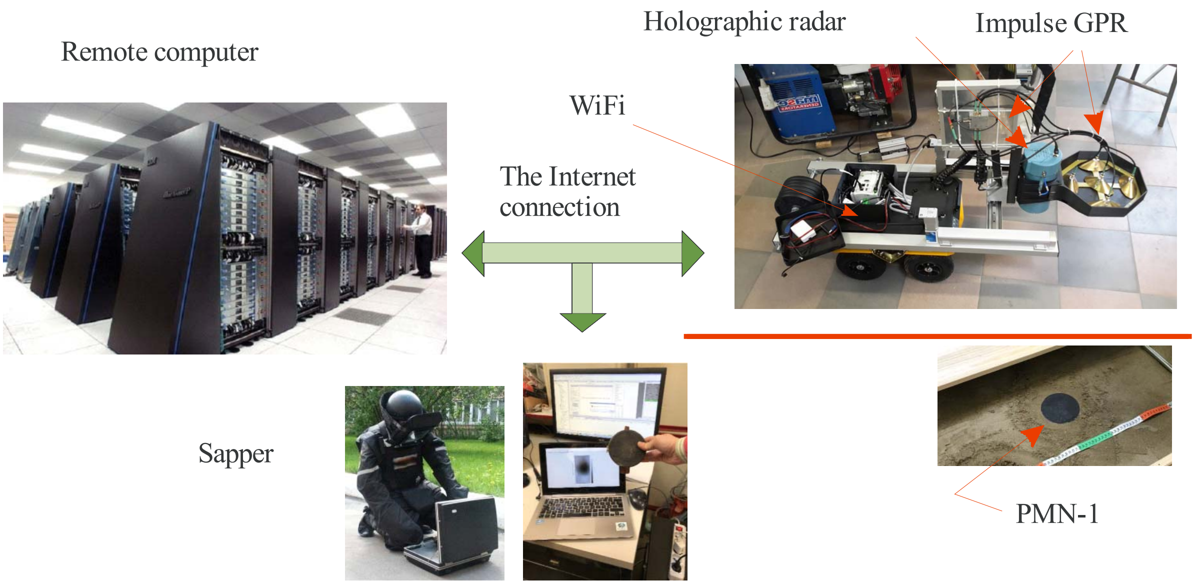

Fig. 5. Illustration of the Industry 4.0 novel approach to humanitarian demining. The upper right photo is the prototype mobile robotic platform under development. The lower right picture shows a simulated PMN-1 landmine of the type commonly used by Separatists in the Eastern Ukraine conflict zone.

In its current design, the robotic platform carries an impulse GPR, HSR, a Pico Flexx (PMD Technologies AG, Germany) 3-D video camera, an articulated arm probe, and a metal detector, with the possibility of adding additional sensors as needed. The task of the impulse GPR is to initially detect and determine the coordinates of an object (located either on the surface of the ground and under the surface) in front of the moving robotic platform. To discriminate mines from clutter among the detected objects, the HSR is deployed. This radar determines the footprint shape of the object, which makes it possible to discriminate mines from clutter with detection probability and false alarm rate (from ROC curve analysis) comparable with existing IR, EMI and GPR systems [14]. However, recording and processing a radar hologram requires time; this time can be minimized by using a powerful remote computer connected to the robotic platform over the Internet. The resulting high-resolution image is transmitted back to the operator of the robotic platform, allowing the sapper to separate mines from harmless objects. If there are doubts about whether the identification is correct, other sensors can be used to measure additional characteristics to facilitate accurate identification. Control of these other sensors is also carried out remotely. Eventually machine learning/artificial intelligence can be incorporated in this identification process [17].

Users of the robotic platform, and its developers from different countries, can observe in real time the results of mine searching using a specially-developed Web application accessing the Internet data feed from the robotic platform.

It is also important to note that in case of breakdown or failure of unique parts of the robotic platform, technologies such as CAD and 3-D printing can be used to recreate these parts (or even improved parts) and assemble the system at the site of operation.

The application of Industry 4.0 approaches also means that the world's leading specialists in the field, who are the best developers of data processing algorithms, the best developers of sensor equipment, the best system designers, etc. can be involved in the creation and operation of a robotic demining platform. In addition, these specialists can participate in a single project, from the comfort and safety of their own laboratories, with the Internet providing quick exchange of information, digital models, simulation results, and coordination of the activities of all developers.

At each stage of development and operation of the robotic platform, from the theoretical analysis of diffraction of electromagnetic waves at various sites, to the design and manufacture of parts, the assembly of sensors and systems on the robotic platform, testing, and finally the use of the completed system for demining, the work can be done by the appropriate team of experts, with all teams in constant communication and consultation. With this synergy from mutual collaboration, a new level of advancement is achieved in solving the problem of humanitarian demining. This is far more than what can be achieved by any one company, firm, or laboratory.

