Abstract

The paper deals with the automation of the firming-up of rocky slopes and walls, to grant safeguard of populated areas, highways, private residences or public sites. The prospected solution looks after a goal-oriented robotic equipment, Roboclimber, for tethered wall climbing and endowed with devices for churn drill, boring and cast-in-situ piling. In the following, a series of the investigated solutions is shown, with marks on the reasons which led to select an architecture with four legs having a rotational joint and two orthogonal telescopic limbs, allowing autonomous climbing on slopes till 30° about horizontal and co-operating with tension ropes for steeper walls. The architecture of the developed control system for the gait management and legs-ropes co-ordination is also shortly illustrated, with focus on its two-level structure, which leaves the possibility of autonomous climbing or manual driving through a remote console. Hints about the geological mapping, the knowledge base system and the control system are given, as well.

1 Introduction

The firming-up of rocky walls is today performed by skilled operators, that climb fastened by ropes and operate manually to pile and fix wire nets, on condition that the unstable zone is not too large. In many cases, drilling hole dimension and strengthening complexity require to place scaffolds on the wall, with expensive supporting set-up. Resort to vehicles carrying articulated arms or specialised operators climbing with ropes. In the first case the solution is applicable only when wide approaching areas are available and consolidating/monitoring work is within 50 m height; in the second case the solution is cost-effective only for targeted interventions (rock blocks, etc.). In Figure 1 different solutions are compared.

<table>
<thead>
<tr>
<th>Scaffolding</th>
<th>✓ High impact on environment</th>
<th>✓ High cost of material</th>
<th>✓ High cost for labour</th>
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<tbody>
<tr>
<td>Cranes or flying vehicles</td>
<td>✓ A free access is needed</td>
<td>✓ The operative range is small</td>
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<td>Robotised solution</td>
<td>✓ Safeguard of operators</td>
<td>✓ Eco-protection</td>
<td>✓ Minimum set-up time</td>
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<td></td>
<td>✓ Control of the drilling device</td>
<td>✓ Gathering of geological data</td>
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Figure 1. Features of different solutions.

For practical implementation, a tethered rover is retained, supplied with limbs for sticking on the wall and proper drilling and piling devices.

Figure 2. Firming-up of rocky walls: novel solution (Zannini’s patent).
Actually, the existing fixture, Figure 2, is man operated for positioning and blocking the cage, handling and steering the drill rods and injecting the hole with reinforced grouting mortar.

Changes look for autonomous rigs, with remote overseeing and, eventually, fit out and reset interventions.

The topic has growing environmental concern, while aiming at the replacement of human operators in the consolidation work, which characterises of risky and unhealthy conditions, such as falling, presence of dust, striking of crashed stones, and the likes. In addition, the work-cycle may be fully monitored, to provide remote evidence whether tasks are performed the right way and to collect relevant (basic geology, on-duty remarks, etc.) data, supplying on-line assessment of the achieved issues.

2 Technical requirements

The Roboclimber project is presently under progress; it started as the 24 months Competitive and Sustainable Growth programme CRAF-1999-70796 about the “Development of a tele-operated climbing robot for slope consolidation and landslide monitoring”. In the project are comprised the built up of an autonomous climbing vehicle, and of onboard equipment, i.e., the drilling rod storage buffer containing all the rods necessary for a mission, the robotic arm for automatic rods picking from/to the buffer and drilling unit load/unload, the system for changing the angle of the drilling head so that rod entrance is made as geological plans request, [1-3]. In the following, the attention will be paid to the locomotion system, while the above mentioned (and no less important) devices will be the subject of further works.

The initial specifications, as regards the climbing, were the possibility of overcome an obstacle having max. size of 200x200x200 mm, the ability to move on walls having steepness between 30° and 60° with the help of ropes and till 30° without assistance. During the evaluation and feasibility stage, it has been acknowledged that extra capabilities may be given the robot, so enhancing operational proficiency: the max. obstacle size is increased to 500x500x500 mm, the max. steepness is now 90° about horizontal and the discontinuities from terracing to wall and vice versa are faced, the robot is able to climb down out of the truck and reach the site.

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The architecture was inspired at modularity whenever feasible, to speed up design process, manufacturing and maintenance operations; the use of off-the-shelf components was strongly preferred to own-made ones for economy aspects and easy replacement but also for high reliability assignment; as a result a short “time-to-market” and low cost and labour for design, manufacturing and assembly are obtained.

2.1 CAD rules

The design phase has been guided by PLM ruling, Figure 3, making use of fully parametric modeling, top-down skeletal representations, hierarchical assembly techniques, generation of different mock-ups and employment of an integrated environment for modeling & analysis. This allowed to assess the behaviour of the robot under expected running conditions and to enable corrective actions still in the early stages of design by means of checks and tests on virtual prototypes.

