Metal Ions in Life Sciences

Onboard Ground Penetrating Radar Solutions for the Badger Project Robot

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Abstract— **The present paper presents some results of EU founded project called Badger, the first underground robotic system that can drill, maneuver, localize, map and navigate in the underground space, and which will be equipped with tools for constructing complex geometry networks of stable boreholes. The proposed robotic system will enable the execution of tasks that cut across different applications including trenchless constructions, cabling and pipe installations, geotechnical investigations. The robot will integrate technology for perception, localization and mapping, in order to sense, map and interpret the surrounding underground environment; the system will merge collected underground data with digital maps to plan and track the motion of the robot with respect to the environment. Finally, the robotic system will be capable to manage and intelligently combine the massive data gathered during underground operation, to continuously improve its perception and cognition abilities. In particular, with reference to the cognition system, in this paper is reported the design of an on-board integrated GPR system, whose purposes is collision avoidance as well to provide input to Simultaneous Locating And Mapping (SLAM) system. Innovative design and resulting performance are reported, where miniaturization of radiating elements without decrease bandwidth and working frequency represents the main challenge.**

Keywords—Ground Penetrating Radar, Badger, robot, underground, trenchless

I. INTRODUCTION: BADGER PROJECT

A great number of various applications of strategic importance can take place in subterranean space, which would highly benefit from underground mobile robotic systems, systems that would combine drilling tools and tunnelling technologies with advanced motion capabilities, navigation and autonomy. Such excavations and tunneling applications, referred to as subsurface applications herein, span across numerous domains including development of dense underground utilities in urban areas (e.g. construction of pipelines, electricity cables, communication cables, water and waste network), energy and mineral production operations, environmental protection, and scientific exploration, search and rescue applications at disaster sites, as well as defense applications [3].

Underground works, especially in urban areas, necessitate much more elaborate excavation technology that is capable to drill and advance in the earth without opening large trenches. For this reason, many new underground excavation technologies have emerged in the past 30 years that allow installation, replacement, or repair of underground utilities or conduits without excavating a continuous trench from the surface. These are termed trenchless technology methods and typically refer to urban-utility-scale technologies rather than to larger rail, metro, or road tunnel installations. These include auger boring, ramming methods, microtunnelling, horizontal directional drilling and impact mole, and introduce new solutions for minimizing surface disruptions into short and long-term planning, design, and operation of underground systems [3].

BADGER is an EU founded project, whose Consortium aims to improve existing mature trenchless excavation and environment mapping technology and introducing technical approaches and innovations inspired by robotic technology. The output of BADGER design activities is an underground robotic system that autonomously navigates in the subsurface by pulverizing, removing and pushing through the subsurface soil while at the same time using advanced sensing modalities, and cognition to localize itself, map and understand the working environment and make decisions on how to better pursue the goals. The robotic system is designed to enable the tunneling of small-bore networks, support and stabilization of high curvature bores, the automatic detection and annotation of utilities and buried objects as well as the mapping and visualization of the 3D underground [3].

The overall concept of the robotic system is depicted in Figure 1.

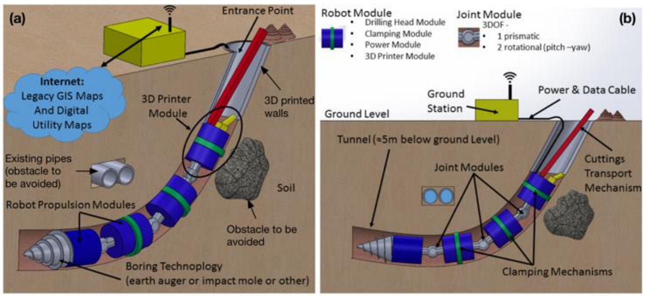


Figure 1: Schematic presenting the underground robot concept. (a) The robotic system comprises robot modules and joint modules. Joints are 3-DOF: 1 prismatic that extends along the joint axis, 2 rotations (pitch, yaw). (b) Lateral view.

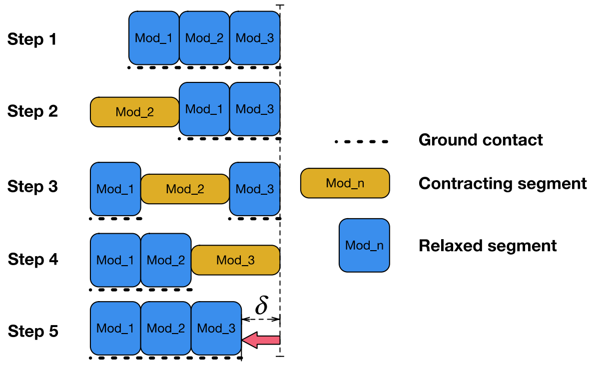


Figure 2: Peristaltic crawling locomotion. At step 5 the crawling mechanism has been displaced by an amount δ.

