A Heavy Climbing Robotic platform for geotechnical applications

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***Abstract*— The paper deals with the consolidation of rocky slopes and walls and proposes enhanced automation and original solution to avoid risky undertakings, when firming-up is accomplished to safeguard peopled areas, highways, dwelling houses or public works. The topic shows growing environmental concern, aiming at removing human operators, unless, possibly, for preliminary in-site set-ups. The prospected solution looks after a goal-oriented robotic rig enabled for tethered wall climbing and equipped for churn drill, boring and cast-in-situ piling. The work-cycle is fully monitored, to provide remote evidence whether tasks are performed the right way and to collect any relevant (basic geology, on-duty remarks, etc.) data, supplying full on-line (with no extra-cost) assessment of the achieved issues. The investigation avails itself of proved technologies and existing fixtures, suitable for compelling requests and dangerous work-conditions and is based on the collaboration with experts currently engaged for rocky wall consolidation and owners of several patented devices. Hereafter few hints on the overall arrangement are given, to enlighten the climbing motion sweeping out the rocky walls.**

This paper deals with the development of the main module of Roboclimber: the climbing structure. The design methodology and the mechatronic solutions are presented and discussed at functional and structural levels.

***Index Terms*— Design methodology, Legged locomotion, Mechatronics, Telerobotics.**

I. INTRODUCTION

Landslide is caused mainly by penetration of groundwater into slippery layers, such as clay layers, or by instability of soil. To prevent landslides, proper measures, roughly divided into prevention works and determent works, are taken on. The purpose of prevention works is to stop or prevent landslide movement by changing nature's asset, such as topography, geology, and groundwater conditions. For example, horizontal boring is done from the ground surface to remove groundwater in shallow layers and create draining elements.

On the other hand, the purpose of determent works is to inhibit, partially or completely, landslide movement with consolidation structures. Geological survey involving drilling and coring to collect samples, measure of subsurface properties, and development of lithologic logs are often used to study unstable slopes. After the geological survey, a series of holes is performed by using drilling bits 1-2 meters long, inserted in the wall up to 15-20 meters depth. An example of drilling map for slope consolidation is reported in the Fig. 1, where the numbers represent the sequential operations. Today all these operations are always unsafe, highly expensive, time consuming and labor intensive.

Technical literature and patent survey have shown that although several developments are being carried out world-wide in the field of climbing robotic systems, typical applications are on almost flat surfaces. An exception is TITAN VII [1], designed for the construction of transportation facilities such as highways and railways in mountainous areas, developed within a Japanese project performed by researchers of the Tokyo Institute of Technology in co-operation with Tokyo Construction Ltd. TITAN VII can move on a steep slope up to 30 degrees but it does not satisfy all the requirements for the considered application of rock drilling and consolidation. The robot has four legs but no equipment onboard [2].

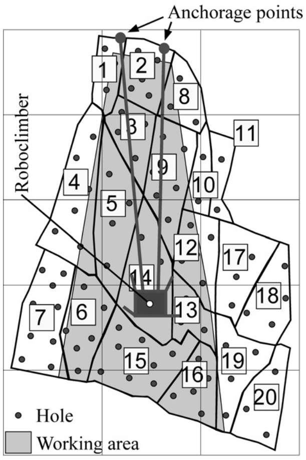

Fig. 1 – The working area (gray area on the map)

The work on unstable slopes is very dangerous for the operators. The most used solution today is a specifically

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This work was supported in part by the European Commission, under Grant G1ST-CT-2002-50160, that is here greatly acknowledged.

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trained man climbing on the unstable wall to perform the drilling, Fig. 2(a), without any proper protection from rock fall, noise, dust, vibration, wind. In order to reach the working area, large scaffolds (4-5 meters wide) are fixed to the wall, as shown in Fig. 2(b) but this solution is not cost-effective, due to the time consuming operations, costs for the scaffolds and personnel involved in their set-up. It is dangerous for the workers (in accordance with ISPESL, the Italian Authority on Work Safety, scaffolds are responsible each year only on Italy each year of about 6000 accidents happen). An alternative solution is the use of vehicles carrying articulated arms, Fig. 2(c); however, this solution is applicable only when wide approaching areas are available and consolidating/monitoring work is within 20 m height [3].

