Project no. COOP-CT-2005-016842

SAFERDRILL

A remotely controlled autonomous walking and climbing robot for faster and safer landslide monitoring, slope stability analysis and consolidation

Co-operative research Project

Full Project Activity Report

First Release

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Project coordinator organisation name: I.C.O.P.

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Publishable Executive Summary

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. They are caused mainly by penetration of groundwater into slippery layers or by instability of soil. Geological survey, soil drainage and deep drilling are common practices to prevent them but today all these operations are always unsafe, highly expensive, time consuming and labour intense: specialized operators climb with ropes on the unstable slope to perform the drilling without any proper protection or, in order to reach the working area, large scaffolds are fixed to the wall, but this solution is dangerous and not cost-effective. Use of vehicles carrying articulated arms with the drilling unit is applicable only in few cases when wide approaching areas are available (see Figure 1).

a) working hanging up b) Drilling process on scaffolds c) Drilling unit on board a crane

Figure 1: Common methodologies to perform deep drilling

SAFERDRILL project developed a safer and faster innovative technology usable by SMEs, replacing the actual unsafe, highly expensive, time consuming and labour intense actual procedure. **The SAFERDRILL innovative robotic platform is capable of autonomously move on irregular and rocky walls and perform automatic drilling and slope stability analysis.**

The project builds on feasibility studies previously performed demonstrating that a climbing robotic structure carrying an automatic drilling unit is a viable solution to perform deep drilling on rocky slopes. SAFERDRILL system provides a cost-effective system to remotely and automatically perform deep drilling and slope stability analysis thus reducing operating costs and working time, while avoiding the human presence in unsafe and harsh environment.

The achieved scientific objectives are the development of:

- a robust climbing mechanical structure able to move horizontally or vertically over any surface thanks to the use of a legged platform completely controlled by remote;
- a drilling unit capable of automatically drilling holes more than 20 meters deep and on any slope conditions;
- a navigation system able to process on real-time stereo-images to extract the value of depth to help the operator with information on obstacles dimension;
- an innovative mechanism for rope tensioning completely remote controlled and capable of motion inversion and a tiny control (+/- 1 cm) of positioning over a fix rope;
- a geophysical knowledge based system integrating on real-time the drilling values and properties of ground samples, providing information on slope morphology.

A schematic view of the system architecture is provided in Figure 2.

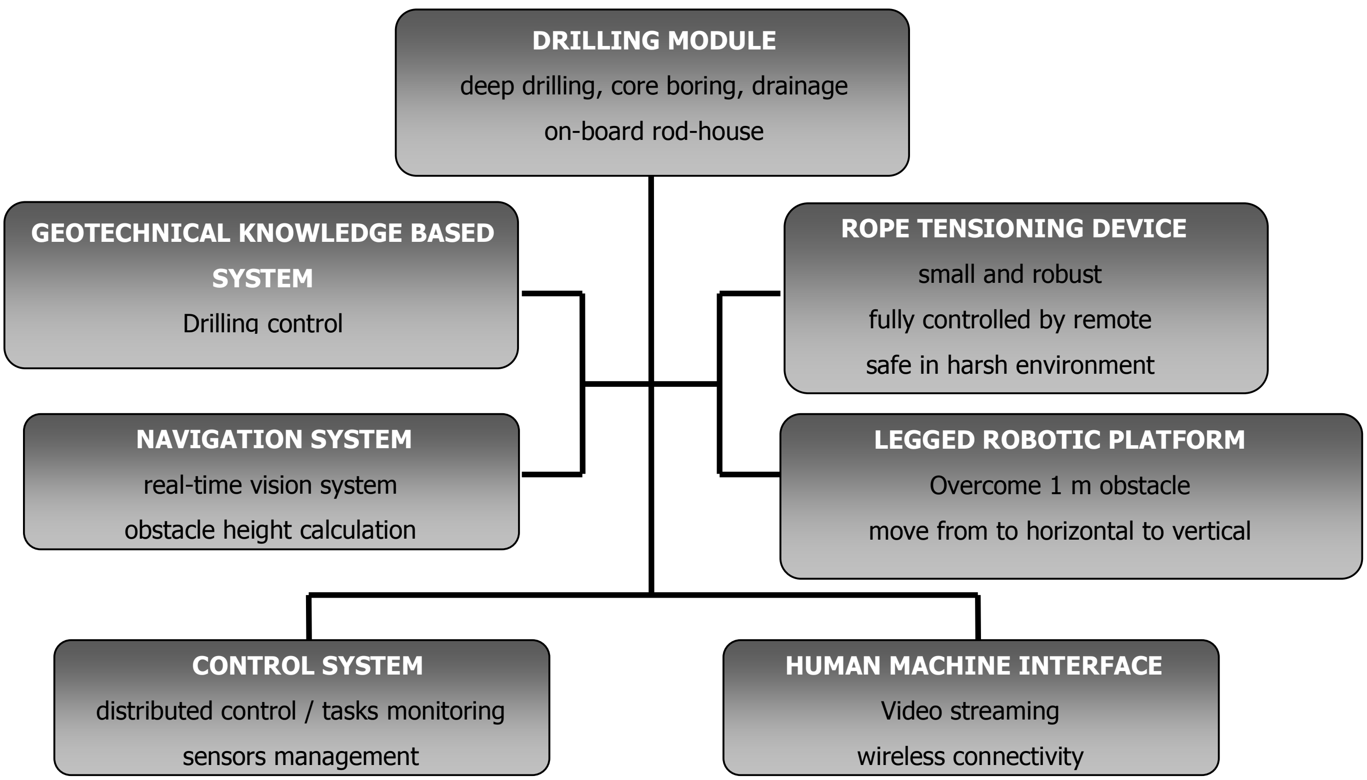


Figure 2: Schematic view of the system architecture

SAFERDRILL project was an opportunity for the **6 SMEs** to establish a trans-national cooperation with European R&D centres of the consortium and a complete European supply chain among themselves. The complementary expertise of the partners at an European level guaranteed an effective approach to problem solving and to the accurate definition of the application requirements, thus having a greater impact than national projects. **The project consortium has been setup in**

order to address all research themes and provide the necessary expertise to reduce the identified risks at a manageable level. RTD Performers have been recruited for their deep experience in geo-technical engineering and integration of real time vision systems for industrial inspections (DAPP), mechanical design of industrial and services robots and automatic industrial machines (DIMEC), design and remote control of big climbing robots (IAI-CSIC). Expertise in camera-based navigation system and advanced human machine interfaces to control robots comes from SAS, a Belgian SME. Know-how in robust and complex industrial electronic and control drivers is detained by the Czech SME IMC while the Italian SME COMACCHIO has great experience in design and manufacturing drilling unit. Finally the Spanish SME MACLYSA has great experience on prototype design and development of automatic machinery and hydraulic systems.

Specifiche tecniche - *Technical Specification*	
Diametro aste - *Rod Ø*	3 in (76 mm)
Coppia max. - *Torque max.*	240 daNm
Giri max. - *Max speed*	100(600) rpm
Corsa utile - *Feed stroke*	1200/2000 mm
Forza di spinta - *Feed force*	1200 daN
Forza di tiro - *Retract force*	1200 daN
Potenza motore - *Engine power*	27,5 Kw
Pesi - *Weight*	3500+300 Kg
Dimensioni - *Dimension*	2 m x 2,5 m

Figure 3: General technical specification of the SAFERDRILL robotic platform

During the project the following results have been achieved:

- A **robotic platform**, composed by an automatic drilling module and a legged platform, able to work on any kind of slope, from horizontal to vertical, and to perform deep drilling in rocks up to 20 meter depth (Figure 3).
- A **distributed control system** able to collect data from a distributed network of sensors, to actuate a set of hydraulic valves and pumps, to communicate by Wi-Fi with the remote user control unit;
- A **Human Machine Interface**, integrating traditional industrial commands (buttons, joythicks, switches) and advance IT components (Tablet PC with touch screen, remote Wi-Fi connections) enabling an easy control of the system by remote;

- An innovative **rope tensioning device**, fully controlled by remote and with intrinsic high safety standards has been conceived, designed, prototyped and tested;
- A support **navigation system** using stereo camera for automatic obstacle height calculation has been designed, prototyped and tested;
- A **geotechnical knowledge system**, composed of the distributed sensor network and a friendly end-user interface has been developed and tested.
- The different subsystems has been integrated and tested in several laboratories and working condition tests.

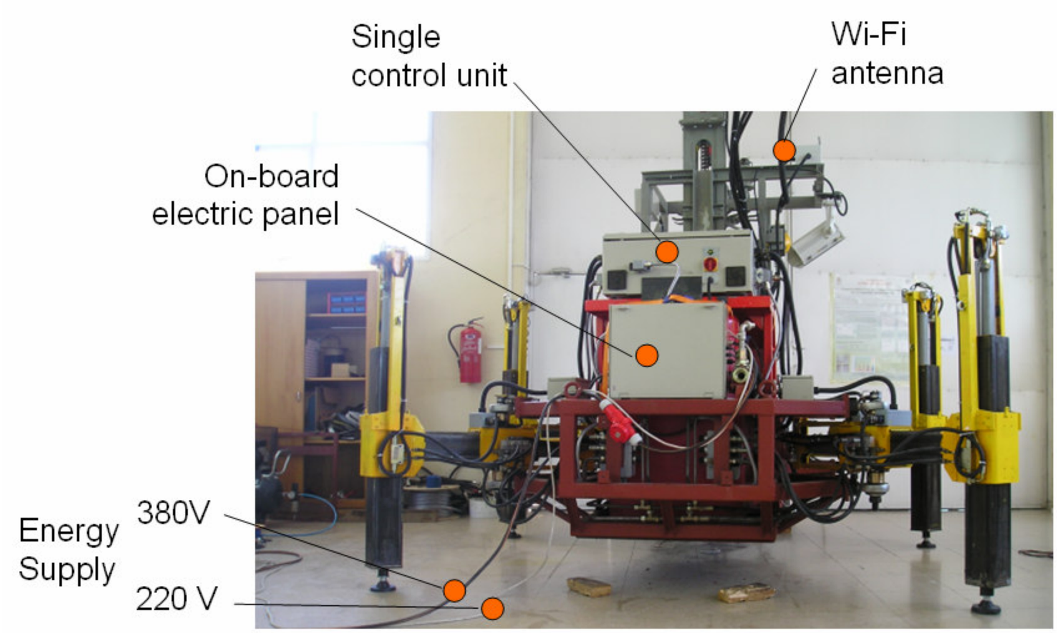


Figure 4: General view of SAFERDRILL system

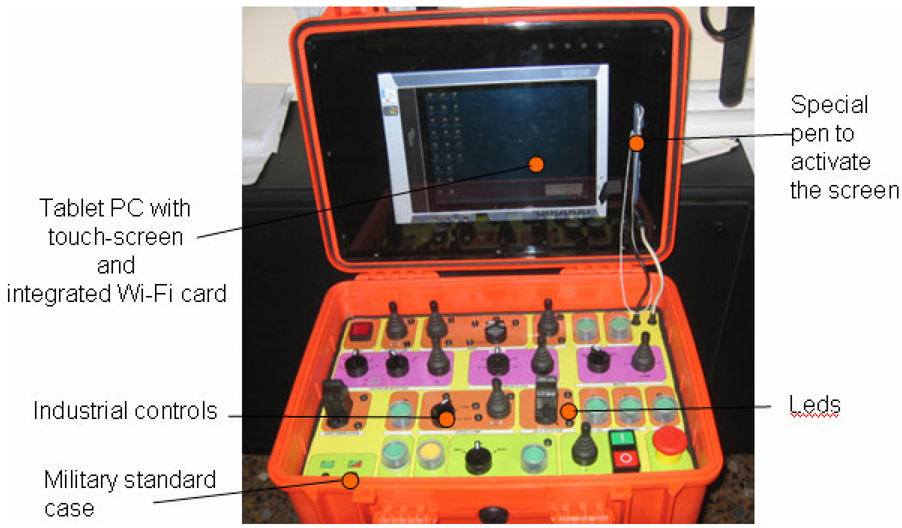


Figure 5 Remote Human Machine Control

Project result has been presented to several international conferences (SYROCO 2006; RISE 2008) and fairs (GEOFLUID 2006; R2B 2007). The project website (www.dappolonia-research/saferdrill) has been developed and continuously up dated to help the easy communication among partners and disseminate project results.

Figure 6: On-Field test of vertical position

Figure 7: **On-Field test of vertical drilling**

Section 1 - Project Objectives and Achievements

The overall objective of SAFERDRILL is to develop a climbing robot able to remotely operate in harsh environments while performing deep drilling. During the first reporting period the main activities were concentrated on the definition of the requirements for the system and its single components, on the design of the conceptual design of the different modules, on the selection of the best solutions and configurations, on the manufacturing of the climbing and drilling modules of the prototype, on the design and development of the remote control system.

As described on Deliverable D1 “System requirements”, the system requirements are fully defined according to the original Work Programme, taking also in account the sever condition where the system will operate. These requirements represent the set of specifications used in the conceptual design of the system and in the definition of the control architecture. During the first period, the conceptual design of the main components of the robotic system has been completed and final configuration selected for each module. At the start of the activities the consortium decided to manufacture directly the final prototypes of the modules, when possible, to minimise consumable costs. This was possible thanks to the complete virtual prototyping developed for each components that allows to detect most of the possible issues already during the design phase and to guarantee a final integration of the different modules. The consortium decided also to concentrate the prototyping efforts in the first period on the most fundamental modules, in order to start as soon as possible with some basic tests of the assembled system: the legged robotic platform module, the drilling module, the control system module, the human machine interface modules have been fully prototyped and at the end of July 2006 laboratory and field tests in Madrid already demonstrate the good design and performance of these modules. Figures 6-9 shows details of the prototypes of these four modules that were prototyped.

Figure 8: Legged robotic platform module

Figure 9: Drilling module

Figure 10: Control system module

Figure 11: Human machine interface module

The remaining three modules have been only defined during the first period and have been completed on the second period. During the first year of the project, the rope tensioning device modules have been completely design; a final configuration has been selected among the different proposed; a first laboratory prototype started to be constructed. The navigation system module has been completely designed. Finally the specification, sensors and signals, Human Machine Interface (HMI) of the Geotechnical Knowledge based system module have been defined.

On the second reporting period the consortium spent important resources, both economic terms and in terms of men hours, to perform important modification and improvement on these modules (legged robotic platform, drilling module, control system module, human machine interface module) and to test the SAFERDRILL system in different working conditions. The SAFERDRILL system complexity and the fact that it needs to work on severe out-door environment requested the redesign of several components, the improvement of the robustness of hydraulic, electrical and mechanical parts, as well as the constant update of the different control modules.

In parallel with these activities, full scale prototype of the SAFERDRILL remaining modules (rope tensioning devices, navigation system, and geotechnical knowledge system), only designed in the first year, have been fully developed, manufactured and tested.

An innovative **Rope Tensioning Device Module** has been manufactured and successfully tested. It is able to be controlled by remote and allows motion inversion as a tiny control of position of the SAFERDRILL platform. Moreover it is able to work safely in harsh condition. The development of this module was very challenging and involved the participation of all partners as it needed experience not only on mechanics but also on hydraulics and electric control. From the first tests of the SAFERDRILL robotic platform, the consortium realised that a better control of the rope tensioning devices was fundamental for the practical use of the SAFERDRILL platform on the field. For these reasons it was decided to give priority to the development of this module and all partners agreed to provide all the necessary resources until a full scale prototype has been successfully tested. The results of this effort were so promising that the Consortium decided to deposit a request for a Patent, aiming to protect the innovations developed.

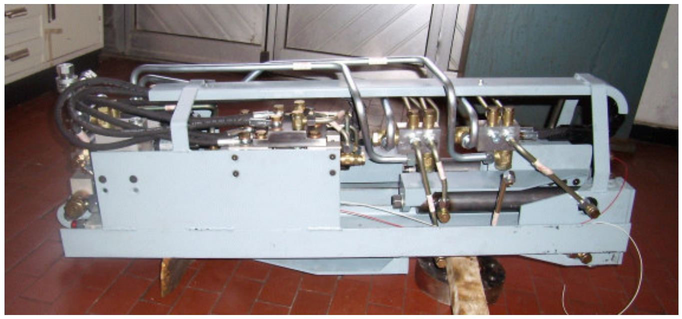


Figure 12: Full Scale Prototype of the Rope Tensioning Device

Moreover on the second reporting period the design of **Navigation System Module** has been completed and a fully scale prototype manufactured. The system has been tested at laboratory scale demonstrating that the major requirements were achieved: the hardware has been developed to be insensible to vibration, dust, rain and shocks contemporaneously a flexible control interface has been developed to take in account the different light conditions and allows the user to tune camera setting accordingly. A 3D imaging processing software has been developed enabling the automatic extraction of depth.

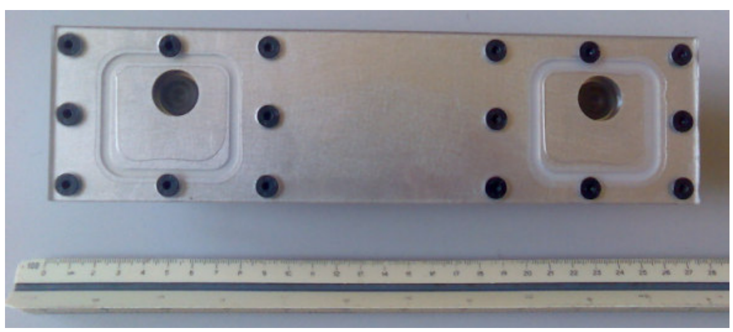


Figure 13: Stereo Head of the Navigation System module

On the second project period the **Geotechnical Knowledge** system has been completed and tested. A set of distributed sensors, able to work in hard and harsh environment, has been installed on the SAFERDRILL robotic platform and connected with the on-bard control unit. In parallel, dedicated software has been developed to read and analyse the data from the sensors and give in real time the necessary information to the operator to perform the correct operations.