3 The Roboclimber equipment

The proposed robotic equipment has the following main components: • a cage, with active limbs for its motion across the sloping surface of the wall to be treated; • a drilling head; • a buffer, for storage of the drill-rods; • a robotic arm, picking the rods from the buffer to the drilling head which inserts them until the desired hole depth is reached (afterwards, rods are recovered through reverse operation); • a modular supervising unit, to control task progression and help remote re-setting jobs.

3.1 The hanged cage

The cage grants the operation posture, based on a couple of (almost vertical) carrying ropes, hanged on the wall’s top. The lateral and vertical motion requires combined action of ropes, while a leg moves a step in the proper direction. The ropes allow firming-up operations for a vertical strip of the wall; they are then, generally, moved to new position for the next strip.

3.2 Leg architecture

Several options have been compared, finally choosing a three DOF limb with one angular and two linear joints, all driven by hydraulic actuators: a variable-length thigh is connected to the cage frame by a rotation joint and ends with a perpendicular variable-length tibia.
3.3 The drilling head
World-wide suppliers provide proper components. The study compares offers as for weight, cost, dimensions, power consumption and, in particular, reliability and maintainability for long uninterrupted missions.

3.4 The buffer
A buffer stores the rods necessary to make a hole having the required depth, once connected by means of their threaded ends: its geometry is chosen to simplify rods picking and manipulation.

3.5 The handling robot
The device is specifically designed to manipulate the rods according to the following actions: • to pick a rod out of the buffer; • to transfer/rotate the rod and to place it in the right position on the drilling head; • when drilling is finished, to perform the rod extraction from the wall. The power source of the handling robot might be either hydraulic or electrical.

3.6 The overseeing unit
The unit, besides overall monitoring and command setting for remote operations, records the all work-cycles to confirm whether the required actions have been fulfilled the right way. This allows to set-up a growing data-base, including the geologic data, among others. At the end of the firming-up process, the complete wall geologic map is available: it is a very useful option, since offers proper on-line assessments, without the costs for in-situ survey by further (onerous) investigations.

4 The examined alternatives
Before selecting the optimal architecture of the robot, several candidate solutions to perform the requested gait have been analysed. Hereafter, some of them are concisely outlined, with explanation of the peculiar advantages and drawbacks.

4.1 Skier I
The vehicle has four 2-DOF translational legs and four skates, Figure 4: each pair of skates is pushed against the wall by a hydraulic actuator (overall DOF: 10); the vertical motion is accomplished retracting legs L3-L4 and skates S3-S4, while legs L1 and L2 perform pulling, and skates S1-S2 slide; the lateral motion is similar, given that extension of legs and skates are inverted.

The drawbacks are that gait is a mix of walk by legs and skates sliding which hinder diagonal motion, agility in a horizontal plane is limited since the pressure on skates is the highest, the design is quite complex and the modularity is not well exploited.

4.2 Skier II
In this case, there are four 2-DOF translational legs and four skates as in the Skier I for an overall DOF of 12: the difference is that, now, skates are mounted on the legs and may rotate of 90°, so that they act as grips or slides, depending the orientation, Figure 5.

Figure 4. Skier I: skates may be only extended in direction normal to bottom shield, legs mobility is shown by dashed lines.

Figure 5. Skier II: upper skates are rotated to grant grip through pins; related legs perform pulling, while lower skates slide.

A vertical motion needs that S1-S2 plant on tiptoe, L1 and L2 retract to make the cage go up, S3 and S4 slide, with L3-L4 staying still; lateral motion is akin vertical, simply inverting the attitude of skates and legs commands. The disadvantages are the same of the previous solution with the addition that the design of the
skates is critical design due to the rotational joint which is loaded by very high forces and moments.

4.3 Caterpillar
Caterpillar has 6 legs, each with 2 DOF (Figure 6). During the vertical motion L1 and L2 will rise the cage, while the other legs are retracted: the structure skids on the bottom shield. Switching the state, i.e., retracting only L1 and L2, the other legs easily provide the lateral movement which occurs without contact between the shield and the surface. This solution avails of good modularity as the legs are identical, lets the robot walk laterally on the plane to reach autonomously the working site, but characterises of high weight and size, a lot of actuators (12), and the fact that sliding still occurs when moving upward.

4.4 “Human” robot
This robot has four legs, each having 3 DOF (Figure 7). The three rotations allow the best placement of the tip in the two directions: lateral and vertical.

4.5 Roller
The Roller robot, Figure 8, has four straight rollers: M1 and M2 are both driven, while rollers S1 and S2 are idle. Four positioning pistons are needed for avoiding cage movements while drilling is performed. During the vertical movement the robot climbs thanks to ropes traction and free rotating of the idle rollers; in this phase rollers M1 and M2 are retracted.