IV. Preliminary Results from Test Field

A preliminary test was carried out on three buried targets in natural soil at shallow depth. The three targets were buried in a line and only clutter from natural soil variations was considered. The maximum relief of the soil surface was estimated to be 2.5 cm. The operator (see Fig. 6) drove the robot along a reference straight line with a maximum error of

±2 cm. This error quantification was possible thanks to the real-time 3-D video recorded during the scanning traverse. The signals from the impulse GPR where acquired every 3 cm and processed automatically to determine the target position on the ground relative to the antenna reference system. Fig. 7 shows the results of auto-detection of a PMN-4 plastic-cased landmine (diameter 112 mm) by the GPR. Ideally, the positions on this graph should be on a straight vertical line and separated by 3 cm. The errors are within the experimental uncertainties, and are due to the variable speed and soil surface influence on the GPR reflected signals. In Fig. 8 are shown the images of the PMN-1 landmine acquired with the holographic radar in a sandy soil. Both magnitude and phase describe well the circular geometric shape of the plastic case.

Fig. 6. Picture of the robot scanning a lane with width (30 cm) on a natural ground. Three buried targets (PMN-1 , PMN-4 plastic-cased landmines and a metal tobacco tin) at depth about 5 cm and relative distance about 50 cm.

The same landmine PMN-1 was buried in natural soil (see optical reference in Fig. 9) and left resting for 20 days in a dry season. The robotic platform was then used to scan the same target as in Fig. 8, in order to compare the holographic images against the natural soil effects due to inhomogeneity of characteristics and uneven surface. The amplitude and phase images describe very well a circular shape with dimensions' compatible with PMN-1 target, similarly to Fig. 8.

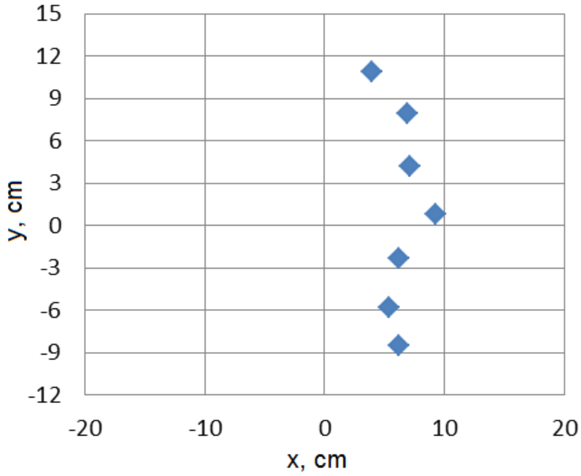

Fig. 7. Results of real time detection of a target by the impulse GPR at various robot positions along the lane, with 3cm step along vertical axis. Vertical axis shows offset of the auto-detected target from the center of the impulse antenna array. Horizontal axis shows offset from the scan traverse.

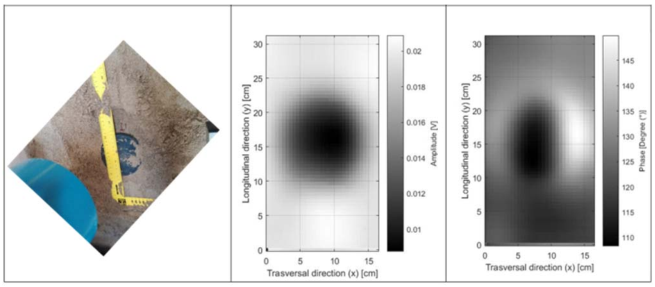

Fig. 8. On the right, holographic images (magnitude [Volt] and phase [°]) of the PMN-1 target in sandy soil at natural moisture content. On the left is the optical reference image.

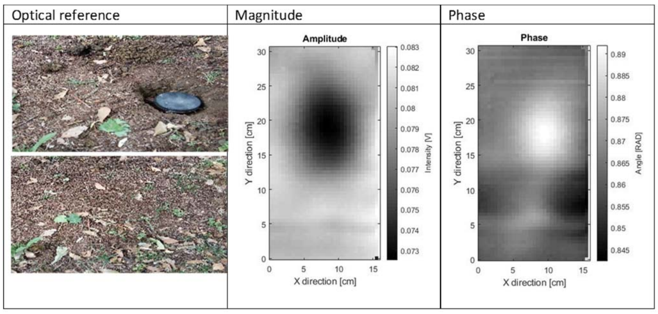

Fig. 9. On the left is the optical reference image during deployment in the ground at about 5 cm depth (top) and when buried after 20 days in dry season (bottom). On the right, holographic images (magnitude [Volt] and phase [Rad]) of the PMN-1.

V. Conclusions

We have described an integrated robotic demining platform that is under development using the Industry 4.0 approach. This includes the integration of different sensors (including UWB impulse radar) and other sensors, and communications and movement modules, into a single coherent system. The application of Industry 4.0 concepts also allows replication of our robotic platform (as well as improvement and adaptation of its design) in different parts of the world, with delocalized manufacturing of the physical components. Both experimental and operational field data from the system can be shared and accessed in real time at different locations owing to the web-based software architecture. The generation of large data archives by the system will soon be possible with the design and deployment of continuously-connected radar systems. In addition, the application of artificial intelligence for sensor data fusion and mine identification is a possible development in the near future.

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