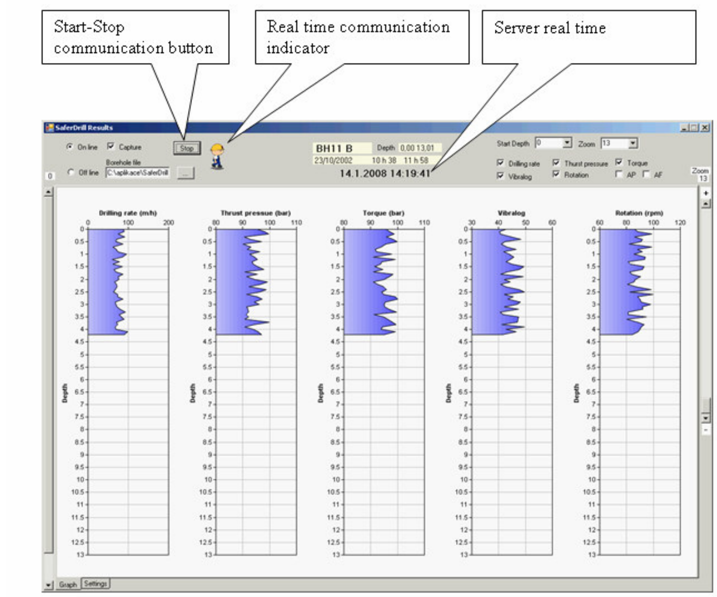


Figure 14: Screenshot From the Geotechnical Knowledge System

The results show that all planned milestones have achieved as planned in the DoW:

- Definition of functional requirement of the system (**M1**);
- Conceptual definition of architectures of the climbing (**M2**);
- Constructive drawings of the Robotic Platform, Drilling Module and Rope Tensioning Device has been developed and used to manufacture the full-scale prototypes (**M3**);
- System Navigation and Geotechnical Knowledge base system has been validated on laboratory testes and preliminary field tests (**M4**);
- A full scale demonstrator of all SAFERDRILL modules have been developed (**M5**);
- Several laboratory and field tests were performed for system evaluation (**M6**);
- A patent to cover the innovative rope tensioning device has been submitted (**M7**).

The work has been carried out according to the original Work Programme. Even if at the end of first year, the project was head of schedule, an extension of four months has been requested to allow the Consortium to implement all the modification and improvement into the SAFERDRILL system to overcome the problem discovered during the several field-tests performed. This extension allowed the Consortium to complete the validation of the system and to achieve all the expected results expected by SAFERDRILL project.

Section 2 – Workpackage Progress

In the following sections an overview of the actions carried out during the project is given. For each workpackage are given: the general objectives, the progress towards objectives, possible deviation from the workprogramme and list of deliverables and milestones achieved.

2.1 WP1 System Requirements

Starting Date :	**Month 1**	Date of End :	**Month 3**
Related Deliverable/Milestones :	D1 – System Requirements (December 05) M1 – Definition of functional requirement (December 05)		
Partner Involved :	**ICOP, IMC, COMACCHIO, ZANNINI, DAPP**		

Scope of this workpackage was to identify the system requirement through the analysis of a series of specific activities and of the end-users indications.

2.1.1 Task 1.1 – User Requirements

At the kick-off meeting of September 2005 and during following meetings held in Basiliano (Italy) and Genoa (Italy), the technical discussion was mainly focused on the aspects concerning the technical specifications of the SAFERDRILL both from the end-users and geo-technical point of view. In order to define these requirements, a questionnaire was prepared by D'Appolonia and discussed during the three above mentioned meetings. IOCOP and ZANNINI have provided the operative specifications such as a complete description of the purpose of the system, the expected performance, the expected dimensions and other specific needs.

2.2.2 Task 1.2 Geo-Technical Requirements and Task 1.3 System Requirements

The industrial partner, namely ICOP, IMC, COMACCHIO and ZANNINI, contributed with their experience and knowledge to the definition of the system requirements: ICOP covered the requirement for the general usability of the system inside a generic building site; IMC contributed to define the control requirements from an industrial point of view; COMACCHIO defined the hydraulic and mechanical specification of the drilling part; finally ZANNINI covered the specific requirements for a consolidation work.

DAPP stimulated the discussion by e-mail, phone call and during the meetings, and collected the system requirements. A summary of the system requirements define in this workpackage is reported in Table 1.

Material	• Steel • Aluminum • IP65 for electrical materials
Moving Platform	• motion using crawler tracks • self-powered using on-board diesel engine • transported using standard road-trailer
On-board equipment and weight	• 20 rods (15 kg each): 300 kg • drilling machine frame: 300 kg • hammer: 150 kg • rod loader: 100 kg • rod store: 50 kg • tool box: 30 kg • operator: 80 kg • aluminium shield: 30 kg
Total weight of drilling/climbing unit (including drilling machine and rods)	• 2 tons
Max weight of the largest piece	• 300 kg
Overall dimensions (including legs)	• Height 2000 mm • Length 2400 mm • Width 1200 mm • Shelter on the bottom part • Must be possible to carry the unit on a standard trailer
Power supply (through an umbilical coming from electrical generator)	• Pneumatic: compressed air (12-20 bar) for drilling unit (hammering and flushing) • Hydraulic: oil (200 bar) for drilling unit (rotating and advancing) and for legs. Distribution system on-board • Electric: for lighting (night work), TV camera (visual monitoring), sensors, control system
Power pack	• Generator Downhill
Electrical power	• Electrical board on-board • Downhill general switch • On-board industrial PC communicating with the control room
Moving device	• Ropes + shield for the quick/emergency vertical movement • Ropes + legs for normal vertical movement (no slipping on the shield) • Ropes + legs for the lateral movement • No wheels
Anchoring	• No
Acceptable Slope Geometry	• 45°-80° angle (no negative angle) • Flat geometry • Max obstacles 80x80x80 cm
Special equipment on-board	• TV camera closed circuit (for visual monitoring) • Rope tensioning devices • Navigation system

Drilling rig	• MC 200 provided by COMACCHIO
Drilling rods	• Max diam rod: 73 mm • Max diam hole: 100 mm • Length 1000 mm
Flushing fluid	• Air + sprayed oil
Parameters to be checked	• Torque • Advance speed • Drilling depth • Thrust • Hammer beating frequency • Extracted material quantity and humidity • Input/output air variation
Navigation system	• Provide real time 3D obstacle height in the radium of 3 m • Easy to be integrate or removed from the control panel • Capability to memorize data for further off-line analysis • Able to work in harsh conditions (dust, vibration, rain)
Knowledge based system	• Provide real-time value of main drilling parameters • Provide real-time alert and suggestion to the operator • Easy to be integrate/activated or removed/deactivated from the control panel • Able to filter sensor noise and work in hard conditions • Memorize drilling parameters into a database and able to perform off-line morphologic analysis of the data.

Table 1: general system requirements

WP1 activities terminated in schedule with the work programme and the first milestone was successfully achieved.

2.2 WP2 Design of Robotic System

Starting Date :	**Month 4**	Date of End :	**Month 9**
Related Deliverable/Milestones :	D2 – System Conceptual Design (March 06) D3 – CAD modules and procedures (May 06) M2 – Conceptual definition of architectures (May 06)		
Partner Involved :	**ICOP, COMACCHIO, ZANNINI, MACLYSA, DAPP, DIMEC, CSIC**		

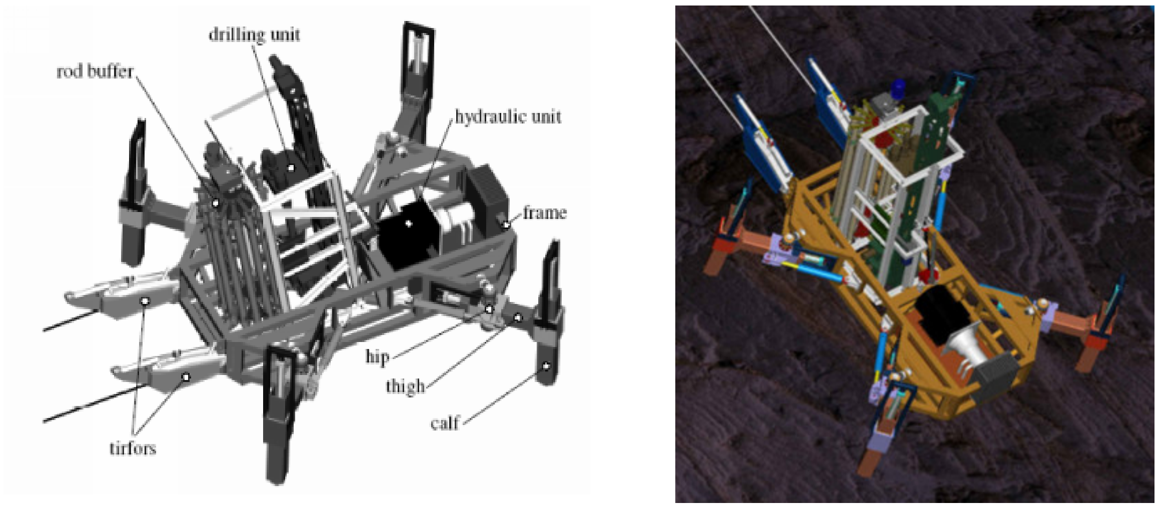
Objective of this Work Package was to produce a conceptual design of the main components of the robotic system, namely the basic structure of the climbing vehicle, the articulated legs and the rope tensioning devices, the on-board drilling system, based on the requirements defined in WP1.
SAFERDRILL is mainly composed by a mobile platform and onboard automatic drilling unit.

2.2.1 Task 2.1 - System conceptual Design

The main SAFERDRILL modules have been designed simultaneously in order to consider the multiple influences and parameters coupling for the heuristic optimization of the robotic system.
Most of the design activities have been performed by DIMEC in closed connection with CSIC to assure a consistent design of the control part. ZANNINI supported DIMEC regarding the definition of the drilling module and has been deeply involved in the definition of the robotic sequences. COMACCHIO designed the general hydraulic circuit and defined the commercial components to be used for it. MACLYSA reviewed the structural design and manufacturing process. Finally DAPP contributed in the evaluation of the integration degree of all modules to insure an easy integration during the second project phase. Thanks to the strong interaction with industrial partners during the system design, a common approach for the definition of the modules has been adopted to ensure a minimum effort, to evaluate the possibilities of adopting common basic components, with preference to the off-the-shelf ones with the aim to reduce costs, to simplify maintenance and to allow interfacing possibilities between the single modules.
From the mechanical point of view the structure is basically made up of:

- A mobile robot having active devices (legs) for its motion across the sloping surface, composed by:
  - A frame structure;
  - Four articulated legs;
- Two rope tensioning devices;
- An on board drilling system, composed by:
  - a buffer containing a ‘sufficiently high’ number of drilling rods;
  - a drilling unit;

- a robotic arm for picking from a buffer, in the right sequence, the drilling rods, mounting them on the drilling unit until the total length of the stacked rods equals the desired depth, and then making the above mentioned operations in reverse order.



a) main components of the system b) working position

Figure 15: General layout of the system

2.2.2 Task 2.2 - Study on Modular Robotic System Structure

The main feature of the mobile robot is to move and climb on a sloped wall and to hold up the drilling unit with the right attitude while it is operating.

During the first conceptual phase, three different kinds of locomotion has been analysed: by wheels, by crawler tracks or by robotic legs. As detailed explained in Deliverable D2, the layout with four legs and two ropes, symmetrically arranged on the supporting frame, has been selected as the best compromise between the specified working conditions and operational tasks.

Leg's architecture has been chosen considering the required mobility, walking functionality and control considerations: different solutions (Cartesian, anthropomorphic, geometrical shaping, number, etc.) were compared and the semi-cartesian (also called semi-orthogonal) leg has been selected.

The frame has been conceived trying to comply with all the specifications required. The frame main feature is to house all the devices needed for drilling and for moving the whole system. Taking into account the system requirements summarised in D2, the solution selected was modular, compact and easy to manufacture. A welded steel pipes structure has been chosen because it is lightweight and it allows high versatility with acceptable behaviour under torsion.

The on board drilling system is composed of a drilling unit, a buffer containing a sufficiently high number of drilling rods and a robotic arm for picking from a buffer, in the right sequence, the drilling rods, mounting them on the drilling unit until the total length of the stacked rods equals the desired depth inside the wall, and then making the above mentioned operations in reverse order.

2.2.3 Task 2.3 - Study of the Rope Tensioning Device

The robot is able to climb thanks to the four legs and two ropes manoeuvred by two rope tensioning devices, one per rope. After consideration about the harsh environment, rock instability and more generally on safety, it has been decided to fix the steal ropes and that the two rope tensioning devices move over them trailing the robotic structure. Detailed requirements of the rope tensioning devices in accordance with Deliverable D1, “System requirements report”, are:

- Continuous or almost continuous traction of the rope in both forward and backward directions of motion;
- Range of pulling/releasing velocities of the same order of the gait velocity of the robot;
- In case of placement onboard the robot the overall mass and size limitations as defined in Deliverable D1 have to be satisfied;
- Safety especially against unforeseen release of the rope.

Because the robot can climb for several meters, the ropes can not be stored onboard due to their volume and weight. So it has been decided to adopt rope tensioning devices with crossing rope.
During proposal writing a deep investigation regarding commercially available systems was performed. For this kind of application two main classes of crossing rope tensioning devices exist: continuous and discontinuous (see Figure 16). As explained in D2 these devices do not satisfy system requirements.

a) Tirak: continuous device b) Tirfor: discontinuous device

Figure 16: Example of commercial device for rope tensioning and pulling

Therefore the system needs a new design for rope tensioning device with a discontinuous architecture (thus satisfying the size and mass requirements) able to generate continuous motion by an intelligent control system and sensors.

The following consideration has been done to define the location of the system:

- the preferable location of the rope tensioning devices onboard the robot is in the frontal region so that they can directly engage the ropes;
- because the ropes are supposed to cross the tensioning devices and fall down along the wall, the devices have to be placed outside the frame of the robot;
- the connection of each tensioning device to the robot will be by a joint with 2-3 rotational freedoms so that the axis of the tensioning device can remain always coaxial to the rope;
- as the main power source selected for the robot is hydraulics, this is natural choice as well for the rope tensioning devices.

Two solutions were considered and evaluated for the tensioning device control: the first one is by hydraulic commands, e.g. operating on the exchange of fluid between the tensioning device and the robot (opening-closing of valves). The second one is by electrical signals exchanged between the robot and the tensioning device. The first solution would be the better only in case that the tensioning device would be entirely hydraulic moved but in this case the realization of the internal logics governing the tensioning device would be difficult, costly and require lot of space compared to the space occupied by the linear actuators operating the rope. The second solution is then preferable and it is in accordance with the choice of a mixed hydraulic-electrical internal organization of the tensioning device. In this way a logic unit like a PLC can be used to codify the functioning sequences internally to the tensioning device, with higher flexibility compared to rigid hardware logics.

Regarding the general rope tensioning architecture, a complex analysis has been performed as described in D2. The selected solution is based on two linear actuators disposed laterally with their axes coplanar and not coincident and the operation of the rope done by a system of leverages connecting the actuators to the cam yaws.

The development of this module was very challenging and involved the participation of all partners as it needed experience not only on mechanics but also on hydraulics and electric control. From the first tests of the SAFERDRILL robotic platform, the consortium realised that a better control of the rope tensioning devices was fundamental for the practical use of the SAFERDRILL platform on the field. For these reason it was decided to give priority to the development of this module and all partners agreed to provide all the necessary resources until a full scale prototype could be successfully tested. The results of this effort were so promising that the Consortium decided to deposit a request for a Patent, aiming to protect the innovations developed.

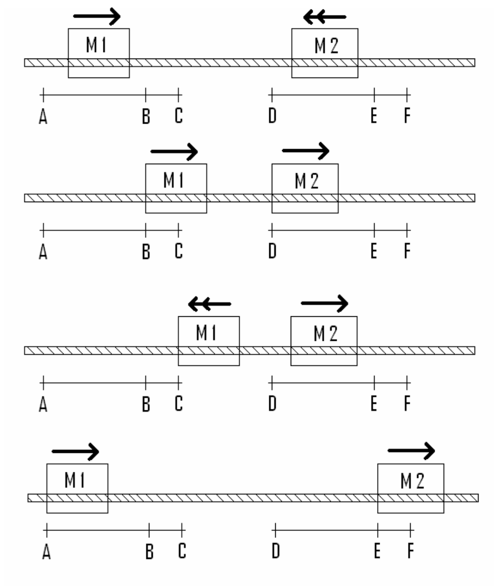


Figure 17: Working cycle for continuous rope motion: with two hands

Cad modules for the climbing structure, drilling and rope tensioning devices

The main difficulty while facing a climbing robotic structure is the right assessment of the stability figures while performing typical operative tasks. In the case of SAFERDRILL, the situation is quite complicated by the presence of devices that work together and have to be precisely coordinated.

