Application of the Industry 4.0 Paradigm to the Design of a Dual GPR System for Humanitarian Demining

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Introduction

The earliest computers filled entire rooms and were used for modest calculations compared to today's standards. But they evolved quickly and became ever smaller, while their ability to rapidly perform large and complex calculations grew larger. Computers are now critical to the design and simulation of various mechanical, physical, and electrodynamic processes, representing not only the means for virtual simulation, but also for producing physical things. For example, miniaturized computer numerical control (CNC) machines are used to manufacture many modern objects or their components.

In all fields of science and engineering, computer simulations enable the study of physical phenomena using mathematical models, thereby eliminating the need for a significant number of actual experiments. Computers can create their own software for the simulation and optimization of physical models involving interactions between different devices (e.g., Warren et al., 2016; Szymanik et al., 2016). These models accurately simulate properties of their real counterparts and incorporate multiple physically-interacting phenomena. In industry, specialized software-controlled robots have come to replace humans for many tasks, some very complex. Thus, both research and development for new products, as well as their actual production, are managed by computers (Schlick, 2012).

As part of this, computer-aided design (CAD) programs facilitate simultaneous 2D or 3D design, simulation, and analysis for improved product development. These CAD systems and digital representations of physical objects antiquate manual blueprints and product prototypes. CAD is now widely used in computer animation and media special effects (Zhang and Yuen, 2000), as well as product and industrial design (Evans and Campbell, 2003).

High-speed internet and cloud computing technologies connect CAD systems with commonly-remote manufacturing facilities that feature adaptable production lines, which can produce a huge number of different and unique items quickly and inexpensively. Modification of an item's digital design 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 radio-frequency identification (RFID) parts with built-in instructions down the production line). In this paradigm, objects are fabricated at any level of detail or complexity, with no unique specialists or craftspeople physically present. For example, after delivery of a 3D printer to the International Space Station, it is now possible to produce any necessary tools or replacement parts on board, eliminating the need for expensive and time-consuming launches of delivery missions (NASA, 2017).

This paper discusses the application of these approaches, recently dubbed Industry 4.0, to creating a robotic humanitarian landmine detection platform carrying multiple sensors. This platform was created with the support of the NATO/OTAN Science for Peace and Security (SPS) Programme, Project G5014 - "Holographic and Impulse Subsurface Radar for Landmine and

IED Detection" (http://www.nato-sfps-landmines.eu/).

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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 high-risk, high-cost task can benefit greatly from the Industry 4.0 approach. This paper illustrates the ways in which the systems interact; UWB ground penetrating radar (GPR) and holographic subsurface radar (HSR), along with GPS positioning and LiDAR and optical sensors for tripwire detection, obstacle avoidance, and HSR image correction, along with preliminary field-testing results. Our system has been named (only partly tongue-in-cheek) Ugo 1st.

What is industry 4.0?

Industry 4.0 is the latest stage of industrial development. In brief, the recognized industrial revolutions are:

Industry 1.0. The first industrial revolution, in the late 18th and early 19th 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 19th century and the beginning of the 20th 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, in the 1970s, involved the integration of electronics and information systems into production, providing intensive automation and application of mechanical/robotic manipulation in production processes.

In the closing decades of the 20th century, the proliferation of electronic devices such as transistors and integrated circuits allowed more complete automation of individual machines, often 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 21st century, Industry 4.0 exploits the "Internet of Things," or IoT, (Ashton, 2009) with wired or wireless communications connecting cyber-physical systems (CPSs), which share and analyze information and use it to guide actions. Industry 4.0 is based on six principles (Hermann et al., 2016):

