Autonomous drilling robot for landslide monitoring and consolidation

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Abstract

The paper proposes a new highly automated drilling system able to create holes up to 20 m depth in rocky walls using standard 1.5 m length rods. The drilling system, to be used to automate rocky walls consolidation, has to be positioned in the points of the map earlier defined by the geologist; for this reason it is hosted onto a semiautonomous climbing platform, with rods stored on-board. An automatic system is also required to feed the drilling head with new rods while the hole progresses and to recover the rods once the hole is up. The drilling system mainly consists of: a commercial drilling rig with the requested modifications for the interfacing to an automatic feeding system; a manipulator (endowed with a suitable gripper) for the loading/unloading of the rods; a storage buffer for allocating the rods. In the paper, the alternatives considered for the design of the whole drilling system are shortly recalled, explaining the guidelines which led to the final architecture, as well.

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1. Introduction

Worldwide landslides are one of the major types of natural hazards killing or injuring a large number of individuals and creating very high costs every year. There are innumerable small to medium-size slope failures that cumulatively impose costs to society as great or greater than the occasional catastrophic landslides that draw so much attention. Due to the high costs of the actual intervention and remediation methodologies, very time consuming and labour intensive, minimum landslide prevention is carried out and remediation is always a long and expensive process.

This work today is performed in different ways distinguishing two cases: first, the area to consolidate is little and, second, the area to consolidate is large.

In the first case, the area is traditionally approached by skilled rappelling operators who set up fixed wire nets using holes drilled manually. An alternative solution is the use of vehicles with articulated arms carrying a drilling unit on the top: this solution is applicable only when wide approach areas are available and consolidating/monitoring work is within 50 m height. Both these solutions are cost-effective only for targeted interventions (rock blocks, etc.) and the consolidation operations are performed manually.

In the second case, the dimension of the operation area and the high number of holes require scaffolds to be placed on the wall. This solution is highly expensive, time consuming and labour intensive, involving a lot of man-power exposed to highly dangerous tasks for low-added value operations. Furthermore, scaffolds hinder and prevent prompt recovery as well as limit the number of intervention per unit of time, with direct social and economic impacts.

The topic has growing environmental concern, which aims at the replacement of human operators in the consolidation workspace. This workspace is characterised by risky and unhealthy conditions, such as falling down, presence of dust, striking of crashed stones, and the likes. In addition, another concern is to fully monitor the work-cycle to provide remote evidence whether tasks are performed correctly and to collect relevant data (basic geology, on-duty remarks, etc.), supplying on-line assessment of the achieved issues.

The technology proposed in the paper really helps in fast remediation and prevention of landslides. This new technology

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enables: *deep drilling for slope consolidation or landslide remediation at lower cost than today; *setup of drainage elements reducing groundwater penetration into slippery layers (such as clay layers), in limited time and at lower costs than today; *fast and repeatable analysis of soil instability to prevent landslides.

As a contribution in the development of this technology, an innovative robotic system, named Roboclimber, was developed to this purpose, with the capabilities to move on irregular rocky walls [1–4] and to perform automatic drilling and slope stability remediation [5].

The Roboclimber system has the following advantages: reduction of the operating costs both in case of slope consolidation and (much more) in case of monitoring and small interventions; improvement of the overall efficiency by reducing time consuming operations; improvement of safety of the operators thanks to the remote control of the system, avoiding accidents related to operating at high heights on scaffolds. Furthermore, the replacement of humans with machines in the field of consolidation presents several positive aspects; first of all, operators are not subjected to health’s danger for the generated dust and vibrations and to accidents like falling down or when rocks fall; then, tasks are performed all in the same way and more quickly.

2. Roboclimber

Roboclimber is a modular robot. The main modules are hereby briefly summarised [6].

