ROBOVOLC

IST–1999-10762

A ROBOT FOR VOLCANO EXPLORATION

D 8.a (Including D8.mid)

Final report with test results and validation report

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With contributions from all other partners.

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Project Co-ordinator: Prof. Giovanni Muscato, DEES University of Catania, Italy

Partners :

- UNICT Università degli Studi di CATANIA - Dipartimento Elettrico Elettronico e Sistemistico, Italy
- INGV - Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Italy (formerly CNR-IIV Istituto Internazionale di Vulcanologia - Consiglio Nazionale delle Ricerche)
- IPGP - Institut de Physique du Globe de Paris, France
- UNI-PO- University of Portsmouth, Higher Education Corporation, United Kingdom (Withdrawal from March 2002)
- PORTECH - Portsmouth Technology Limited, U.K. (Withdrawal from Oct.2000)
- ROBOSOFT – SA, France
- BAE SYSTEMS - Advanced Technology Centres Sowerby, United Kingdom
- UNIVLEEDS – University of Leeds, United Kingdom

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DELIVERABLES SUMMARY SHEET

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Title: A ROBOT FOR VOLCANO EXPLORATION

Deliverable *D8.a Final report with test results and validation report* and *D8.mid Mid term summary report on WP8 activities*

Due date: September 2003

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Short Description:

This document is a summary of the results achieved and of the test activities performed during the project ROBOVOLC. A short description of all the test campaign is reported and a validation report is also included with a comparison between the achieved results and the specification of the system that were stated in the Deliverable D3.2a

Partners owning: All.

Partners contributed: All.

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1. Contents

1.1 List of Figures

2. Introduction

This report is a summary of the final objectives achieved in the Robovolc project including all the results of the test campaign performed in the final phase of the project.
The document is organised as follows: Sections 3 includes a summary of the objectives of the project from the technical annex, while section 4 describes the activities performed during the project. A short description of the technical activities and of the Robovolc system with respect to the objectives is included in Section 5. Sections 6, 7,8,9,10,and 11 are a description of the test campaign performed with a discussion on the results obtained. In particular three main different test campaign have been organised in the last year of the project:

1) September 2002 : *This preliminary test campaign allowed to test the integration of most of the subsystem sincluding the manipulator and the science package. Traction capabilities of the rover were tested and manipulation tests performed. The test performed allowed to prepare a ling of modifications for each subsystems.*

2) June 2003 : T*his test campaign was performed following the final integration of the system. The system was in the final configuration. At the end a small list of modification to be performed in the manipulator and in the traction control was prepared.*

3) August 2003 : *This was the last test campaign of the system within the project. In this period all the subsystems were validated with respect to the specifications.*

In section 13 the Validation of Requirements for Functional Blocks are reported.
In the appendix 1 the test report on the navigation system and on the HCI system prepared by the University of Leeds is included. In the final part all the reports concerning the technical visits performed during the project are included.

3. Project Objectives from the technical annex

3.1 Summary of the project:

> *The main objective of this project is the development and trial of an automatic robotic system to explore and perform measurements in a volcanic environment. A major aim of the proposed robot will be that of minimising the risk for volcanologists who are involved in work close to volcanic vents during eruptive phenomena. Observations and measurements of the variables relating to volcanic activity are of greatest interest during paroxismal phases of eruptions, which unfortunately are also the time of greatest risk for humans. Technical objectives of the project are : 1) The design, implementation and trial of a prototype robot suitable for autonomous and/or semi-autonomous exploration of natural and extremely rough unstructured environments. 2) The design, implementation and trial of a small measurement system for lava and volcanic gas analysis and sample.*

3.2 Project Objectives

The main objective of this project is the development and trial of an automatic robotic system to perform measurements in a volcanic environment.

From as early as Greek and Roman times volcanic activity has been well recorded and reported because of the huge impact that eruptions have on human activities. Ancient populations lived in awe of unpredictable eruptions. They suffered huge damages that eruptions caused to their towns and lands and human lives were often lost. As a result, some people began to venture near to active volcanic vents in order to understand volcanic phenomena. Philosophers as Empedocle, Plinius the Elder and Plinius the Younger observed eruptions too closely and paid for their thirst for knowledge with their lives. Thereafter, many scientists studying eruptions from unsafe places suffered serious injuries. In the last decade alone, due to both the unpredictable timing and to the magnitude of volcanic phenomena, several volcanologists have died surveying eruptions.

So a major aim of the proposed robot will be that of minimising the risk for volcanologists and technicians who are involved in work close to volcanic vents during eruptive phenomena. It should be noted that observations of, and measurement of the variables relating to volcanic activity are of greatest interest during paroxismal phases of eruptions, which unfortunately are also the time of greatest risk for humans.

The proposed robot for volcano exploration is a tele-operated robot capable of:

- approaching an active volcanic vent
- collecting samples of the volcanic products erupted
- collecting physical and chemical data on the eruptive processes
- surveying close to vent openings

Material such as volcanic gas quickly mixes with the atmosphere and so is not practical to collect it for analysis far from the eruptive vent. This environment is very dangerous for human life due to the unpredictable magnitude of the eruptive phenomena, so a robust rover robot will be required to collect samples and data, otherwise very difficult to get or is contaminated by the mixing process in the atmosphere.

The sites to be examined are lava flows, ash and spatter cones and large fractures on the ground; in general they are very rough and disconnected surfaces close to or inside volcanic craters. The ground often has a steep gradient and its surface is unstable due to rolling rocks or sliding materials, so the robot is likely to need a sophisticated leg-wheel assembly to move safely and surely. Sometimes the place being investigated will be previously unexplored so a video link between the rover robot and the operator is essential. A ranging system (ie laser ranging) will be useful for both driving and measurement purposes. Finally an efficient data link will be required to drive the rover and to download the collected data.