In order to move and effectively maneuver within the harsh underground environment, the propulsion mechanism of the underground robot replicates the worm-like crawling motion, which combines peristaltic motion with anchoring. Such biomimetic propulsion has been optimized by nature to propel within the soil and is advantageous from an engineering point of view compared to conventional engineering solutions such as wheels. By sequentially changing the ground contact force of the body segments the whole-body structure is used to generate a stepwise motion as is shown schematically in Figure 2.

The underground robot can be classified as heterogeneous and modular, because it consists of four fundamentally different modules: *drill-head module*, *service modules*, *joint modules* and *3D printer (or tool) module*. Their interfaces enable easy swapping so that the structure of the robot can be reconfigured depending on the application. The drill head module integrates the cutting tool, which is interchangeable depending on the application, i.e. different type of soil requires different cutting tools. Service modules are equipped with the clamping mechanism, PLC controllers and with power units, communication units and a set of embedded heterogeneous sensors such as ground penetrating radar antenna, IMUs and inclinometers. Joint modules on the other hand integrate Stewart type mechanisms for generating propulsion and steering mechanisms. They are responsible for the thrust force as well as the steering angle of the underground robot. The tool module is located at the very end of the chain and it follows the rest. It can host various tools for tasks that may be necessary during the underground robot's operation. Currently it is equipped with a 3D printing-like module, responsible for stabilization of the newly opened bore, but could also be equipped with other type of tools such as welding tool or a manipulator for executing construction tasks.

The main functionalities implemented by the four modules are summarized below, while more details on the real prototypes for each module, which have been developed so far as core parts of the BADGER underground robot, are provided in the next Section.

Drill-head: The drilling mechanism is based on rotary drilling technologies, which will ensure maximum efficiency and compact design. The rotary technology will be based on existing trenchless technology, into which, a novel ultrasonic drill-tool will be integrated to foster pulverization of the rock, a concept inspired by space technology that can reduce the required drilling force by 30% and lead to more efficient and compact design.

Propulsion mechanism: Novel biomimetic propulsion is developed that is equipped with clamping mechanisms and generates peristaltic crawling motion among the modules resulting in a net forward (or backward) displacement of the robot center of mass (CM). The propulsion mechanism combines the clamping mechanism of the service modules and the Stewart type actuators of the joint modules. A synchronized sequence of actions dictated by the on-board PLCs generates the desired inchworm motion.

Steering mechanism: The underground robot shall be able to steer during drilling at a desired direction (pitch, yaw, angles) by means of a novel mechatronic steering mechanism that employees actuated joints to direct the drill head at pitch, yaw angles and z-direction. The steering mechanism design shall target maximization of robot maneuverability, i.e. maximization of the curvature of the curved path of the robot, a key capability of BADGER robot.

Transportation of cuttings mechanism: The cuttings pushed back by the bore-head will be moved to the surface by means of a pump. The pump is a commercially available one.

Tunnel wall support: The last module of the underground robot is equipped with a printer head and a cylindrical manipulator. Its task is to 3D print the walls of the bore with additive material (resin or other) and construct pipe wall support.

On-board Ground Penetrating Radar (GPR): The underground robot chassis is equipped with novel, compact, GPR technology to act as active collision avoidance sensor and to sense the surrounding environment [3].

II. GPR SYSTEM DESIGN WITHIN BADGER

A. *System specifications*

The Ground Penetrating Radar (GPR) technique is widely known as one of the best Non-Destructive Testing technology for assessing underground condition, providing a proper resolution that allows to identify the typical objects of interest in construction field present in this environment: utilities, cavities, conduits, area interested by geological differences. As a part of the cognition system, a properly designed GPR system will be hosted on the drilling head of the robot.

Table 1: GPR unit system requirements

Id	Requirements		
	Table column subhead	***Min***	***Max.***
1.	System settings / adjustments via Laptop / PC prior to the use		
2.	An interface to transfer data to a Laptop / PC in order to create an alarm event report		
3.	A communication protocol that ensures there is a permanent communication between down-hole electronics and the operator at the surface		
4.	The System auto-diagnosis		
5.	The Data logging to an external device: Laptop/SBC		
6.	Weight	<2 kg	
7.	Power consumption	<20 W	
8.	Operating temperature range	-20 °C	+50 °C
9.	Water resistance	IP65	
10.	Radar Dynamic Range	70 dB	
11.	Radar Detection range @Bore-sight Direction	1 m	2 m
12.	Radar Resolution (min. distance between objects to be located @ 0.5m)	300mm	
13.	Antennas size (Transmitter or Receiver)		200x 90x 50 mm

Underground usage of a GPR system has been proposed and proved in the FP7 project called Orfeus [1]. In BADGER, the purpose of this unit is, in addition to improve the reliability of the underground objects initially mapped by a surface GPR rover, to provide collision avoidance capabilities.