– A mobile robotic platform: robust, able to climb and work on irregular ground and rocky walls in harsh environment, to overcome obstacles, to work outdoor in presence of vibration, dust, rain; fully remote controlled by using a wireless connection, moving automatically up, down and laterally with no human intervention and always keeping in statically stable equilibrium [7, 8].
– A robotized drilling system composed of: *an advanced automatic drilling unit capable to drill holes till 20 m in depth, using different types of rods, automatically performing all complex operations required as screwing/unscrewing of rods and loading/unloading; *an on-board rod-warehouse able to store different types of rods; *a robotic arm able to manipulate the rods.
– A navigation system for real-time gait planning.
– A full remote control human interface, based on wireless connectivity and allowing an easy control of the system also by a not computer-literate operator [9].

The paper is mainly concerned with the design and functionalities of the robotized drilling system.

3. Drilling system state of the art

Traditionally rocky wall consolidation requires an operator to place manually the drilling rods onto the drilling machine spindle, because none of the automatic feeding systems available on the market are capable of working horizontally with small diameter rods. Furthermore, deep drilling requires skilled operators as several parameters have to be monitored in order to efficiently drive the machine and avoid mechanical damages. Today, descriptive logs of the drilling process heavily rely on visual observations that are subjective and prone to human bias, sometimes resulting in different descriptions, between loggers, of the same material extracted during the drilling.

The consolidation of rocky walls and slopes is performed today by deep drilling. Geological surveys indicate position, inclination and depth for each hole; holes are made by using a set of drilling rods, 1–2 m long, screwed to each other and inserted in the wall.

Today’s industrial state of the art presents systems with very heavy and large buffers, being addressed to fixed installations. The buffers for mining machines from Atlas-Copco (www.atlas-copco.com), Ingersoll (www.ingersoll.com), and Tamrock (www.tamrock.com) may hold a limited number [6–10] of long rods (3 m and more). Buffers of piling machines, e.g. from Klemm (www.klemmbt.de), store rods with large diameter (76 mm minimum), 3 m in length or more, and above 2000 kg mass.

Some machines for directional drilling have dimensions and rod sizes comparable to the ones for rock/slopes consolidation and the angular drilling range is similar, e.g. the Straightline Manufacturing (www.straightlinehdd.com) and the HolyDrilling Companies (www.holydrilling.com), offering machines with buffer (storing a high number of rods) and a loading system. However in these machines the drilling cycle is not performed automatically: the loading, drilling and unloading sequences are piloted by an operator standing close to the machine (and thus exposed to noise, dust, and danger).

An Atlas-Copco commercial machine closer to the needs of rock/slopes consolidation is used in quarries and mines to realize holes for explosives. The rods are 3 m long. Also in this case buffer, rod loader and drilling machines are fixed to each other. The sequence for rod loading on the drilling spindle includes the following steps: the buffer rotates until one rod is ready in loading/unloading position; the loader gripper picks the rod and fetches it to the spindle; a frontal drilling yoke closes blocking the rod which is then screwed to the spindle (detection by a sudden rise of the head rotation torque); the gripper comes back to the buffer; the rod is screwed at the other side to the rods battery already in the rock or, if it is the first, to the hammer; the frontal yoke opens and the rock drilling process starts until all the rods have been inserted in the rock. This cycle is repeated till the required drilling depth is achieved. All the operations are hydraulically actuated. The main advantages of this system are the simple (one degree of freedom) loader configuration, the reduced size of the buffer and the possibility for the operator to command the process from a remote console in a safe area afar from the system. The main disadvantage is the limited number of rods.

The analysis of the market made clear that none of the above solutions is good and feasible: buffers for mining machines are too long, cannot handle rods as the desired ones (1 m length and
76 mm diameter), and are not efficient in the horizontal position; buffers for piling machines are able to operate even horizontally but are too heavy and long, manage diameters higher than 76 mm, and are hardly compatible with nonproprietary hydraulic systems.

