European Commission

BADGER

RoBot for Autonomous unDerGround trenchless opERations, mapping and navigation

System Handbook

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Robot for Autonomous Underground Trenchless Operations, Mapping and Navigation
System Handbook

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Introduction

The expansion of construction activities to the underground, the so-called 4th constructional dimension, is expected to be massive in the near future. The usage of underground space subsurface has enormous potential social, environmental and financial benefits such as land use efficiency, land cost savings, less construction disruption to the cities, aesthetics, etc.

The traditional approach for accessing the underground space has been open-cut excavation. However, this technique entails the destruction of surface infrastructures, traffic disturbances, noise, and environmental implications among other inconveniences. As a result, in most cases, open-cut excavation is not a viable solution for systematic underground access and utilization. One alternative solution is the horizontal directional drilling (HDD) for trenchless underground works. This technology solves many of the problems associated with open-cut methodologies, but many challenges are still open.

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 surface 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, micro-tunneling, 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.

BADGER is an attempt to face the challenges existing in HDD technology. Despite the major recent advances in robotic autonomous systems technologies, smart robots that can operate with increased autonomy in subsurface applications is still an open challenge. Autonomous robotics has a high potential impact on numerous economically and socially significant applications. BADGER focuses exactly on this challenge, aiming to leverage a series of existing well-performing trenchless technologies. They will be integrated with novel easily deployable smart robotic components that can enable the autonomous performance of underground excavation operations. Through research spanning the fields of advanced mechatronics, perception, cognition, and more, BADGER will develop a novel underground robot system. It will have advanced technical capabilities, increased autonomy and dependability, introducing a step change in the way that underground operations are currently performed. In this line, BADGER will develop not only a novel underground robot but a complete integrated highly modular robotic system. It can be practically applied in numerous underground applications performed in the everyday practice of companies, citizens, authorities, etc.

BADGER project

The Robot for Autonomous Underground Trenchless Operations, Mapping, and Navigation project (BADGER) is leading European efforts in trenchless underground construction through the creation of a new horizontal directional drilling system. It is an industry-led collaborative research project on Underground Construction, part-funded by the European Commission. Commencing in January 2017, it is a 3-year project involving 7 partners from 5 countries across Europe.

The goal of the proposed project is the design and development of the BADGER autonomous underground robotic system. It can drill, maneuver, localize, map and navigate in the underground space, and which will be equipped with tools for constructing horizontal and vertical networks of stable bores and pipelines. The proposed robotic system will enable the execution of tasks that cut across different application domains of high societal and economic impact. It can include trenchless construction, cabling and pipe installations, geotechnical investigations, large-scale irrigation installations, search and rescue operations, remote science and exploration, and defense applications.

Key technologies, applications, and industrial cases

This book, “BADGER: Key Technologies, Applications, and Industrial Cases” is the first book launched by the BADGER project consortium. The aim of this book, “BADGER: Key Technologies, Applications, and Industrial Cases” is to showcase some of the recent developments in the area of trenchless horizontal directional drilling.

The portfolio of chapters in this book presents the modular structure of the BADGER robotic autonomous robotic system. The control architecture is the frame that enables the design and operation of the BADGER robotic system. Following, the different modules are presented: steering and propulsion, clamping system, ground penetrating radar, etc. Finally, integration and testing scenarios are presented.

Design and development of the drilling head

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Keywords: trenchless technology, bore head, cutting transportation, sucking system

Background: Trenchless technologies are gaining increasing importance in the installation of pipes and cables. Common to all methods is the goal to install various pipes in the underground by avoiding the destruction of the surface. For creating holes for pipes the soil cuttings have to be transported to the surface.
In terms of labour costs and efficiency, autonomous systems are becoming increasingly important. For such a drilling system a compact bore head with integrated cutting transportation mechanism has to be developed.

Objectives: The main goal of this project is the development of a drill head, which is to produce a borehole of approx. 300 mm diameter. The resulting soil cuttings get into the interior of the drill head. From they are to be transported to the earth's surface. In addition to the required mechanical drive elements and the drill mechanism for the drill cuttings, three radar antennas are to be integrated into the drill head, which allow observation of the drill head environment and the detection of obstacles.

Methodology: The schematic structure of the bore head to be developed is shown in Fig. 1 and Fig. 3:

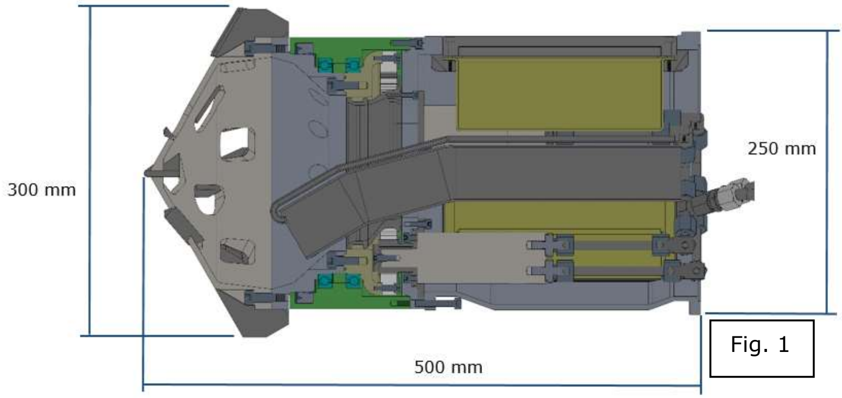

Fig. 1

The bore head consists of four main components:

- Scraper plate
- Suction pipe for cutting transportation
- Driving motors/gear drives/bearings
- Radar antennas

The scraper plate (Fig. 2) is driven by hydraulic motors. There are holes through which the cuttings reach the inside of the drill head. From there, the cuttings are sucked off by the suction pipe by a suction box, supported by a small water flow and transported to the earth's surface.

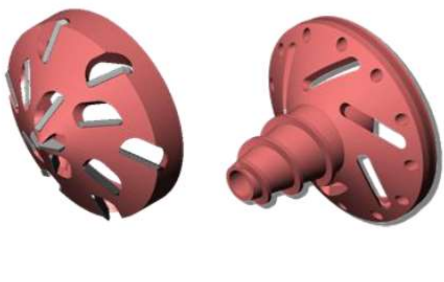
Fig. 2

The radar antennas are integrated in the rear area of the bore head.

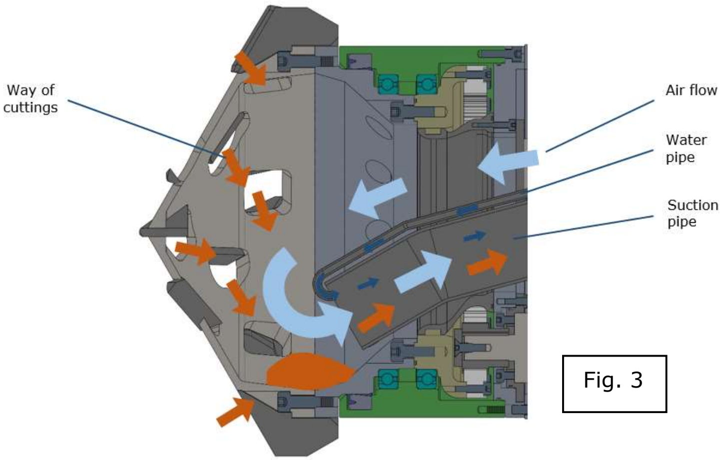

Fig. 3

Impact: The new bore head is very compact and makes it possible to create holes with comparatively small diameters. This is made possible by a space-saving design. The cuttings are sucked off from the inside of the drill head. There is no need to use fluid.

The integration of a radar system for the detection of obstacles in the surrounding of the bore head avoids damaging of pipes and cables which are already in the ground. The combination with control, feed and clamping modules enables the construction of an autonomous drilling robot.

Ultrasonically assisted boring

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Keywords: Granular materials, fluidisation

Background: Drilling and penetration could be facilitated, across a broad range of applications, if the forces required to advance through the terrain could be reduced. One mechanism by which this might be achieved is ultrasonic fluidisation of the terrain.

Objectives: The goal is to demonstrate whether the forces and torques required to advance a representative drill head into a granular material may be reduced by the application of ultrasonic vibration.