System specification has been defined for the GPR system. These are briefly reported in Table 1, as a quick recap of the input for the system design.

B. System design

All the requirements have been examined, in particular the mechanical constraints have been analyzed and discussed in order to design a proper GPR system that can be fully hosted in the drilling head. In the following figures Figure 3 and Figure 4, the 3D drawing of the drilling head and the detail of one of the antenna housing are shown.

Figure 3: drill head 3D drawing

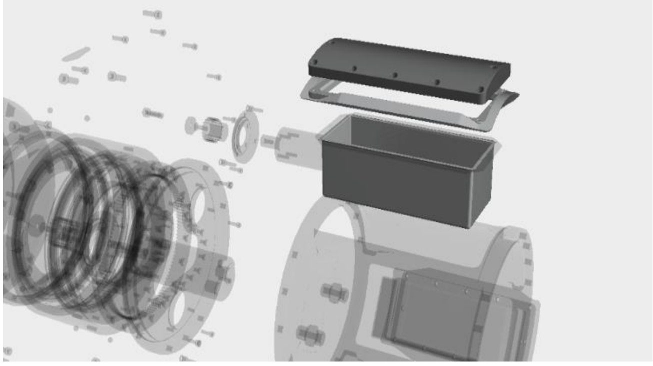


Figure 4: exploded 3D drawing of the drilling head, focus on GPR antenna mechanical slot

According to the mechanical and geometrical constraints, it has been defined the GPR antenna configuration as well as the location of the required electronic boards (micro-wave source and GPR control).

The GPR system is composed by some GPR modules, each one connected directly to the Radar Control Unit. The radar control unit is a single board providing power supply, triggering and control signals to the microwave sources (transmitter and receiver) and, integrating a CPU and ADC, provide the digital data output on standard Ethernet interface. A PC can interface through this and, running a specifically developed driver (Software Development Kit) can control the system as well as log all the collected data.

A GPR module includes a transmitting GPR antenna, connected to the RF transmitter, and a receiving antenna, connected to the RF receiver. Giving the dimensional constraints, the challenge concerned the possibility of including in a single 186x75x71 mm sized slot the whole GPR module, thus getting a fully functional transmitting-receiving module integrated in a single slot.

In this configuration the GPR module acquire radar data in so-called Vertical (VV) polarization (i.e. with the electrical field distributed parallel to scanning direction). Typical GPR antenna's beamwidth exceeds 100° on the H plane (magnetic field plane is perpendicular to Electrical field plane), so this enable the possibility of covering the whole space surrounding the robot just using three modules uniformly distributed along the circumferences of the robot's drilling head, as schematically reported on Figure 5.