For these reasons a new solution has been conceived, designed and realized. This new drilling system on-board Roboclimber is able to execute the holes autonomously till a given depth in a pre-programmed direction, both using downhole hammer or bore-coring bit. To grant the due autonomy, it is necessary that all required rods are on-board and an automatic system is necessary to feed the drilling head with new rods as the hole progresses and to recover the rods at the end. The planned drilling system basically consists of:

⁎ a from-the-market drilling head modified to adapt to the automatic feeding system;
⁎ a manipulator specially devoted to loading/unloading of the rods: the task requires at least 3 degrees of freedom;
⁎ a buffer storing the rods;
⁎ a robust and reliable control system, even a sequencer, with the capability to recover eventual mismatching and errors by tele-manipulation.

This novel drilling system has to work on-board the robotic mobile platform, a 1.5 t vehicle, Figs. 1 and 2, climbing slopes till 85° thanks to the coordinated action of its four legs, moved by hydraulic jacks, and of two lifting devices putting ropes in tension, the Tirfor®s [5].

4. Drilling system layouts

Different layouts of the drilling system were considered and evaluated [10]. They mainly refer to the configuration of the rod buffer and its position with respect to the drilling machine. The automation of the rods loading and unloading operations implies that the rods lay orderly and are easily reachable. Taking into account also cost, robustness, low maintenance, compactness and flexibility, two buffer configurations were considered: *a traditional cylindrical revolving buffer storing the rods in separate rooms and *a gravity cage buffer based on a suitable combination of slanted rails allowing rods loading, holding and the accurate positioning of one rod at a defined location reached by the serving arm of the drilling machine. In the following, different buffer configurations and layouts are compared.

Revolving buffers can be easily realized: actuation is required and the rods are moved one by one in the loading/unloading position by suitable buffer rotations. In case a high number of rods are needed (long holes) the buffer diameter rises significantly. A better distribution of the rods (from mass point of view) is possible with the buffer axis parallel to the platform plane. With buffer axis parallel to the drilling spindle, the centre of mass of the system moves afar from the rocky wall reducing the robot stability. If the buffer is mounted perpendicular to the drilling machine the system static equilibrium is enhanced but the arm needs one more degree of freedom to load/unload the rods (rod–spindle alignment). In case of vertical positioning of the revolving buffer, the total weight is applied to a restricted area of the platform that has to be suitably sized. The reduction of the platform covered area is only apparent since the rods need to be rotated to become parallel to the drilling machine: this operation requires space and one more degree of freedom for the serving arm.

Cage buffers are more compact compared to revolving buffers and their use can be convenient if the layout allows rods movement by gravity. In fact, for vertical positioning, the access to the rods may be difficult and some tricks to avoid rods fall are needed; furthermore, rods cannot move inside the buffer only based on gravity and a suitable actuation is required. In case of gravity cage-type buffers placed with rod axes parallel to the supporting platform plane, the positioning of the cage with rods...
parallel to the drilling spindle shows advantages compared to positioning with rods perpendicular to the drilling spindle, e.g. reduced mobility of serving arm required, but the overall system stability is reduced because the centre of mass is more distant from the wall.

5. Design overview

The development of the drilling system required the use of application oriented design tools obtained by integrating specific modules into functional and structural general purpose modelling packages. Our experience demonstrated that the construction of the prototype of such a heavy robotized system is very complex, time consuming and expensive, because of the size of the machine and the complexity of the on-board systems. For this reason the development of the whole system was organized in modules following the simultaneous engineering paradigm and using advanced virtual simulation to reduce time and cost of the development. Each module has been defined and implemented using mathematical models in suitable software packages to be interfaced and included within the general purpose CAD/CAE packages.

In the final layout of the drilling system on-board the Roboclimber platform, the drilling head, the manipulator and the buffer are rigidly connected by a frame, Fig. 3, and tilted as a whole: this reduces the required mobility of the manipulator, as the rods are always parallel to the spindle of the drilling head; the slope of the frame is set, before the mission starts, by means of a manual screw type jack.

The modularity approach used along the design phases of the drilling system allows an easy maintenance, reconfiguration and upgrading of the same.