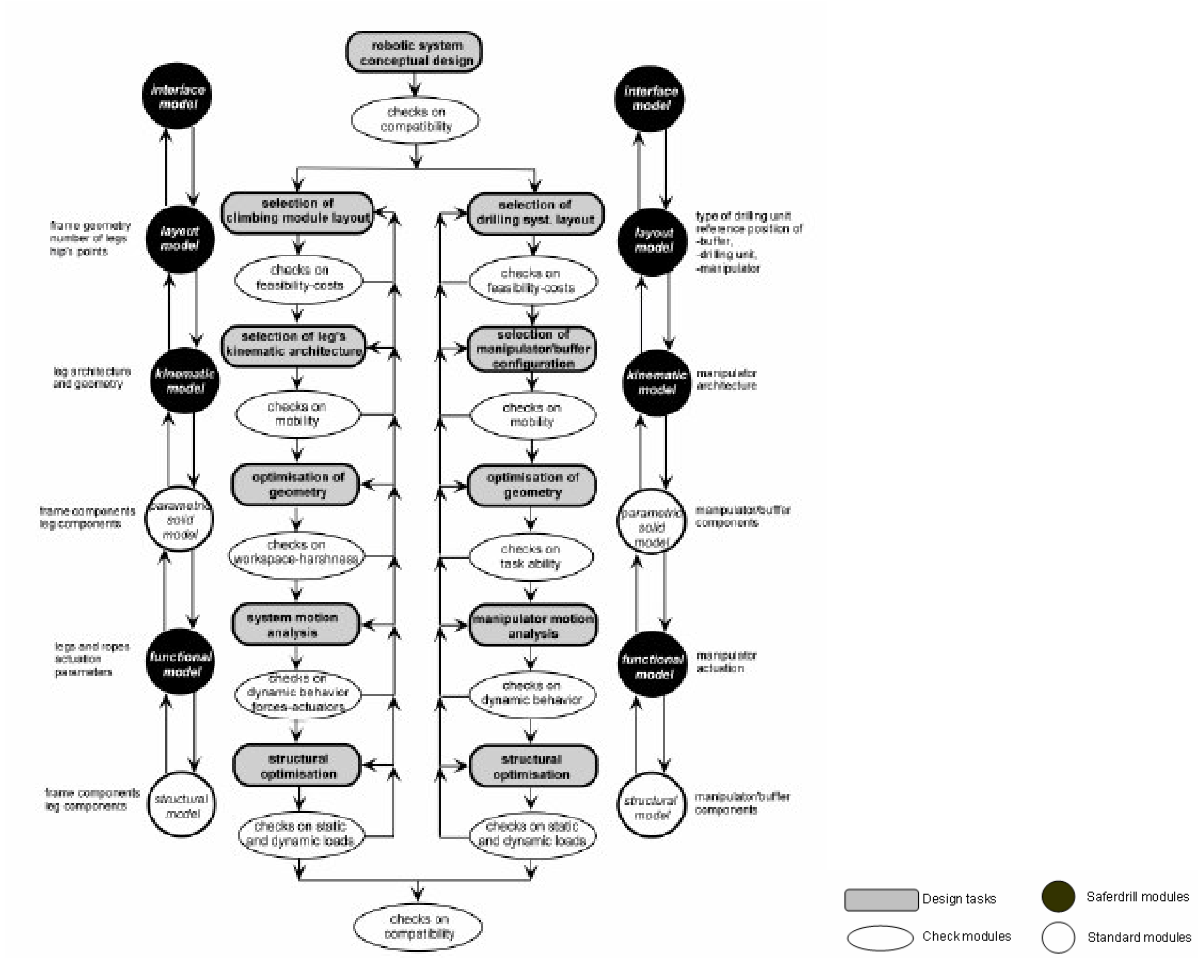


Figure 18: Saferdrill design steps

Different models and software modules have been developed and set-up to improve the design process on the SAFERDRILL system.

The program software Pro/Mechanica Motion was used for preliminary assessment of the robot behaviour during climbing and to identify critical aspects and possible robot setups. Then, a parametric analytical model of the robot was developed and used to assess alternative robot architectures and finally to select the robot geometry. Because it is fully parametric, it was used as well to compute maps of the workspace and equilibrium maps during climbing and drilling.

The parametric model implemented in Pro/Mechanica Motion can be used to evaluate the wideness and extent of the working strips of SAFERDRILL as functions of the wall steepness and of the locations of the anchorage points. This information are used to plan the operation of the robot and the simulation results has been used to help the construction of the logics used in the control system and to define the points of connection of the ropes to the robot (including determination of forces applied to the robot frame for structural design).

The discussion of the number of ropes lead to the conclusion that the additional ropes, while enhancing stability, require a too sophisticated control system reducing robustness and reliability of the robot.

The parametric analytical-numeric model of the robot is quite complex. The unilateral problem is solved based on the bilateral model by adaptation of SW modules developed by DIMEC.

This parametric model has been used in the control system of SAFERDRILL for online evaluation of stability and equilibrium in every phase of the gait (continuous monitoring) in order to assure the highest safety. The model has also been used for gait planning to generate gaits which are intrinsically safe. Drilling forces and other external forces applied to the robot has been taken into account; in this way where and under which conditions the robot can drill are part of the results of the analysis and indications about that has been derived for offline use, e.g. mission planning.

In the design phase, the analytical-numeric model was used to determine the number of legs and ropes of robots moving on walls using ropes. We used the model to validate the working hypothesis to use minimum number of legs and ropes, i.e. four legs and two ropes, and to asses their architecture from the point of view of gait generation.

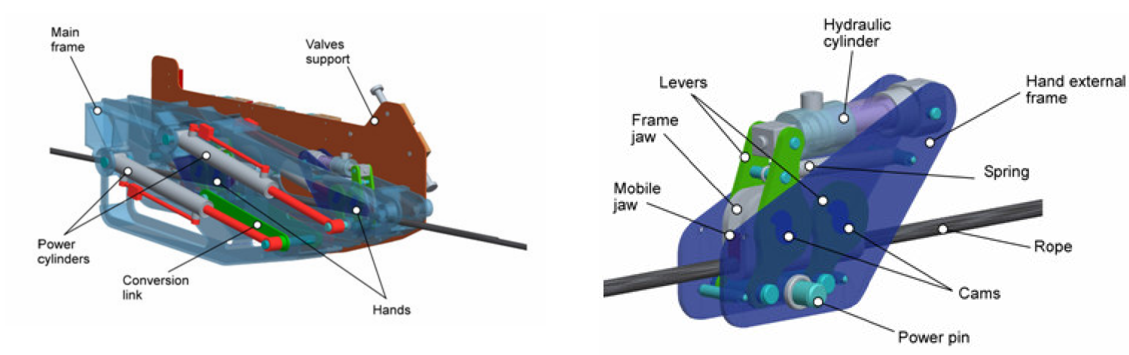
2.3 WP3 Selection and Development of Robotic System

Starting Date :	**Month 8**	Date of end :	**Month 14**
Related Deliverable/Milestones :	D5 – Selection of configurations (August 06) D9 – Constructive drawing (October 2006) M3 – Construction Drawing (October 2006)		
Partner Involved :	**ICOP, MACLYSA, DIMEC, CSIC**		

The objective of this Work Package was to develop the selected modules up to detailed design. A simulation campaign, using "on purpose" virtual models, has been performed in order to asses the target characteristics. All robotic modules has been completely designed, configuration selected and constructive details defined apart from the mobile platform module even if the final configuration has been selected.

2.3.1 Task 3.1 - Development of Virtual Model and Simulation

Computer-aided analysis of the configurations of the climbing robot and automatic feeding system for the drilling unit has been developed. Virtual prototypes were modelled with every necessary detail and functionality, with the aid of state-of-the-art software tools.



a) rope pulling system virtual model b) model of hand

Figure 19: Example of use of virtual modelling and analysis

3D-modeling of mechanisms and structures were exploited by means of a parametric modeller integrated with a FEM package. By virtual testing the critical components and the motion limitations were early identified and the layout specifying the cinematic and static behaviour was properly up-graded. Different solutions were identified, which fulfilled the target specifications in terms of intrinsic reliability, employed material, manufacturing cost&time to different grades and ways.

2.3.2 Task 3.2 - Selection of the Configuration

Using results of activities performed during Task 3.1, different constructive solutions have been comparatively evaluated. By means of simulation tools, it was possible to identify critical components and motion limitations and to optimise the structure concerning the kinematics and static behaviour. The contribution of the end-users partners was giving fundamental suggestions for the discussion and the selection of the definitive configuration of the modules. All systems components have been simulated and final solution selected.

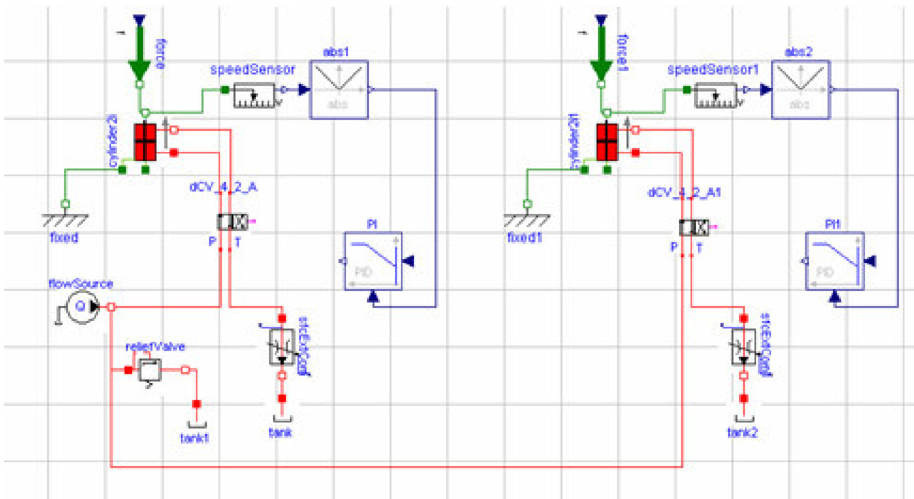


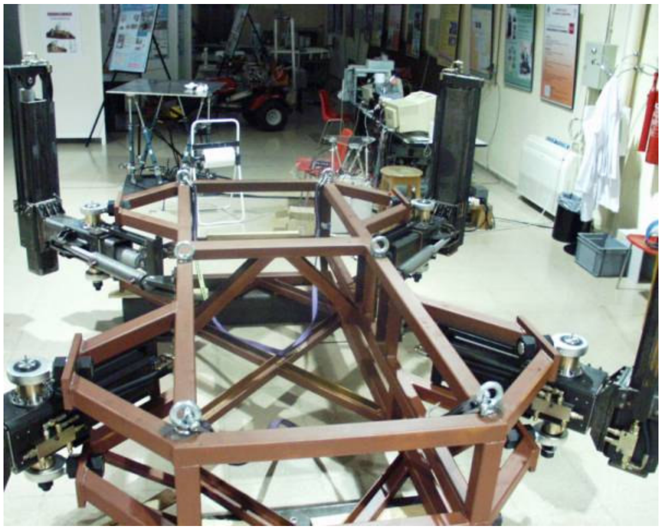
Figure 20: hydraulic circuit simulation

2.3.3 Task 3.3 - Design and Development of the Robotic Modules

Starting from the result of previous simulation, analysis and configuration selection, full constructive details to proceed with the manufacturing of the prototypes started to be developed.

The work has been concentrated on following activities:

- final design of the rope tensioning device taking in account off-the-shelf components in order to minimise development time for the prototype and the overall cost of the system;
- construction of a first prototype of the new rope tensioning device to be laboratory tested;
- construction of a reviewed full-scale prototype of rope tensioning devices to be on-field tested;
- design of constructive details of the rope tensioning device;
- design of a carriage platform able to self-unload the robotic platform and position it on the working area without the need to crane.



a) Frame module development

b) Rod warehouse module development

Figure 21: Development of system modules

DIMEC is the responsible of this WP and developed the virtual models and simulation, involving deeply MACLYSA and COMACCHIO in the design and validation of rope tensioning device and carriage platform. To easy develop the virtual model and exchange data among partners it was decided to use Pro-E software.

During a first phase:

- COMACCHIO defined the design of the drilling unit module and he was deeply involved in the robotic hand and rod warehouse design; COMACCHIO, with the support of ZANNINI and ICOP validated also the full drilling sequences.
- MACLYSA reviewed the design of the main frame module and worked closely with CSIC and DIMEC on simulating the different possible gaits. He was also responsible for the prototyping and integration of the frame with the robotic legs.

During the second project period, DIMEC completed the **Rope Tensioning Device** design taking in account the integration of commercial components in order to speed up the prototyping phase and to minimise the overall costs. DIMEC worked in close collaboration with the other partners, in particular:

- COMACCHIO supported DIMEC into the design of the hydraulic actuators and into the selection of industrial components; COMACCHIO, with the support of ZANNINI and ICOP validated also the full moving sequence of the rope tensioning device.
- MACLYSA reviewed the design of the mechanical design in order to use off-the-shelf parts. He was also responsible for the prototyping of the mechanical parts.

Moreover during this task, DIMEC coordinated the design of an innovative **mobile carriage platform** able to position the SAFERDRILL robotic unit without the need of crane. The idea was that SAFERDRILL robot arrives to the operative area by a trunk but, subsequently, needs a carriage to get off the trunk and reach the rocky face. The designed undercarriage has a size 3775x1800x1500 mm (LxWxH). Its mass is about 2500 kg and it receives the power from a Diesel engine. The carriage is remote-controlled by an operator. When the drilling robot is close to the mountain, it can be moved by means of the Tirfor from the horizontal position to the vertical one. The carriage can be driven as close as possible to the mountain and put in the best place so that the robot climbs the rock. When the two Tirfor work, the robot slants and slides on the carriage, so it can reach the vertical position onto the rocky face (Figure 22). The robot can also use its legs to move onto the carriage and to get the right position to climb the mountain.

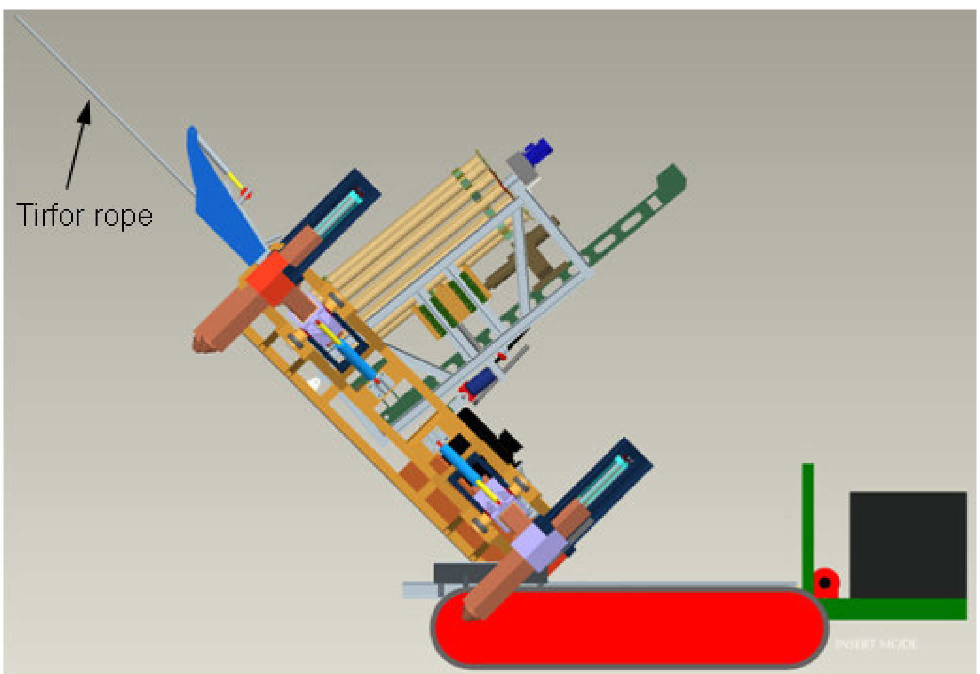


Figure 22: the robot slants and slides on the carriage

During the rising phase on the rock, robot legs don’t work, only the two Tirfor supply the force required to move the robot. When the drilling robot descends from the mountain, instead, there is a combined effort between the Tirfor and the hydraulic winch (Figure 23): while the Tirfors release the rope and make the robot come down, the winch winds the rope and sets the robot onto the carriage.

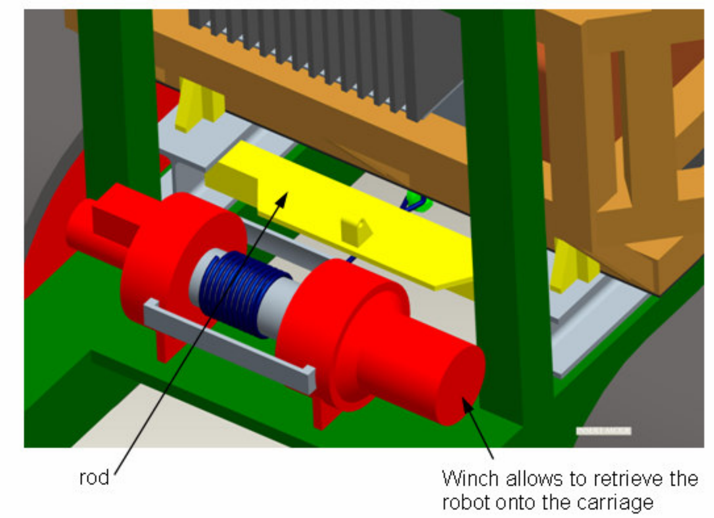


Figure 23: the hydraulic winch

The rod slides in the inner surface of the two HE-120 beams for reasons of space; it allows the rope to be centred in the middle of the carriage during its winding and, therefore, allows the robot to get the right initial position on the carriage.

To minimize the dimensions of the carriage, avoiding the addiction of connection elements between the robot and the carriage, the winch rope is hooked up to the robot. In fact, the hook is direct-coupled with the lower shield of the robot: an anchor ring strengthens the contact zone where the hook is attached. The two HE-120 beams act as rails where the robot slides, and provide the right distance between the undercarriage and the robot frame to avoid the interference between the robot and the crawler tracks. In the outer sides of the two beams there are two sloping plates to improve the robot positioning on the carriage. The winch is hydraulically powered.