Methodology: An auger (Fig. 1) was advanced into a barrel filled with glass microspheres of between 150 and 250 micrometres in diameter (Fig. 2). The force and torque required to advance and rotate the device, both with and without ultrasonic excitation applied to the auger itself, were recorded.

Impact: Both force and torque were reduced, although there were some subtleties.

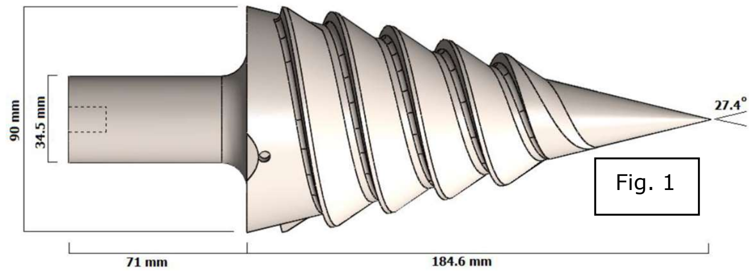

Fig. 1

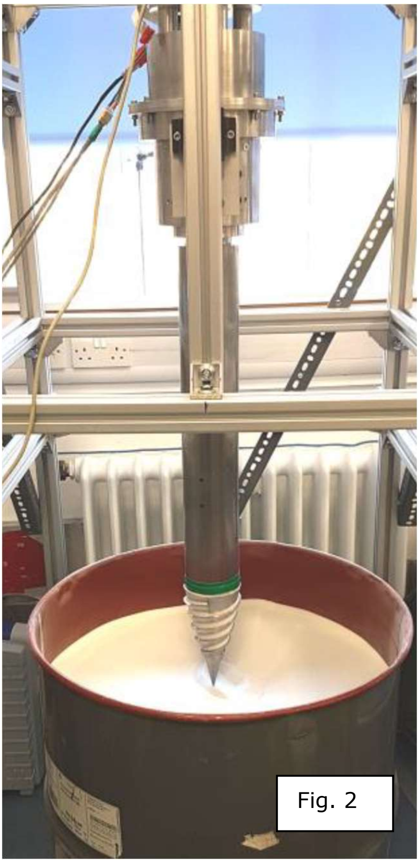

Fig. 2

The effects of ultrasonic vibration on overhead force can be seen in Fig. 3, showing the peak reacted force for both the rotary and non-rotary experiments. Force increases steadily with depth, with the maximum depth of 30 cm corresponding to the peak force. It is clear that the non-rotary penetration requires significantly more force than in the rotary tests. Overhead force is reduced from roughly 600 N to 100 N in the non-ultrasonic case, whereas it is reduced to roughly 350 N at maximum amplitude for no rotation. This suggests that the cork-screw effect caused by rotation has a much larger impact on force reduction than ultrasonic vibration does. This would explain why increasing vibration appears to have no effect on reducing overhead force in rotary augering; the force has already been reduced by more than ultrasonics can provide.

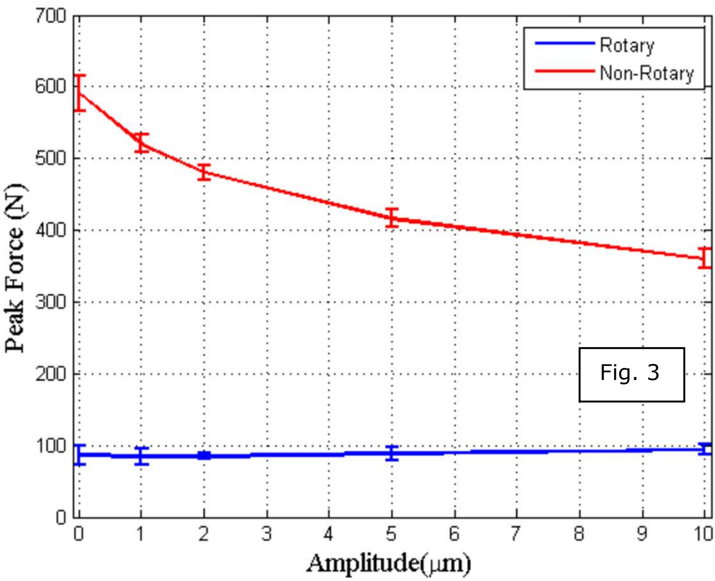

Fig. 3

The effects of ultrasonic vibration on torque can be seen in Fig. 4. Similar to force, the torque steadily increases with increasing depth, reaching a peak at the maximum depth of 30 cm. Here, a clear decrease in the peak torque with increasing ultrasonic amplitude is evident, decreasing from 120 Nm to 85 Nm at 10 μm; a 30% overall decrease. The ultrasonic vibration causes granular fluidisation in the immediate surrounding of the auger, reducing the surface friction.

It is important to note the power consumption from loading the ultrasonic transducer in this way. The power consumption at the maximum depth was measured to be roughly 10, 25, 120, and 300 W for 1, 2, 5, and 10 μm respectively.

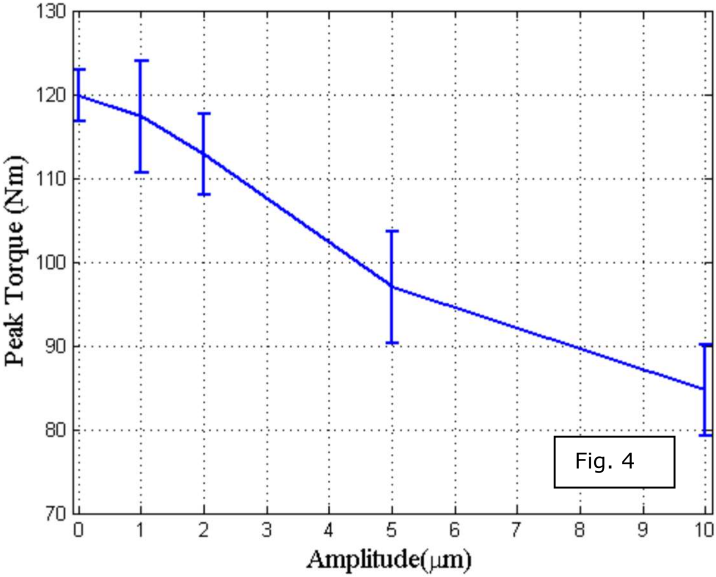

Fig. 4

Underground robot on board GPR system

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Keywords: GPR, robot, underground, trenchless, bandwidth.

Background: 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.

Objectives: 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 BADGER robot. In particular, with reference to the cognition system, the designed on-board integrated GPR system has as purposes 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.

Methodology: According to the mechanical and geometrical constraints determined by the design of the robotic system, 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 to integrate the system in the underground robot, the challenge concerned the possibility of including in a single 186x75x71 mm sized slot the whole 600 MHz GPR module, thus getting a fully functional transmitting-receiving module integrated in a single slot (typical commercial equipment at this working frequency has 200x200x100 mm size).

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 Fig. 1.

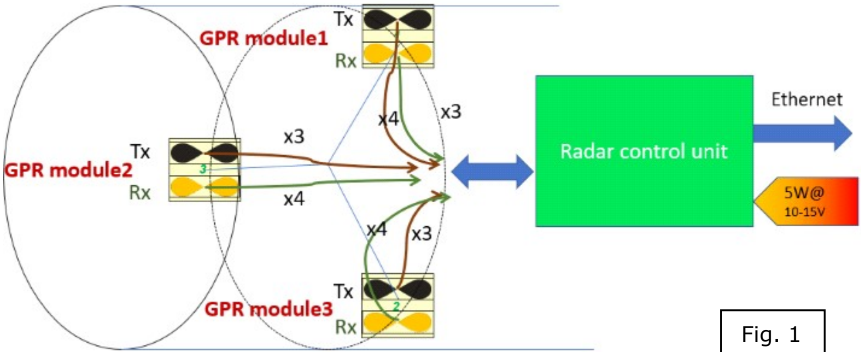

Fig. 1

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). the studied solution is an electrically loaded dipole, following the principle determined by Wu-King configuration (Fig. 2).