The storage buffer has been designed to host the required number of rods within the minimum space: the final asset was singled out among several feasible alternatives, preferring the simplest architecture granting reliability under varying sloping conditions and firmly holding up the rods even in occurrence of impulsive loads or shocks.

High accuracy of the manipulator and high repeatability of the rods buffer positioning avoid misalignments of rods which might hinder the correct screwing up operations (to the spindle of the drilling head and to the other rods already inserted in the rock) and the later storage back inside the buffer.

Different architectures of the manipulator were examined, considering multiple requirements as low cost, simplicity, high reliability, easy maintenance, accurate rods handling and positioning.

6. Drilling unit

6.1. Drilling machine specifications

For the drilling, a modified off-the-shelf Comacchio unit (model MC 200) was used, powered by a separate Comacchio diesel portable hydraulic power unit. The hydraulic drill rig has the following technical data: max torque: 2400 Nm; max speed: 100 rpm; feed stroke: 1200 mm; feed force: 12,000 N; retract force: 12,000 N; engine power: 27.5 kW; mass: 1050 kg [11].

The rig was equipped with a Numa Mission reverse circulation down-hole hammer and a 92 mm drill-bit with carbide inserts. The drilling fluid is air provided by a Compair Holman 400–170S portable compressor with a nominal flow rate of 12 nm³/min at a nominal pressure of 12 bar.

The rig has been instrumented using a set of Jean Lutz sensors for the real-time monitoring of the drilling parameters providing the system’s status. Such data can be used to warn the remote operator about possible criticisms during drilling, and provide useful information about soil conditions. The following parameters were monitored: depth below rock surface, instantaneous advance speed, thrust, torque, rotation speed, vibration, inclination, air pressure and air flow rate.

6.2. Power supply

Three sources of power are needed for the drilling operations. Pneumatic: compressed air (at 12–20 bar) for the
drilling unit (for the operations of drilling and flushing). Hydraulic: oil (at 200 bar, 60 l/min) for the drilling head (to rotate and advance), and other services. Electric: for sensors, control system, cameras (for visual monitoring) and lighting.

After evaluating different solutions, it was decided that pneumatic power is generated on ground by a compressor and supplied to the robot through an umbilical cable: a low-pressure ball valve (actuated by a hydraulic jack which is commanded through a proportional valve) is adopted to vary the air flow rate to the hammer; hydraulic power is generated on-board using a 380 V, 20 kW electric pump with double outlet and variable volume; electric power is generated at ground and supplied through an umbilical cable at 380 V: voltage can be varied on-board using transformers. The hydraulic pump supplies oil to the drilling head and to the legs of the robot through the main outlet, while the second port (at 15 l/min) hands out the services and the rope tensioning devices. Pressure tuning is made acting on the pilot circuit of the pump, which has a draining and a flow controller. The drilling rig and the rods manipulator exploit mainly proportional solenoid valves. More precisely, for the driller, one valve controls the spindle rotation, one the head translation, three the opening/closing and the rotation of the yokes; for the manipulator, a proportional valve manages the finger, while two on/off valves allow the manipulator translation.

7. Buffer for rods storage

The first layout for rods storing was a cage with sloped rails, such that the rods reach the location for the manipulator’s grasp thanks to the gravity effect [10]. This solution was judged unreliable and discarded because free rolling of rods along rails may be stopped by pieces of rocks or dust, and because, when drilling is made vertically, gravity’s useful component for moving rods vanishes.

So, the design was addressed to revolving buffers; from the requirements about the maximum hole depth (20 m), a buffer containing 20 rods 1 m length has been initially considered. Due to the limited room available for the buffer, the rods are placed on two coaxial circumferences; this implies having two different pick points (one per circumference) and a greater complexity of the manipulator.

The idea was, then, to use 1.5 m length rods (Fig. 4): in this way fewer (13) rods are necessary and they may be placed on a
single circumference, simplifying their fixing and picking and reducing the number of operations per drilled hole.