In order to overcome the limitations of the current solutions, Roberto Zannini developed a manned structure to perform deep drilling for slope consolidation without the need of expensive scaffolds or supporting structures set-up (Patents ITPD20020286, IT1263667). A working prototype, consisting of a steel frame, carrying a conventional drilling equipment, operated by means of steel ropes and positioned by a man (staying on-board) using linear hydraulic actuators, has been developed and tested, demonstrating the viability of this novel concept.


(a) (b) (c)

Fig. 2 – Traditional consolidation practices. (a) Operator working hanging up. (b) Operators working on scaffolds. (c) Drilling unit on board a crane

II. THE ROBOCLIMBER PROJECT

A. *Aim of the project*

The Roboclimber project aimed to develop a safer and faster innovative technology replacing the present procedure [4]. An innovative robotic platform was developed, capable of autonomously move on irregular and rocky walls and to perform automatic drilling. For this reason the scientific and technical objectives of the project were the development of:

- a robust climbing structure, able to work on irregular and rocky steep walls up to 85° on harsh environment, capable to self-positioning on the working area without any need of cranes and be completely controlled remotely;
- an advanced automatic drilling unit capable to drill holes more than 20 meters deep, automatically performing all complex operations as screw/unscrew of rods and load/unload based on an on-board rod-warehouse storing different types of rods;
- a full remote control human interface and navigation system, based on wireless connectivity and allowing an easy control of the system also by a no-computer literate operator;
- innovative support methodologies for the design of the system under mechanical, control, geological, life cycle and economical constraints.

During the first part of the project, the combined knowledge from scientific literature, Research Centers expertise, and industrial practitioners has been used to define the technologies and methodologies for the system design and development. A multidisciplinary approach has been adopted to solve the problem with a wide use of mathematical modeling, computer simulation, digital mock-up and virtual reality testing tools in order to compare and evaluate several conceptual solutions and find out those improving the overall system performances while limiting the physical prototyping effort. The mechanical and control architecture have been conceived simultaneously while considering modularity and lifecycle issues [5]. The user has been included in the design loop at every level in order to assure the system effectiveness and work suitability.

B. *Project approach*

The development of the new concept service robotic system required the use of application oriented design tools obtained by integrating specific modules into functional and structural general purpose modeling packages. The aim was to study all the main life-cycle design aspects and costs in a simultaneous way and to develop a modular architecture and a scalable service-oriented climbing structure, e.g. for the maintenance of buildings, artistic monuments and dams.

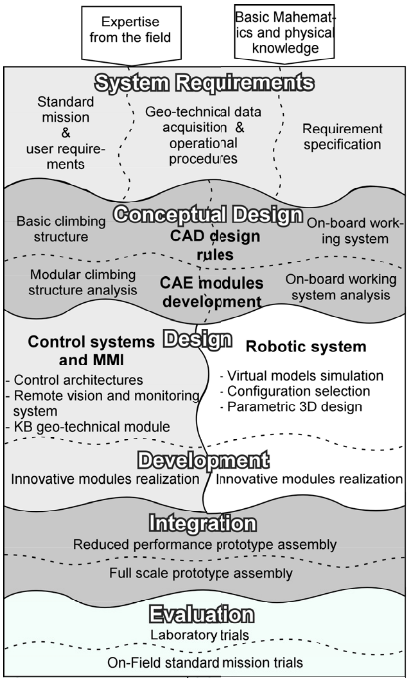


Fig. 3 – The Roboclimber platform design and realization methodology

Several specialized tools, rules and procedures have been defined to guide the development; both state-of-the-art packages for CAE and codes purposely written to solve particular aspects were used, allowing: parametric design by

3D CAD packages [6]; kinematics and dynamics analysis and simulation; digital mock-ups implementation and virtual reality testing; models tuning with purposely developed blocks (in particular using C/C++, Matlab, Maple, Simulink codes); to deal more precisely the reference kineto-dynamics, statics and stability outputs [7]. Figure 3 shows the main phases of the project.