In order to achieve such results, new algorithms and software for autonomous and/or semi-autonomous navigation of a robot in unstructured environments will be developed. For autonomous navigation, we intend that the robot should be capable of reaching a given position in the volcanic area autonomously and automatically perform the tasks required to perform measurement. In the case of very difficult or dangerous situations (e.g. proximity to lava flows or fissures), the robot will be tele-operated, acting in a semi-autonomous way. In this case, by using a specifically designed user interface, an operator will be able to drive the robot effectively. For semi-autonomous use, we intend that the robot will have the capability to decide autonomously some sub-tasks, e.g. the control of the position of individual wheels or legs, measurement operations, etc.

Data collected by the robot will be used primarily to enhance knowledge of the volcanic process and to produce computer simulation software of the volcanic phenomena. The capability to furnish updated information during eruptions will be used as input data for the simulation software to adjust the trend forecast for long-lived volcanic phenomena such as lava flow eruptions.

The principal objectives of the project are then :

Development of a tele-operated robot able to approach active volcanic vents.

Design (on a modular basis), implementing and trialing of a prototype robot suitable for autonomous/and or semi autonomous exploration of natural irregular and extremely rough unstructured environments. The locomotion system of the robot should be able to operate in a typical volcanic environment scenario. In particular, the materials to be adopted will need to be resistant to the high temperatures and contaminated atmosphere encountered during missions and to the impact of volcanic bombs and blocks.

Development of a small measurement system for lava and volcanic gas analysis and sample collecting.

The system carried on the robot should enable (not necessarily at the same time):

- sampling of volcanic gas and particulates, molten lava or rocks near the active vents
- analysis of volcanic gas using a small spectrometer configured for wavelengths from UV to very-near IR
- measurement of gas and lava temperatures using both an IR radiometer and thermocouples
- measurement of physical parameters of the volcanic jets such as gas and particle speeds, and gas-particle mixture density
- measurement of the physical parameters of the lava stream such as temperature, mass flux and rheological behaviour

- determination of the volcanic vents morphology and topography to update real time GIS.

The project activities have been divided into nine different Workpackages with each one divided into tasks:

WP1 Project Management, Assessment and Evaluation
    Task 1.1: Project Management
    Task 1.2: Project Assessment and Quality Assurance
    Task 1.3: Project Evaluation
WP2 Requirements Engineering
    Task 2.1: Current state analysis – volcanology, robot, sensing, etc.
    Task 2.2: Definition of user and general requirements – wish list from all partners
    Task 2.3: Specific system requirements and likely costs
WP3 System specification and design scheme
    Task 3.1: Systems architecture, protocols and informatics
    Task 3.2: Mechanical structure and materials
    Task 3.3: Internal sensors, actuators and controls
WP4 External sensors and manipulator
    Task 4.1: Selection of location methodology
    Task 4.2: Modelling of environment
    Task 4.3: Selection of sensors for physical data collecting
    Task 4.4: Selection of a system for chemical analysis of gas
    Task 4.5: Manipulator design and build
    Task 4.6: Integration of sensors and devices
WP5 Robot design
    Task 5.1: Mechanical design
    Task 5.2: Electrical/electronic design
    Task 5.3: Motion control strategy and software structure
WP6 Robot navigation and operator intervention
    Task 6.1: Navigation and path planning strategies
    Task 6.2: Navigation and path planning implementation
    Task 6.3: User interface and environment representation
WP7 Prototype implementation
    Task 7.1: Manufacture and assembly of robot
    Task 7.2: Implementation of motion control software
    Task 7.3: Physical integration of sub-systems
    Task 7.4: Sub-system software tests
    Task 7.5: Integration tests
WP8 Trials and demonstrations
    Task 8.1: Trials of subsystems
    Task 8.2: Final trials
    Task 8.3: Contribution to eruption forecasting
WP9 Exploitation, Dissemination and Implementation
    Task 9.1: Exploitation
    Task 9.2: Dissemination
    Task 9.3: Technology Implementation Plan

Five important Milestones for the global verification of the expected results have been scheduled:

MS1 = Requirements Engineering complete

MS2 = Definition of the specification and design scheme for the system and for all subsystems

MS3 = Final and validated design of the robot

MS4 = Integrated and laboratory tested prototype robot system

MS5 = Final Review with demonstrations in volcanic environments completed.

4. The Robovolc project activities

4.1 Short summary of project activities

The project activities started as scheduled on 1st March 2000 and have been concluded on 31st August 2003.

During the project twelve project meetings, two technical submeetings (Sensors for science and Navigation) and several technical visits to different volcano sites , have been organised (Details in the periodic reports). Three review meetings with the European Commission have been attended. Three amendments to the contract have been also prepared. Many different conferences have been attended and several articles published to disseminate the results of the project, moreover many articles have been published in newspapers and magazines, some appearance in TV (RAI1, Canale5, Antenna Sicilia, Telecolor) and a press conference was organised (See Deliverable D9b.3 for the details).