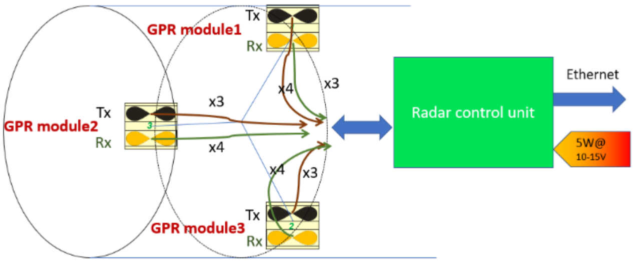


Figure 5: GPR system scheme

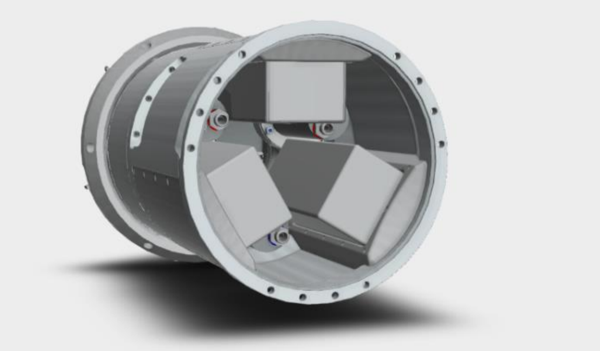


Figure 6: Drilling head rear view, GPR modules slots and containers

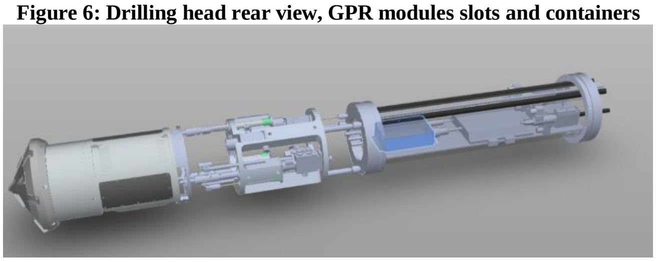


Figure 7: General system drawing – Radar Control Unit highlighted

The resulting design is represented in Figure 6, where the three rectangular GPR dedicated slots are visible.

Thus, GPR module will be hosted in the first part of the system (i.e. the drilling head), whereas the RF connections and the radar control unit will be placed on the second module of the BADGER system. The size of the sole radar control unit is 100x150x 20 mm; having it integrated in an IP65 container, the final size is slightly bigger, i.e. 202x120x55 mm (Figure 7).

III. GPR ANTENNA DESIGN

Once the system design was set as reported in the previous paragraph, the activity continued with the design of the single GPR module, more specifically the transmitting/receiving UWB antenna.

Since the working frequency and bandwidth of the GPR unit are strictly related to the antenna dimensions, the main challenging task was to obtain the desirable performance in terms of working frequency, bandwidth and beamwidth with a “small-sized” antenna. As a matter of fact, reducing antenna dimensions generally leads to an increase of the radiated main frequency at the expenses of a bandwidth reduction. Both these effects are undesirable as a higher radiated frequency signal penetrates poorly into the ground, whereas a narrower bandwidth reduces the resolution (i.e. capability of identify close targets as separated). In the course of the project, dimensions of the antenna were subjected to several revisions, mitigating conflicts about available space and mechanical interferences amongst all the items to be included into the drilling head; at the end, a further shrinkage of the module (several cm in width and height) was requested for fitting the module in the newly re-designed drilling head, resulting in a real challenge for the design of well-performing antenna.

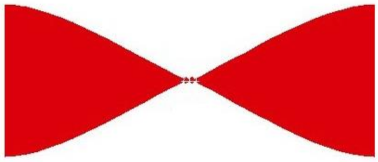


Figure 8: standard bow-tie dipole used in GPR system

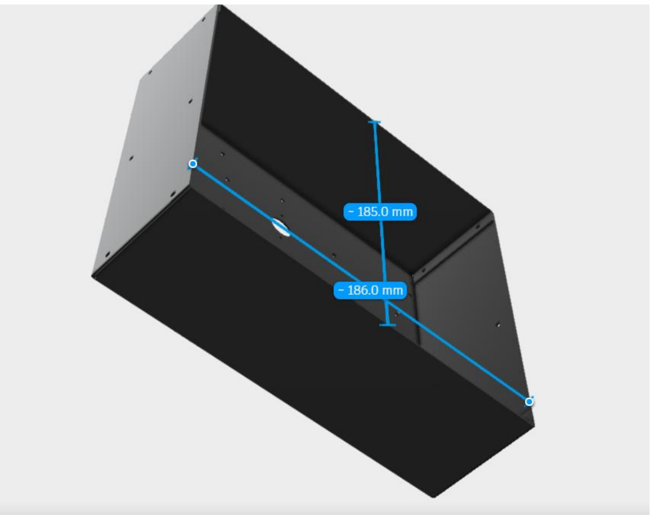


Figure 9: standard size for a 600 MHz GPR module

In Figure 8 and Figure 9, the layout of a typical 600 MHz IDS GeoRadar antenna is depicted. It can be noticed that the standard dimensions are 186x185x90 mm, not even comparable to the geometrical constraints required by the project (186x75x71 mm).

Moreover, considering the further integration in the drill head housing, other constraints had to be taken into account since the beginning; for instance, there were requirements on the size and placements of RF connectors and on the GPR antenna assembly and setup.

At the end, the studied solution is an electrically loaded dipole, following the principle determined by Wu-King configuration [2]. The designed antenna is represented in Figure 10. The loading effect is obtained through a layer of high electrical conductibility material, shaped in order to increase the ohmic load towards the extremities.