The drawbacks of this solution are that a larger drilling unit and a longer hosting cage are needed, increasing the inertia and the distance of the centre of mass of the drilling system with respect to the wall. This has been considered in the design of the mobile platform of the robot. In the following, concepts about the buffer design are briefly recalled from the earlier version to the final one.

7.1. Buffer with holding plugs

In this solution, two parallel plates are connected to a shaft receiving the motion by an electric motor. The shaft is supported by housings connected to the main cage. In the plates, holes on two circumferences are provided. The rods (20 of length 1 m) are arranged in two coaxial patterns to reduce the diameter of the buffer. The support of a rod is made through plugs that are pressed by springs in the hollow ends of the rod; because the ends of the rod have different sizes, one plate has holes (and plugs) bigger than the other one. The release of a rod, when it has reached the position over the axis of the drilling slide, is performed by acting — at the same time — on the two plugs holding the rod: two actuators simply lift the head of the plugs through forks when the rod is in the right position for the grip. Of course, before the plugs movement starts, the manipulator has to firmly clamp the rod.

7.2. Buffer with elastic sockets

This solution presents rods placed on one circumference (13 of length 1.5 m). Two disks have contoured retain springs radially placed, Fig. 5 left, suitably sized to safely hold the rods. To avoid axial movement of the rods two additional plates are appropriate.

To release the rods, the manipulator overcomes the elastic force of the retain springs. Note that in this case a coaxial allocation for the rods is impracticable.

7.3. Buffer with open bands

The buffer consists of two disks having 13 cuts for 1.5 m rods, regularly distributed except a circular sector required for manipulator positioning, Fig. 5 right.

Two bands fixed to the supporting frame envelop the rods, leaving one opening, located over the drilling machine near the point where the rod is picked by the manipulator.

A Teflon® layer is applied on the inner surface of each band to reduce the friction between rods and band.

Two plates are added at the ends of the buffer to avoid rods axial movement.

7.4. Buffer with modular leaf springs (adopted)

The ultimate buffer is a cylindrical unit, Figs. 5 (right) and 6, rotating at very low speed (1 rpm), by an asynchronous 380 V electric motor (power: 120 W) joined to a reducer with gear ratio $i = 1500$.

The buffer hosts 13 rods 73 mm diameter and 18 kg mass each; the whole capacity of the buffer is not exploited, as an angular sector of 60° width has to be set free to avoid the manipulator from hitting some rod during the loading/unloading operations, Fig. 6.

The buffer consists of a steel shaft (54 mm diameter, 1980 mm length) connected to the moto-reducer. The shaft is supported by two bearings fixed to the drilling cage and upholds two hubs on which both the plates for rods axial constraining and the leaf spring are screwed (see Fig. 6).

8. Rods anchoring systems

The systems for holding up the rods inside the buffer may be actuated or not actuated. For actuated solutions, a chance is using properly shaped plugs endowed with compression springs; the plugs enter the hollow ends of the rods (pushed by the springs) and release the rods once actuated; this solution is quite expensive and unreliable (an actuator could fail and the manipulator may try to pick a locked rod).

For non-actuated solutions, balls and springs, cams, clips, and leaf springs have been analyzed. Balls and springs: two different spheres are required as the holes at the ends of the rods have different diameters (30 mm and 60 mm); this implies that the rod hits first the bigger ball and then the smaller with misalignment problems; furthermore, a ring giving a sufficient preload to the springs in all the positions, except the grip ones, might be adopted. Cams: cams assure the rods are rightly let loose, but they present difficulties in profile generation; in addition, rod loosing is made during buffer motion with the risk that the rod might fall before the manipulator firmly grasps it. Clips in harmonic steel: specially shaped springs are placed inside hosting sockets of the buffer disks. Rods are secured thanks to the elastic force of the deformed clips, whereas their release simply requires a thrust strong enough to overcome the elastic grip. Leaf plane springs: they are conceptually similar to clips and have been adopted for the prototype. The holding
system of a rod consists of two pairs of harmonic steel leaves (1 mm thick) screwed to a support and equipped with plastic (Ertalon®) blocks at one extremity leaving a gap narrower than the rod diameter, Fig. 6.