The Workpackages have been executed in the following periods:

WP1 Project Management, Assessment and Evaluation	Mar 00 – Oct 03
WP2 Requirements Engineering	Mar 00 – Aug 00
WP3 System specification and design scheme	Sep 00 – Feb 02
WP4 External sensors and manipulator	Jan 01 – Feb 02
WP5 Robot design	Jan 01 – Feb 0
WP6 Robot navigation and operator intervention	Jan 01 – Feb 0
WP7 Prototype implementation	Mar 02 – Feb 03
WP8 Trials and demonstrations	Oct 01 – Aug 03
WP9 Exploitation, Dissemination and Implementation	Jun 00 – Aug 03

The Milestones have been achieved as scheduled :

MILESTONE N	DATE ACHIEVED	MILESTONE OBJECTIVES	DECISION CRITERIA FOR ASSESMENT
MS1	August 2000	Requirements engineering complete	Consortium agree common understanding of the user requirements and outline specification.
Go/No Go Review meeting with EC at month 8-9			
MS2	April 2001	Definition of the specification and design scheme for the system and for all subsystems.	Consortium agree detailed specification and design scheme.
MS3(a,b,c,d,e,f)	February 2002	Final and validated design of the robot	Consortium agree designs.
Mid Term Assessment at month 24			
MS4	February 2003	Integrated and laboratory tested prototype robot system	Test report signed off by the consortium.
MS5	August 2003	Final Review and demo in volcanic environment	Demonstrations in volcanic environments completed

4.2 The role of each partner in the consortium

Partner 1: UNICT

UNICT's main role in the project was that of co-ordinator for the whole project. This involved Project management and Evaluation management. This resulted in overall synchronisation of all the activities of the partners and assessing the results produced against validation criteria agreed by the partnership. Another role of this partner was be that of interfacing volcanologists with robotic engineers. This partner lead Task 1.3 of WP1 (Specific user requirements) and the Workpackage concerning the detailed specification and design scheme of the robot (WP3) and contributed to those aspects concerning system control in the other workpackages. In particular was involved in the design and implementation of the sensors for science subsystem, designed and implemented the localisation subsystem, designed traction control strategies and contributed significantly in the organisation of all the trials.

Partner 2 INGV and Partner 3 IPGP:

The role of INGV and IPGP in the consortium was that of providing their long and recognised experience in the study of volcanoes. These co-operated closely together in the work concerning :

- The definition of the requirements engineering for the robot with an analysis of the volcano environment (WP2 leaded by IPGP).
- The design of sensors for the localisation of the global position of the robot (Task 4.1) and for the reconstruction of the volcanic environment inspected (Task 4.2).
- The design of a sensor system to collect physical data of gas and molten lava during the robot inspections (Task 4.3)
- The design of a measuring system for chemical analysis of gas (Task 4.4)
- Assisted with the organisation of trials of the robot system on different volcanoes in Europe. Most of the trials were done on Mt. Etna (Italy), but trials were also performed in other active volcanoes such as Stromboli Island (Italy) and Vulcano Island (Italy). (WP8 led by INGV).
- In general all those questions related to the peculiarities of the volcanic environment for a robot were addressed by INGV and IPGP.
- Liaison with other volcanologists in Europe and beyond for requirement gathering and dissemination purposes.

Partner 4: UNI-PO

This partner contributed in several tasks of the project by using its experience in the design and control of mobile robots. In particular it led WP 6 on Robot navigation and operator intervention where robot navigation strategies and a user interface for the tele-operation of the system were developed. The activities of this partner ended in March 2002.

Partner 5: PORTECH

This provided inputs to Tasks 2.2 and 2.3 (WP2). This partner terminated its activities in October 2000.

Partner 6: ROBOSOFT

This partner led the activities of WP 4 with particular attention to the design of the manipulator for the robot. It provided inputs to Task 2.2 and 2.3 and WP3 the detailed specification and design scheme of the robot system and partially supported WP7 for the implementation of the external sensor system in the prototype machine. As one of the industrial partners it contributed to WP 9 in the dissemination and commercial exploitation of the results developed in the project.

Partner 7: BAESRC (Start of activities on 1st January 2001)

This partner led WP5 on the designing the mobile robot and WP 7 where the Prototype implementation of the machine was carried out and WP9 on Exploitation and dissemination of the results of the project. It provided significant input to the specification of the robot (WP3).

Partner 8: UNIVLEEDS (Start of activities on 1st March 2002)

This Partner led in WP7 the implementation phase of the activities performed in WP 6 on Robot navigation and operator intervention.

5. The Robovolc system

In this section a short description of the project objectives and technical activities performed is reported.

5.1 Robots and Volcanoes

From as early as Greek and Roman times volcanic activity has been well recorded and reported because of the huge impact that eruptions have on human activities. Ancient populations lived in awe of unpredictable eruptions, suffering loss of human life as well as huge damage to their towns and lands. As a result, people began to venture near to active volcanic vents in order to understand volcanic phenomena. The philosophers Empedocles and Pliny the Elder observed volcanic eruptions too closely and paid for their thirst for knowledge with their lives. Since then many scientists and observers studying eruptions have been killed or suffered serious injury. In the last decade alone, due to both the unpredictability and magnitude of volcanic phenomena, several volcanologists have died surveying eruptions [1],[2][3].

At this time 1,500 volcanoes on Earth are potentially active, approximately 500 of which have been active during the 20th century and about 70 are presently erupting. At the beginning of the third millennium, 10% of the world population live in areas directly threatened by volcanoes, without considering the effects of eruptions on climate or air-traffic for example. About 30,000 people have died from volcanic eruptions in the past 50 years, and billions of euros of damage has been incurred. Significant advances in eruption prediction and forecasting have been made in recent years, partly as the result of studies of the major volcanic eruptions at Mount St Helens (USA) in 1980, Nevado del Ruiz (Colombia) in 1985, Pinatubo (Philippines) in 1991 and Unzen (Japan) in 1991. Over the same period significant progress has been achieved in the understanding of how volcanoes work. This is especially true for a few volcanoes in which particular effort has been made. This is the case for Etna, Vesuvius and Vulcano (Italy), Santorini (Greece), Teide (Spain), Furnas (Portugal), Sakurajima (Japan), Merapi (Indonesia), Popocatepetl (Mexico), however many other volcanoes are not sufficiently monitored and a catastrophe like that of Nevado del Ruiz can occur again.