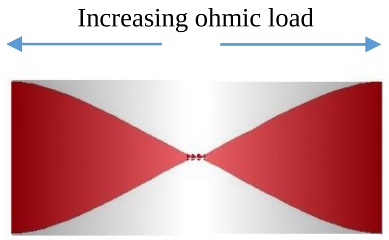


Figure 10: new dipole concept developed within Badger

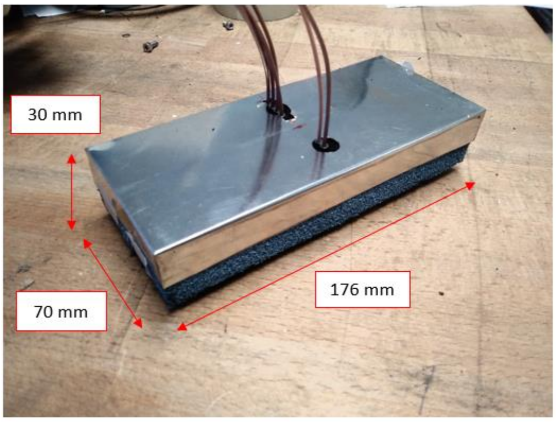


Figure 11: 600 MHz transmitting-receiving GPR module and relative size.

In Figure 11 a prototype of the antenna module is shown. The dipole is the one shown in Figure 9, one for the transmitting section and the other for the receiving part. The GPR module, in addition to the transmitting and receiving dipoles, is generally back-shielded by a metallic box to reduce radiations other than in the desired direction. The cavity between the dipole and the metallic shield is filled with a proper lossy material; this material is carefully selected to damp back-reflections from the metallic box and to electrically load the dipole in order to create a good matching with the ground electrical physical properties.

The key feature of the new module is the reduced width, as already reported in the beginning of the chapter, but, above all, the height was reduced to 30mm only, i.e. the half of the maximum allowed size (standard height for an equivalent GPR module is about 100 mm). In Figure 11 the size of the prototype is reported; the height's reduction permits also tilting the module, in order to orientate the antenna's beam by several tens of degrees towards the forward direction, instead that exactly orthogonal to the lateral surface of the drilling head as the mechanical position imposes.

Finally, the main characteristics of the GPR antenna module are as follows:

- Size of the metallic box: 176mm length, 70mm width and 30 mm height;
- a layer of 30mm of lossy material is placed on the back part of the antenna;
- the bistatic separation (i.e. distance between transmitter and receiver) is 35 mm, which is lower than in a standard 600 MHz antenna. This can enlarge the direct coupling between the transmitter and the receiver, thus reducing the maximum allowed dynamic range. To prevent this, a metallic separation between Tx and Rx has been placed.
- A thin layer (~3mm) of lossy material covers most part of the dipoles, with the effect of lowering the central frequency and increasing the bandwidth.

IV. TESTING RESULTS

Antenna performance were evaluated in the IDS GeoRadar test sites. For testing purpose, the GPR module as described in the previous paragraph has been placed in a plastic box, just to check its performance avoiding to affect them by introducing possible reflections from other metallic parts;

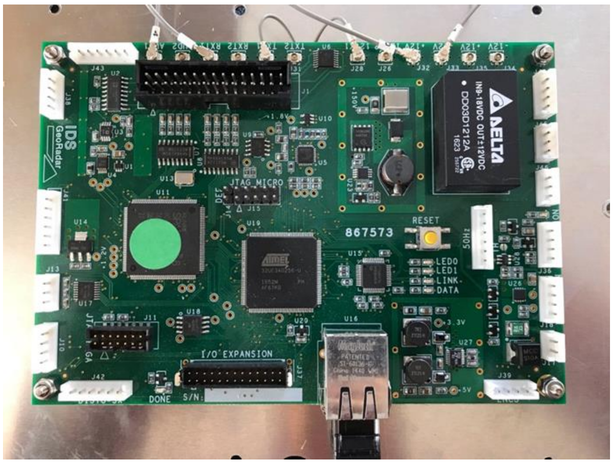
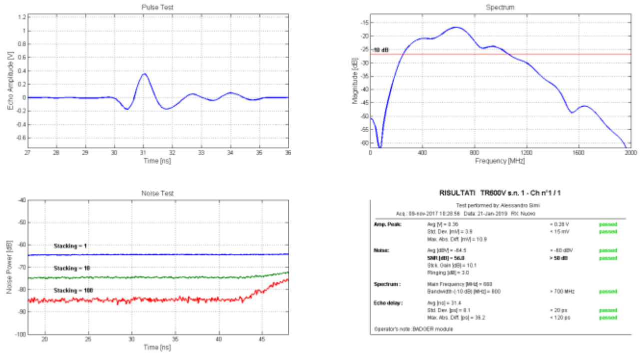


