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Abstract

The modern world is characterized by the pervasive presence of electronic sensors, microprocessors, robotics, and wireless connectivity. Powerful computers can perform virtual simulations that would previously have required physical models or experiments. Conversely, these same machines can control robotic devices that take virtual models and produce physical objects (e.g. 3-D printing). In manufacturing, this represents a new industrial revolution, dubbed "Industry 4.0."

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 (e.g. weaving looms and other mechanical devices driven by water wheels and steam), and advances in metallurgy.

Industry 2.0.

The Second Industrial Revolution (spanning the late 19th and early 20th centuries) brought the widespread use of electric power, mass production on assembly lines, and division of labor (e.g., the Chicago and Cincinnati meat packing plants, the Ford Motor Company) – all providing greatly increased productivity.

Industry 3.0.

The Third Industrial Revolution 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 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 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).

1. Interoperability: the ability of machines, devices, sensors, and people to connect and interact to achieve a common goal.

2. Virtualization: CPSs monitor physical processes and continuously compare a 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.
3. Decentralization: The increasing 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 all times. In the context of Industry 4.0 "Smart Factories," decentralization might mean radio-frequency identification (RFID) tags on components "tell" production machines which working steps are necessary, making central planning and control obsolete.
4. Real-Time Adaptability: CPSs collect, share, and analyze data in real time. Thus, the plant can react to the failure of any system component and re-route information or parts to another machine.
5. Service Orientation: The services provided by "smart" systems can be shared by other participants across company, discipline, and international boundaries. All CPSs can offer their functionalities as a stand-alone service, making it possible to assemble the proper combination of CPSs to make a specific product or service that meets any end-user needs.
6. 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 and requisitioned automatically and can be utilized immediately.

Thus, 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.

With the support of NATO/OTAN Science for Peace and Security (SfPS) Program, Project G5014 - "Holographic and Impulse Subsurface Radar for Landmine and IED Detection" (http://www.nato-sfps-landmines.eu/) and its successor Project G5731 "Multi-Sensor Cooperative Robots for Shallow-Buried Explosive Threat Detection," we are developing Demining 4.0; designing cooperating robotic search-detection-discrimination platforms for humanitarian demining. The platforms are intended to exploit new electromagnetic and physical-acoustic methods and technologies for landmine detection in an open design environment. Humanitarian demining is a high-risk and high-cost task that can benefit from the Industry 4.0 approach. This paper illustrates the ways the systems interact. The first platform, "Ugo 1st," incorporates ultrawideband (UWB) ground penetrating radar (GPR) for rapid target detection and XYZ coordinate determination, as well as holographic subsurface radar (HSR) for discrimination of mines from clutter. These are combined with GPS positioning (real time kinematic for sub-cm precision), and light detection and ranging (LiDAR) and optical sensors (PMD Pico Flexx and Teraranger) for remote navigation, obstacle avoidance, tripwire detection, and HSR image correction. These systems and their connectivity are depicted in Figure 1 on the next page. The prototype Ugo 1st operating in an outdoor test bed is shown in Figure 2 on the next page. In the newly begun successor project, the sensors will be spread across four robotic platforms that will sequentially scan a designated area. The UWB robot will first detect targets and send coordinates to the others, who will interrogate them with HSR and a metal detector. The team will be protected by a "shepherd" robot which provides detection of tripwires and obstacles that could impede the others.