Such reasons together with recent advances in robotics have inspired a new EC project named ROBOVOLC with the aim of designing and building a mobile robot for volcanic exploration whose activities started in March 2000 [4]. The final partnerships includes two Universities (Università degli Studi di Catania, Italy and University of Leeds, U.K.), two industrial organisations (Robosoft, France and BAE Systems, U.K.) and two research organisations who provide expertise in volcanology and cartography: the Istituto Nazionale di Geofisica e Vulcanologia, Italy and the Institute de Physique du Globe de Paris, France.

A major aim of this project is to minimise the risk to vulcanologists and technicians involved in work close to volcanic vents during eruptive phenomena. It should be noted that observations and measurement of the variables relating to volcanic activity are of greatest interest during paroxismal phases of eruptions, which unfortunately are also the periods of greatest risk to humans.

Vulcanologists have identified that a volcano exploration robot should be able to carry out a number of key operations, the most important being the ability to:

- approach an active volcanic vent
- collect samples of volcanic eruption products
- collect other physical and chemical data
- survey close to vent openings

Volcanic gas is quickly contaminated by the atmosphere and is thus empirically worthless to collect for analysis far from the eruptive vent. As this environment is extremely dangerous for humans this is a task suitable for a robust rover robot which can collect more reliable samples and data, close to their volcanic source.

Sites of interest include lava flows, ash and spatter cones and large ground fractures; in general these surfaces are very rough and disconnected and occur close to, or inside, volcanic craters. The ground often has a steep gradient and unstable surface due to loose rocks and sliding materials, therefore the robot needs a sophisticated assembly to move safely and surely. Sometimes the location being investigated will be unexplored so a video link between the rover robot and the operator is essential for safe navigation. A ranging system is useful for both driving and measurement purposes. Finally an efficient data link is required to control the rover and to download collected data.

In order to achieve these goals, new algorithms and software for autonomous and semi-autonomous navigation of a robot in unstructured environments have been developed. For autonomous navigation, we intend that the robot be capable of reaching a given position in the volcanic area autonomously and automatically perform the tasks required to perform the measurements. In the case of very difficult or dangerous situations (e.g. proximity to lava flows or fissures), the robot will be tele-operated and able to act in a semi-autonomous way. In this case, by using a specifically designed user interface, an operator will be able to drive the robot effectively from a safe location. For semi-autonomous use, we intend that the robot will have the capability of autonomously selecting and executing some sub-tasks, e.g. position and speed of individual wheels, measurement operations, etc.

Data collected by the robot will be used primarily to enhance knowledge of volcanic processes. For example close field data collected by the robot during eruptions will be used as input data for computer simulation of volcanic activity to improve forecasts for long-lived volcanic phenomena such as lava flow eruptions.

5.2 Past volcano robot projects

The first stage of the ROBOVOLC project involved the analysis of the state of the art in rough terrain robotics. If attention is concentrated on recent projects with the specific objective of volcanic exploration only a few systems have been developed. However it should be observed that following the successful results of the Sojourner robot on the surface of Mars, many new robots have been designed for planetary exploration. In many cases these robots have been tested in volcanic environments, because of the strong terrain similarities.

In particular this section reviews three distinct volcano robot projects which involve a legged, a wheeled and a flying robot, all of which were tested in volcanic environments. The complete results of all the systems review has been reported in the Deliverable D2.a and partially published in [5].

5.2.1 Dante II

Dante II is a multi-legged frame walking robot designed by NASA and Carnegie Mellon University to investigate live volcanoes and test robotic technology [6],[7],[8],[9]. The robot is a framewalker with eight pantographic legs arranged in two groups of four, on inner and outer frames. A tension-controlled tether was connected to Dante II, to maintain stability and to allow rappelling on steep slopes [10].

In 1994 Dante II underwent a trial exploration of Mount Spurr volcano in Alaska. For more than five days the robot explored alone in the volcano crater using a combination of supervised autonomous control, and tele-operated, control. The robot travelled one-quarter of its 165-m descent autonomously, relying only on on-board sensors and computers to plan and execute its motion. The terrain was very rough including crossing 1-m boulders on ash-covered slopes, navigating areas of deep snow, ditches and rubble. The robot measured the gas composition of several large fumarole vents [7]. However while climbing out of the crater, Dante II lost stability and fell on its side thus ending its mission. The Dante II/Mt. Spurr expedition was considered a success because of the amount of data and experience that was accumulated. Dante II was successful in retrieving data from a very harsh environment such as might be expected on other planets. This trial gave NASA valuable experience in determining what improvement considerations would be needed for future robotic missions.

5.2.2 Marsokhod

The Marsokhod rover is an all terrain vehicle developed by the Mobile Vehicle Engineering Institute (VNIITransmash) in Russia for planetary exploration [11]. The chassis (100cm wide, 150cm long, 35kg unloaded mass) consists of three pairs of independently driven titanium wheels joined together by a three degree of freedom passively articulated frame. This design enables the rover to conform passively to very rugged terrain. The amplifiers, motors and batteries are mounted inside the wheels to provide a very low centre-of-gravity. The robot can travel at speeds up to 12 cm/sec and can traverse obstacles up to 30 cm high and slopes up to 45°. The duration of operation with batteries is approximately 6 hours.