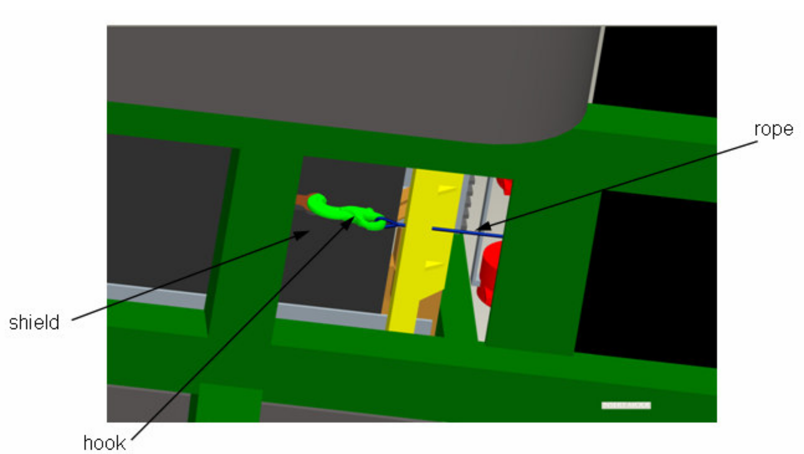


Figure 24: the hook is direct-coupled with the shield

The pulling winch gets its hydraulic power from the Diesel engine of the carriage. It generates a maximum force of 2700 N that is enough to recover (by pulling) the robot on the carriage. Both front and rear fixings are useful during the transport of the robot on a trunk to avoid possible movement of the robot on the carriage. Besides, they are required during the horizontal drilling phase (Figure 25): in this stage the robot legs also work to provide stability to the robot, in fact they are extended and in contact with the ground. Rear fixings are welded on the HE-120 beams and their position corresponds to the end for the rope winding (Figure 26).

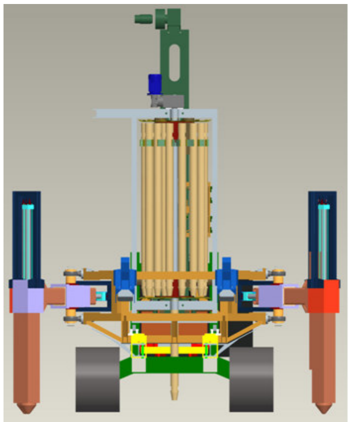


Figure 25: horizontal drilling phase

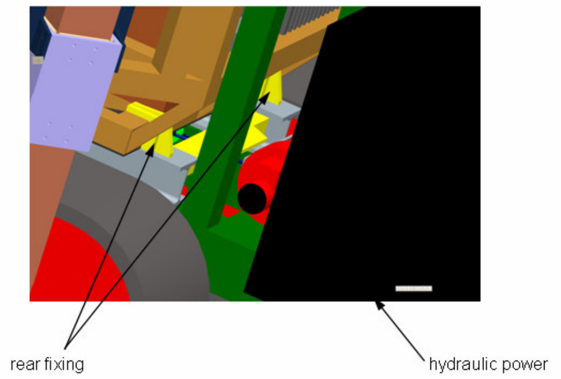


Figure 26: rear fixing layout

Front fixings, instead, are mobile; they slide on the HE beams (Figure 27). They are fixed by means of pins in contact with the robot frame during the operations of transport and horizontal drilling; whereas they are taken away while the robot is approaching to the rocky face (leaving off the carriage). Front fixings, also, are not commercial parts but are realized by welded steel plates. The inner section have the same dimensions of the HE beam in order to permit the sliding between the two elements. They held up a Von Mises stress of 112 MPa and a maximum displacement of 0.2 mm, when the carriage is lifted on as for the rear fixing case.

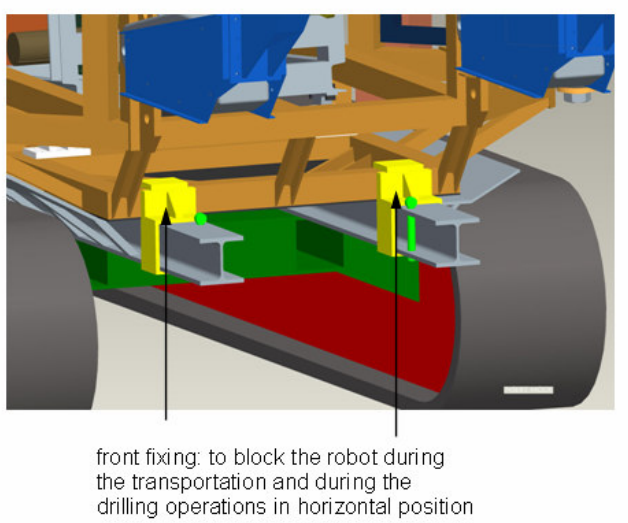


Figure 27: Front Fixing

DIMEC worked in close collaboration with the other partners, in particular:

- COMACCHIO supported DIMEC into the design of the hydraulic actuators and selected the industrial components;

- ZANNINI and ICOP validated the working sequence;
- MACLYSA collaborate into the mechanical design;
- DAPP verify the integration of this module with the other SAFERDRILL components.

2.4 WP4 Design and development control system

Starting Date :	**Month 5**	Date of end :	**Month 26**
Related Deliverable/Milestones :	D4 – Report on control architecture (April 06) D11 – Visual navigation system (September 07) D12 – Prototype of knowledge based system (October 07) D13 – Control system and HMI prototype (October 07)		
Partner Involved :	**SAS, IMC, COMACCHIO, ZANNINI, MACLYS, DAPP, DIMEC, CSIC**		

Objective of this Work Package was the design and the realisation of four modules:

- the complete Remote Control Unit;
- the Human-Machine Interface (HMI);
- the Navigation System;
- the Knowledge Based System.

By the end of the first year of the project, all four modules have been designed and initial prototypes of the remote system and HMI were available. During the second project period, these initial prototypes have been modified and adapted to implement the modification decided after each laboratory or on field tests and all four modules have been consequently re-designed and final configuration decided. The consortium decided to give priority on the prototyping of the remote system and the HMI modules because they are essential for any tests. For this reason these two systems have been released in a first version to allow preliminary tests in July (see WP5 and WP6).

2.4.1 Task 4.1 – Distributed Control and Architecture & Task 4.4 – Control System and HMI

A first phase of study of the required features and architecture of the control system has been done. In fact it was important to understand the control architectures needed to menage the climbing system from a HMI unit and how to integrate the data coming from the navigation system and geotechnical knowledge based system before proceeding to the development phase.

As the Control System and Human Machine Interface modules are the core of any robotic system, most of the partners provided input to this WP as explained below:

- CSIC defined the overall architecture of the distributed control system on the system, designed and developed the electronic cards, selected and implemented sensors and actuators, cables and connections; studied and implemented the gait strategies; developed the software running on the on-board and supervised all activities of the WP;

- SAS defined and implemented the wireless connectivity and exchange protocol among the different modules; defined the architecture of the signal manager developing and implementing the Data Conversion and Processing component and of the HMI Control Board; defined, developed and implemented the video streaming channel;
- DAPP worked extensively in the definition of the system architecture taking in account both the usability of the system and the operations to be executed by the system. DAPP extensively contributed in the overall design the HMI architecture; manufactured the HMI hardware and contributed to define the software modules;
- IMC defined the industrial requirements of the control system, selected the industrial components as connectors, cable, electronics boards, contributed in the definition of the overall architecture, and provided support in the HMI definition and development.
- DIMEC contributed in the definition of the close loop control of hydraulic actuators of the four legs and drilling components.

The robot is based on a mechanical structure, having a total weight of over 2500 kg and able to work in a remote harsh environment. For these reasons hydraulic powered cylinders have been selected rather than electrical motors to actuate the robot. The main advantages of the hydraulic servo-actuators are the capability to transmit movements to high payloads, and the ability to be controlled with different types of feedbacks like pressure, flow, position and/or force sensors. Finally, because this application does not need high velocity, actuators can move slowly and provide soft movements; this property can be very useful in the gait generation where the synchronisation of the different actuators is critical.

The machine has to work both walking on horizontal uneven terrain and climbing on extremely inclined walls. Each of the four legs has 3 DOF, one rotational and two prismatic joints. Each joint is controlled in speed and in position. A regular encoder measures the angle of the leg respect the axis in case of rotational joints. A linear encoder is used as position transducer for prismatic joint.

Gait strategy

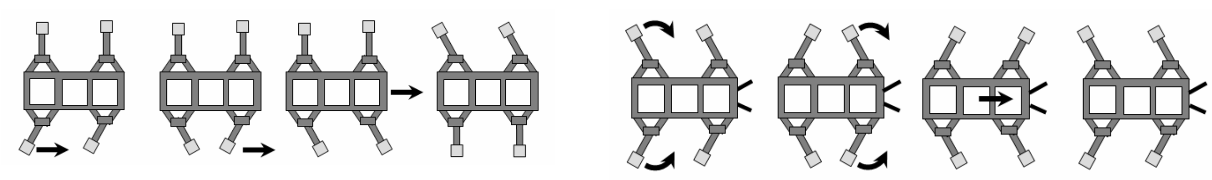
Walking and climbing strategies for several environments and working conditions have been the subject of previous investigations by many authors. In particular, climbing strategies have been developed in order to be able to climb on slopes lower than 30º (Hirose, 1997; Nagakubo, 1994). Because of safety and practical reasons SAFERDRILL has to be hold by steel ropes and helped to be pulled up from the top of the mountain to cope with slopes ranging from 30º to almost 90º. It was then necessary to develop climbing strategies that combine gait generation with the coordination of the required pull up power, so that it can be easily controlled by an operator located in a remote place.

In follow the chosen solution for the gait control is explained.

Proportional valves control the fluid direction and flow from a hydraulic power supply to actuation devices according to the requirements of the system. In this case, a double-acting cylinder allows the hydraulic force to be applied in both directions. The velocity and the position of the actuator are monitored to close the control loop. The control unit controls a power drive unit that generates a Pulse Width Modulation (PWM) signal for the position of the aperture of flow in the proportional valve on the desired direction of the cylinder. When simultaneous movements of the legs joints are made, the control loop must be closed by a velocity feedback, waiting the computed time that each joint need to reach a calculated position.

Predefined gaits are programmed on the control unit. These gaits are enough complex to position and maintain the robot in a position parallel to the surface, flat or a sloped terrain, in order to guaranty always the stability and safety of the machine.

The climbing and walking gaits are different: for the walking process a two face discontinuous gait is applied and for the climbing process a one phase discontinuous gait is generated. The control system is designed to generate the coordination of the joints to move the robot from the kinematics.



a) Walking gait movements (half cycle). b) Climbing gait movements

Figure 28: Gait definition

Control Architecture

The general control architecture (Figure 29) is distributed on the robotic platform and on the HMI unit. The end-user can full control the robotic platform from a secure remote location using the wireless connection between the HMI unit and the on-board single control unit. The HMI unit has been designed to be light and easily carried because the end-user should be able to move around the working area. The HMI unit is powered by a group of batteries into a rucksack while the HMI unit is carried over user's shoulder. The user can control all operations using an 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. Integrated into the tablet PC where is the Wi-Fi antenna for the wireless connection with the robotic unit.

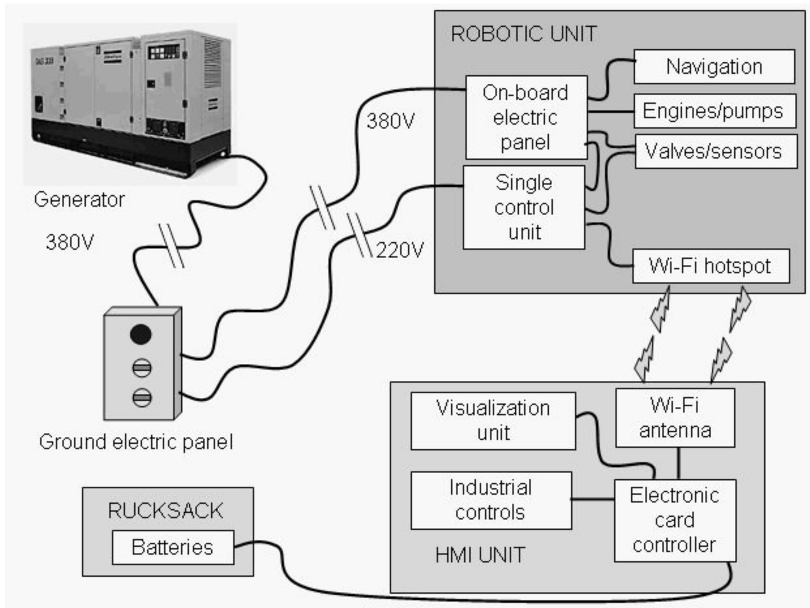


Figure 29: General Control Architecture

On-board Control Unit

The on-board control unit and the linked Wi-Fi hotspot are powered directly from the ground by a dedicated 220 V connection. The control unit is responsible to start/stop all engines and pumps, to control the hydraulic valves, to read the signal from the sensors and the video signal from the navigation system. Finally, being powered on a dedicated line, the PC controller can shutdown the output lines of the on-board electric panel in case of emergency stop without loosing the wireless connection with the remote HMI unit. The single control unit is composed by a CPU, control cards, data acquisition cards, electric power supplies and power conversion. QNX 6.2 real-time based operation system is used to make the reading and the data processing of all sensors information and controlling the different actuators in real time. The use of many sensors and the coordination of all actions in real-time is necessary for generating the right gait and for the control of the working tools. So the control system has to process information from the sensors in order to maintain the system in the correct position and attitude while performing drilling and consolidating work.

The main control systems are based on a control card designed by the CSIC (Figure 30). This card implements a Proportional Integral Differential (PID) with position feedback and with Pulse Width Modulation (PWM). The PWM output is transformed into an analogical signal of ±10 Volts necessary to control the hydraulic power units. This kind of electronic cards have the advantage that with only one command the system is able to control various actuators simultaneously and with autonomy; this properties reduces significantly computational power. These cards also allow the implementation of digital and analogical inputs and outputs as needed to control sensors and external devices.

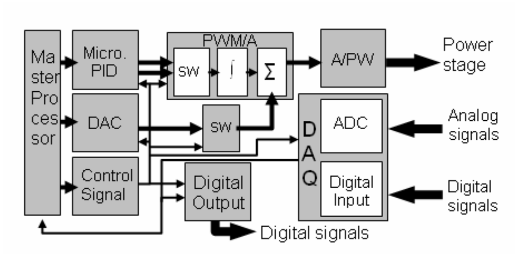


Figure 30: Control card design

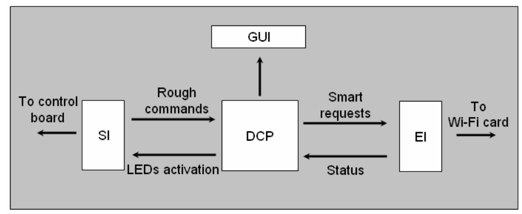


Figure 31: Signal manager architecture

Signal Management

The signal management processes the rough commands received from the HMI controls board in order to generate smart requests for the robot on the other side it processes the robot status in order to provide relevant information for the operator. The architecture of the signal manager (Figure 31) is composed by a Serial Interface (SI) for communication with the industrial controls board, an Ethernet Interface (EI) for communication with the robot, a Data Conversion and Processing (DCP) component which is the heart of the signal manager, and a Graphical User Interface (GUI) which displays monitored data and relevant error messages.

The DCP is shared in two parts: the requests processing (from the controls board toward the robot), and the status processing (from the robot to the GUI and the Industrial controls board). Both are based on a "conditions and events" scheme. Indeed, requests and status are linked to “triggers”, defined in terms of the following elements:

- A set of pre-conditions: when all the pre-conditions are satisfied, the trigger is enabled;
- A set of triggering events: if at least one of the events occurs AND the pre-conditions are satisfied, then the effect is triggered;
- A single effect: this trigger type is enabled simply by command activation or error message production.

This generic approach provides a convenient way to "connect" conditions and events (position of the controls on the controls board, robot state...) with given effects. Through the GUI, the operator can easily modify the connections between the controls board and the actual robot commands. In the same manner, the status generated by the robot are linked to effect such as illuminating LEDs onto the controls board, or producing error messages, and can be changed as well according to the needs. This approach makes the signal manager highly flexible regarding future updates or modification of the robot's commands and status.

Human Machine Interface Control Board

The HMI control board (Figure 32) is the interface between the industrial control panel, made of buttons, witches, joysticks, and the signal manager. After a preliminary analysis of the possible solutions, a single micro with 1kbit EEPROM and 8kbit Flash Memory has been selected and it is connected trough a I^4C bus to 7 general purpose port expanders, each of them with 16 channels that can be programmed as input or output lines. 32 channels are used as digital output at 5Vdc 30mA for the LEDs indicating the position of components on the robotic platform or the status of the commands. 80 channels are used as digital input low-side for buttons and witches. Two analogical inputs are directly connected to the micro. These lines are used to read the signal from 2 joysticks controlling the head rotation and head translation of the drilling unit. A fine control of these two parameters is critical during the drilling operation as described in Figure 32.

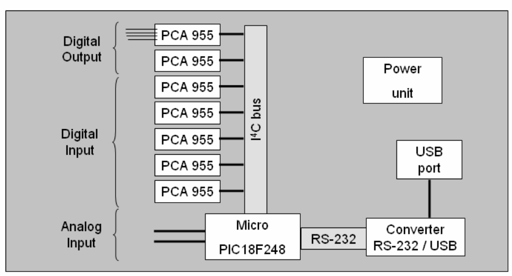


Figure 32: HMI control board architecture

During the second year activities, a tests campaign was performed both with laboratory and on field testes. The results achieved by the testes were analysed and permitted to improve the control system and the HMI. It is difficult to describe all the modifications introduced on the control system and HMI during the second project year. In the following a short list of the improvements is reported.