- *Interoperability:* the ability of machines, devices, sensors and people to connect and interact with each other to achieve a common goal.
- *Virtualization:* CPSs monitor physical processes and continuously compare a virtual model of the actual world (based on sensor data) with an editable model of the desired world. CPSs even monitor each other and provide alarms when they sense a failure.
- *Decentralization:* The growing demand for customized products and services makes it increasingly difficult to control systems centrally. Embedded computers enable CPSs to make decisions on their own. Nevertheless, it is still necessary to keep track of the whole system at any given time. In the context of Industry 4.0 "Smart Factories," decentralization might mean RFID tags on components "tell" production machines which working steps are necessary, making central planning and control obsolete.
- *Real-Time Adaptability:* CPSs collect, share, and analyze data in real time. For example, the plant can react to the failure of a particular system and re-route information or components to another machine.
- *Service Orientation:* The services provided by "Smart" systems can be shared by other participants – across the company, multiple disciplines, and international boundaries. All CPSs can offer their functionalities as an encapsulated service, making it possible to assemble a combination of CPSs to make a specific product or service to meet any end-user needs.
- *Modularity:* Systems can adapt to changing requirements by replacing or expanding individual "Plug & Play" modules. With standardized software and hardware interfaces, new modules can be identified automatically and used immediately.

Industry 4.0 is a new way to develop and adapt manufacturing technologies based on automation and instantaneous exchange of data across potentially physically-separated CPS components. Currently, Industry 4.0 is the topic of many scientific conferences (e.g., Industry-4.eu, 2019), which are held all over the world and address both general organizational issues and individual tasks. In fact, every scientific conference is in one way or another a stage in the advancement of Industry 4.0 technology.

NATO SPS project G5014 - "Holographic and Impulse Subsurface Radar for Landmine and IED Detection"

We designed Ugo 1st with a system architecture that uses sensor integration combined with wireless data communication and control. The following diagram (Figure 1) is a schematic of the architecture for this platform, with the numbered component systems as follows:

1. Impulse GPR

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

This is an impulse GPR for rapid detection and precise location of buried targets.

1.2 Signal decoder and A/D converter

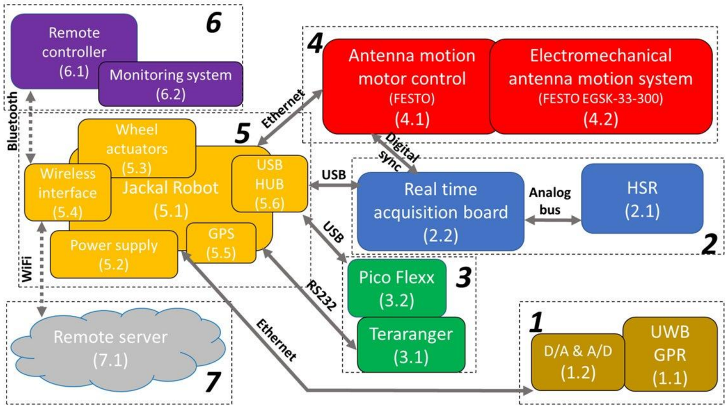

Figure 1. Schematic of the architecture of the robotic platform

2. Holographic Subsurface Radar (HSR)

2.1 HSR antenna system

The HSR is for identifying/discriminating targets (once detected and located by the impulse GPR) as either possible landmine, IED, or harmless clutter.

2.2 Real-time acquisition board

3. Machine Vision

3.1 Time-of-flight (ToF) distance laser scanner (Teraranger)

3.2 3D camera (PMD Pico Flexx)

These provide real-time imaging and terrain analysis for tripwire detection, obstacle avoidance, and correction of HSR images for distortion due to ground surface relief.

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

The HSR requires precise scanning of a series of 2D profiles (5 mm spacing and 5 mm sampling interval) over an area of about 35 cm by 70 cm. The FESTO electromechanical scanner provides this precision at a relatively fast scanning speed (approximately 3 minutes per 35 x 70 cm2 image).

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 Wi-Fi interface

5.5 GPS

6. Wireless remote controls

6.1 Remote control system (joystick style)

6.2 Control and monitoring data

7. Remote Server

7.1 Computer in (possibly far) offsite location that monitors all systems in real time, processes data, communicates with local operators, and archives survey data and results. The server can also override the joystick controls (6.1) to drive pre-programmed survey patterns.

This architecture relies upon sensors and 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 operates within the Robot Operating System (ROS) environment.

Examples of Industry 4.0 Principles in the Design and Construction of the Robotic Platform

Based on our mission to build a device for a specific conflict zone, we measured the electromagnetic and morphological characteristics of in-situ local soils during expeditions in the intended deployment area: eastern Ukraine's Donbass conflict zone (Pochanin et al., 2017; Bechtel et al., 2016). 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 HSR and GPR propagation and scattering in realistic soil models, which defined the frequency and temporal characteristics of the 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.