III. THE CLIMBING PLATFORM

The main requirement was to develop a robust climbing mechanical structure and control system, able to

- walk without the help of ropes on 30 degrees slopes and climbing on irregular and rocky walls till 85 degrees slope by coordinating rope winches and legs
- cope with irregular rocky walls, cubes of 500 mm side are considered as maximum obstacles to overcome;
- work out-door in harsh environment with vibration, dust and rain;
- be completely controlled by remote using a wireless connection;
- automatically move up, down and laterally without any human intervention and always keeping static stability.

In the first design stage we analyzed three different locomotion strategies: wheels, crawler tracks and legs. From the experience of operators in the consolidation fields, only the solution based on legs was considered suitable for the harsh environment and very irregular wall surfaces where Roboclimber works. Hydraulic power was chosen to actuate the legs and to drive the rope winches.

The ropes are manually anchored at the top of the wall and have the function to hold the mobile module on, see Fig. 1. Once fixed to the ropes, the platform is able to perform vertical movements (from the base till the top of the wall), and transverse movements by means of the simultaneous and coordinated actions of ropes and legs under the remote-control commands. The maximum horizontal range is limited for stability reasons. The wall region where the robot can operate (grey area in Fig. 1) depends on the distance between the anchorage points and on the locations of the points where the ropes are fixed to the robot frame.

The layout of the climbing platform was defined and virtually tested with reference to different operative conditions. A general-purpose mathematical model of the robot was prepared accepting all the parameters defining the working pose as input data: geometry and architecture of the robot frame and legs, position related to the wall, field of external forces acting on the frame, elastic properties of all the frame elements, and the kind and layout of the terrain which the robot acts on. A specific simulator was used taking into account the consolidation tasks features, wall slopes and heights range, weight, volume and geometry of the payload as well as the characteristics of the ground [8]. The equilibrium of the robot is assessed by means of the mathematical model, which adopts an iterative solving methodology taking into account the structural and actuators compliances, see Fig. 4. By means of this model, the layout with four legs and two ropes symmetrically arranged on the supporting frame was selected as the best compromise for the specified work environment and operational tasks.

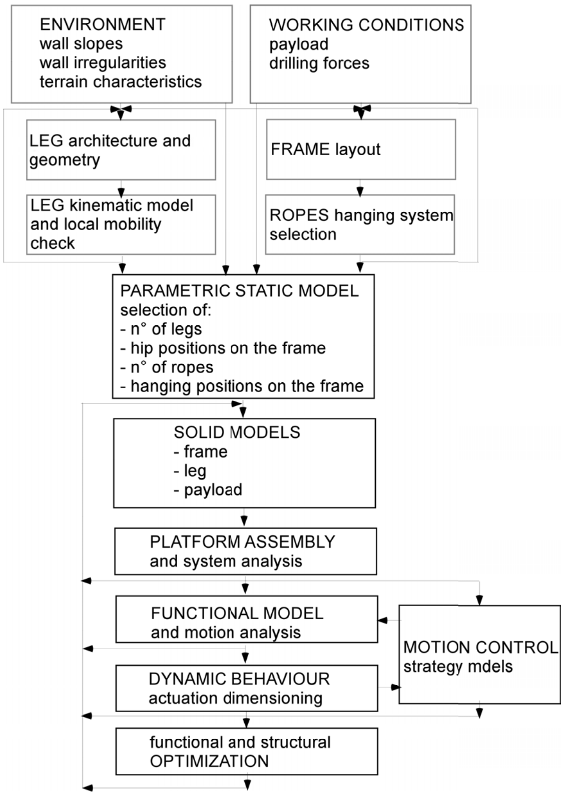


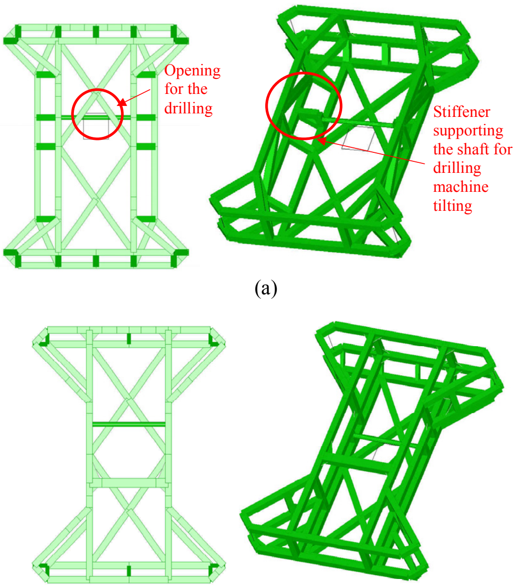
Fig. 4 – Main steps of the design process