Related to the hardware, some changes on the relais controlling the ON-OFF electrovalves have been done. A snubber circuit has been introduced in order to reduce extra-current generated at the opening / closure of the relais. Also the electronic board has been improved: the control of the hand has been changed to avoid over-heating of the electronic system. Thanks to this new electronic board it is also possible to control the timing of the switches. Same tests to check on-board control unit under vibration or shock stresses have been done: the hard-disk running the on-board control SW has been consequently changed with a compact flash to prevent failure. Also the electronic boards responsible for the upper and lower clamp have been changed. Moreover the wires of the encoders into the legs have been recabled.

Figure 33: Compact flash running the on-board control SW

Also some software modifications have been implemented: the control logic of the electrovalves has been modified to avoid over-heating. To obtain the exact timing of the warehouse rotation an integration of an additional control signal into HOLD macro has been developed. Also the communication protocol has been changed to reduce the signal noise. A new set of command to control each Tirfor during the execution of the STEP macro has been introduced while the macro INIZIALISATION has been changed to avoid failure when only two legs are touching the ground.

The contribution of the partners involved was:

- CSIC completed and continuously update the control SW running on the on-board control unit according to the improvement and modification requested; improvement of cabling and connections of system to increase overall system robustness;
- SAS completed and continuously update the control SW running on the HMI control unit according to the improvement and modification requested;
- DAPP covered different aspect as :
    - The selection and the installation of a network of distributed sensors to monitors actuators and platform operations;
    - The update of the layout and hardware components of the HMI to take in account the need of additional commands and control;
    - The upgrade of the several components of on-board control unit to replace faulty components, to increase reliability and robustness of the control system;
    - The definition of the new specification;

  - The work coordination among the different partners;
- IMC contributed in the selection of industrial components to be integrated into the control system and provided support in the HMI definition and development;
- ZANNINI, with the support of ICOP, performed the testes and was responsible to review the control unit specifications and to propose improvement on the system.

2.4.2 Task 4.2 - Navigation System

Scope of the visual navigation system is to help and alert the operator about obstacles in front of the robotic platform. The navigation and 3D generation system has been designed and developed based on a stereo-camera and on a processing software able to calculate in real-time the morphology of the slope. During the second project year, a full scale prototype of the navigation system was developed and tested at laboratory scale also in out-door environment. The Navigation system was not integrated into the robotic platform because it was designed to be used also as a stand-alone system.

The developed Navigation system is composed by stereo bench containing a pair of cameras, a FireWire cable, a mini-ITX PC used as a server for pictures acquisition and a client laptop used for pictures processing and visualization. All these components have been fully designed and implemented as a prototype.

Camera

The most important part of a stereo-head system consists on the cameras to be used. IEEE1394 (FireWire) cameras has been chosen because of their standard interface. As the camera bench has mounted on the mobile robotic platform, the cameras experience quite some stress from vibration both during platform moving and drilling. For this reason small cameras with fixed, small lenses have been chosen. The UniBrain Fire-i™ Digital Camera for the stereo-head has been then selected. This camera has the following main characteristics:

- Digital IEEE1394 camera
- NTSC resolution (640x480)
- Color camera (via Bayer pattern)
- Fixed focal length of 4.65mm with a fixed lens
- Pixel size of 5.6µm
- This boils down to a horizontal opening angle of 42° (according to the spec sheet)

- A calibration procedure of two Fire-i cameras produced an opening angle of 40°, the difference due to a larger focal length (4.9mm), coming from focusing the lens.

a) camera in its plastic casing b) camera without plastic casing

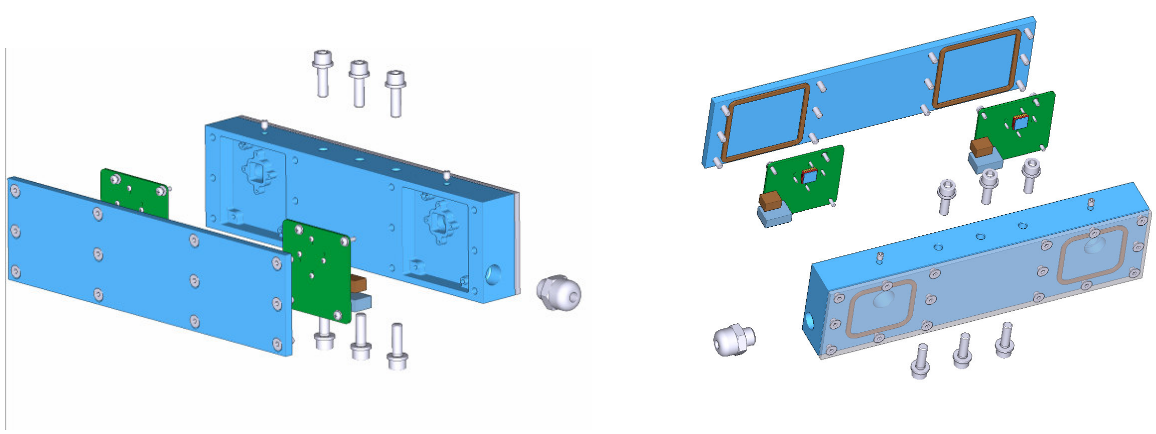
Figure 34: **Main UniBrain Fire-i™ Digital Camera**

The camera-board contains a CDD With fixed lens, an IEEE1394 interface and a power supply interface. The camera can draw power from the IEEE1394 interface, in which case the power supply interface is not used. The lenses provide focusing from 5mm to infinite.

Stereo-Head System

Since the camera system experiences vibration stress from the drilling platform, the stereo-head has been designed in a very sturdy way and an aluminium case holding. The housing is waterproofed with elastic sealing rings. Lenses are fixed with screws in order to prevent them from shifting due to vibration. The lenses are covered by a removable and renewable polycarbonate protection plate for protection against drilling dust and water.

Two FireWire cables of maximum 4.5m leaves the housing through watertight screw-seals.



a) view from the back b) view from the front

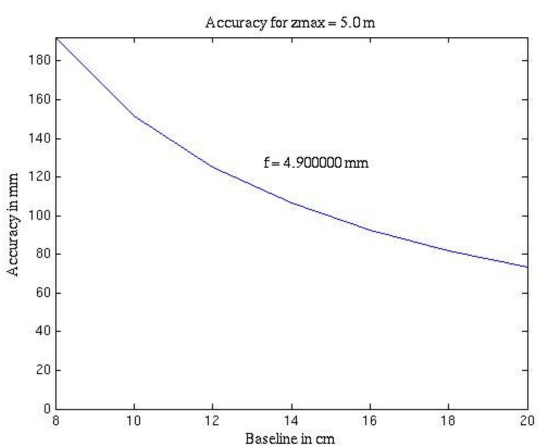
Figure 35: **Model of the stereo bench**

Vision

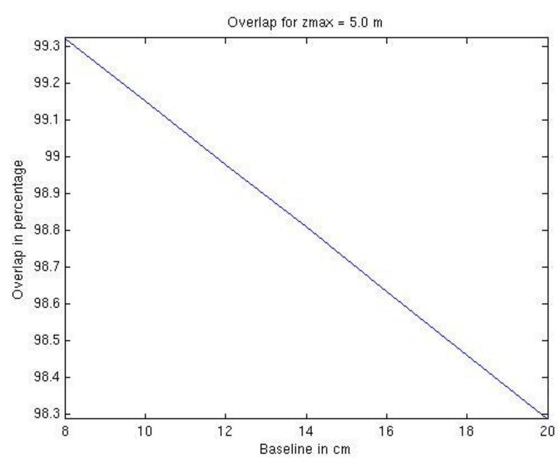
From a preliminary study on the stereo-head system the following degrees of freedom has been identified:

- The baseline between the two cameras; the baseline is the distance between the two cameras. The large distance means accurate depth computations, but also the small overlap between the two cameras. Moreover, larger baselines mean larger stereo-heads which are less sturdy, more susceptible to the vibration of the platform and heavier;
- The working distance; the working distance is the distance between the scene and the cameras. The large distance means small accuracy;
- The angle between the optical axes of the cameras.

The working distance can be changed but during the design it has been decided to have a fixed working distance of 5 meters to have a balance between accuracy and vision space. Figure 36a shows the theoretical accuracy for a depth of 5m. This accuracy is measured in the worst direction, i.e. the direction perpendicular to the stereo-head baseline. All other directions accuracy is better. Figure 36b shows the theoretical overlap between the two cameras.



a) Accuracy of depth estimation for different baselines



b) Overlap between two parallel cameras for different baselines

Figure 36: Optical properties of the stereo cameras bench

The overlap clearly doesn't change much for the different baselines. This is due to the large distance, equal to 5 m respect to the different baselines and to the large opening angle of 40°. From these curves, a baseline of 15 cm between the two cameras has been selected.

Figure 37: The Mini-ITX PC used as Server for Pictures Acquisition

Figure 38: Stereo image of SAFERDRILL robotic platform taken by the stereo-bench

SAS and DAPP collaborated closely to develop the hardware and software components and to perform the tests over the system.

2.4.3 Task 4.3 – Geotechnical Knowledge Based System

Scope of the Knowledge Base System is the continuous monitoring of drilling parameters to give a qualitative interpretation of soil formation changes while holes are being drilled and to provides real-time information that can be used to warn the remote operator about possible criticisms during drilling (for example void and soil discontinuity).

During the first reporting period the system specifications have been fully defined including the type of sensors and data to be processes; commercial sensors have been analysed; geotechnical parameters analysis has been performed and basic algorisms proposed; the requirements for the database and the user interface have been defined.

System Specification

Typical problems, which could arise while drilling over slopes, are to find discontinuities in the rock mass (filled with soil or debris or empty) or the presence of water or other accidents. Frequently these situations result in borehole occlusion with different degrees of severity.

The main critical conditions occurring during the drilling can be classified as:

- presence of voids/discontinuities;
- loss of air circulation;
- presence of water;
- blocking/sticking of bit;
- discontinuity.

These conditions are often inter-related. For these reason the system provides to the operator the values in real-time of several drilling parameters and generates alert messages when a critical or abnormal situation will be recognised. The drilling parameters are saved also in a database to be analysed off-line and to provide geotechnical information regarding soil stratification. Knowing the drilling direction in the 3 axis and the position of the robotic unit on the wall, a 3D map of the collected parameters could be generated to allow an easy interpretation of the geotechnical data.

Drilling Parameters & Analysis

There are six drilling parameters that can be recorded during an instrumented borehole drilling. Each of these drilling parameters has certain obvious correlations with soil characteristics. For example, if other parameters remained unchanged while the drilling speed increases, it indicates that a looser or softer material is being encountered.

The system is able to display in real time all the most important drilling parameters as

1. **Torque –** It is measured on the drilling head, applied to the drilling rod, and transmitted to the drilling bit, while aiming to keep a constant rotation speed. It is closely related to the nature of the formation being drilled, for example, gravel gives scattered torque values and clay gives smooth and sometimes high torque values.
2. **Down-thrust** – This is the main parameter that affects the drilling speed because for a given soil formation the drilling speed is roughly proportional to the down-thrust. Hence, to obtain information directly from the drilling speed it is recommended that the down-thrust be kept as constant as possible during the drilling process.

3. **Air pressure and air flow rate** – Air is pumped to the base of a borehole through the drilling rod and drilling bit in order to generate the percussion of the hammer and clean the hole from dust. Normally, a compressor is used to provide a relatively constant air flow into the borehole at constant pressure (12 bar). Clayey ground tends to block the bit and raise the air-pressure.

4. **Drilling speed** – It is closely related to the 'hardness' of the strata being drilled when the down-thrust is kept reasonably constant. For example, fracture zones, voids and sand pockets produce a relatively fast drilling speed while hard and compact formations produce a lower value.

5. **Rotation speed** – It is normally chosen to suite the drilling conditions, taking into account the type of drilling rig, and the wear and tear of the bit. A reasonably constant value of rotation speed should be used throughout the drilling process in order to obtain more meaningful information from the drilling speed and torque measurement.

6. **Time** – This is the time required to drill 5 mm of soil because the logging system is configured to record the drilling data at every 5mm of drilling. It is the reciprocal of the drilling speed and because of this reciprocation; it can be used as a "magnifying glass" when the drilling speed is very low (close to zero).

The accuracy and location of each instrument installed on a drilling machine are shown in Table 2.

Parameters	**Instrumentation**	**Accuracy**	**Locations**
Air Pressure	35 bars transducer	±3 %	As near as possible to the compressor to avoid fluid pressure losses.
Torque	250 bars transducer	±3 %	As near as possible to the rotation head to avoid head losses and possible interference with hydraulic fittings (valves).
Down-thrust	250 bars transducer	3 %	As near as possible to hydraulic cylinder to avoid head losses and possible interference with hydraulic fittings.
Depth, Drilling Speed, Time to drill 5 mm	Movement transmitter sensor and internal clock	±3 %	Fixed at the top of the drilling mast and connected to the rotation head by a rope (or a wire). It transmits continuously the head position as well as the feed speed at any time.
Rotation Speed	Electromagnetic proximity sensor	±3 %	Located on the gear of the rotation head
Direction of drilling	Magnetic compass	±3 %	Located on the mast of the drilling unit

Table 2: Sensor optimal location

SAFERDRILL can detect ground fractures by the recorded drilling parameters. Using individual hole measurements, fractures may be identified by observing a sudden increase in rate of penetration and/or sudden decrease in water/mud pressure as well as an increase in water inflow and an associated decrease in return flow. Nevertheless, variations in the drilling parameters are interpreted to indicate the presence of fractures, changes in litology, and competency of the bedrock. In fact drilling parameters are also directly joined with lithological characteristics of soil.

Starting from literature review and using the experience of ICOP and ZANNINI in drilling, the expected trend of drilling rate has been defined, such as thrust and torque for massive rock, fractured rock and cavities without filling.

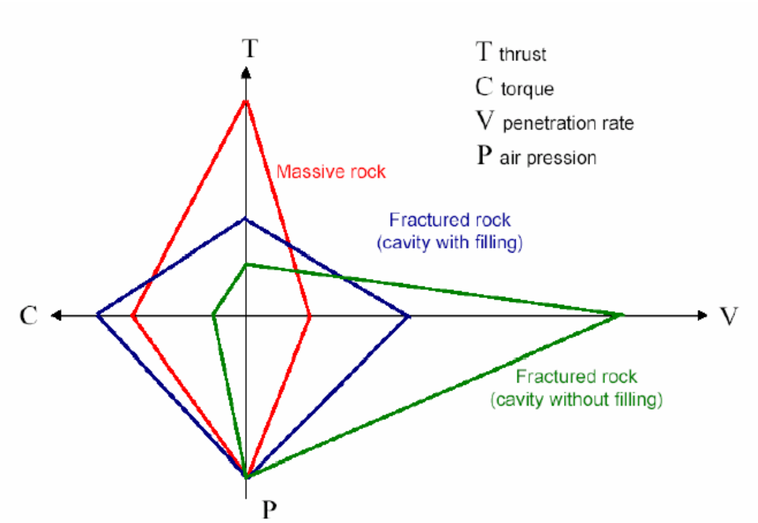


Figure 39: Expected trend of drilling rate, torque and thrust

These trends are used to define the algorithm used to define the working condition and to individuate the abnormal or potentially critical condition.

Situation	Presence of voids and cavities	Stacking of drill bit or rods
Drilling parameters with abnormal decrease in value	- thrust, - torque;	- advanced speed, - rotation speed, - air flow
Drilling parameter with abnormal increase in value	- advanced speed, - rotation speed.	- thrust, - torque.

Table 3: Example of trends in the drilling parameters to be monitored

Drilling parameters are collected using a distributed network of sensors installed on the SAFERDRILL prototype. Data collected by the sensors are sent, via the Wi-Fi network, to the HMI.

The system can be used for On-Line analysis or for Off-Line analysis.

When on line mode is selected, the sensors data are processed on real time and show to the operator using a easy-to-understand interface. The alarm situations, as void and discontinuations, are calculated on background. The calculation is based on deviation of the data values in comparison to the last value and the previous value. Once the danger situation has been detected, the text message informing the user occurs.

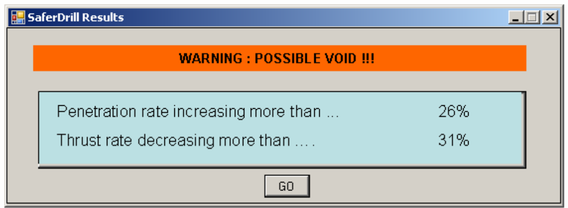


Figure 40: Alarm window for possible void situation

Recorded data can be used off-line to develop a geotechnical knowledge database to perform stratographic and orphological analysis of the drilled area. For each drilled hole, all parameters are recorded and can be shown against drilling depth or time.

To test the Geotechnical Knowledge system, a real-drilling test has been performed on 29 March 2007 in Fella (IT). Other several testes are performed to fully validate the system. For example an artificial void situation has been produced putting a rock against an existing wall (Figure 41).