The data on the morphology of the soil surface, as well as its mechanical properties and variability, became the basis for selecting the robotic platform, and were used in computer simulations of the expected platform behavior (stability, vibration, potential nose-in or hang-up failure, etc.) during field operations (Bechtel et al., 2018). The simulation results also allowed us to formulate the criteria (i.e., 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 trials in the dangerous conflict zone.

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, 3D 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

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

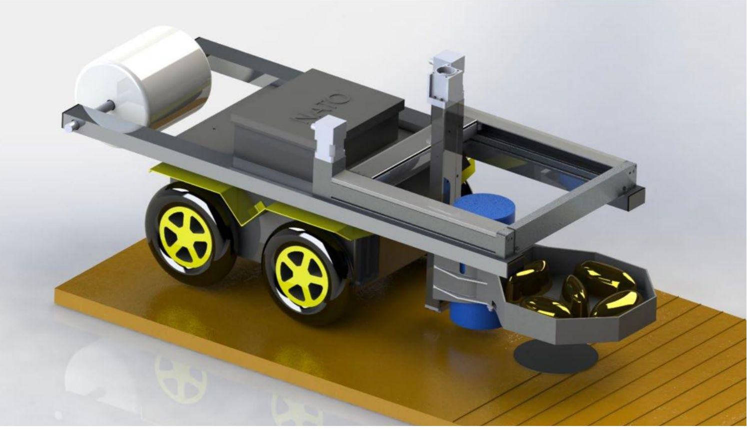

Figure 3. Digital mechanical model of the robotic platform. The flat octagonal case suspended below the ends of the two extended horizontal bars contains the impulse radar antenna array. The blue vertical cylinder between the impulse radar and the robotic platform is the HSR in a defined x-y-z position within the FESTO electromechanical scanner.

electronically-controlled articulated arm manipulator (Figure 2), which will be used to deploy a sensorized prodder for discriminating compliant buried mines from rigid objects such as stones (Borgioli et al., 2014), or for placing target markers. This arm design was an adaptation of a shared 3D model available on the web. Similarly, the mountings used to put the GPR, HSR, and machine vision sensors on the platform were designed in CAD, with compatibility and virtual testing performed using a digital mechanical model of the full system (Figure 3). Parts designed at different institutions were 3D printed at the system assembly location.

Figure 4 shows the case containing the actual “1Tx+4Rx” antenna system (Pochanin et al., 2017). The case was designed in Italy to fit the robot, using antenna specifications from the GPR laboratory in Ukraine. The case was then easily manufactured in Ukraine using the digital model sent from Italy over the Internet.

Examples of Industry 4.0 Principles in the Operation of the Robotic Platform

A mine-detecting radar instrument that is built and deployed following Industry 4.0 principles is much more than a device that simply detects a buried object and provides an alarm as the operator moves through the minefield, like a hand-held metal detector would. 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 it can consist of a set of instruments for collecting, transmitting, archiving, and analyzing geo-referenced data. In the future, this may also form the basis for making automated decisions.

Figure 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 presuppose 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, which 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 with a considerable variety and number of objects buried under the surface, most of which are not mines, and represent time-wasting false positives.

The multiple sensors on Ugo 1st can detect and discriminate mines from harmless clutter with high detection and low false alarm rates (Bechtel et al., 2015). However, analyzing large datasets from an array of sensors consumes computing resources and time, and adds considerable weight and power consumption if performed on board. Here, high-speed Internet and Wi-Fi connections provide the solution. In a recent test, the robot searched a test bed in Italy while under the control of a laptop computer in Switzerland. Impulse GPR data were analyzed in Ukraine to determine coordinates of a detected object. Swiss control deployed the HSR, and the resulting image was elaborated in the USA where the call was made the target was not a mine, but in fact a hammer. The entire procedure took less than five minutes.

For our system, the operator can be a sapper in a safe area, not in the minefield. Or the operator could even be a specialist in a distant office of the mine-clearing service. Eventually, target discrimination using HSR images will be at least partially automated by machine learning (Windsor et al., 2012).

Figure 5. 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.