A. Frame

The frame has to comply with various aspects. First, it houses all the devices needed for drilling, rod storing, rod manipulation and loading/unloading, the hydraulic power generator and the legs hips. The other function of the frame is to allow sliding of Roboclimber in some situations: the sides are suitably shaped to allow obstacles overcoming and the bottom acts both as a skid, for quick vertical movements, and as a shield against rocks.

Different frame structures were examined and compared [9]. Two solutions are represented in Fig. 5. The first solution exploits hollow beams to reduce mass still granting a good overall stiffness, Fig. 5 (a). The junction among the beams is made through welding, and the critical areas are reinforced with triangular elements.

The second solution, Fig. 5 (b), in comparison with the previous one is more compact as regards the lateral side, and very much easier to manufacture; stress and displacement analyses, Fig. 6, have been made to check both resistance for the heavier load conditions and the avoiding of unwanted excessive deformation which might imply in some occurrences the contact of elements that from a pure geometrical consideration (neglecting load-induced shape change), do not touch themselves.



(a)

(b)

Fig. 5 Two alternative frame solutions

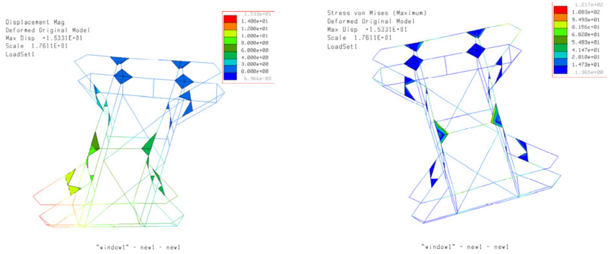


Fig. 6 – Displacements (left) and stress (right) of the second frame

The structure finally selected is shown in Fig. 8 left.

B. *Legs*

Several leg kinematics for legged robots designed for uneven terrains were examined. A simple classification criterion is the number of mobilities (equal to the nonsingular degree of freedom of the leg). It is usual to keep the dof (degree of freedom) of the leg less than four, although in this way the orientation of the last leg link with respect to ground cannot be actively controlled. Usually only revolute and prismatic joints are used. The joints are all actuated in the most of cases, although sometimes passive joints are introduced, e.g., associated to compliant adaptive mechanisms to fit with the terrain geometry (additional leg passive freedoms).

Fig. 7 shows the most common leg kinematics of realized robots. The first picture presents a leg with both revolute (R) and prismatic (P) joints. This is the only architecture such that the last link keeps at a constant orientation with respect to ground. The second picture presents an architecture particularly suitable for locomotion on flat terrains. It is common (simplifying a bit) of higher animals such as mammals and it is not good for quasi-static locomotion on uneven terrains. In the pictures from the third to the sixth, the hip R joint is vertical, while four possible dispositions of the other two R joints are considered. These leg architectures cope with the requirements for locomotion on irregular terrain and are typical of arthropods and such simpler animals. This brief survey of the leg architectures used in realized prototypes of legged robots allows to point out some main critical points to be investigated for the design of a new robotic platform for irregular terrain with a good obstacle overcome capability. The architecture shall allow simple control of the gait, i.e., the forward and inverse kinematics of the leg shall be simple. From another point of view, on the contrary, additional mobility is required in order to make the leg in some way deployable with a larger workspace (for obstacle overcome). Telescopic dofs can be taken into account, but stiffness and structural resistance problems arise. Additional redundant joints can be adopted, e.g., Nuremberg scissors and zig-zag mechanisms. Lots of new structural and stiffness problems are encountered.