Figure 41: Void situation artificially generated during a test

During the test, real-time alarms where generated and off-line analysis confirmed that the Geotechnical system was able to recognize the void situation (Figure 42)

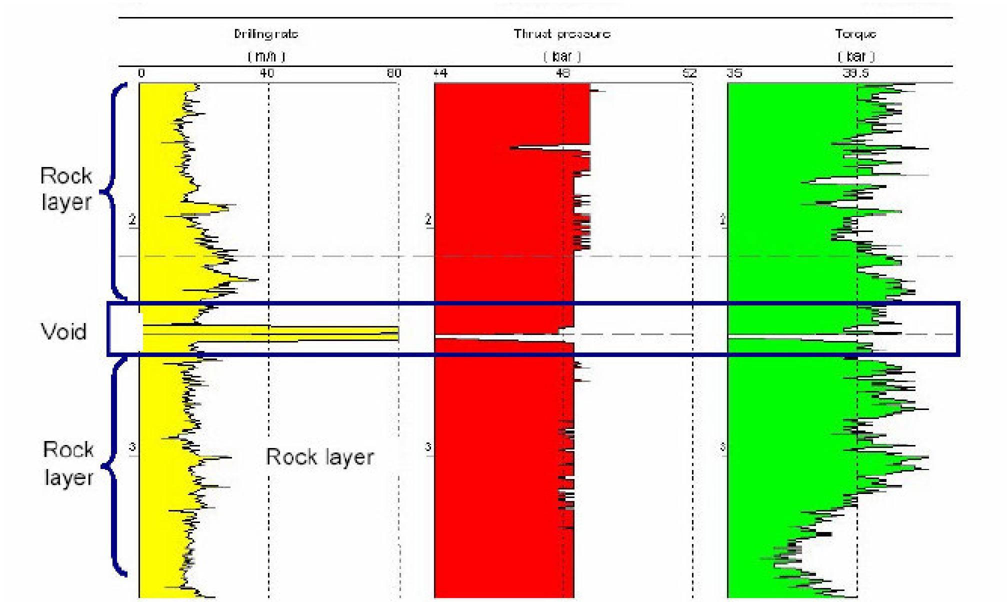


Figure 42: Void situation off-line analysis

DAPP developed the system with the collaboration of other partners, in particular:

- IMC contributed on the design, development and testing of the software;
- COMACCHIO supported DAPP into the selection of the sensors for the collection of drilling data;
- ZANNINI contributed in the review of the software and the validation of the system.

2.5 WP5 System integration

Starting Date :	**Month 11**	Date of End :	**Month 26**
Related Deliverable/Milestones :	D10 – Preliminary Prototype Components (November 06) D14 – Full scale demonstrator (October 07) M5 – Full Scale Demonstrator (October 07)		
Partner Involved :	**SAS, IMC, COMACCHIO, ZANNINI, MACLYSA, DAPP, DIMEC**		

Objective of this Work Package was to integrate the overall system, in particular the climbing structure, the on-board drilling module, the navigation system, the geotechnical knowledge base system and the remote control system, including the drilling monitoring system

In the first reporting period, the activities under this WP are head of schedule because the first version of the full scale demonstrator of drilling module, legged robotic platform, control system and human machine interface are already been developed and integrated.

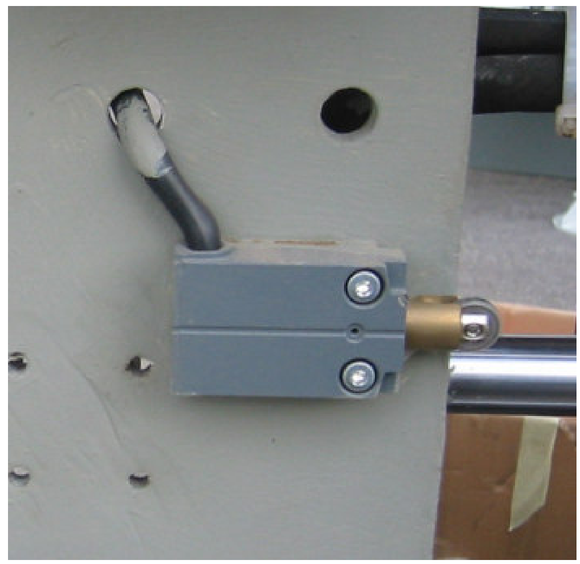
Figure 43: Integration of drilling module, legged platform and control system

The integration demonstrated the importance of a detail design of the component, the use of virtual modelling and simulation to fully define the interfaces and detect at design stage any possible problems.

During the integration special attention was put on the modular aspects. For example all hydraulic to manage the drilling is on-board of this module. So it is possible to remove the full drilling component in a very "easy" way. Also the legged platform was designed and built taking in account of modularity: the four legs are identical and most of their components are modular.

During manufacturing and integration the consortium put special and continuous attention on the durability and robustness of each single components. This aspect is very important because of the severe conditions of use of the system (vibration, dust, shocks, etc..) and the difficulty to mix any possible failure or breakdown during on-field tests.

a) MIL-spec connectors



b) Water-proof and dust-proof switch

Figure 44: Example of robust components used in the prototype

In the second reporting period, the first performed tests showed that the system demonstrated that some system components need a re-design and re-integration.

To better integrate the movement of the legs with the Tirfort, two digital strain-gauge has been integrated on the join between then SAFERDRILL platform and the Tirfort (Figure 45). A set of new feet have been designed and installed to improve the reliability of the leg's ground contact signal and to improve the mechanical performances (Figure 46). Additional shields to protect the robotic legs and the front of the platform has been added (Figure 47) and all hydraulic pipes have been further protected with a plastic sheath (Figure 48). A new ultra-fine filter for the oil to the two Tirfort has been installed to avoid that their block as during some tests. Many other work have been performed to improve the integration of the components also on the SW side.

Figure 45: integration of digital strain-gauge

Figure 46: new foot for the robotic legs

Figure 47: additional shield to protect the legs

Figure 48: protective shealth

Beside these activities, on the second reporting period have been performed several activities to integrate the different components of the remaining sub-systems, as the rope tensioning device and the geotechnical knowledge system, before in a full scale prototype and then in the SAFERDRILL platform.

Activities have been lead by DAPP with the constant support of the SMEs:

- ICOP provided support both hosting the SAFERDRILL platform on its workshop then providing components and parts;
- COMACCHIO provided support both hosting the SAFERDRILL platform on its workshop, then manufacturing and integrating custom components;
- ZANNINI, performed the laboratories testes and oversaw the integration activities both in ICOP and COMACCHIO workshops;
- MACLYSA oversaw the design of the mechanical parts.

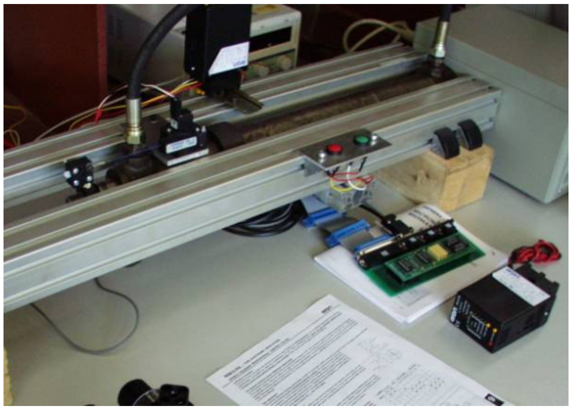
2.6 WP6 System performance evaluation

Starting Date :	**Month 11**	Date of End:	**Month 28**
Related Deliverable/Milestones :	D16 – System performance demonstration (December 07) M4 - Validation of Laboratories Prototypes (March 07) M6 – Prototype System Evaluation (November 07)		
Partner Involved :	**ICOP, SAS, IMC, COMACCHIO, ZANNINI, MACLYSA, DAPP, DIMEC, CSIC**		

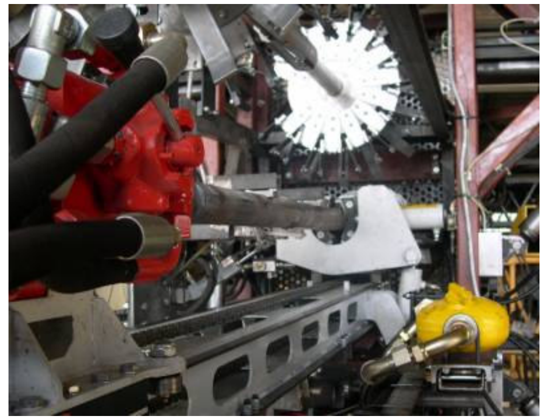
Objective of this Work Package is to proceed to the trials on the assembled climbing system and to evaluate its performance in comparison with the requirements defined in WP1.

During the first reporting period, laboratory tests have been performed during the component manufacturing and assembly to test each element before final integration. Figure 49 summarises same of laboratory tests performed:

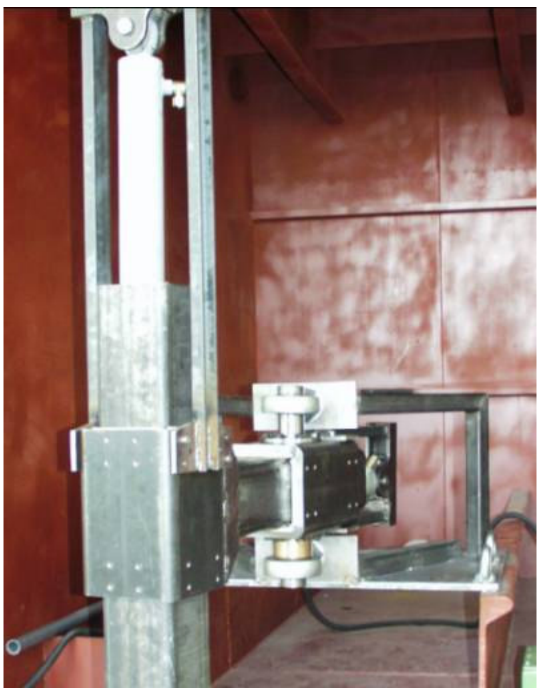
a) laboratory test setup by IMC at CSIC to test hydraulics cylinders and related electronics;
b) laboratory tests performed by ZANNINI and ICOP on drilling module construction;
c) laboratory tests performed by MACLYSA on the robotic legs before assembly;
d) laboratory tests performed on the HMI by DAPP and SAS.



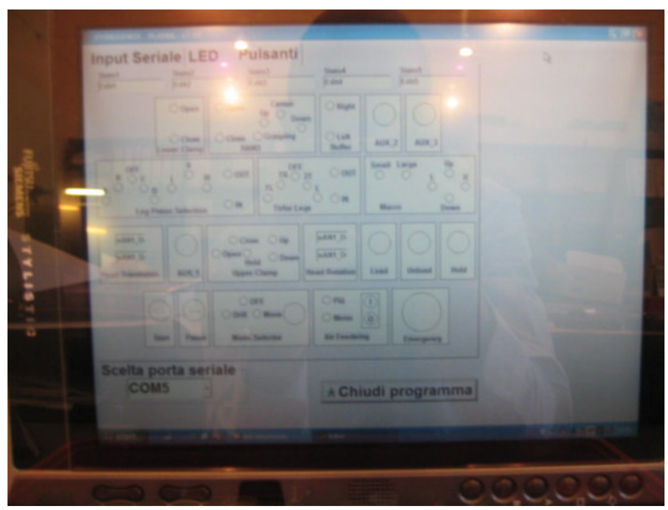
a) Test of hydraulic components



b) Test on drilling module



c) Test on robotics legs



d) Test on HMI

Figure 49: Laboratory Tests

Due the overall dimension and the weight of demonstrator the organization of the on-field trials is complex. For this reason the first on-field test have been performed inside CSIC campus in Madrid. These tests have been used to validate the integration of the different components. A standard pair of Tirfor has been used for these tests because the new rope host devices are still under development. However it was possible the test different gaits of the mobile platforms, sensors data flow, overall distributed control system

A first integration of the major modules (drilling, mobile platform, control and HMI) was performed at the end of the first reporting period (July 2006) but the first tests highlighted that further work was needed to have a fully working and stable system. On September 2006 the first integrated platform was transported from MACLYSA headquarters (Spain) to Italy at COMACCHIO headquarter (Riese Pio X). During the second reporting period the platform, weighting more than 4000 Kg, has been transported in different locations in Italy both for laboratory than on-field tests. Laboratory and outdoor tests of the integrated platform lasted always several days because of the complexity of the setup of the test environment, the need of support equipment (electric generator, air compressor, etc..). Also the laboratories and outdoor test of the Rope Tensioning Devices needs special equipment and structure. For these reason they have been performed mainly in Genova, at DIMEC location and in ICOP.

Table 3: List of principal tests and trails performed

Date	Location	Test type	Description of the testes
25-29/06/06	MACLYSA	LABORAT.	First tests on the integrated system. Fixed problem on actuation for 2 legs and setup of communication wireless network.
24-27/07/06	ARGADA (ES)	ON-FIELD	First on-field tests over a 40° slope on soft ground. Tested coordination of legs/Tirfort. Hydraulic pipe leakage and false contact on the legs.
30/01/07 - 02/02/07	COMACCHIO	LABORAT.	Improvement of mechanical protections . New sensor for the ground contact of the feet. Testes on the movements and change of the speed of legs/Tirfort to get the right setting. Check of the anchor point location of the Tirfort to improve overall stability.
08-16/02/07	PRIMOLANO (IT)	ON-FIELD	Check of the control macro. Failure of the Wi-Fi hub. Problem on the down movement due to bad coordination legs/Tirfort. No lateral step. Error on Hold macro.
12-16/03/07	ICOP	LABORAT.	Replacement of feet. Check on the overall wires. Problem on the solenoid of some electro-valves. Upper scamp command unstable. Replacement of hard-disk with compact flash.
26/03/07 – 04/04/07	FELLA (IT)	ON-FIELD	Test of new compact flash. Check on the solenoids powering. Test on the drilling unit: need of two working pressure of oil between drilling and moving.
08-18/05/07	COMACCHIO	LABORAT.	New ultra-fine oil filter for Tirfor. Update of QNX operative system. Modification loading/unloading rods.
20-23/06/07	ICOP	LABORAT.	Integration test of new rope tensioning device. Skidding of the rope under heavy loads.
15-20/07/07	FELLA (IT)	ON-FIELD	Test on the geotechnical knowledge based system.
17-19/07/07	ICOP	LABORAT	Navigation system tests..
15-28/09/07	DIMEC	LABORAT.	Final test on improved rope tensioning device
23-27/11/07	ORVIETO 1	ON-FIELD	Test on lateral steps. Problem on the legs movement. Failure of encoders.

Details regarding test and trails could be found in D16 “System Performance demonstration”.

25-29/06/06
laboratory tests at MACLYSA

24-27/07/06
On-field trails at CSIC

30/01/07 – 02/02/07
Laboratory tests at COMACCHIO

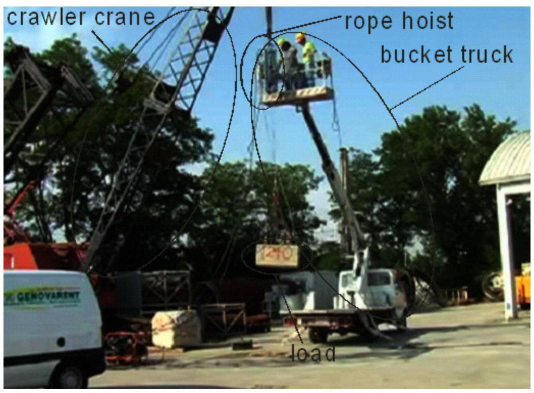
08-18/02/07
On-field tests at Primolano

12-16/03/07
Laboratory tests at ICOP

26/03/07 – 04/04/07
On-field tests at Fella

08-18/05/07
Laboratory test at COMACCHIO

15-20/07/07
On-Field tests at Fella



20-23/06/07
Outdoor test at ICOP

17-19/07/07
Outdoor test at ICOP

15-28/09/07
Outdoor test at DIMEC

23-27/11/07
On-field tests at Orvieto

Figure 50: Picture of laboratory and on-field trials

2.7 WP7 Innovation related activities

Starting Date :	**Month 1** Date of End: **Month 28**
Related Deliverable/Milestones :	D6 – Draft plan for using and disseminating Knowledge (August 06) D8 – Short no-confidential Summary (August 06) D15 – Public presentation of project result (June 07) D17 – International patent application (December 07) D18 – Plan for using and disseminating knowledge (December 07) D20 – Presentation of project results to an Inter. Fair (December 07) M7 - Patent of the system (December 07)
Partner Involved :	**ICOP, SAS, COMACCHIO, ZANNINI, MACLYSA, DAPP, DIMEC, CSIC**

Scope of this Work Package was to facilitate and encourage the industrial and commercial exploitation of the results and define the measure to ensure that the SME proposers will be able to assimilate and exploit the results of the project as well as the dissemination of the results.

2.7.1 Task 7.1 Protection IPR

Following the feasibility study and preliminary studies performed by the consortium partner before and after the proposal submission, a first PTC request (PTC/IT2004/000450) was deposited on August 2004 to cover the general architecture design of the SAFERDRILL system. The PTC has been accepted and published on February 9th 2006. The Consortium decided to proceed with a PTC submission before the official start of the project because:

- partners were fully committed on developing the SAFERDRILL ideas;
- due the time frame between a patent application and the effective acceptance, the consortium wanted to be sure to cover the innovative ideas before the dissemination activities planned during the project;
- the consortium use the International Search Report provided as part of the PTC evaluation to review the design of the system.

All partners of the consortium has been included as inventors to recognise their contribution to the design of the system. The applicants were ICOP, as project coordinator and exploitation manager, and two other SMEs, ZANNINI and COMACCHIO, because in the front line of the exploitation of the results: ZANNINI will be responsible for the operation and further tests of the SAFERDRILL prototype to build up a consistent record of successful cases where the system has been used;

COMACCHIO will be responsible for the industrial re-design of the prototype, manufacturing and commercialisation of the SAFERDRILL systems.