The Marsokhod robot, originally designed for Mars exploration, has been extensively tested in volcanic environments such as in Kamchatka, Russia (1993), Amboy crater in California (1994) and Kilauea Volcano in Hawaii (1995). Kilauea Volcano was selected primarily for its great diversity of geological features similar to those expected on Mars and the Moon [12].

5.2.3 Yamaha Helicopter

Yamaha has been involved in a project for the surveillance of the Mt. Usu Volcano in the Hokkaido region of Japan. For this purpose a special version of the unmanned helicopter RMAX has been developed. Due to the large distances of operation an autonomous flight system has been developed and the cruise autonomy of the helicopter increased to 4km. In April 2000 the helicopter, equipped with four CCD cameras, was successful in performing several surveillance missions observing the hazards caused by volcanic sediment and debris flow [13].

5.3 Requirements and specifications

Technical visits to volcanic sites (Etna, Stromboli and Vulcano) were organised in the spring-summer 2000 and detailed discussions were carried out with vulcanologists, in order to investigate the requirements of a system. An important consideration that was immediately apparent was the extremely rough and difficult volcanic terrain. In Fig. 1 two examples of typical terrain are shown. Moreover ground surface change can occur in a short distance changing from rough lava to rocky surfaces or sandy slopes. As a consequence it was clear that the design of a system capable of coping with all of the possible situations exceeded current robotic capabilities. It was therefore important to concentrate on specific kinds of missions that could be accomplished by the robot on specific types of terrain. It was also decided to place a limit on the negotiable slope of the ground to avoid the necessity of an umbilical cable. In this way the autonomous range can be considerably increased. In particular the distance required for a round-trip mission was assumed to be not more than 2 km. Another important aspect concerned the speed of the system. Many volcanic sites are at a very high altitude, where weather conditions can change rapidly. Moreover during a mission volcanic activity can change suddenly and make the site very hazardous for the robot. An important consequence was a requirement for a driving speed of at least 1.5 km/h. Other specifications have been drawn on the basis of direct measurement of the site, also taking into account that the direct locomotion over hot lava is not required for scientific purposes. Moreover in most situations even if the shortest direct path is very rough and difficult, there was always an alternative path to the target which was easier to negotiate. Other important considerations were dictated by practical and logistic reasons. For example the weight and the dimension of the system was chosen to allow the system to be transported easily to the proximity of a volcanic crater. Usually the roads to reach these sites are not suitable for any type of ground vehicle and in some cases the helicopter transport is the only option.

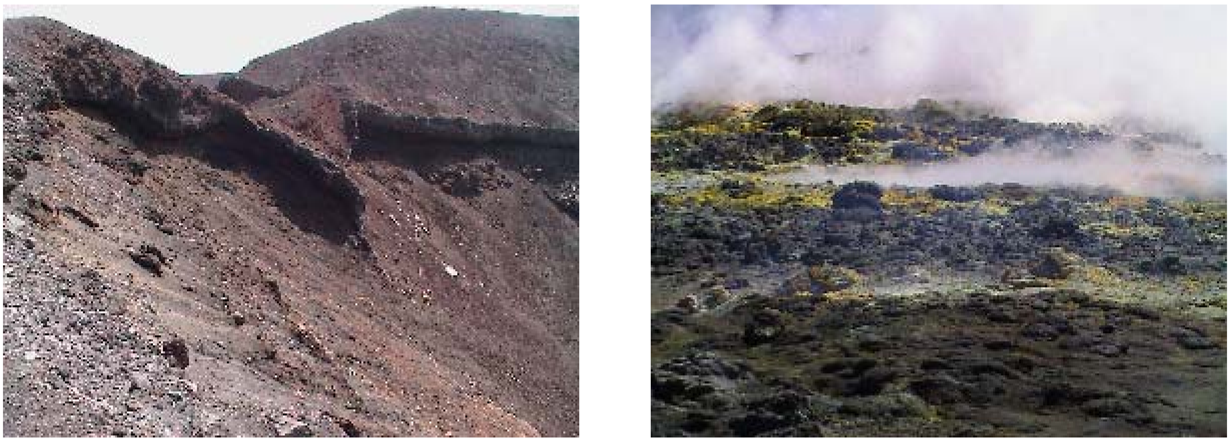
(a) (b)

Fig. 1. Typical terrains found in volcanic sites.

In order to measure volcanic terrain features a four wheel probe was built. This cart, shown in Fig. 2, was manually driven into quiescent craters, to simulate possible paths taken by a robot inside the craters. The probe carried the following instrumentation GPS, encoders in both wheels, a video camera, temperature, humidity and pressure sensors. A more detailed description is reported in the deliverable D2.b and in the articles [14] and [15].


(a) (b)

Fig. 2. The Four wheel probe (a). Trial on volcanic site (b).

Using the measurements and following discussions with the end users the technical requirements for the ROBOVOLC robot concerning the selection of the platform were prepared (Deliverable D2.b). these requirements were then converted into the specification for the system (Deliverables D2.c, D3.1, D3.2).