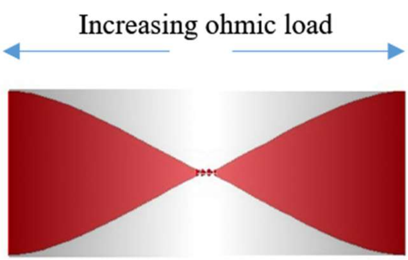

Fig. 2

The designed antenna is represented in Fig. 3. The loading effect is obtained through a layer of high electrical conductibility material, shaped in order to increase the ohmic load towards the extremities.

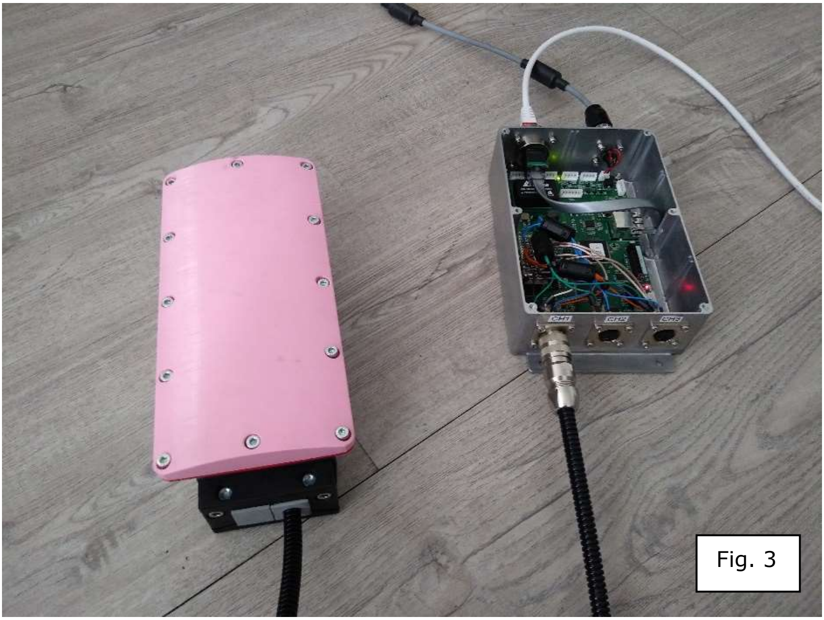

Fig. 3

Results: Antenna performance were evaluated in the IDS GeoRadar test sites, consisting 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). Resulting B-scans (radargram) collected were analyzed, with the purpose to check the detection capabilities as well as any possible ringing effect (very common in GPR module with reduced dimensions). The antenna module provided very good and remarkable results; all the pipes buried within 2.5 m deep were detected as highlighted on Fig. 4; 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. 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.

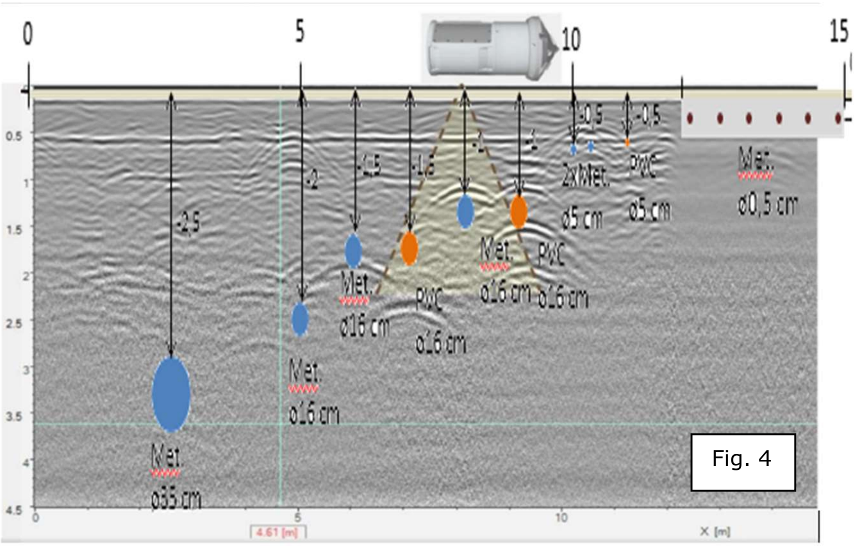

Fig. 4

Autonomous subsurface utility mapping

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Keywords: subsurface mapping, utilities detection, hyperbola detection, autonomous operation, boustrophedon path planning, GPR processing, SLAM.

Background: Construction with trenchless technologies is a challenging task and so far witnessed limited automation, albeit the abundance of the technological advancements that took place during the last years, mainly in the domain of computer and robot perception. Synchronous arrays of Ground Penetrating Radar (GPR) antennas have been developed that can provide massive subsurface data collection, however the existing technological background is focused mainly on the processing of 2D radargrams in point-wise manner and hardly any progress has been achieved in the construction of consistent 3D maps of the subsurface environment. Such maps annotated with semasiological information regarding the buried utilities (e.g. pipes, manholes etc.) could augment the existing CAD files and, thus, greatly benefit the construction domain by providing prior information regarding the existence of buried infrastructures, to be available before the initialization of the construction processes.

Objectives: The main objective of this work is to develop a robotized solution consisted of a surface operating rover and a GPR antenna in order to perform autonomous subsurface scanning. Fig. 1shows the surface rover and a trailer with GPR antenna. The outcome of this procedure will be the construction of a consistent 3D volumetric map of the scanned subsurface area augmented with semantic information, describing the topology, the pose of the existing infrastructures and their type as well.

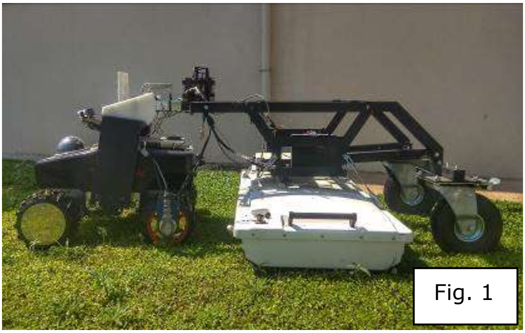

Fig. 1

In order to create a globally consistent map, accurate robot localization and its registration with the GPR data is required. Efficient robot control is necessary to regulate robot motion, ensuring full coverage of the area to be scanned, while controllable GPR data acquisition, their synchronization and processing is mandatory for the meta-data registration along the robot's path. Refinement of the constructed map should be performed in case the surface operating rover revisits the same spot, correcting, through loop closure optimization, both the robot's localization as well as the progressively built subsurface map.

Methodology: Initially, the area to be scanned is defined by the user (Fig. 2) and by considering the rover's embodiment and the motion constrains of the trailer with the GPR antenna, a Boustrophedon global path is computed, so as to force the rover to pass from the same area with small overlap between the traces of the GPR antenna. During robot motion, stereo-based graph SLAM is performed to estimate the robot's pose and keep track of its trajectory. Tracking of the robot's pose within the path is applied through a Model Predictive Controller (MPC), which exploits the robot dynamics and the current pose estimation obtained from SLAM, in order to estimate the desired velocity commands at the rover's wheels.