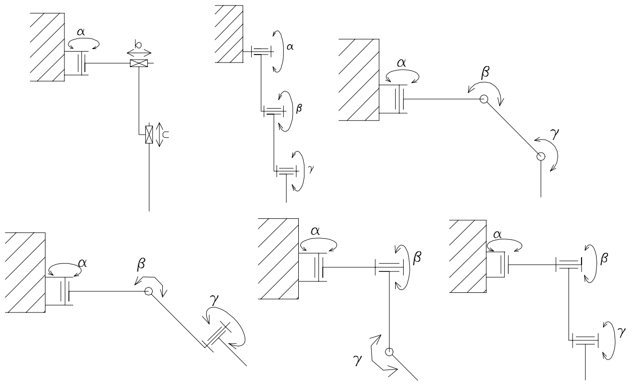


Fig. 7 – Some leg kinematics chains

These different leg alternatives have been examined from the point of view of energy efficiency, stability, obstacle overcoming, lightness and robustness to support the heavy loads and against bump loads (falling rocks), easiness of control, assembly and maintenance [2]. Finally, a quasi-Cartesian leg was selected and realized (Fig. 3 center, right). The reach is related to the maximum obstacle size that might be encountered on the wall; the gait ought to be an intermittent crawl gait adapted, at each step, at the unevenness and steepness of the wall [10].

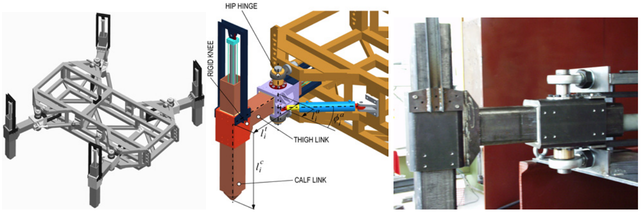


Fig. 8 – The legged mobile platform (left); digital mock-up of one leg (center) and the detailed view of a leg (right)

C. *Rope tensioning device*

To climb on leaning slope, the platform is sustained by ropes. However these ropes should be fixed, anchored to the top of the slope, to avoid that their motion over a irregular, rocky and abrasive surface damage them. For this reason we need a “winch like” mechanisms on-board of the robotic platform.

We applied two special Tirfor winches by Tractel fixed to the robot frame. The rope runs through each Tirfor without being winded up or gathered and then falls down along the wall. Two jaws, inside each Tirfor, clamp the rope and pull it rhythmically, "hand-to-hand", like a man pulling a rope. This system is very simple and reliable.

Furthermore the tensioning system satisfies the following requirements:

- it is able to hold at least 4 ton, lift the machine for at least 50 meter, work in any position horizontal, vertical or angled;

- it allows ropes do not move again the rocky wall but the system moves over it. For this reason the system is mounted on-board, on the front of the machine.

- it works safely on harsh condition as dust, mud, rain, vibration

- the system can be completely controlled from remote

D. *Robotic platform prototypes*

All the modular elements described above have been assembled in the virtual mock-up of the robot (Fig. 9).

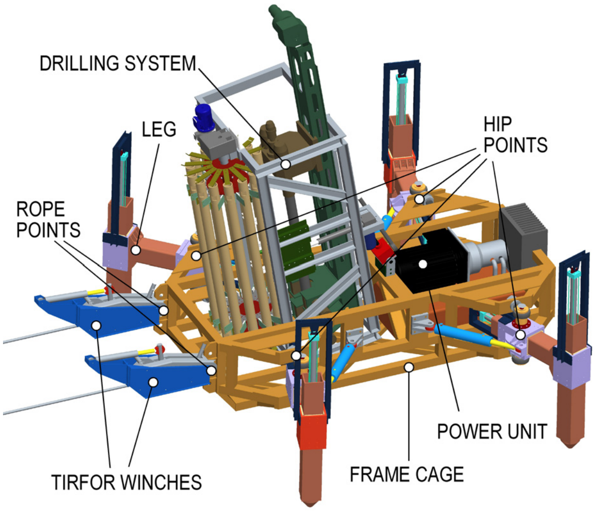


Fig. 9 – The Roboclimber virtual prototype

Virtual tests have been performed in order to check the correct matching of the modules and the overall functionality of the system. The final prototype, whose mass is about 3500 kg, has been realized and tested in laboratory. Real field tests have been performed in the summer 2004 in Friuli, with excellent results. Roboclimber was able to climb on a rocky wall 80 degrees sloping, receiving commands from the remote-operator console via radio frequency, and to autonomously perform drills (Fig.10).