The main criteria are:

- Modular components of system mass limit : 200Kg
- Maximum overall dimensions of modules: height- 0.8m, width- 1.2m, length- 1.7m

- Static Stability: 40°
- Maximum slope: 35° (minimum requirement is 30°)
- Maximum lateral obstacle height: 0.4m
- Speed: > 0.5m/s
- Maximum payload (scientific instruments and rocks collected): 30kg
- Travel time for a 24 hour mission: 1.5hours

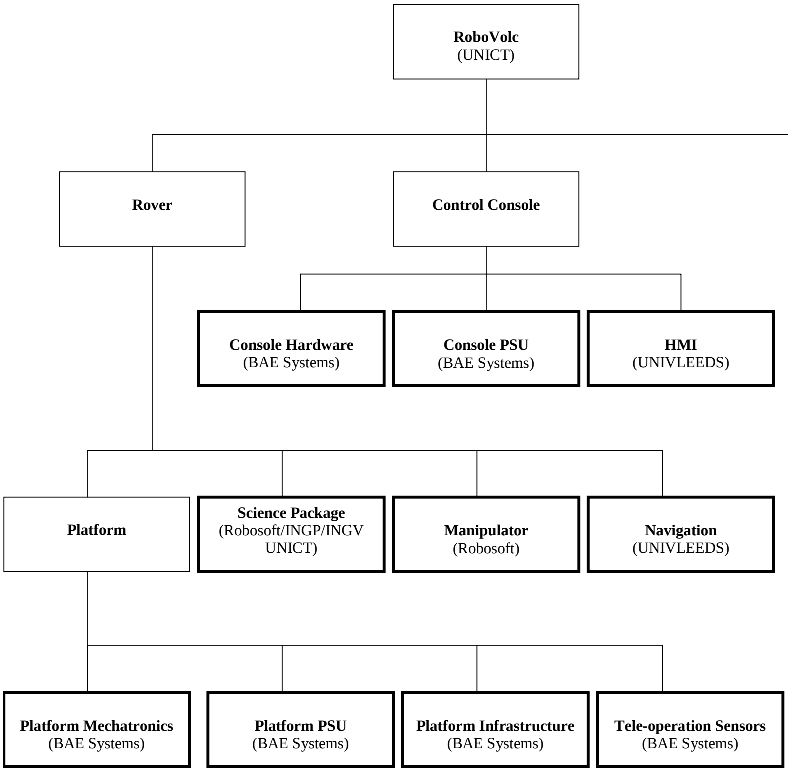

Fig. 3. Block diagram of the ROBOVOLC system.

Is important to stress that the preparation of such requirements and the consequent specifications arose from the fact that the ROBOVOLC consortium decided to design and build a system that could be extremely useful for volcanologists. As a consequence the final system is not a simple demonstrator made for the sake of academic robotic research.

The list of requirements was translated into a detailed list of specifications for the robot subsystems. In particular the subsystems considered are those described by the block diagram shown in Fig. 3.

5.4 Selection of a locomotion architecture

The selection of the most appropriate locomotion technique for the ROBOVOLC system was carried out by evaluating the most promising techniques by comparing certain criteria e.g. reliability, rough terrain performance, suitability for purpose, etc. Eight techniques were evaluated; Tracked, Purely wheeled, Articulated and Cartesian walking robot, Frame walker, Hybrid “legs with wheels”, Flying (Fixed wing and rotary) and a Wheeled rover with High adaptive chassis. The initial selection was based on performance criteria derived from the user requirements, from this the most suitable concepts were under further review. The final contenders for the locomotion system were: Wheeled Rover with High Adaptive Chassis, Hybrid “leg with wheels” and Tracked Robot. These techniques have the potential to meet the requirements. Walking systems are, in fact, best suited for rough terrain but are too slow and difficult to control. Flying robots though extremely promising would have to contend with the additional hazards of strong winds and ash rain that occur near volcanic peaks. Flying robots need complicated control systems and the high payload requirement to carry all the scientific instruments would make the flying robot solution very expensive

Hybrid systems are very promising, since they should have both the advantages of wheeled and legged machines. Some investigation of hybrid systems was also carried out by the University of Catania with the WHEELEG system [16],[17],[18],[19],[20],[21]. Though some successful results were obtained, in some situations the drawbacks of wheeled systems (low traction) and of walking systems (unstable and difficult to control) were apparent.

The final selection of the most suitable concept was achieved by a qualitative assessment against key criteria. The criteria being that the solution be; able to achieve the user requirements and specifications; robust and reliable; easy to use and maintain; and have exploitation potential (cost effective).

The favoured vehicle concept was a six wheeled chassis with a large range active or passive suspension. It is expected that differential steering will be adequate for the specified requirements and improve robustness and reliability.

The selection of a hybrid system with adaptive chassis was based on the trial of two prototypes: the M6 and the L4 platform. The M6, shown in Fig. 4, has an articulated chassis capable of adapting to very rough terrain [22]. However not having a substantial central body, the payload of this system was low. The other solution, trialled with the L4 platform, (without prismatic joints connecting the rear and front wheel axes to the central body) allows higher payload capabilities (Fig. 5).

Fig. 4. The M6 Platform.

Fig. 5. The L4 Platform.

5.5 System description

In this section the main subsystems of the ROBOVOLC system will be described in some detail.

5.5.1 Control console

A user friendly man-machine interface was designed to allow the final users (the volcanologists) to drive the vehicle during the missions without specialist knowledge of the system. The control console allows users to remotely control the robot from a safe area. Two separate PCs make up the control console. The first one is specifically dedicated to drive the vehicle, while the second one is to control the scientific instruments.
The robot control console will be situated at a base station a safe distance from the volcano. The control console will operate software with which the robot will be commanded and feedback displayed. The control console's user interface is designed with the intention of providing the final users with the functionality to tele-operate the robot without specific knowledge of robotic systems, see Fig. 6 for user interface component designs. The control of the robot is accomplished by two joysticks and touch-screen/mouse input. Ergonomic considerations have been taken in account in the design of the HCI as a mission can be expected to be several hours in duration so employing graphics and customisable GUI (graphic user interface) is intended to reduce the eye-strain involved in understanding the various information displayed in the screens.