An electrical motor supplies the first turning while the other rotations are provided by two hydraulic actuators. The main disadvantage of this solution are that the control has to manage simultaneously the 2 DOF of each leg (motion is coupled) and the ropes tension force and length, each leg has 8 rotational joints and legs cannot retract completely (as requested).

4.6 Modular robot
This robot implements four legs: each leg has three degrees of freedom. All the actuators are linear and consist of the same module, Figure 9. This solution offers a really high degree of freedom and modularity: all 12 actuators are the same type and stroke so each leg is the “sum” of three identical structures.

A sharp tip at the end of each leg assures the grip onto the sloped wall. The foot (end effector) has a hollow cylinder shaped workspace. Hydraulic jacks are put inside the tubes of the modules for diminishing size and protection reasons. In front of a lean and effective
architecture, major difficulties are the complicated design of the connection joints and the intrinsic low strength of the leg.

Figure 9. Upside view of Modular robot.

5 Architecture of the leg

Before selecting the optimal architecture, several candidate solutions for performing the requested gait have been studied, Figure 10.

Figure 10. Evaluation of candidate alternatives.

The best compromise among, especially, economic, weight, easy control, agility, manufacturability, reliability, maintainability aspects, resulted in an orthogonal leg. Noteworthy features are the possibility to build a leg by replicating a basic module, equal stroke length for both the leg and foot, insensitivity of the exerted thrust at the varying of foot position, faculty to set a motion “free” or to command a single actuator due to uncoupled effects, quite simple control system.

5.1 Orthogonal leg with guides

With this arrangement, three actuators are employed: one for the hip rotation, one for the thigh extension, the last for tibia lengthening, Figure 11.

The relative sliding between the hollow square members is made by using commercial linear guides; the seemingly benefit of off-the-shelf components is though balanced by the necessity of using at least four guides for each leg to withstand twisting and bending with negative fall-off on weight, cost and additional manufacturing for proper housing of guides.

Figure 11. Leg with linear guides.

5.2 Orthogonal leg with tubes

To avoid the earlier mentioned troubles, an architecture using hollow square beams is chosen, Figure 12. It is a successful design for several reasons: tubes offer high resistance to torsion, the manufacturing is plain and the assembly easy, reliability and robustness are significant, the protection from water, dust, mud is good, and mass and cost of tubes are low.

Figure 12. Leg with tubes.

6 Virtual testing

The feasibility of the overall outfit and related work-cycle is investigated by simulation and assessed by testing a virtual mock-up to duplicate the multi-body dynamics. By that way, checks are accomplished to verify the hawsers pull control algorithm to grant proper stability margins for the work phase and during the step-wise transfer; wall’s slope and rock’s properties are taken into account by respect to task progression, job allotment and work management in view of the current equipment dynamics.
The execution of dynamic analyses under varying operative conditions allowed to recognise the more critical conditions; the higher loads have been transferred to a FEM package to evaluate the stresses, strains and displacements in the structural components. The results were used to refine the assumed shapes, thickness, material, arrangement in order to maximise the overall effectiveness of the Roboclimber, Figure 13.

Figure 13. FEM analysis of the leg (VM stress).

Extended resort to simulation for the whole life-cycle of the artefact will allow to test, since earlier design phases, competing solutions for the mechanical lay-out, the behavioural setting and the decisional logic, so that overall figures of merit will be found and choices carried maximising given options. Referring to the pre-feasibility study, the addition of actuated hawsers is an example fall-out; redundancy, due to co-operation of the chosen 3 d.o.f. legs and four fastening hawsers, is exploited by means of suitable control algorithms, in order to achieve effective manoeuvring stability.

7 Distributed controls and control architecture

Both for climbing and for the working tools it is required the use of many sensors and the co-ordination of all actions in real-time. So the control system has to process information from the sensors in order to maintain the system in the correct posture and attitude while performing drilling and consolidating work. To achieve a high performance within reasonable safety and operational margins the control architecture must deal also with the data from the monitoring system, in order to get useful information about the stability of the wall or slope. Communication needs from the on-board CPU to/from the HMI (Human-Machine Interface) is clearly addressed. Simulations on the behaviour is performed through computing software tools. Specifically real-time operating systems like QNX 6 (QNX Real Time Platform, Neutrino) that is showing excellent performance in industrial applications have been tested.

7.1 Control System and HMI

The development of the chosen control system, safety devices (including the launching of an emergency recovery strategy) and HMI for the climbing module is still in progress; communications between on-board computer and the HMI unit will be done, too. The CPU on board the Roboclimber will have in charge many functions, as to control the drive system of the climbing robot and the drilling device, to integrate the different multi-sensory devices that give the feedback information; to communicate with the HMI unit. The on-board CPU must perform intensive calculations and the corresponding software will be robust and modular. The HMI development is of special relevance, and because it is the interface with the operator in an outdoor environment, it has to be comfortable and easy to use. Only minimum required information for the actual operation will be displayed.