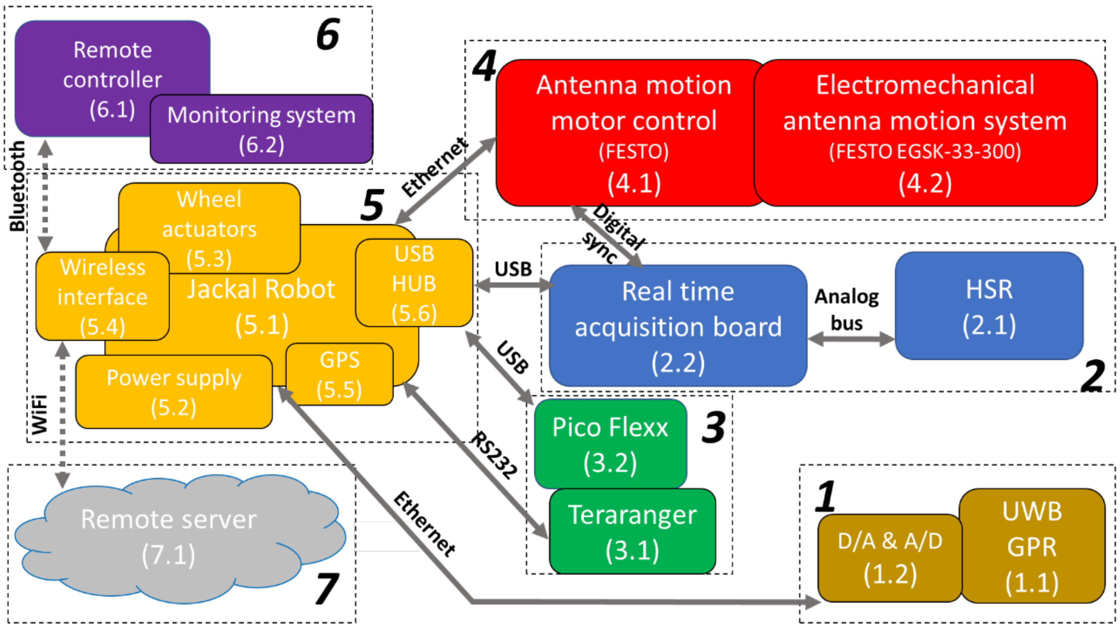

Figure 1: Schematic of the architecture of the Ugo 1st robotic platform.

Figure 2: Ugo 1st deployed in the field.

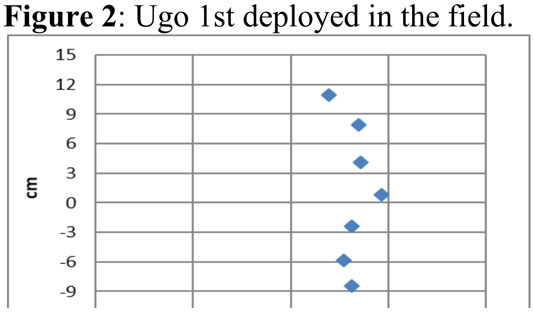

Figure 3: Results of real-time detection of mine by moving GPR robot. Vertical axis shows along-lane offset of the auto-detected target from the center of the impulse antenna array. Horizontal axis shows lateral offset from the center of the scanning lane.

Additional Industry 4.0 principles are invoked in the ways data from these systems can be shared, archived, and processed in a decentralized manner accessible to the worldwide community, and in the use of artificial intelligence to standardize the detection and classification of targets according to their level of potential threat. In the successor project, additional platforms "Ugo 2nd" and "Ugo 3rd" will incorporate an imaging metal detector and the HSR, while "Shepherd" looks ahead for boobytrap tripwires, pits, and other obstacles to be avoided. In true Industry 4.0 fashion, these robots will cooperate autonomously.

A preliminary test with Ugo 1st was carried out on three buried targets in natural soil at shallow depth for 20 days. The operator (see Figure 2) 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 3 shows the results of repeated auto-detection of a single PMN-1 plastic-cased landmine (diameter 95 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 4 depicts the plan-view HSR image of the buried landmine on a remote computer screen.

The Industry 4.0 paradigm 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.

Figure 4: Plastic-cased mine and its HSR image when buried at 30 mm depth in natural soil.

Conclusions

Using the Industry 4.0 approach, the work can be done at each stage of development and operation of the robotic platform. Each stage of development is possible through the appropriate team of experts with constant communication and consultation – 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 the use of the completed system for demining. 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.

References

Ashton, K. (2009). That 'internet of things' thing. RFID journal, 22(7), 97-114.

Hermann, M., Pentek, T., Otto, B., Pentek, T., & Otto, B. (2015). Design principles for industry 4.0 scenarios: A literature review. Dortmund, Germany: Technische Universität Dortmund.

http://www.industry-4.eu/, accessed 12/11/2020