The science instruments will be controlled via a separate PC connected to the robot via LAN, using a http connection this will allow the science sensors to be controlled via a web-page interface.

Control of the low level functionality of the Rover (e.g. accessing localisation data, arm and Pan Tilt control) is implemented by RPC (remote procedure calls).

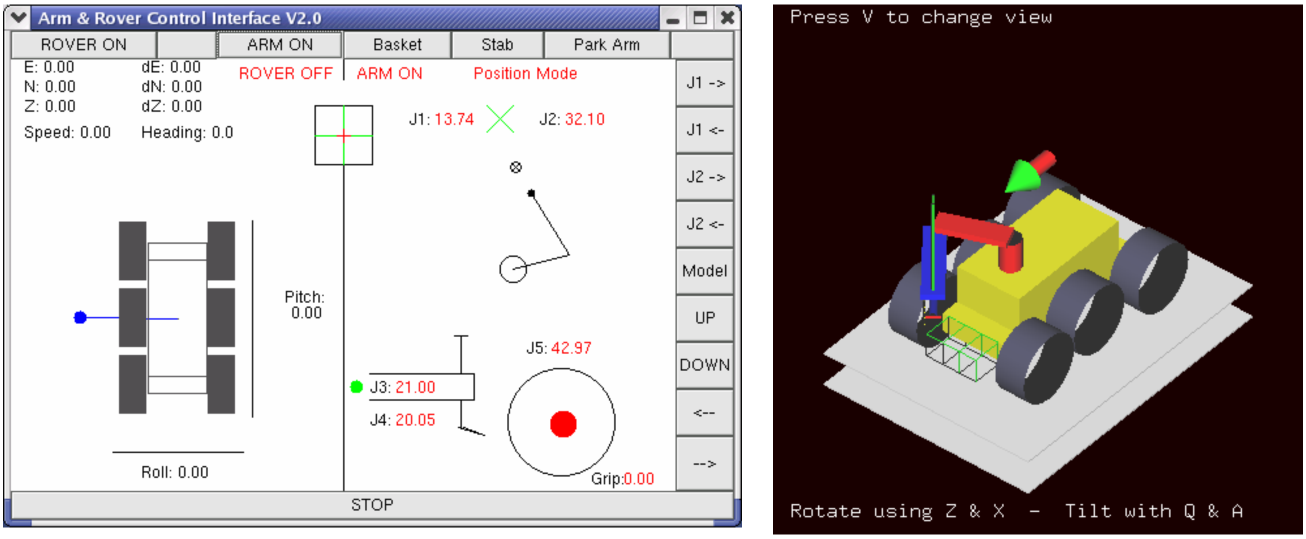

Fig. 6 User interface design.

5.5.2 Communication system

The telecommunications system is based on a redundancy system. This uses a standard high-power wireless LAN interface, for most of the data exchange at a high data rate (10Mbps) and a low speed radio modem (100kbps), for essential tele-operation e.g. when the robot is out of the line of sight of the base station.

5.5.3 Navigation system

Navigation can be divided into several stages. The position of the robot must be determined (localisation); its surroundings must be sensed and mapped; and finally decisions must be made as to how best to proceed. For most operations the decision-making process will be handled by a human operator (teleoperation), though a limited amount of autonomy is included for simple tasks such as repeating a previous path. This leaves the issue of sensing the robot’s position and environment.

Localisation system

The function of the localisation system is to determine the exact location of the robot both for navigation purposes and also to allow the volcanologists to reconstruct the terrain morphology. The main sensor adopted for localisation is a DGPS (Ashtec model Z-Xtreme) based on a Real Time Kinematic Differential GPS (RTK-DGPS) algorithm with an optimum position accuracy lower than one centimetre.

The precision of the DGPS can vary drastically. This can be caused by the loss of communication with the differential correction signal or to the interference of satellite signals reflected by nearby rocks. In these cases the accuracy of the DGPS can drop to several meters. However, a data fusion algorithm has been designed to optimise the accuracy of localisation data from the DGPS by merging it with input from other sensors. The sensors inputs include odometry data from the wheel encoders, rate of turn from a gyroscope, absolute orientation from a magnetic compass and the attitude of the robot measured by a two axis-inclinometer. The optimisation algorithm is based on an Extended Kalman Filter and the inputs are pre-filtered using a Fuzzy logic rule based procedure. When the DGPS signal is not reliable the algorithm automatically selects the most accurate sensor at the time. The shortcomings of each sensor are briefly described here (Details enclosed in Deliverable D4.fin and D7.fin). Encoder odometry is good for rectilinear trajectories, but is very bad during turning phases. In fact the skid-steering system does not allow a precise orientation measurement from the wheel positions during turns. On the other hand the gyroscope is an accurate sensor during turning phases, but it can only be relied on for brief time periods, the ever present drift in the sensor produces an accumulating orientation error. The compass is a good absolute heading sensor but is subject to the magnetic fields generated by the electrical brakes and motors, and is unlikely to be very accurate during motion.. Moreover volcanic rocks are often strongly magnetic, thus the compass orientation cannot be expected to be highly reliable. However, when the robot is stationary, the magnetic compass should provide a practically accurate heading estimate and is the only sensor available that can give an absolute orientation at the beginning of a mission or after a change of orientation.