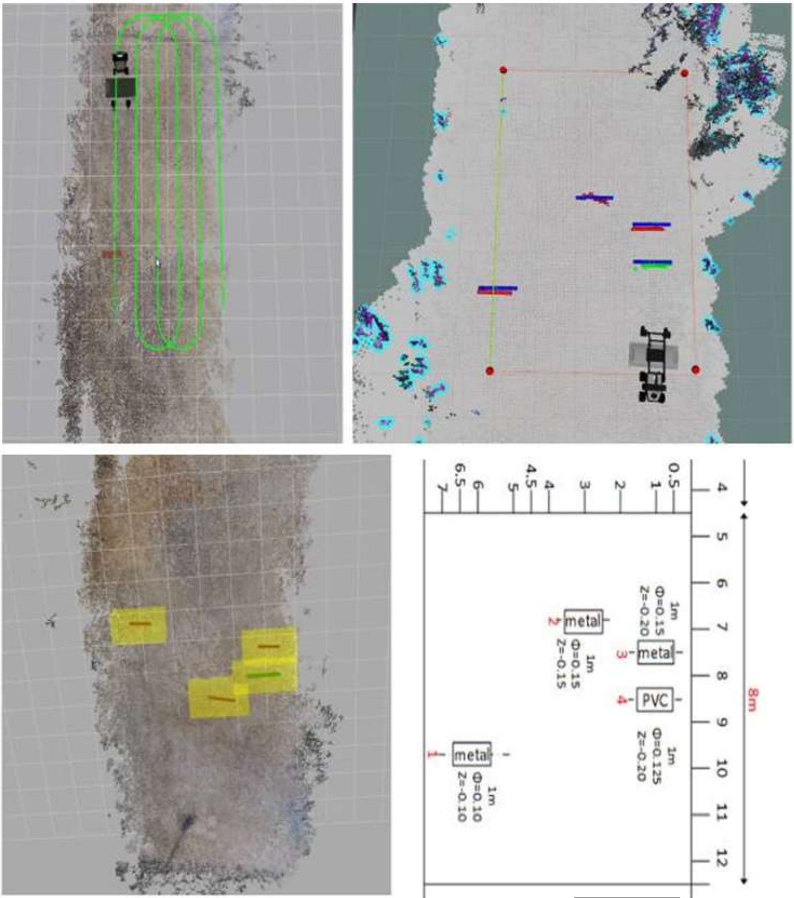

Fig. 2

Fig. 2 shows: in the top left, the selected area to scanned with the boutstrophedon path; top right, the detected pipes in the subsurface (red pipes constitute to the metallic ones and green pipes to the plastic); bottom left, the 3D volumetric surface/subsurface metric map and; bottom right, the ground trough CAD model.

During the surface rover's travelling, the graph is expanded by adding new nodes, when a new rover pose is computed. GPR antenna measurements are registered to each node, inheriting also the rover's pose transformed to the GPR model's retina. Along the rover's straight routes, GPR readings are concatenated and formulate a B-Scan on which image processing based on HOG feature extraction and hyperbola geometrical fitting is applied, to isolate candidate regions of buried infrastructures in the form of point clouds. Exploiting the array of sensors mounted in GPR antenna and the overlap of the GPR trace during scanning, multiple points are gathered in the areas where buried utilities exist, formulating a sparse 3D metric map. Considering that the subsurface of urban areas typically consists of structured utilities such as pipes, manholes and box-like objects, these utilities are modelled with primitive geometrical shapes such as lines, circles and rectangles. Therefore, the 3D metric map is further processed, to produce an enhanced semantic representation referred herein as a "utility map" (Fig.2).

Impact: The robotization of the subsurface utility mapping process constitutes a novel method that can significantly boost the construction services. It provides 3D semantic representations that are essential for numerous applications, which include assessment of dense underground utilities in urban areas, evaluation of the subsurface for energy and mineral production operations, as well as detection of buried objects (e.g. landmines and structured utilities) for search and rescue applications at disaster sites. Additional benefits of the autonomous subsurface utility mapping are the reduction of the operation costs in construction domain and the acceleration of the subordinate processes.

Generation of collision-free and curvature-bounded trajectories for underground robots

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Keywords: Path planning, non-holonomic robot, curvature-bounded, smoothing process.

Background: The motion planning module is one of the most important elements of any autonomous robotic system. It is responsible of the generation of the trajectories without collisions from the initial position to the goal position. The generated trajectory must be smooth and kinematically feasible by the underground robot. In addition, the sensors processing, the SLAM module to update the pose of the robot and the map, and the trajectory planner must work in an online manner to react to changes of the environment.

Objectives: The main goal consists in developing a motion planning module which generates feasible and collision-free trajectories for the underground robot to follow. The underground robot cannot move sideways and must always move forward to steer, due to the external constraints imposed by the bore hole that is drilling. This robot is restricted to follow trajectories with bounded curvature and the orientation of the drill head is tangential to the displacement.

Methodology: In order to generate a trajectory from the current pose of the underground robot to the goal point, a modular design of the motion planning module has been adopted. Initially, the obstacles of the underground environment are enlarged with a “safety” radius to ensure the generation of a safe trajectory and successful obstacle avoidance maneuver.

Then, a piecewise straight-line path is generated using an optimal variant of Rapidly-exploring Random Tree (RRT*) algorithm (Fig. 1). This algorithm finds an initial trajectory quickly, and the improves the quality of the trajectory with time. This is achieved by minimizing a cost function that depends on the Euclidian distance and the difference with respect to a predominant orientation.

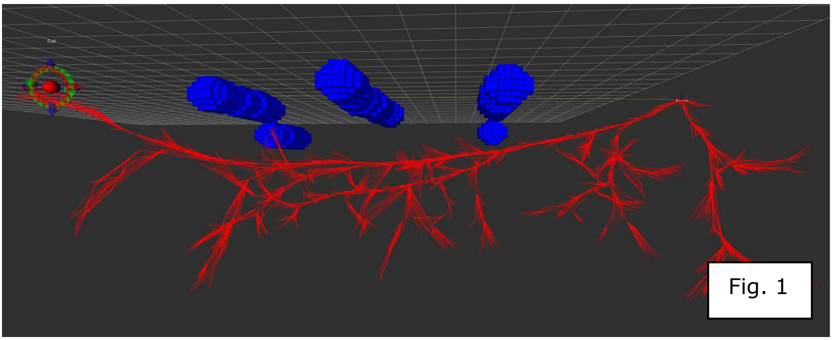

Fig. 1

This initial path is used to initialize a sequence of connected free space 3D grids, called corridor. These 3D grids are inflated to increase the free space which is used in the final phase of the trajectory.

The final phase consists in the generation of smoothing trajectories using Sequential Quadratic Programming (SQP). SQP is applied to minimize the curvature and the length of the trajectory, always satisfying the constraints imposed by the bore-hole. The output of this phase is a smooth trajectory as piecewise cubic Bezier curves. These curves are bounded by a maximum curvature and do not collide with the obstacles.

Fig. 2 shows the calculated straight-line trajectory from the starting point to the goal (red arrows) is used to generate a tunnelling corridor (blue cubes). This tunnelling corridor is then utilized to generate a smooth path (green line).

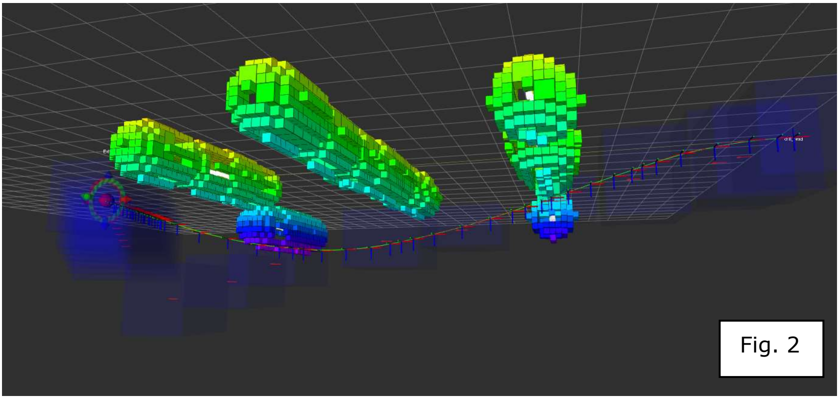

Fig. 2

Impact: The motion planning module must generate feasible and collision-free trajectories taken into account that the robot motion is limited by the drilling operation that is performing.
Another important issue is the collision avoidance method once the GPR sensor detects a new obstacle. For this reason, the definition of risk zones in the GPR field of view must be specified in order to check whether the new obstacle will cause a collision.

Design and development of propulsion and steering unit for autonomous underground robotics

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Keywords: Propulsion, Steering, Design, Module, Robot.

Background: Service Robotics are now used in several domains, leveraging new technologies that reduces cost, difficulties and risks. On the other hand, Robotics field is very wide at the moment, comprising from inspection drones to logistic AGVS.
In this sense the “RoBot for Autonomous unDerGround trenchless operations”, namely Badger robot, is introducing a new robotic paradigm addressing Underground Robots.
To adapt the current robotics knowledge for this harsh environment with special focus on motion strategies and capable hardware means a big technological challenge that has not been faced until now.

Objectives: The main goal of this work consists of designing and developing a module or modules that could handle the movement of the Underground Robot Badger, with special attention to both steering and traslation movements relying on a bio mimetic paradigm.

The starting idea is to replicate an earthworm movement, which grips to the soil and then extends or retracts parts of the body.