Fig. 10 – Roboclimber at work

E. *Control and Human Machine Interface*

The architecture and functionality of the control system [11-14] and human machine interface (HMI) [15] satisfy several severe constraints: the system should work on open and harsh environments with dust, vibration, rain; the operator should be able to work from remote, away from the drilling area; even if far from the machine, the operator needs to have a close look to the drilling components. To address these requirements, the control system was developed implementing the following features: using as hardware a light tablet PC and a wireless connection with the computer on-board, the HMI allows the operator to act remotely from the machine (Fig. 11 left); the control system allows the operator to move the robot as a whole or component by component depending on the context (climbing, pre drilling positioning, walking,...); the control system allows the operator to manage and monitor the drilling, using high level macros or low level primitives; the HMI can operate in a harsh environment and in a bright environment thanks to a special case and screen; the HMI is user friendly and accessible to non computer-literate users (Fig.11 right).

The HMI [15] is based on a multi-modal structure in which the operator can act at different control levels ranging from motion of an individual axis to the coordinated legs ropes control. In this way the operator can perform the variety of actions required for facing different situations along diverse operative conditions of a walking machine.

An important part of the work has been the development of the real time algorithms used for the stability check of each step configuration within the planning of the robot gait [5], [6]. Quasi-static locomotion is required for safety and due to the high weight and size of the robot. The remote operator sends to the robot four kinds of commands: up, down, left and right. The control system plans a gait (involving the legs and the rope winches) satisfying the motion required by the remote operator and at the same time fitting with the mapped local geometry of the wall. The planner is based on a search algorithm.

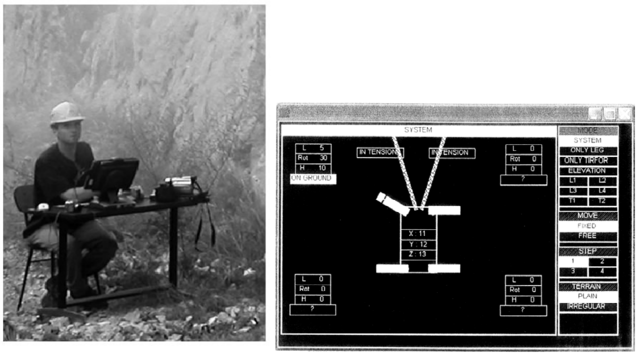


Fig. 11 – The remote control consol (left), the HMI interface (right)

IV. CONCLUSION

Roboclimber is an innovative mobile robot able to climb on steep walls and perform heavy duties of wall consolidation by strong interaction with the environment. The main characteristics of the climbing robotic platform have been illustrated. The innovation achieved within the project concerns the following aspects:

- development of a robust climbing mechatronic system, together with its control system, able to cope with irregular and rocky walls up to 85° sloping in harsh environmental conditions under human remote control
- development of a new control system: the problem of climbing locomotion by coordinating legs and ropes is challenging and the technical literature on this subject is very poor
- development of an innovative gait planning strategy. Robustness and reliability needs are satisfied by introducing within the planning strategy the check of the robot equilibrium at each step.

The expected scalability and cost-effectiveness of the Roboclimber design should allow its application in other industrial sectors. Markets preliminary investigated are in the building sector, for the maintenance of concrete structures (dams, retaining walls, chimneys), nuclear sector, off-shore, mining and stone industry for operative work, remote inspection and maintenance.

ACKNOWLEDGMENT

The authors kindly acknowledge Roberto Zannini for his important role of end-user, precious in all the project phases, and for his fruitful support and discussions. Many thanks to the Roboclimber Project partnership for having created a stimulating interdisciplinary working environment.

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