Figure 12: radar control unit PCB

Figure 13: sand box testsite



RISULTATI TR600V s.n. 1 - Ch n°1 / 1
Test performed by: Alessandro Simi
Acq.: 09-nov-2017 10:28:56 Data: 21-Jan-2019 RX: Nuovo
Amp. Peak: Avg [V] = 0.36 > 0.28 V passed
Std. Dev. [mV] = 3.9 < 15 mV passed
Max. Abs. Diff. [mV] = 10.9
Noise: Avg [dBV] = -64.5 < -60 dBV passed
SNR [dB] = 56.0 > 50 dB passed
Stck. Gain [dB] = 10.1
Ringing [dB] = 3.0
Spectrum: Main Frequency [MHz] = 660
Bandwidth (-10 dB) [MHz] = 800 > 700 MHz passed
Echo delay: Avg [ns] = 31.4
Std. Dev. [ps] = 8.1 < 20 ps passed
Max. Abs. Diff. [ps] = 36.2 < 120 ps passed
Operator's note: BADGER module

Figure 14: test results on sand box

then, the RF cables has been connected to the radar control unit (Figure 12), as per the defined scheme in Figure 5.

The output provided by radar control unit is on Ethernet, so a laptop was used for controlling the whole system and for logging the data. The whole system has been power supplied by a 12V lead battery, power consumption is well below 5W, respecting the set requirement.

The first unit test is represented by static test on sandbox (Figure 13). A set of parameters are measured and compared with standards and benchmark. The obtained results are reported in Figure 14. The results are within the permitted range for a standard GPR module at this frequency, so the test is fully passed.

A second level of test consists in a scan over an asphalted test lane, where several pipes are buried at different depth. The scan was carried out dragging the GPR system with a hand pushed cart (scanning speed about 1 m/s).

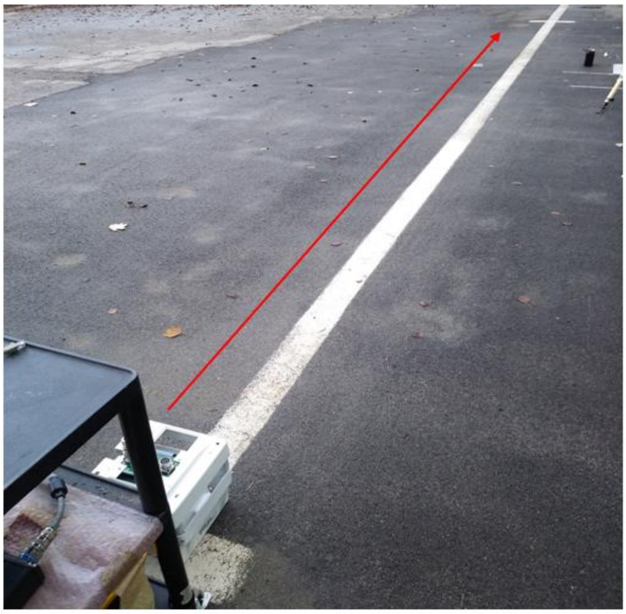


Figure 15: picture of GPR test lane

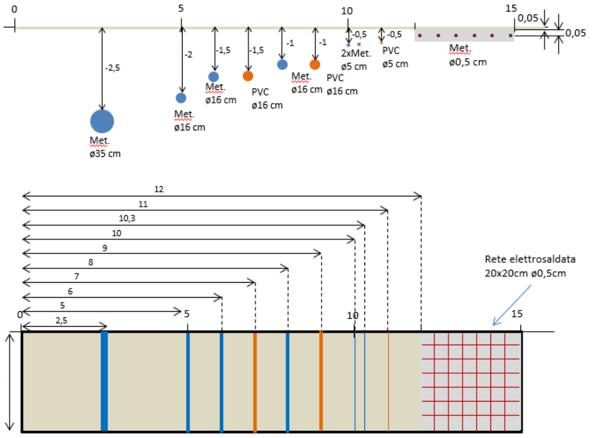


Figure 16: Test lane schematic

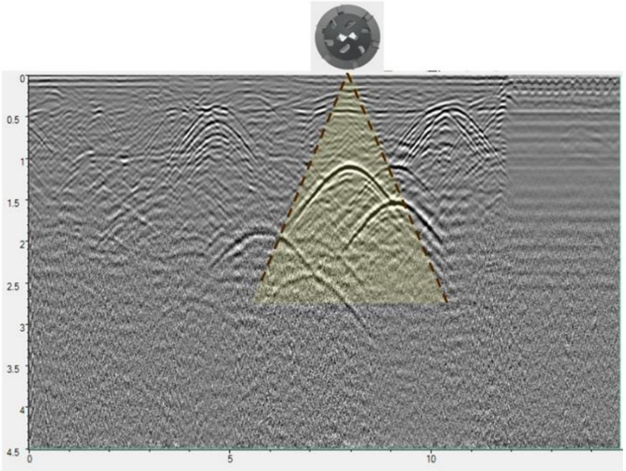


Figure 17: Radar B-scan collected with GPR module having dipoles orthogonal with respect to scanning direction