Methodology: In order to achieve this goal, a first study of the existing technologies that could be adapted for Badger is made. To find the limitations or constraints that the robot must overcome and a feasible hardware construction with capable actuators is prioritized. An iterative process is set up, where our solution is modified and improved as the challenges appear.

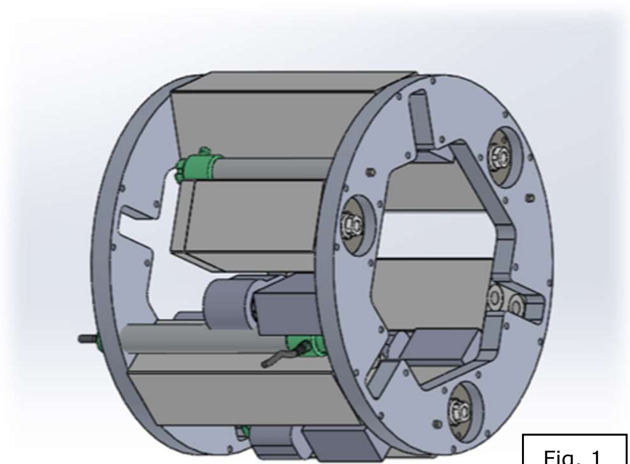

Fig. 1

First of all, a unique robot module joining steer and propulsion actuation is decided (Fig. 1). This module consists of ring-shaped metal parts joined together with linear actuators (cylinders) that are retracting or extending thus modifying the module length. For the robot “steering”, the frontal part will imitate a so-called Stewart Platform in order to control the inclination of the Badger drill (Fig. 2). The kinematics constraints of this work will lead the progress of this solution. Another important milestone in this process is the selection of a power source according to functional requirements derived for related torque and forces study. Apart from electric actuated prototypes, a more robust system with hydraulic cylinders becomes a need (Fig. 3).

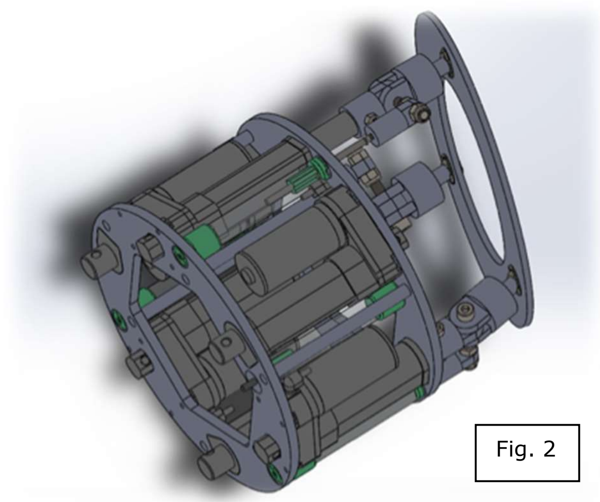

Fig. 2

Impact: The Propulsion and Steering module is a core part of the Badger robot that is fulfilling a challenging and yet to be validated hardware specification, according to the very first results on underground robotics. This module design is also providing a cost effective development, aiming to a future industrial implementation.
This work may also lead the way in this novel field that proposes a solution fitting a number of applications, from trenchless construction to telecommunications or utility maintenance.

Fig. 3

Ground clamps for tunneling robots

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Keywords: Underground robotics

Background: Tunnelling underground requires the reaction of forces and torques, and moving along means that the points of reaction of these forces and torques will need to move as well. A disengagable clamp, able to act against the sides of the tunnel, and with a low applied pressure to accommodate the uncertain terrain, is therefore required

Objectives: The goal is to demonstrate whether a clamping system can be made that would enable the passage of a large, underground robot.

Methodology: Some tests were conducted to determine the force and torque that can be applied to the sides of a borehole in soil using an inflatable bladder. A full-scale system, which has a rigid, hollow core to transmit forces and allow the passage of internal services, was then prototyped. This system has a number of innertubes which serve as air bladders, inside a tough and elastic outer sleeve (Fig. 1).

Air is fed through a pneumatic solenoid into a manifold that distributes the air evenly between the innertubes. A pressure sensor is incorporated into the manifold to allow for controlled pressurisation of the system and failure detection if the device becomes damaged and cannot inflate. Deflation is controlled by a second pneumatic solenoid that can either vent air directly into the inside of the casing or can be connected to a vacuum line for expedited removal of the air, and a faster deflation time (Fig. 2).

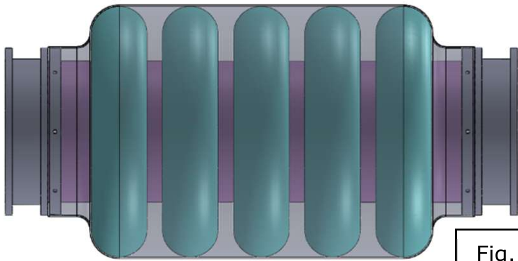

Fig. 1

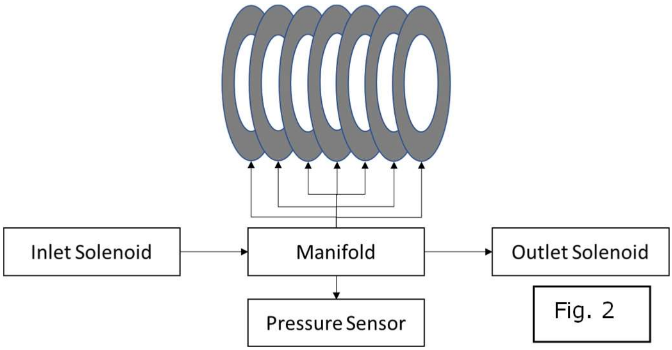

Fig. 2

Impact: When inflated with 200 to 300 mb of pressure, an expansion of several cm in diameter occurs that is able to react end loads of several hundred Newtons, with a predicted torque performance in the order of 400 to 500 Nm. Inflation takes about five seconds, and deflation takes about ten seconds when the overpressure is removed. With full deflation, the clamp returns to its original diameter due to the elastic recovery of the outer sleeve (Fig. 3).

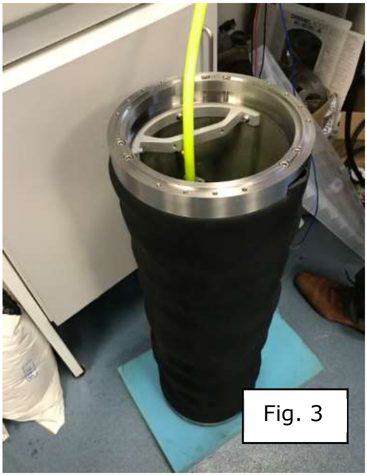

Fig. 3

Experiments are underway to determine if shunting the exhausts of the innertubes into the spoil extraction pipe (which will be 200 to 300 mb below atmospheric pressure) can reduce the deflation time. However, some work will be required to accommodate all the internal air manifolds (Fig. 4).

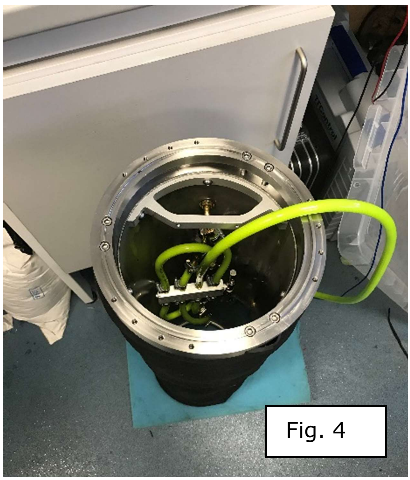

Fig. 4

BADGER Control Architecture

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Keywords: Underground robot, control architecture, multilayer software architecture, supervised autonomy.

Background: Existing trenchless technologies lack feedback control automation and operate in an open-loop mode. Error correction and motion compensation are accomplished solely by the human operator, i.e. the operator estimates the path deviations using a handheld sensor-device, and corrects by manually sending commands to the underground system; this manual approach increases effort, cost and time. Underground robotics will overcome this limitation by developing a novel feedback control system architecture which, in combination with the localization system and maneuverability, will enable autonomous navigation of the robot with on-line motion planning with collision avoidance properties.