Preliminary Results from Field Testing

A preliminary test was carried out on three buried targets at shallow depth. Three targets were buried in a lane with natural soil variations. The operator (see Figure 5) drove the robot along the lane with a maximum deviation of ±2 cm (as quantified from the real-time 3D video recorded during the traverse). The signals from the impulse GPR were acquired every 3 cm and processed automatically to determine target positioning on the ground, relative to the antenna reference system. Figure 6 shows the results of repeated auto-detection of a single PMN-4 plastic-cased landmine (diameter 112 mm, depth 30 mm) by the moving impulse GPR. Ideally, the positions on this graph should be on a straight line and separated by 3 cm. The errors are within the experimental uncertainties and are due to the variable system speed and soil surface influence on the reflected GPR signals. Figure 7 depicts plan-view HSR images of a plastic-cased PMN-1 landmine, which was acquired after 20 days of burial at 35 mm in a loamy soil at natural moisture content (roughly 15%). Both magnitude and phase images describe well the circular geometry of the mine footprint.

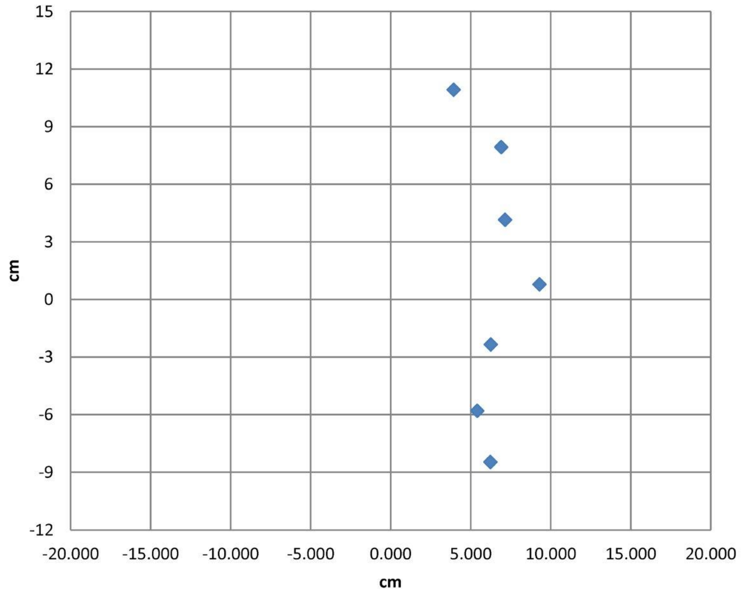

Figure 6.Results of real time detection of a target by the impulse GPR at various robot positions along the lane, with 3cm step along vertical axis. Vertical axis shows offset of the auto-detected target from the center of the impulse antenna array. Horizontal axis shows offset from the scan traverse.

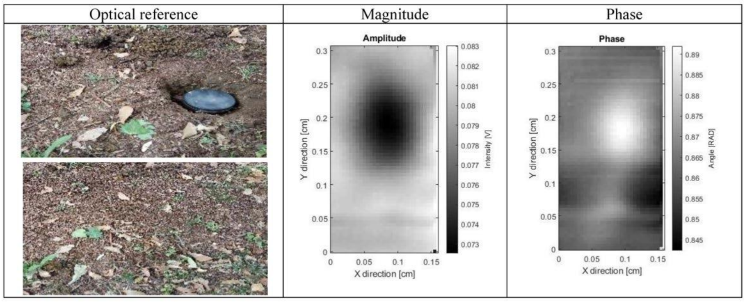

Figure 7. On the left is the optical reference image during deployment in the ground at about 5 cm depth and when buried after 20 days in dry season. On the right, holographic images (magnitude and phase) of the PMN-1.

Conclusions

We have described an integrated robotic humanitarian demining platform developing intentionally within the Industry 4.0 paradigm. This includes the integration of different sensors, with 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. Such large datasets can be used to train artificial intelligence (AI) systems for discriminating explosives devices from harmless clutter.

Using the Industry 4.0 approach, 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 can be achieved by any one company, firm, or laboratory.

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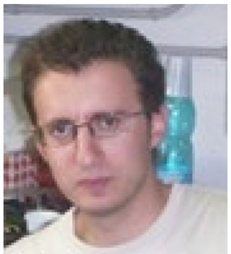

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