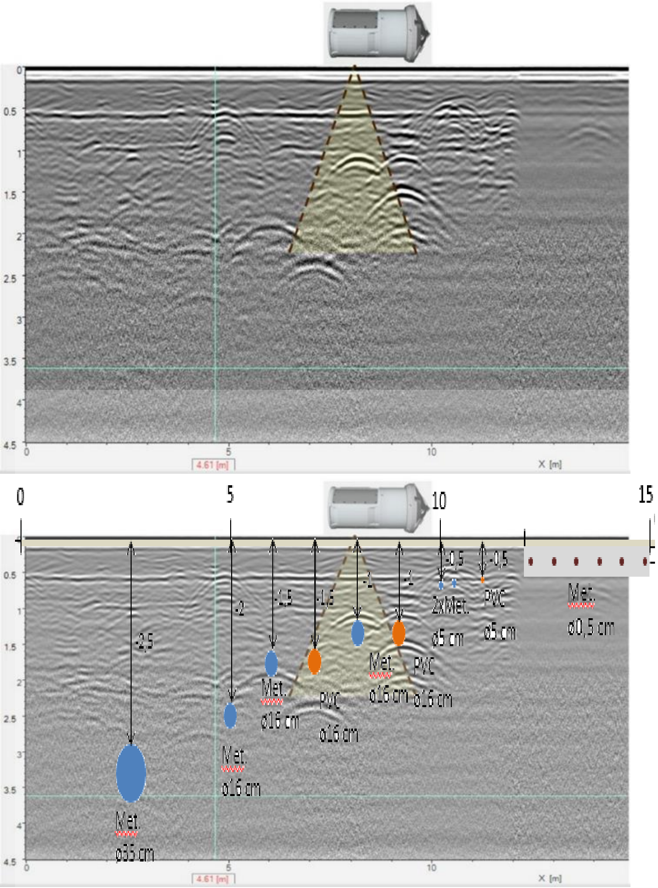


Figure 18: Radar B-scan collected with GPR module having dipoles parallel with respect to scanning direction; overlapped test site signature

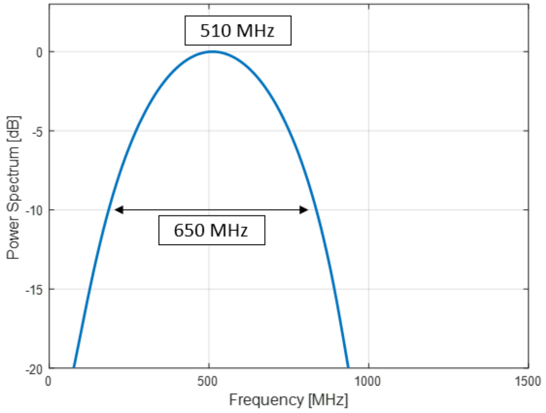


Figure 19: test results - bandwidth measurement on isolated reflection

In figures Figure 17 and Figure 18 are reported the resulting B-scans collected with the new antenna under test. The purpose is to check the detection capabilities as well as any possible ringing effect (very common in GPR module with reduced dimensions, as the one under test). Test lane is reported in Figure 15, and in Figure 16 the relative schematic.

In both the polarizations, the antenna module provided very good and remarkable results; all the pipes buried within 2.5 m deep were detected as highlighted on Figure 18; no ringing signal is affecting the radar performance, even without the removal of the background. This performance is perfectly aligned to the one of standard off the shelf 600 MHz products. The evaluated frequency and bandwidth on an isolated reflection on a specific target (@1 m depth) are within the expected ranges (Figure 19).

Figure 20: drawing of the GPR module slot

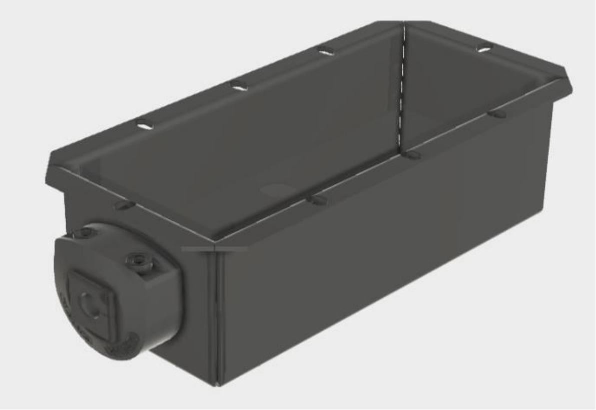


Figure 21: GPR module metallic container

Figure 22: GPR module integrated in slot, covered with robust plastic plate (in pink), connected to IP65 sealed container for Radar Control Unit.