Objectives: BADGER provides a control architecture that ensures supervised autonomous operation of the BADGER robot. To this end, the architecture must bring together five different levels of operation: Graphical User Interface (GUI), task planning, path planning, on-line motion planning with collision avoidance, and low level control. The user specifies the entry point and exit point of the tunnel drilling task on a digital map, and also provides some info (type of soil, etc.). The entire process of drilling and maneuvering from the entry to the exist point is executed autonomously.

Methodology: The BADGER system involves many software modules, some of them operating on different hardware, at different rates, serving different functionalities and specifications. As a result, a layered software architecture was chosen, which puts emphasis on the logical grouping of modules according to distinct logical functionalities and distinct physical infrastructure onto which the software runs.
Five software layers naturally emerged, dictated both by time requirements (loop-rates) and the level of abstraction of the signals which are involved. The layered architecture is schematically shown in Fig. 1.

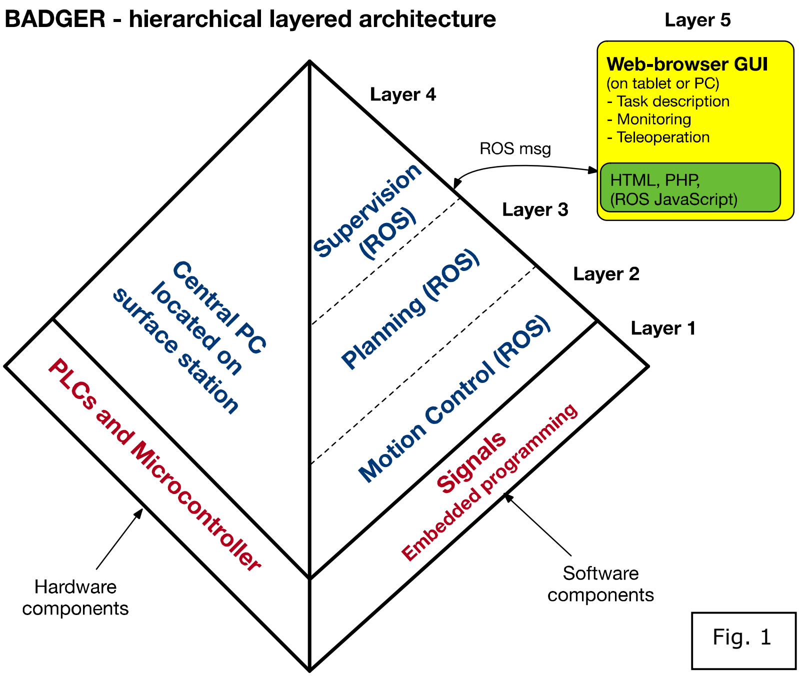

Fig. 1

The shape of the pyramid represents the hierarchical structure. The top layers are higher in hierarchy and are served by the immediately lower layer. The right side of the

pyramid represents the software layers. The left side of the pyramid represents the tier on which the software runs. Layer 1 (Signals), is the lowest level of the hierarchy and runs on embedded PLCs and microcontrollers on-board the underground robot and surface rover. Layer 2 (Motion Control), consists of all trajectory tracking software and runs on the central PC located on the surface station. Layer 3 (Motion Planning) runs all the planning and perception algorithms of the BADGER system. This layer also runs on the central PC. Layer 4 (Supervision) monitors the execution of the process and if needed raises alerts. The code of Layers 2 - 4 is implemented in C++/Python using ROS framework. Layer 5 (GUI), is the top level of the architecture and is implemented using web technology (HTML, PhP, etc.) and ROS javascripts.
The signal flow of the actual control system, i.e. of Layers 1 to 3 is depicted more analytically in Fig. 2.

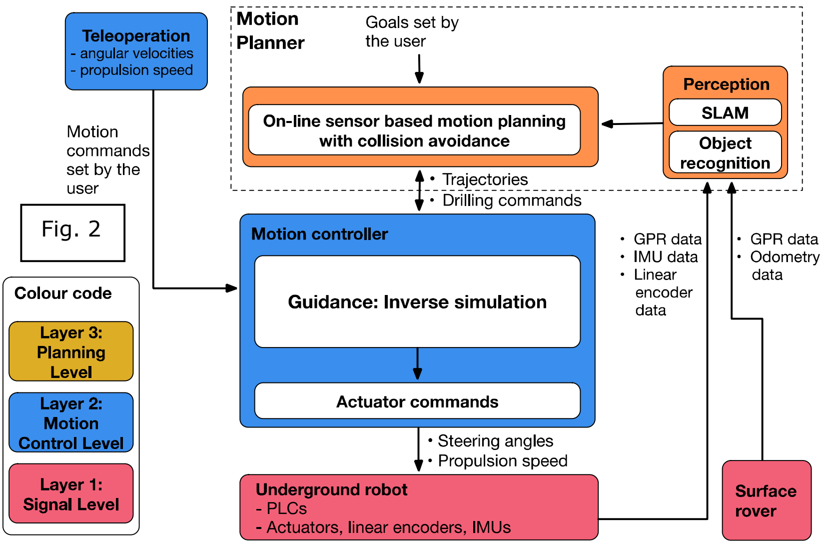

Fig. 2

The BADGER controller executes off-line path planning and motion planning. Next, the drilling motion of the robot is controlled by sensor-based on-line motion planning with collision avoidance properties. The feedback signal is provided by the perception unit which sends to the motion planner robot localization and obstacle localization information. The low-level controller performs trajectory tracking and finally, the embedded controllers (PLCs) execute actuation control.

Impact: Supervised autonomy enables the BADGER robot to perform trenchless tunnel constructions in environments that have buried utilities and other objects. Existing trenchless technologies do not exhibit manoeuvrability and do have perception and decision making capabilities to bypass obstacles blocking their path, hence the technologies can drill straight paths and can be used only in areas that have a subsurface relatively clean from utilities. In addition, the proposed control architecture enables the robot to automatically make decisions on how to better pursue its goals, and there is no need for a group of human operators to measure, then calculate and the execute the updated plan, all these are done automatically by the control system. Hence, the entire process is done faster and is more cost efficient.

System integration for BADGER robot: hardware and software integration, tests and implementations

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Keywords: Integration, hardware, software, underground, PLC, electric, electronic, hydraulic, pneumatic.

Background: BADGER robot presents different subsystems with different applications and functionalities. There are three main subsystems: The hydraulic subsystem, the pneumatic subsystem and the electric/electronic subsystem. Each module has its own subsystems and must be integrated into a one defined standard in order to make the robot modular. Therefore, the integration of all subsystems is the work related on this paper.

Objectives: The goal of this work is to integrate into one underground robotic system the main subsystems presented on the robot. Fig. 1. Shows the integration CAD model of BADGER robot and Fig. 2, the BADGER Control scheme.

The unit connections between modules will be based on the optimization of space available inside the robot to give the possibility of include more devices inside as well as to allocate in a better way these devices. The modules will communicate with each other thanks to the PLC device allocated inside the robot, which will control every signal from sensors to actuators. Furthermore, the PLC will communicate with the central computer through Ethernet protocol.

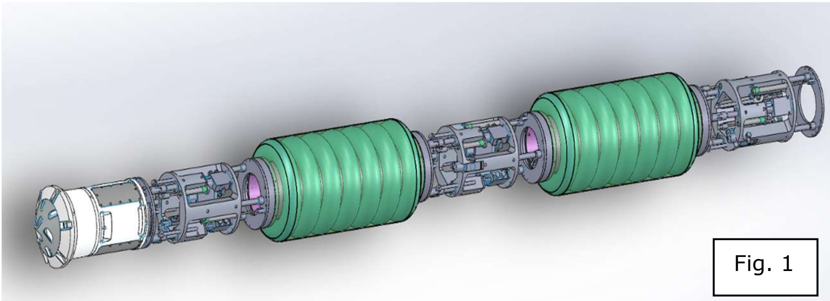
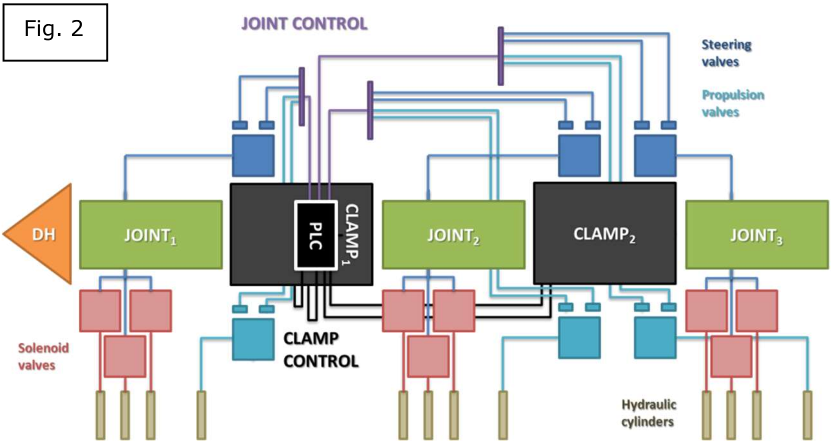


Fig. 1

System (software and hardware) integration is the final task of this work and will include the integration of the developed units and systems under common umbrella of unit connections, communications and control.