At the 21 month meeting, the Consortium decided to deposit a request for an Italian patent to cover the innovative design of the Rope Tensioning Device. The request for the Italian Patent was deposited on December 28th 2007 (Request number GE2007A000129). Scope of the patent is to cover not only the actual design of the Rope Tensioning Device but also the additional developments that are planned after the end of SAFERDRILL project. Patent applicants are three SMEs (ICOP, ZANNINI and COMACCIO) for the same reasons explained before plus Mr. Matteo Zoppi, principal researcher of DIMEC, responsible for the design of the system during the project. The consortium will benefit by the inclusion of Mr. Zoppi among the patent applicants because he agreed to further develop the system after the end of the project, finally providing a better solution for the benefit of the whole Consortium. Instead of a PTC, as previously, the Consortium decided to submit for an Italian patent because this will give one year to the Consortium to further refine the patent application before the final International Patent request.

2.7.2 Task 7.3 Marketing strategy and feedback

During the second period the Consortium validated and confirmed the marketing decided at the start of the project.

The primary commercial exploitation routes for this output of SAFERDRILL project will be through the civil and construction industry. The exploitation has been organised in **three phases** as described below:

I. During the first phase, starting at the end of the project and long one year, the consortium will **further develop the final prototype into a industrial system** ready to be fully exploitable. The consortium has the capability of carrying out such additional development that will mainly consist in the optimisation of the modules and in performing the required actions for the industrialisation. This work will be carried out by MACLYSA and COMACCHIO.

II. At the end of phase I, a first industrial version of the machine will be used by ICOP and ZANNINI during their consolidation works. This will **build up a consistent and large record** of successful application of the system and also **generate the first revenues** from the use of the system. During this phase, COMACCHIO, in conjunction with all the partners, will be in charge of updating the original business plan and the Economic Impact Assessment, including market analysis and sales forecast.

III. After two year from end of project, it will start **the commercialisation of the system**. As a deep experience on the field is needed to push the new system on the market, ICOP and ZANNINI will provide training and demonstration to potential users. COMACCHIO will be responsible for system commercialisation and marketing through its world-wide net of agents well introduced in the reference market.

2.7.3 Task 7.4 Training, exploitation and dissemination

The consortium performed several activities of exploitation and dissemination.

- A poster (Figure 53) summarizing the project objective and the general performance of the Saferdrill system has been developed to be used in the headquarter of each project partner and in the dissemination events. The poster has been written in English and Italian because the partners responsible for the exploitation activities are mainly in Italy.
- An article regarding the project result has been presented by DAPP at "SYROCO 06 - 8th International IFAC Symposium on Robot Control" in Bologna on September 2006.
- A project website has been developed and used as channel to disseminate the project result (Figure 51).

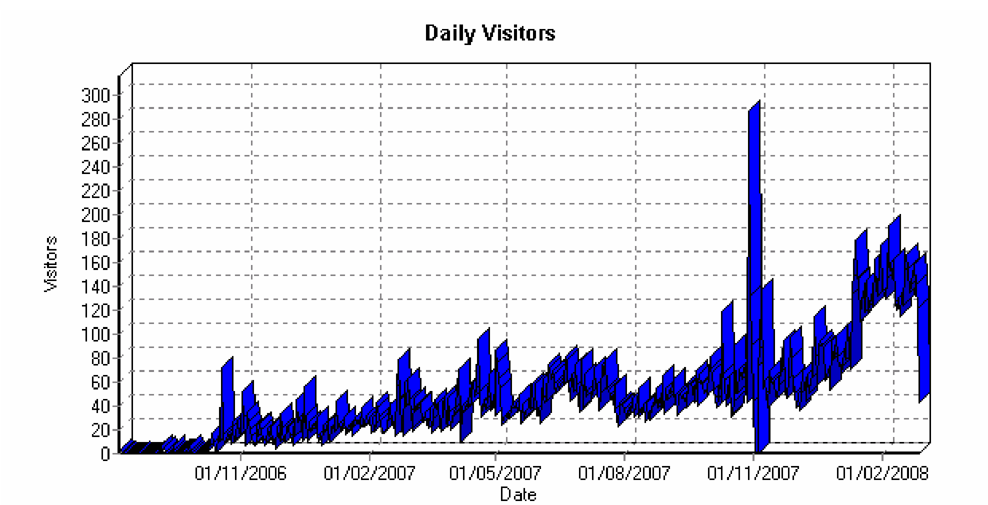


Figure 51: Daily visitor at the SAFERDRILL web site (www.dappolonia-research.com/saferdrill)

- The first integrated platform was exposed in COMACCHIO stand at "GEOFLUID 2006 Drilling & Foundation" international fair. GEOFLUID is one of the major fair about drilling machine and equipment.

- The project coordinator, Enzo Rizzi, presented the SAFERDRILL project into an international fair, “Research 2 Business”, 3-4 May 2007 in Bologna (Italy). “R2B - Research 2 Business” is one of the fast growing fair where Italian and International research leading actors can meet and have the opportunity to put forward new technological innovation proposals, research projects, prototypes and applications to be launched onto the market. Enzo Rizzi made a presentation on SAFERDRILL inside the symposium organized by the Italian platform of Construction and in a symposium about Technology Transfer, sponsorised by ESA and with Franco Malerba as chairmen.

Figure 52: Enzo Rizzi (left) with Franco Malerba, the first Italian Astronaute, at R2B

- A scientific paper has been submitted and accepted at the International Conference “RISE 2008”, IARP/EURON Workshop on Robotics for Risky Interventions and Environmental Surveillance. The symposium was held in Benicàssim (Spain), January 7th-8th, 2008. Jeremi Gancet (Space Application Services) presented an article on the SAFERDRILL control system.

Figure 53: SAFERDRILL poster

Section 3 – Consortium Management

3.1 The performance of the consortium

The collaboration has been characterised by a high level of commitment from the Team Leaders and the participating organisations to the successful outcome of the Project. A good balance has been achieved between the individual contribution of each partner and joint review and decision making with respect to the overall direction of the Project.

Consortium manager kept all partners always and frequently updated on the progress achieved in each WPs to assure a unique view on the development of the different modules and increase the efficiency of the R&D activities carried out by each project team. Several emails and phone calls have been exchange between coordinator and partners weekly. The project website has been used as document repository and as tool to exchange information.

3.2 Milestone Achievements

The progress of the project towards its objectives has been assessed as planned in the work programme and all milestone has been achieved. In particular:

- The first milestone "Definition of functional requirement of the system" has been achieved. Complete and detailed definition of all functional requirements, taking into account climbing, drilling and hoist modules has been produced and used in all workpackages (M1);
- The validation of the models and the evaluation of virtual prototypes with respect to system requirements has been performed and presented during the regular projects meeting (M2);
- Constructive drawings of the robotic platform, drilling module and rope tensioning device has been developed and used to manufacture the full-scale prototypes (M3);
- System navigation and geotechnical knowledge base system has been validated on laboratory testes and preliminary field tests (M4);
- A full scale demonstrator of all SAFERDRILL modules have been developed (M5);
- Several laboratory and field tests were performed for system evaluation (M6);
- A patent to cover the innovative rope tensioning device has been submitted (M7).

3.3 Meetings

The first year of the project have involved considerable communication between partners to discuss the technical specifications system and the technical design and development of the SAFERDRILL system and Table 4 shoes the full list of meetings performed.

Regular general meeting has been organised (Kick-off meeting, 6 month meeting and 11 month meeting). Regular bi-lateral meetings with both the SMEs and the R&D performers to guarantee the maximum efficiency of the work done and the fast integration of the different modules starting already from the design. Finally during 11 month meeting, on July in Madrid, extensive laboratories and on-field tests have been performed to test the first release of the integrated control system and robotic platform.

Date	Location	Description
28/29-Sep-2005	Udine (Italy)	Kick-off meeting
9/10-Nov-2005	Brussels (Belgium)	Technical meeting on WP4
17/18-Nov-2005	Madrid (spain)	Technical meeting on WP1,WP2,WP4
18/19-Dec-2005	Genova (Italy)	Technical meeting on WP2,WP3
10-Feb-2006	Genova (Italy)	Technical meeting on WP2,WP3
13-Feb-2006	Roma (Italy)	Technical meeting on WP1
9/10-Mar-2006	Madrid (spain)	Six month general meeting
23-Mar-2006	Roma (Italy)	Technical meeting on WP1,WP2,WP4
24-Mar-2006	Brussels (Belgium)	Technical meeting on WP4
3-Jun-2006	CastelFranco (Italy)	Technical meeting on WP7
24/28-Jul-2006	Madrid (spain)	Laboratory and onfield tests

Table 4: List of meetings – First reporting period

On the second reporting period, the main activities were the development of the full scale prototypes, their integration and extensive laboratories and on-fields test to evaluate the system performances.

At the start of second reporting period the first integrated platform was transported from Maclysa headquarters (Spain) to Italy at COMACCHIO headquarter. When the platform, weighting around 4000 Kg, has been transported in different locations in Italy both for laboratory than on-field tests. Due the complexity of the transportation and the setup of the test location, outdoor tests lasted always several days. Because of the presence of the robotic platform in Italy and because also the Rope Tensioning Device has been assembled in Italy, all meetings of the second reporting period has been in Italy.

Use of internet services allowed to minimise the travel of the person involved into the tests.

The on-side persons used laptops equipped with high speed wireless card to enable the download of updated SW version for the on-board control system and HMI in real time during trail sessions.

However regular general meeting has been organized among the consortium partner to discuss the progress and the marketing and IPR strategy. The list of meeting organized in the second reporting period is shown in Table 5.

Date	Location	Description
10-Oct-2006	Basiliano (Italy)	Mid-Term Meeting
14/10/06 - 28/10/06	Riese Pio X (Italy)	Laboratory Test of integrated robotic modules
30/01/2007 - 02/02/07	Riese Pio X (Italy)	Laboratory Test of integrated robotic modules
08/02/07 - 18/02/07	Primolano (Italy)	On-Field trails of integrated robotic modules
12/03/07 - 16/03/07	Basiliano (Italy)	Laboratory Test of integrated robotic modules
26/03/07 - 04/04/07	Fella (Italy)	On-Field trails of integrated robotic modules
08/05/07 - 18/05/07	Riese Pio X (Italy)	Laboratory Test of integrated robotic modules
9-May-2007	Basiliano (Italy)	Outdoor Navigation system Test + 21M Meeting
15/07/07 - 21/07/07	Fella (Italy)	On-Field trails of Knowledge Based System
20/06/07 - 23/06/07	Basiliano (Italy)	On-Field Test of Rope Tensioning Device
17/07/07 - 20/07/07	Basiliano (Italy)	Laboratory Test of integrated robotic modules
15/09/07 - 28/09/07	Genova (Italy)	Outdoor test on the rope Tensionig Device
17-Nov-2007	Basiliano (Italy)	Final Meeting
17/12/07 - 21/12/07	Orvieto (Italy)	On-Field Test of integrated robotic modules

Table 5: List of meetings – Second reporting period

3.4 Contractors contribution

Due the complexity of the system and the tight interaction among the different components, partners worked always in cooperation during the development of activities. In general RTD performer led the activities but SMEs were always deeply involved providing the input requirements for each component, validating the work performed by RTD, developing and manufacturing system elements. (see Section 4). All contractors actively contribute to the R&D activities carried out during the full duration of the project as summarised in Table 6.

All partners also contribute to the consumables and other costs expenses needed to carry out the design and prototyping of the SAFERDRILL modules. This confirms again the high commitments of all contractors in the project objectives.

Considering the extension of four month in the project duration, the increase of 15% in the total men month is in line with the planned activities. SMEs person month total efforts are in line with those planned.

Person-Month Status Table		**Partner - Person-month per Workpackage**									
Contract N°:	COOP-CT-2005-016842										
Acronym:	SAFERDRILL										
Period:	01/9/2005 -31/12/2007										
		TOTALS	ICOP	SAS	IMC	COMACCHIO	ZANNINI	MACLYSA	DAPP	DIMEC	CSIC
Workpackage 1: System Requirements	Actual WP total:	**12,50**	**3,0**	**0,3**	**2,2**	**1,0**	**2,0**	**0,0**	**3,0**	**0,5**	**0,5**
	Planned WP total:	11	3,0		2,0	1,0	2,0		3,0		
Workpackage 2: Design of the robotic system	Actual WP total:	**24**	**1,0**	**0,0**	**0,0**	**2,0**	**2,0**	**2,5**	**1,0**	**11,5**	**4,0**
	Planned WP total:	20,5	1,0			2,0	2,0	2,0	1,0	8,5	4,0
Workpackage 3: Selection & develop. of robotic system	Actual WP total:	**24,9**	**0,5**	**0,0**	**1,0**	**4,0**	**0,4**	**5,5**	**2,5**	**9,0**	**2,0**
	Planned WP total:	19	0,5			4,0	1,0	3,5		9,0	1,0
Workpackage 4: Design and dev.Control system	Actual WP total:	**47,7**	**0,4**	**11,0**	**7,0**	**1,0**	**0,2**	**4,5**	**9,1**	**0,0**	**14,5**
	Planned WP total:	45,5		10,5	5,0	1,5	0,5	0,5	10,0	1,0	16,5
Workpackage 5: System integration	Actual WP total:	**33,4**	**0,9**	**3,0**	**2,0**	**5,0**	**2,0**	**8,0**	**6,5**	**3,0**	**3,0**
	Planned WP total:	27		3,0	2,0	4,0	1,0	6,0	9,0	2,0	
Workpackage 6: System performance evaluation	Actual WP total:	**26,3**	**4,4**	**1,5**	**2,5**	**1,0**	**3,4**	**2,0**	**6,5**	**2,0**	**3,0**
	Planned WP total:	21	4,5	1,5	2,0	1,0	1,0	1,0	4,0	3,0	3,0
Workpackage 7: innovation related activities	Actual WP total:	**12,2**	**3,0**	**0,7**	**1,5**	**1,0**	**1,0**	**1,5**	**2,5**	**1,0**	**0,0**
	Planned WP total:	12,5	4,0	1,5		1,5	1,5	1,0	1,5	0,5	1,0
Workpackage 8: Consortium Management	Actual WP total:	**6**	**6,0**								
	Planned WP total:	6	6,0								
	Actual total:	**187,00**	**19,20**	**16,50**	**16,2**	**15,0**	**11,0**	**24,0**	**31,1**	**27,0**	**27,0**
Total Project Person-Month	Planned total:	162,5	19,0	16,5	11,0	15,0	9,0	14,0	28,5	24,0	25,5

Table 6: Summary of actual personal effort against planned

3.5 Project Timetable

The work during the first reporting period has been carried out according to the original Work Programme. The project the work is on schedule and the results expected to be achieved at the end of the first reporting period of the project development have been globally obtained. WP1 and WP2 are fully completed in schedule with the original work-plan. Under WP3 all robotic modules have been completely designed, configuration selected and constructive details defined apart from the mobile platform module even if the final configuration has been selected.

Regarding the Control System (WP4) the consortium decided to give priority to the development of the integrated control system because essential to test the robotic platform and the drilling unit. However the Navigation System and Knowledge Base System were in advance stage of development and they were foreseen to be completed in schedule.

Integration activites (WP5) were well in schedule because the main modules (drilling, mobile platform, remote control) were already integrated. Due the high cost of system components manufacturing, it was decided to develop full scale demonstrators directly when possible. This is possible for all modules apart from the new rope hoist because are request high security standards from the beginning of on-field tests. So for this component it was decided to firstly develop a laboratory prototype and then the final one.

First laboratory and on-field tests have been performed in Madrid during July to start to evaluate the performance of the system (WP6) slightly head in schedule with original plan.

Contractors contacted on July a layer office expert in protection of IPR to investigate the possibility to patent the major innovation developed inside the project and. To disseminate the first R&D results RTDs partners wrote and submitted two scientific articles to international magazine.

After the first reporting period, the project was so far deemed highly successful by the partners both in terms of R&D results achieved and efficient co-operation within the partnership. The main achievements to date in all the tasks were in good agreement with the time schedule and show the soundness of the R&D work as defined in the Work Programme both in terms of technical content and costs. Therefore, no major modifications to the technical scope of work were planned.

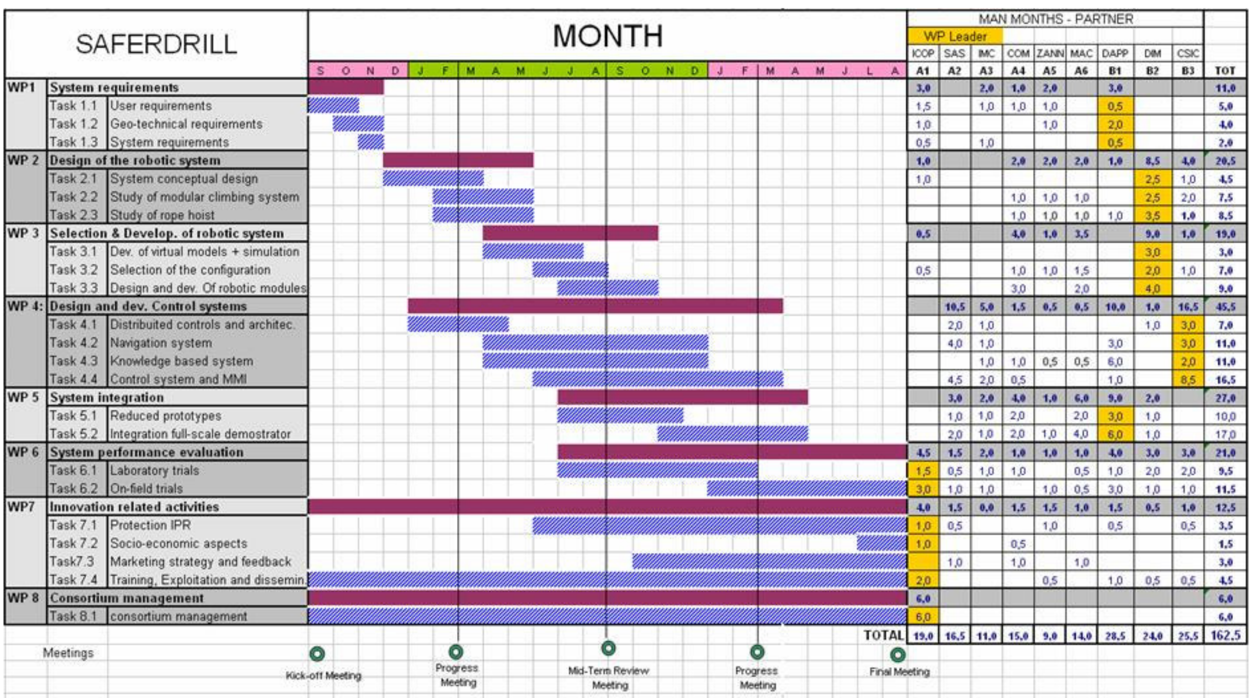


Figure 54: Original Gannt of activites

The main activities during the second reporting period were the development of full scale system prototypes, their integration and the system evaluation using laboratory and on-field tests. Even if several laboratories and on-field were performed among all second year, during 21 month project meeting (May 9th) it was agreed among partners an aggressive schedule to complete all final development, test and integration activities for the scheduled end of the project, August 31st. After the tests performed during the month of June and July, the Consortium realised that further time was needed to reach all project objectives. In particular :

- Tests performed at ICOP on June 20-23 on the tensioning device prototype highlighted that under heavy load there is a skidding of the rope probably due to the shape of the "hands" that require further tests and a possible re-design of them;
- Test performed at ICOP on July 17-19 on the control system highlighted several problem on the control that needs to further investigated and fixed.