The design proceeded with the definition of the connections and the integration of the module on the hosting drilling head. In Figure 20 the drawing of the available slot in the drilling head is shown.

The design foresees a gland applied on the back (with respect to the direction of drilling) to make the RF cables pass through (Figure 21). Then, all the cables are routed towards the container of the radar control unit (a commercial IP65 metallic container as the one shown in Figure 22), which has to be fixed in the second service module and not in the drilling head.

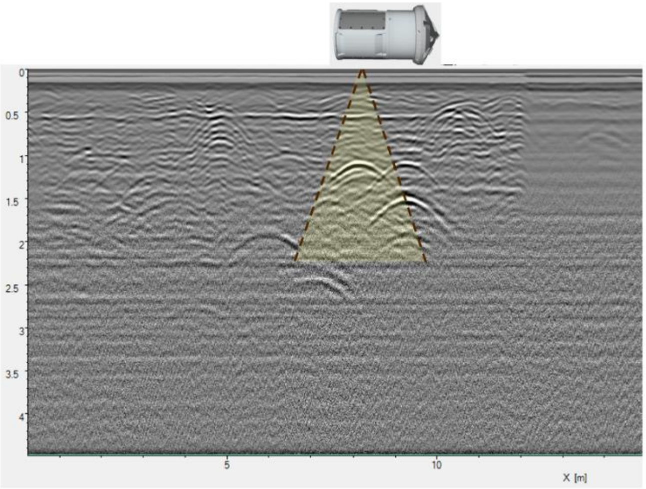


Figure 23: Radar B-scan collected with the GPR module integrated in the slot.

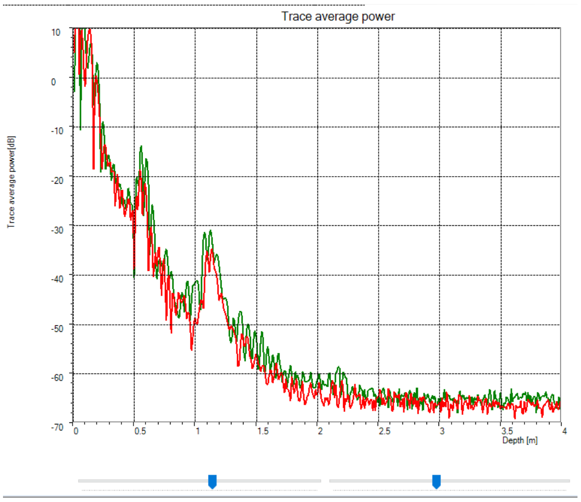


Figure 24: power vs depth chart - green GPR module stand-alone; red: GPR module integrated in slot

In Figure 23 and are reported the results of testing on the test lane. The radargram aspect is aligned to the one obtained by the GPR module when tested alone; by a comparison of a power vs depth graph evaluated around the 1 m deep target (Figure 24), it is possible to notice that the inclusion of the antenna in the slot and adding the plastic cover decreases the received power by ~3 dB and decreases the noise level lower than 1 dB; so, the overall SNR results decreased by slightly more than 2 dB, somehow negligible with respect to a resulting dynamic range in the order of 80 dB. Performance are retained aligned to expectation with respect to requirements listed in par. 2.

V. CONCLUSION

In the presented paper, the EU founded project Badger is described, in particular, the design of an on-board underground GPR for collision avoidance and SLAM has been reported. Important positive results on controlled test sites have been shown, the new strongly size-reduced GPR antenna performs slightly better with respect to standard benchmark on test site, thanks to an intensive research on antenna design and on ohmic loading profile. Then, design activities regard the development and testing of a system prototype to be integrated on the whole system for final validation test; when included in the robot drilling head mock up, the GPR system presents a slightly reduced performance in terms of SNR evaluated on specific buried target, anyway considered a valid performance with respect to initially expressed requirements. Next steps in the project regard the physical integration on robot prototype and in situ test. For doing this, an intensive integration activity is expected, as well as the execution of test in real underground environment. Some improvements to radar performance are expected: given the robot very slow advancement speed (about 6 m/h), a benefit in terms of SNR is expected applying stacking of radar traces, up to a factor 600 with respect to the one applied scanning on test lane hand pushing the system.

ACKNOWLEDGMENT

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