Fig. 2



Methodology: The methodology is started with trial procedures which test the specifications of each of the modules and integrate them after all. These trials consist on propulsion and steering tests, clamping inflation and deflation test (Fig. 3), and rotational test for the bore head of the BADGER. Each module with its own subsystems has its own methodology for testing and integration purposes. Therefore, the joints have been tested separately from the clamping and bore head systems.

Once these tests have been performed, the following process is the integration of the modules and test of each motion all together. This process requires a common design of modules interfaces and some mechanical modifications to allow their union. Some electronic and electric interfaces have also been design to communicate every module's signal with the PLC. Furthermore, a hydraulic and pneumatic scheme has been developed to allocate each device inside the robot. Fig. 4 shows the integration on Lab facilities of real BADGER robot

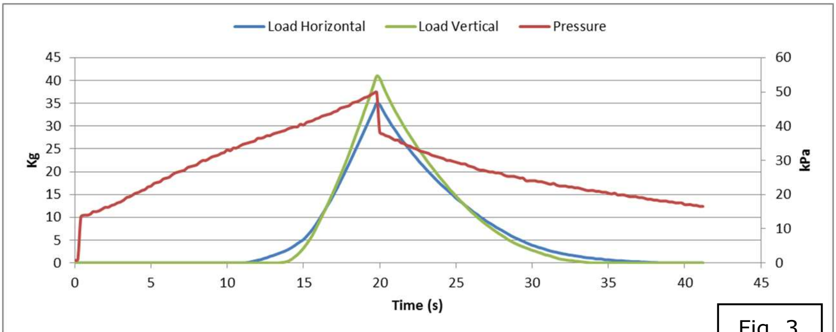


Fig. 3

Impact: The related work has the biggest impact onto the robot system. Each subsystem has to be perfectly designed and integrated for the correct functioning of the real robot. The free space available thanks to the redesign of hydraulic and pneumatic system allow to the electronic components and devices to be allocated inside the robot. Furthermore, until each subsystem isn't finished, the whole robot could not work properly, so the integration of all of them has a crucial impact on the project. The integration of the previous circuits and its components would define a way to design underground robots which include electric, electronic, pneumatic and hydraulic circuits.

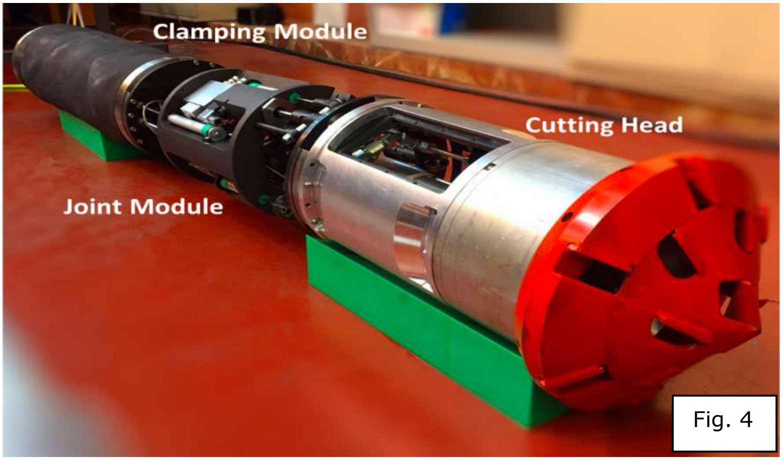


Fig. 4

Testing approach

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Keywords: trenchless technology, testing, test field, BADGER, autonomous drilling

Background: The BADGER- (RoBot for Autonomous unDerGround trenchless opERations, mapping and navigation) consists of different subsystems which are developed by different companies located in different European countries. Subsystems and the completed robot have to be tested on different levels and at different locations.

Objectives: One main part of the BADGER robot (subsystem 1) is a boring robot which is able to drill holes under the surface autonomously. The robot comprises different components as a boring head including a ground penetrating radar, a propulsion and steering unit, transportation system for soil cuttings and a tunnel wall support system. All the components are being developed by different partners. Subsystem 2 consist of a control station for navigation and steering and surface radar system for mapping the surface, developed by different partners, as well. To ensure the required functionality of the components and their combination a staged testing procedure is necessary.

Methodology: In a first step each component is tested by the company, which developed it. These test stage ensures the stand-alone-functionality and the achievement of the required technical properties. In a second step all component are

assembled at the Robotic Laboratory of University Carlos III, Madrid. On this stage functionality and interaction the different parts has to be tested. At the premises of Tracto-Technik GmbH & Co. KG, Germany, At TT a wooden box is available which can be filled with different soils in order tocarry out drilling tests with different drilling tools or machines under welldefined conditions. The wooden box (Fig. 1 & Fig. 2) consists of wooden walls with the inner dimensions of 6000 x 3000 x 3000 mm (LxWxH). Each wall can be opened easily to get access to the drilling tools. With this box the functionalities of the robotic mechanism can be easily tested under different soil conditions like sand, lose rock or gravel.

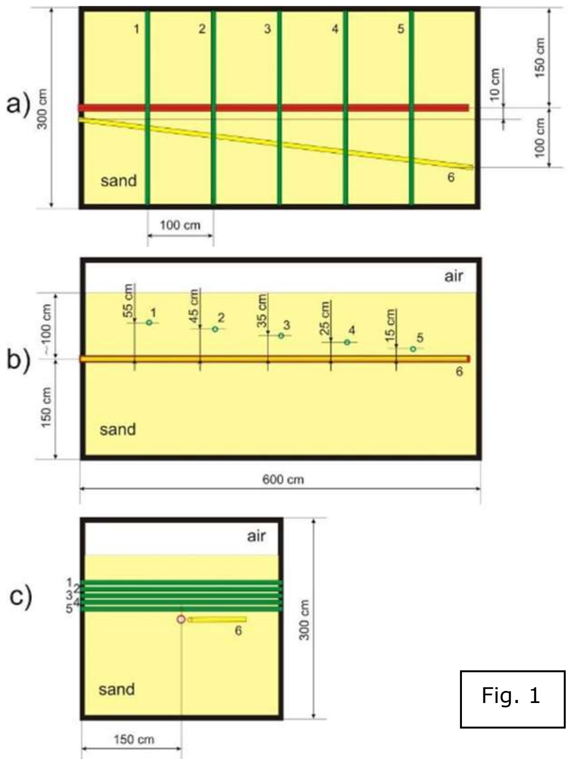

Fig. 1

Fig. 2

A second more close-to-real-operation approach for testing will also be followed: BADGER will carry out drilling tests in the test field owned by TT (Fig. 3), which is also used for drilling tests in real conditions for the HDD drill rigs developed by TT. The underground robot system can be tested in soil mixture of weather shale, limestone and loam in different depth under the surface. The robotic system can be started for the first trials out of a pit or from the surface, then drilling parallel to the surface in shallow depth (approx. 1,0 - 1,5m) and the exit again at the surface of the test field. The drilled lengths can be varied. The maximum length of the test field is about 100 m.

Impact: The BADGER robot is new and complex approach of developing a trenchless technology for drilling holes and install pipes under the surface autonomously. The number of technologies and the complexity of the system requires different and well defined tests under various conditions to verify the results of the theoretical and experimental surveys done in the early stages of the project.