To load a rod into the buffer, the manipulator pushes it against the gap between the blocks which displaces for elastic deformation of the leaf plane springs. The advantage of this solution is the absence of actuated locking/unlocking devices, with simple design and easy manufacturing. Further, these springs, being modular, possess a good adaptability; if one should need to vary the spring stiffness, has simply to add/remove leaves or insert/eliminate the calibrated sheets between the leaves and their support: the latter option consents to manage rods having different diameters, as well.

9. Rods manipulator

Since one of the major requirements for Roboclimber is to reduce human intervention, especially during drilling, it is necessary that the manipulator has characteristics for obtaining high reliability during operations. As already mentioned, rods have to be handled with high precision to avoid misalignments which might hinder their right insertion onto the drilling axis and the subsequent placing back of them inside the buffer.

Four solutions have been examined for the manipulator, with 3 and 2 DOF.

9.1. Manipulators with 3 DOF

A first manipulator has one rotational mobility actuated by two hydraulic cylinders arranged in sequence (to get three angular positions corresponding to their on/off states) and one translation mobility provided by a couple of parallel hydraulic cylinders acting, at the same time, as guide rails. The rod is grasped by two under-actuated hands having two fingers each. The fingers can slide inside the hand case in order to avoid collisions with the rods during the positioning operations of the manipulator. The fingers push the rod against the palm so that the positioning of the rod is accurate, the grasp is safe and the grasping force is constant for rod diameters near the nominal diameter, Fig. 7.

To use a simple on–off control for the jacks, the extreme position sets are to be exploited. In its shorter configuration the jack places the rod on the drilling machine axis, while, when fully extended, it is in the position related to the pick/store of rods in the buffer. Such manipulator architecture is also feasible to serve a buffer with rods placed on two circumferences instead of one.

9.2. Manipulators with 2 DOF

The first solution of a 2 DOF manipulator consists of a gripper sliding on a rail fixed to the frame between two columns, Fig. 8. It presents noteworthy stiffness, with a direct fall-off on precision aspects.

This manipulator has two degrees of freedom, but, because it works exploiting the final and initial position sets, it requires an on–off type control. The first degree of freedom is a translation on a slider running on the milled sides of an off-the-shelf beam, screwed to the structural frame of the drilling unit.

A drawback is the wear of the gibs that causes clearance with misalignment errors. The pick point of the rod is in the plane passing through the buffer axis and the axis of the drilling machine, because the length of the manipulator (perpendicular to the rail) is constant.

The extreme positions correspond, respectively, the first, to the grasp point for the rods from/to the buffer, the other, to the axis of the drilling machine. The gripper is composed of two fingers that close contemporarily on the rod (the motion is transmitted by two beams pushed–pulled by a jack) and have an internal shape allowing self-centring.

During the phases of loading and unloading of the rods, the gripper has to open till the fingers are aligned, to avoid
interference with the other rods and with the drilling head; the rod is, in fact, moved through a plane passing between the axis of the rotating buffer and the axis of the driller.

A second solution, which has been finally adopted, consists of a three-finger unit having only one pivoting finger in order to simplify its design and realization. This unit is moved, in a first version, forth and back by an electric linear actuator (with trapezoid screw); due to low reliability of this actuator, an improvement will be made, consisting in the choice of hydraulic jacks; the pivoting finger rotates by means of a double-effect (on–off) hydraulic jack, Fig. 9.

The linear actuator has a speed: 10 mm/s, maximum thrust: 2500 N, and it is equipped with three set-position switches.

It might seem that two positions would be enough, the rod being moved from the buffer to the drilling axis and back; actually, because the gripper has only one rotating finger, it is necessary to go ahead with the fixed fingers of about 25 mm, in order to avoid collisions among them and the rod (see sequence in Fig. 10).