For achieving the control architecture the following issues has been taken into account: - a legged climbing platform is, by its own nature, a very complex machine, - possible leg configurations and arrangement (overall machine kinematics), - final algorithms should work on a harsh, industrial environment.

The main features of the proposed architecture are: - to provide a modular, easily expandable architecture for supervisor control of the climbing platform, - the architecture should allow the implementation of a controller able to govern the climbing platform.

For the control of a climbing platform, Figure 14, the following requirements has been established: control of multiple actuators, processing of multiple sensors signals, movement coordination of legs, legged climbing platform stability, remote interaction with human operator, capability to run pre-defined tasks, terrain adaptability.
The control system for ROBOCLIMBER has been separated in two main subsystems: a) one on-board the legged platform, Figure 15; b) the other on the supervisor station, Figure 16.

Figure 15. Hardware architecture for Roboclimber control at leg level.

Figure 16. Human Machine Interface of Roboclimber.

8 Geo-technical requirements

Parameters are collected from the drilling through commercial sensors and monitoring system of the processing methodologies, in order to get information on slope morphology and stratification and all the necessary practical knowledge on deep drilling. A database able to manage the information gathered during deep drilling and system operation will be created: data will be stored in an appropriate format together with geographical coordinates to form the basis for the development of a knowledge base system. A data-set will be defined to support in the training of the knowledge based system.

8.1 Knowledge based system

It is under construction a knowledge based system which will process the out-puts from the drilling unit and sensors to derive information on slope morphology and stratification and optimize therefore the process (number of holes, depth and positioning) and the robot mission. Based on the data-set collected, relationships among the considered parameters will be identified, with the objective of contributing to define possible criticisms for the malfunctioning of the drilling unit. The information on drilling performance and slope stability will be then derived by developing correlation algorithms. The development of this task will run in parallel with drilling tests using a traditional drilling module equipped with sensors and recording all the events and anomalies through specific paper forms. Extraction of ground samples through hollow rods will support in the development of correlation rules. Geotechnical laboratory analysis will be performed and compared with signals from the sensors to validate the approach. The output from the knowledge based system will be the input for updating the geotechnical model which will be performed on the reference slopes through commercial software packages (3DEC, FLAC, ...). A specific software interface will be developed to appropriately feed the data in the software.

9 Trials

Laboratory trials on a reduced performance prototype will allow to assess the development of the project and highlight any necessary action to minimise risks. On-field trials, after a period of training, will allow to evaluate the system performance in a real working environment.

9.1 Laboratory trials

The objective is to test a reduced performance prototype with laboratory trials to assess the level of results that have been achieved and validate the design methodology. The climbing module is complex; its main frame carries the legs, the drive systems, the control system and the energy supply. Checks will concern cabling, input and output signals, current voltage, critical working conditions, labour, interfaces. During the laboratory tests, Roboclimber performance will be assessed with respect to the dynamical, energetic and vibrations analysis performed on its model. During laboratory trials an assessment of the on-board drilling module will be done.

9.2 On-field trials

The objective of this task is to perform on-field trials with the final demonstrator and to carefully evaluate system performances and behaviour in harsh conditions. The fully assembled Roboclimber should be able to complete different kind of "standard missions"; each "standard mission" will be performed on different slopes and walls. In order to evaluate the performance of the drilling module, tests must be executed in a site where a representative set of terrains ("standard terrains") is available. Drilling test has to be done several times on each "standard terrain" in different working conditions, evaluating the out-put of the
monitoring system as far as geo-technical data are concerned. A vehicle with a telescopic arm and platform will allow to monitor the progress of the tests and provide on-board access in case of malfunctioning.

10 Conclusions

Further developments will join with testing a set of critical mechanical components; these will be assembled, with hydraulic actuation, and their performance established in view of the working displacement manoeuvres. Similarly, a user friendly, intelligent interface will be studied for a bi-directional data exchange; all the data coming from the field to the controller and to the operator, and vice-versa will be processed, to increase, by significant, efficient and non-redundant means, the knowledge on the system behaviour and on the geologic mapping of the considered rocky wall.

Technical solutions will be studied with particular focus on manufacturing, maintainability, controllability, sensorization and life-cycle aspects. Strong attention will be dedicated to the issues of cage shape (ergonomy, adaptability and scalability), steep slope walls climbing ability, support and recovery system feasibility, actuators and manoeuvres energy efficiency.

The project covers up even the details of the operation work-cycle (rods handling to set/reset the articulated spindle; job sequencing to cast the pile, etc.), and describes the basic duties of the modular supervising unit. At the moment, remote control (rather than autonomy) is main concern; the robotic equipment is developed to make the cage manoeuvring possible from afar, based on built-in task sequences properly assessed through virtual reality testing.

References