This delay was mainly due to the innovative and research aspects of the project: Saferdrill is one of the biggest robots ever built and during the project duration the consortium was daily facing with new technical challenges. The construction of the Rope Tensioning Device run slowly behind schedule and the development of a robust complex controls system was taking more time than originally planned. During the second year partners put in place contingency plans , which allowed proceeding on parallel when it is possible, but a final integration for some components was still needed. Considering that August was period of holiday in Italy and Spain and most of the partners involved on the previous tasks are from these countries, the Consortium decide to ask for an extension of the project duration up to end of the year. The extension was approved and the revised Gannt is shown on Figure 55.

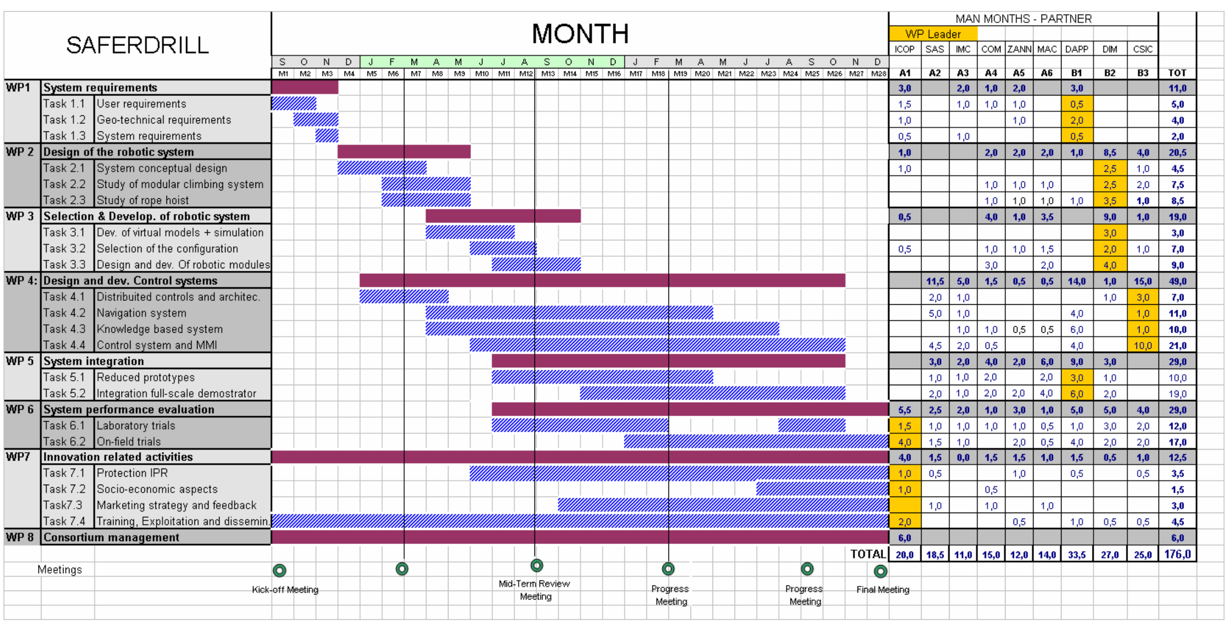


Figure 55: Revised Gannt of activites

Section 4 - Other issues

On this section we summarised the overall contributions of the group of SMEs and RTD performers for each workpackages. Due the complexity of the system and the tight interaction among the different components, partners worked always in cooperation during the development of activities. In general RTD performer led the activities but SMEs were always deeply involved providing the input requirements for each component, validating the work performed by RTD, developing and manufacturing system elements.

ICOP

ICOP divided its activities between management / project coordination and R&D activities.

Regarding R&D activities in the first reporting period, ICOP has mainly involved into the definition of the system requirements (WP1) being one of the main end-user of the system: thanks to its large experience on civil engineering and consolidation works, ICOP led the activities on the user requirement definition (Task1.1) and contributed on the selection of geo-technical requirements (Task 1.2) and full system requirements (Task1.3). ICOP contributed as well on validating the ideas developed during the system conceptual design (Task2.1), the modular climbing system (Task2.2) and rope tensioning device (Task2.3). ICOP contributed in the construction of the prototype especially for carpentry works and drilling components. ICOP actively participate to the laboratory and fields tests. ICOP started to work with the other industrial partner in the protection of IPR discussing regarding possible patents, draft a general patent description of the system, analysing the states on which to protect the IPR.

Regarding R&D activities in the second reporting period, being ICOP a company doing civil engineering works, has mainly involved into the following activities:

- Support in the integration activities both hosting the SAFERDRILL platform on its workshop then providing consumable materials, components and parts (Task5.2).
- Support in the laboratories tests, when performed at ICOP headquarter (Task6.1).
- Support in the on field trails, providing trucks and crane for SAFERDRILL platform transport and installation, on field logistic, supply of air compressor, generator, electrical board etc… (Task 6.2)

- Exploitation of project results to international fairs (as at R2B), analysis of socio-economic and IPR aspects based on trail result of the full scale prototype, contribution into patent application for the Rope Tensioning Devices (Task 7.1, Task 7.3, Task 7.4).

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Regarding consortium management activities, ICOP organised (and hosted) regular general project meetings and constantly monitored the advance in the project by periodic email, phone call and company visits. An extension of four months has been required from the consortium in order to complete in a proper way all the tasks allocated. An amendment to the contract has been signed by the Commission (Task 8.1).

SAS

SAS deeply contributed in the design and development of the control system.

During the first reporting period SAS activities were concentrated in the definition of the general architecture of the system (Task 4.1) and in the development of the prototype of Human Machine Interface (Task 4.4) and Navigation System (Task 4.2). Working closely with the other partners involved on these tasks, SAS contributed to fully define the architecture of the system. In advance with the project schedule, SAS design and implemented the SW on the HMI to control the robotic system. During the end of the first year several laboratory and field tests have been performed on the innovative Human Machine Interface. SAS defined the general specification of the Navigation system and already design and prototype the cameras bench.

During the second reporting period SAS activities were concentrated in :

- Support in the integration of HMI control system into the SAFERDRILL system (Task5.2);
- Support in the laboratories and on-field trials also remotely (Task 6.1, Task 6.2);
- Continuous update of the SW of the HMI to implement modification and enhancement decided after trails (Task 4.4)
- Development of the different components of Navigation system, their integration in a full-scale prototype and laboratory in-door and out-door trails (Task 4.2).

IMC

During the first reporting period, IMC contribute with its experience on industrial control system in the definition of the architecture of the control system (Task 4.1), suggesting technical solution and components and validating the work performed by the other partners. IMC contributed in the specification of the Navigation system (Task 4.2) and Knowledge base system (Task 4.3). IMC contributed also on the testing phase for the control part.

In the second reporting period IMC contributed in:

- Support in the selection and integration of industrial electronic components into the upgrade control system (Task 5.2);
- Support into the definition of the hardware components for the Navigation system (Task 4.2);
- Co-development with DAPP of the SW for the Geotechnical Knowledge system (Task 4.3);
- Support on the definition of industrial components for the Rope Tensioning Module and remote control to laboratories and on-field trials (Task 3.2, Task 3.3).

COMACCHIO

Being a drilling machine designed and manufactured, the contribution of COMACCHIO has important in all project activities.

During the first reporting period, COMACCHIO deeply contributed in the user requirements definition (Task 1.1). COMACCHIO experience on mechanic and hydraulic was important on the definition of the system design (Task 2.1) and on the selection of the best configuration for the robotic system (Task 2.2) and rope hoist unit (Task 2.3). COMACCHIO contributed as well in the design and development of the system components thanks to its large experience on designing mechanical components for drilling machine and hydraulic circuit design (Task3.3). COMACCHIO extensively contribute on the system prototype manufacturing especially for the drilling module (Task 5.1 and Task 5.2). COMACCHIO experience of the drilling machine market has important to define a common strategy on the exploitation of the system, in the estimation of market potential (Task 7.3). COMACCHIO has also great experience on patenting innovative solution for drilling machine and for this reason its contribution on the patent analysis and discussion was important. (Task 7.1)

In the second reporting period COMACCHIO deeply contributed in :

- Support into the positive solutions of problems and malfunctioning related to hydraulic components of the SAFERDRILL integrated platform (Task 3.3, Task 5.2);
- Support into the positive solutions of problems and malfunctioning related to hydraulic components of the Rope Tensioning Device module (Task 3.3, Task 5.2);
- Support in the laboratories tests, when performed at COMACCHIO headquarter (Task6.1)

- Exploitation of project results to international fairs (as at GEOFLUID), analysis of socio-economic and IPR aspects based on trail result of the full scale prototype, contribution into patent application for the Rope Tensioning Devices (Task 7.2, Task 7.3, Task 7.4).

ZANNINI

ZANNINI is a company specialised on consolidation works (the first idea for a robotic unit able to perform consolidation works come from Roberto Zannini) and for this reason it was the partner that worked more closely with DAPP into integration and trials.

In the first reporting period, ZANNINI experience and knowledge was essential on whole tasks regarding the system requirements definition (WP1). ZANNINI has been deeply involved in the design and validation (Task 3.2) of the different solutions of the modular climbing system (Task 2.2) as well as the new rope tensioning device (Task 2.3). ZANNINI contributed to the prototyping and test of the SAFERDRILL system providing a platform able to climb beside the SAFERDRILL prototype, essential to support on-field test activities (WP5 and WP6). ZANNINI contributed also in the initial activities on marketing and exploitation (WP7).

In the second reporting period ZANNINI deeply contributed in :

- Execution of laboratories tests of the integrated robotic platform at ICOP headquarter and at COMACCHIO workshop (Task 6.1).
- Execution of on field trails of the integrated robotic platform (Task 6.2).
- Support in improvement of the design of HMI and on-board control unit (Task 4.4);
- Support in analysis of tests data and in redesign of components and parts (Task 5.2);
- Support in the design and manufacturing of the rope Tensioning Device (Task 3.3, Task 5.2);
- Support in the laboratory and on field trials of the Rope Tensioning Device module (Task 6.1, Task 6.2).
- Support into analysis of IPR aspects and contribution into patent application for the Rope Tensioning Devices (Task 7.1).

MACLYSA

In the first reporting period, MACLYSA has been extensively involved in the study of the modular climbing system (Task2.2) and study of new rope hoist (Task2.3) because of its specialisation on industrial prototype design and development. In particular MACLYSA has been involved in the selection of the final configuration of system (Task3.2) and also in the design of the robotic modules (Task3.3) thanks to its large experience on using Pro-Engineer tool. Head in schedule with the planned work, MACLYSA contributed in the manufacturing of the prototype especially regarding the mobile platform module and all electrical cabling.

In the second reporting period, MACLYSA has been extensively involved in the second reporting period in:

- Oversee of the design and manufacturing of improved mechanical parts for the drilling module and the mobile robotic platform (Task 5.2);
- Support on the laboratory trials and integration of the SAFERDRILL system (Task 5.2, Task 6.1);
- Support into the design of mechanical components for the Rope Tensioning Device (Task 3.3).
- Continuous update of cabling and improvement of electrical circuit and components of the integrated platform (Task 5.2)

DAPP

In the first reporting period, as WP1 leader, DAPP coordinate and collected all activities regarding system requirements. In order to define these requirements, a questionnaire was prepared by DAPP and discussed during three meetings with the other partners (WP1). DAPP has analysed and selected the parameters to be collected from the drilling monitoring system and defined also the processing methodology (Task 1.2). Due to the strong link between the design and the integration phase, DAPP has also involved in the selection of the final design of each system components (Task 3.2) assuring then on easy integration of the part during the prototyping phase. Based on the work performed under WP1, DAPP defined the general specification of the Knowledge Based System and its design and integration with the rest of system (Task 4.3). DAPP defined the general architecture of the remote control for the usability point of view (Task 4.4) and it has been responsible for the design and manufacturing of the hardware and electronic components of Human Machine Interface (Task 5.1). DAPP and SAS worked closely in the definition of the Navigation System: all hardware components have been selected, purchase and integrated in the camera bench (Task 4.2). DAPP coordinated all partners in the system integration assuring a smooth and effective work, system manufacturing and final integration of the different system components (Task 5.2). DAPP organised and lead the laboratory tests of the single system components and the first field tests already performed on the system (Task 6.2). Finally DAPP developed the project website helping to the dissemination of project result (Task 7.4).

In the second reporting period, DAPP was deeply involved into WP5 "System Integration", WP6 "System performance evaluation", and WP4 "Design and development of Control system" regarding the Knowledge Based system and HMI. In particular in this second reporting period the major activities of DAPP were:

- Development and test of a full prototype of the Knowledge Based System including integration of distributed network of sensors in the drilling module (Task 4.3);
- Execution of laboratories tests of the integrated robotic platform at ICOP headquarter and at COMACCHIO workshop (Task 6.1);
- Execution of on-field trails of the integrated robotic platform (Task 6.2);
- Analysis of tests data, redesign and integration of electronic components and parts on the on-board control system (Task 5.2);
- Continuous update of the HMI interface in order to implement modification decided on the base of trails (Task 4.4);
- Modification and optimisation of the integration of drilling module, robotic platform, control system and Human Machine Interface (Task 5.2).
- Update of Web site for document exchange among partner and dissemination; development of a poster for the International Fair SYROCO (Task 7.4)

DIMEC

In this first reporting period DIMEC activities covered all Tasks in WP2 and WP3 where DIMEC was WP Leader. First DIMEC produced the conceptual design of all main components of the robotic system, taking in account the life cycle and the system requirements defined in WP1 (WP2), then developed different virtual demonstrators helping the other partner to select the best configuration of the system and finally developed the full design of each system component (WP3). DIMEC studies were concentrated in three main areas: development of the robotic drilling system; development of a methodology and corresponding platform to allow the positioning of the robotic system on the hall without the need of external help (ex. crane); development of the innovative mechanism for rope tensioning. DIMEC contributed the general control architecture design especially regarding the hydraulic control to allow a perfect integration with the mechanical design developed (Task 4.1). Regarding the new rope design DIMEC performed extensive laboratory tests and analysis of commercial Tirfor to fully understand its limitations and use this experience on the design of the new innovative design (Task 6.1).

In the second reporting period DIMEC activities were concentrated into the full design of a Mobile Carriage Platform and into the design, development and test of the Rope Tensioning Device. In particular DIMEC activities were:

- Selection of the configuration of the Mobile Carriage Platform (Task 3.2);
- Design, development of constructive drawing and selection of components for the Mobile Carriage Platform (Task 3.3);
- Constructive design of the Rope Tensioning Device (Task 3.3);
- Development of a full-scale demonstrator of Rope Tensioning Device (Task 5.2);
- Laboratory and on-field trail of Rope Tensioning Device (Task 6.1, Task 6.2);
- Support on patent definition of the rope Tensioning Device (Task 7.1).

CSIC

In the first reporting period, CSIC, for its great experience on robotic design, has been deeply involved in the validation of the design of the robotic system (WP2). Especially regarding the mobile robotic platform, CSIC studied with MACLYSA the different possible gaits using virtual models and innovative algorithms (Task 2.2).

As WP4 leader, CSIC coordinated and provided the main contribution in all Tasks and activities related to the design and development of the control system. CSIC designed the control taking in account the severe requirements defined in WP1: the control architecture is intrinsically safe and with operational margins; all components, cables, connectors, sensors are suitable for harsh environments use; data from sensors and signals are processed and elaborate in real-time. CSIC designed and developed a special control board card having the advantage that with only one command the system is able to control various actuators simultaneously and with autonomy; this properties reduces significantly computational power. Head in schedule with the original working plan CSIS was able, with contribution of the other partners, to develop a full first prototype version of the control system (Task 4.4). CSIC validated the work performed with extensive laboratory tests and first field test (Task 6.2).

In the second reporting period CSIC has been involved in further development of the SW of the control system. In particular CSIC was involved in the following tasks:

- Support on laboratories and on-field tests of the integrate robotic platform (Task 6.1, Task 6.2);
- Continuous improvement of the SW running on the on-board control module to perform bug-fix and further development (Task 4.4, Task 5.2);