10. Control system

The hazardous environment where the drilling system has to be employed requires highly safe operation. By this reason, the drilling operations’ success also relies on the design and implementation of a robust control system architecture within reasonable safety and operational margins, able to process and elaborate in real-time data coming from many sensors and signals from the video cameras in order to get useful information about the working status of the overall machine and its subsystems and to quickly react to any relevant event [12].

The requirements of the distributed control and of the control architecture needed the management of the system by means of an HMI unit, where appropriated displays and tools serve to...
monitor and command the operations, Fig. 11. For autonomous drilling purposes, use of different sensors and the coordination of all actions in real-time are required. So, the control system processes information from the sensors in order to suitably launch and drive the drilling operations taking into account the state of the different units in standard operation mode. If something goes wrong the control shifts in emergency mode and informs the tele-operator through the HMI about the reckoned wrong status.

With respect to hardware, the solution is based on industrial PC (so assuring heavy duty use and low cost) with the required performance. The Roboclimber overall control architecture has three major subsystems, one applied to the drilling operations, the second for motion control planning of the robot [13], and the third devoted to the HMI. All tasks are processed by the main system CPU and supervised by an HMI-located operator which receives the necessary feedback: in such a way the user is capable of taking decisions to operate efficiently the machine from a remote distance.

The control (Fig. 12) is distributed between the robotic platform and the HMI unit. The robotic platform can be governed by the end-user, standing in a — safe — remote location, thanks to the wireless connection between the HMI unit and the on-board control unit. The HMI unit has been designed to be light and compact to help the end-user freely move around the working area. The HMI unit is powered by batteries into a rucksack, while the HMI unit is in the user’s hands. The user can control all operations using a set of industrial buttons, switches and joysticks and can read the telemetry, sensor output, video camera and navigation output on the screen of a tablet PC, used also to change the configuration parameters of the HMI. The Wi–Fi antenna for the wireless connection with the robotic unit is integrated into the tablet PC. The on-board control unit and the linked Wi–Fi hotspot are powered directly from the ground by a dedicated connection.

The control system integrates not only external sensors, but also HMI and the control of both positioning and drilling operation, including specific modules for safety management [14,15]. These features are of special relevance, due to the importance on the safety of the machine processes and its components, and so, the development for the control architecture is based on a system capable of making decisions while working and informing the user in a real-time based structure about the warnings or problems and even to decide how to solve problems. In this hierarchical structure the basic levels of decisions are based on the information given to the machine from the sensors where the capability of making decisions is crucial for the movement of the different actuators. All these functions are assured by using real-time object-oriented modelling.

One relevant and very important element for the control system to be robust and with industrial characteristics is the
design and realization of special control boards ready to implement their counterparts in the overall architecture. Digital PIDs with position feedback and with PWM (Pulse Width Modulation) output transformed to an analog signal of ±10 V necessary to control the hydraulic power units and other interfacing requirements have been used. This kind of electronic cards has other useful advantages. The first advantage is that with only one command the card is able to control various actuators simultaneously and with autonomy: this property reduces significantly computational power. Another benefit is the implementation of digital and analog inputs and outputs; in this case, this property is very useful for the sensing process and to control external devices.

10.1. On-board control unit

The drilling control system is hosted in the on-board control unit that is responsible to start/stop hydraulic engines, to control the valves, and to read the signal from the sensors. The same unit is used to read the video signal from the navigation system. Finally, being powered on a dedicated line, the PC controller can shut down the output lines of the on-board electric panel in case of emergency stop without losing the wireless connection with the remote HMI unit. The single control unit is composed of a CPU, control card, data acquisition unit, electric power supplies and power conversion. A real-time based operation system is used to make the reading and the data processing of all sensors and to control the different actuators in real-time.

Use of many sensors and real-time coordination of all actions are required: the control system has to process information from the sensors in order to perform drilling and consolidation work while maintaining the system in the correct position and orientation [16].