Fig. 3

BADGER Consortium members

BADGER project has seven partners from five different European countries (Fig. 1).

Fig. 1

The **Universidad Carlos III de Madrid** (UC3M) is a public university founded in 1989. Its main goal is to provide specialised training in Law and Social Sciences and Engineering, as well as to become a prime European research centre. In addition, the Universidad Carlos III de Madrid pursues the creation of an innovative university and seeks to offer a University model based on a quality-oriented philosophy. In this sense, modern, flexible and multidisciplinary curricula have been designed trying to suit the scientific and technological demand of the Society. The university is located in the southern metropolitan area of Madrid and consists of five centres, 2 Faculties, 1 Technical School, 1 School of Graduate Studies and 1 Doctoral School in 4 Campuses.

Concerning the training area, the Universidad Carlos III de Madrid was the first in Spain to be fully adapted to the requirements of the European Higher Education Area (EHEA) (The Bologna Process) and offers studies in most of the scientific disciplines.

The Robotics Lab, led by Dr. Carlos Balaguer, Dr. Miguel Ángel Salichs and Dr. Luis Moreno, is a pioneer group in robotics and automation both nationally and internationally and is formed by a consolidated and multidisciplinary group of over 70 engineers, computer scientists and science graduates who are experts in the automation of systems and processes by means of advanced robotic technologies with a high content of technological innovation. The main work areas of the group include robotics (humanoid robots, social robots and assistive robots), industrial automation, robotics and automation in construction, mobile manipulators and aerospace applications. The RoboticsLab research team is characterized by its object-oriented and cross-disciplinary research in areas that include robots for construction & mining industries, humanoids robots, assistive robots, human-robot interaction, service and social robots, personal robots, intelligent control, computer vision, artificial muscles, climbing and legged robots postural stability. RoboticsLab researchers work toward spreading the use of robots in industrial applications of robotics, participating intensively in collaborative national and international R&D projects with companies and institutions.

The **University of Glasgow** was founded in 1451 and is one of the world's top 100 universities. Alumni or former staff of the University include the philosopher Francis Hutcheson, engineer James Watt, economist Adam Smith, physicist Lord Kelvin, surgeon Baron Lister, seven Nobel laureates, and two British Prime Ministers. Our research continues to be world leading, with a major announcement of our role in the direct detection of gravitational waves having been made in the past few days.

The **Centre for Research and Technology-Hellas** (CERTH) is the only research centre in Northern Greece and one of the largest in the country and it was founded in 2000. It is a legal entity governed by private law with non-profit status, supervised by the General Secretariat for Research and Technology (GSRT) of the Greek Ministry of Education and Religious Affairs. CERTH has important scientific and technological achievements in many areas including: Energy, Environment, Industry, Mechatronics, Information & Communication, Transportation & Sustainable Mobility, Health, Agro-biotechnology, Smart farming, Safety & Security, as well as several cross-disciplinary scientific areas.
The Information Technologies Institute (ITI) was founded in 1998 as a non-profit organisation under the auspices of the General Secretariat for Research and Technology of Greece, with its head office located in Thessaloniki, Greece. Since 10.3.2000 it is a founding member of the Centre for Research and Technology Hellas (CERTH) also supervised by the General Secretariat for Research and Technology (GSRT).
CERTH-ITI is one of the leading Institutions of Greece in the fields of Informatics, Telematics and Telecommunications, with long experience in numerous European and national R&D projects, It is active in a large number of research domains such as Security and Surveillance, Image and Signal Processing, Computer & Cognitive Vision, Human Computer Interaction, Virtual and Augmented Reality, Multimedia, Database and Information Systems and Social Media Analysis. CERTH-ITI has participated in more than 60 research projects funded by the European Commission and more than 85 research projects funded by Greek National Research Programmes and Consulting Subcontracts with the Private Sector (I&T Industry). In 2008, the Information Technologies Institute attracted an income of 14 M€ from National and European competitive R&D projects. For the last 10 years, the publication record of ITI includes more than 250 scientific publications in international journals, more than 450 publications in conferences and 70 books and book chapters.

IDS GeoRadar Srl, ince July 2016 is part of Hexagon AG, a multinational company operating worldwide with 16,000+ employees. Hexagon mission is to deliver actionable information through technologies that empower customers to reach their full potential and shape smart change across diverse industry landscape. Formerly IDS GeoRadar was the Radar Division of IDS Ingegneria dei Sistemi SpA and started the business in Ground Penetrating Radar in 1991. At that time, the company developed the first multi-frequency, multi-channel array systems which enables the construction of detailed 3D images of large underground areas, dramatically improving utilities detection. Building on this success IDS GeoRadar has become, today, one of the largest global provider of GPR products; during these 30 years of operation IDS GeoRadar developed a set of systems suitable for a wide spectrum of applications, spanning from subsoil deep objects detection to utilities mapping, road and railway assessments, structure investigations etc.
In the early '2000 IDS GeoRadar started studying the development of a novel ground-based interferometric radar (GB- SAR), capable of performing a synthetic aperture processing and measuring sub-millimeter movements of landslides and structures. This family of products (called IBIS) has been commercialized from 2007 on and constitutes today a major revenue for IDS GeoRadar.

Singular Logic is currently the leading Software and Integrated IT Solutions Group in Greece. With a full understanding of the entire range of market requirements, we offer advanced and integrated IT systems as well as full support services, investing capacity and internal infrastructure. This is based on experience, technological know-how and the existence of specialized Singular Logic solutions and products as well as on an array of companies that collaborate with our Group. SingularLogic is member of Marfin Investment Group, with highly skilled personnel,

specialized know how, large product portfolio, large customer install base with 40.000 SME clients and 700 large enterprises, dynamic distribution network consisting of 400 business partners nationwide and significant implementations of 400 large and complex IT projects for the private and public sector is the reliable and credible partner that guarantees the investment of its customers. In addition, SingularLogic operates in various South East Europe countries through direct subsidiaries in Bulgaria, Romania and Cyprus, having set the foundations for substantial development in the region.
Comprehending new technologies and utilizing them in a creative manner is the key for developing innovative applications and effective IT services. Each year at Singular Logic, we invest a significant part of our turnover into R&D and into the development of new, pioneering methodologies and state-of-the-art technological tools. The European Projects Department of Singular Logic works on the design and implementation of innovative applications and platforms targeting different business sectors as well as on the engineering and management of business services. The activities of the department span over three main different application areas: Smart Cities, Future Internet Enterprises and, E-accessibility, health and independent living.

Tracto-Technik is the largest European manufacturer of steerable and non-steerable trenchless pipe / cable laying systems. The company operates world-wide and has sister companies in the UK, France, USA, Australia, Switzerland and Morocco. Through 5 production plants and 5 service stations in Germany as well as a tight partner network all over Europe / the globe the equipment is supplied to contractors in all European countries / world-wide. Tracto-Technik was founded in 1962 by Mr Paul Schmidt and is today operated by his son, Mr Wolfgang Schmidt. Today, Tracto-Technik (Germany), and her sister companies TT UK (United Kingdom), Tracto-Techniques (France), TT Technologies (USA), TT Asia Pacific (Australia), Tracto-Technik Schweiz (Switzerland) and Tracto-

Technik Afrique (Morocco), as well as Prime Drilling (large HDD rigs) and other affiliated companies form the TT Group of companies, offering the broadest range of equipment for trenchless laying and replacement of pipes and cables. The company has its own training department and participates in standardisation working groups to establish qualification and quality regulations for trenchless technologies. Three R & D and Technology Centres research provide an in-house capability for development and engineering covering all aspects of trenchless technologies, with the focus being on innovation. More than 10% of the company's personnel of about 400 people are employed on R & D projects. Thus, more than 400 patents and several international innovation awards have been generated and are owned by Tracto-Technik.

Robotnik started its activity in 2002 and is currently a leading company in the European service robotics market. Robotnik is specialized in:

- Robotics product manufacturing and reselling (mobile robot platforms, mobile manipulators, arms, hands and humanoids)
- Robotics R&D end Engineering projects
- Service Robotics Applications: i.e. development of robots for performing autonomous tasks for the well-being of humans or machines, excluding manufacturing.
- UGV Engineering: specific unmanned ground vehicle engineering.