10.2. HMI control unit

The HMI control unit is the interface between the industrial control panel (made of buttons, switches, joysticks) and the signal manager that drives the communications with the on-board control PC [9]. A single micro is used and it is connected through a bus to seven general purpose port expanders, each of them with several analogical and digital channels that can be programmed as input or output lines. Simple LEDs are used to indicate the status of the commands and of the main components on the robotic platform. Two analogical inputs are used to read the signal from 2 joysticks controlling the head rotation and head translation of the drilling unit: a precise control of these two parameters is critical during the drilling operation.

10.3. Drilling remote control

To control the drilling operations different macros and single commands can be issued by the user: the more sophisticated macros are applied in standard operative mode for automatic driving of the drilling operations. In case of unexpected events the drilling control is shifted to the tele-operator: in the following it is described as the logic of the manual control of head rotation and head translation being this critical in operative conditions.

10.3.1. Head translation

During the hole drilling process the head translates at the maximum speed the hammer drilling may accept, depending on the local condition of rock and terrain. During the two rods assembly and disassembly operation the translation speed has to be very low and carefully tuned to the head rotational speed to facilitate the threads joining. The control is able to rapidly switch from standard (full autonomous) to emergency mode if some unwanted event happens; e.g. in the case the sensors reveal borehole occlusion or discontinuities in the mass rock the operator should be able to sharply accelerate (or decelerate) the head translation. For these reasons, the operator controls this parameter using a proportional joystick. The speed (oil flow in the hydraulic motor) law depends actually on the joystick bending, proportional to the acceleration. When the user releases the joystick, the acceleration becomes zero and the head continues to rotate with constant velocity. The user can stop the head translation immediately if he bends the joystick in the opposite direction of the motion.

10.3.2. Head rotation

During standard drilling operation, to screw the drilling rods together, head clockwise rotation is used. Head counter clockwise rotation is used only to unscrew the rods. During normal drilling operation the rotational speed is the highest one but during the screw (or unscrew) operation it is very low and needs to be set according to the actual translational speed.

11. Conclusion

The sharing of knowledge from scientific literature, expertise and experience of the Research Centres, and of the industrial firms involved in the Roboclimber Project were used to derive the technologies and methodologies for the system design and development. A multidisciplinary approach was adopted to solve the problem with large use of mathematical modelling, computer simulation, digital mock-up and virtual reality testing tools in order to compare and evaluate several conceptual solutions and single out those maximizing the overall system performances. Mechanical and control architectures have been conceived simultaneously while considering modularity aspects and lifecycle issues. The end-user has been included in the design loop at every level in order to assure system effectiveness and work suitability.

The result, Roboclimber, is the fastest system available today for the setup of consolidation networks on rocky walls. The drilling velocity is a bit higher than the one of a hand-manoeuvred equivalent drilling system, due to the efficient working cycle and the higher feeding force that Roboclimber can apply. The time to move from one hole location to the following, for Roboclimber, is 2 to 5 times lower than for traditional techniques (especially scaffolds requiring dismounting of the drilling system and remounting at every hole location). The setup time is the lowest as well, requiring just the preparation of
some anchorage points. This is especially clear for scaffolds, for which the mounting time is almost equivalent to the drilling time.

Future developments are considered for the drilling unit and the rods manipulator. For the driller an improvement will be the capability of folding up the rail along which the drilling head runs: this will avoid the disassembly of the drilling system out of the Roboclimber before its transportation on trucks as, when the rail is folded, the maximum height will be adequate to standard road tunnels size.

The rod manipulator will be modified based on field experience showing that, during severe trials, dust and small rocks tend to block the good sliding of the fingers on the prismatic rails; the change will focus on the rails replaced with cylindrical ones and on the actuator for the translation which will be made of two paired hydraulic cylinders, instead of the actual electric one, to achieve higher force and reliability, and three fixed positions managed with no need of control switches.

It is worthwhile noting that the appreciated characteristics of autonomously operating Roboclimber and its drilling system in non-structured environment suggest their usefulness in extraterrestrial exploration: in fact, Roboclimber’s efficiency in various terrain conditions and its good mobility performances assure the successful accomplishment of un-manned tasks even in regions not earlier mapped.

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References