The results of the data fusion algorithm have demonstrated a capability to maintain an accuracy of position lower than 3cm during periods of DGPS failure, even when the vehicle is continuously turning.

Mapping and obstacle avoidance

The Autonomous Navigation is based on Meystel's hierarchical structure that models the cognitive processes employed in human navigation (e.g. when a person drives with a map). The rover will need to autonomously navigate in situations where the tele-operation is not available e.g., when the control signal is broken.

The autonomous navigation is implemented in a four-layer structure, shown in Fig. 7 (these layers are; long range planning, short range planning, instantaneous path and the motion control layer). These are described below.

The long range layer is concerned with the definition and management of the map based way-point path for the robot, this component informs the short range path layer what the current set of nearby way-points is.

This short range layer manages the navigation of the robot to the current waypoint objective (and signals to the long range layer when this is achieved). Also it communicates to the instantaneous path layer which direction the robot should head in and the preferred alternative direction if an obstacle is encountered.

This instantaneous path layer receives the heading instructions from the short range path layer and decides what path to take from the terrain data that it has. The terrain data is based on the scanning laser terrain model and tilt/attitude data from the localisation unit.

The motion control layer processes the low level motion control commands sent to it from the instantaneous path layer.

The four layer structure is shown diagrammatically in Fig. 7.

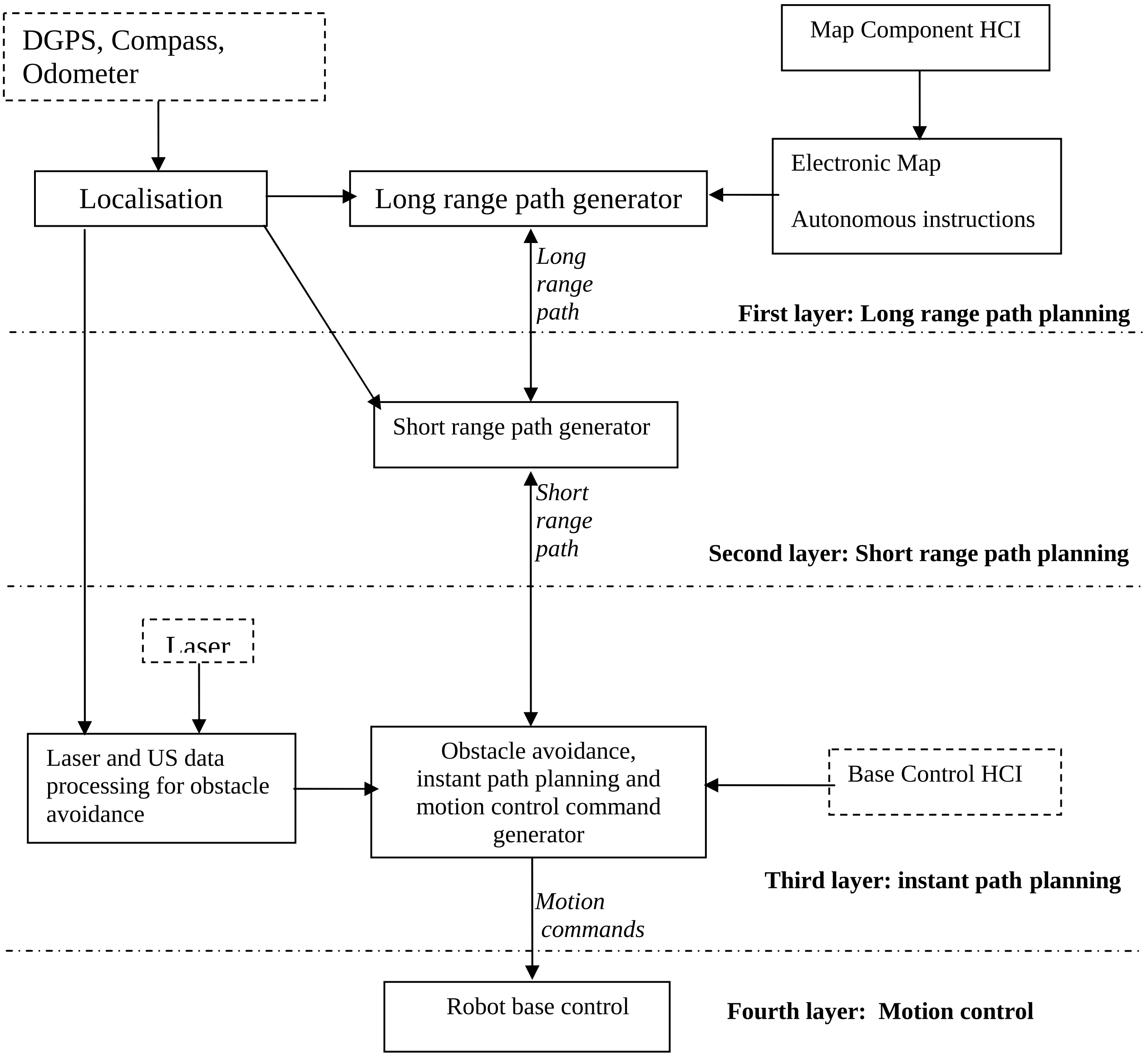

Fig. 7: Four layer autonomous navigation structure.

5.5.4 Platform

Platform mechatronics

As described earlier the platform is a six-wheeled system with an articulated chassis. The system has been equipped with semi-active joints connecting the front and rear axes to the body. These joints consist of two springs which have controllable stiffness. Tests over volcanic surfaces have revealed that this system outperforms some of the requirements coupled with the quality of mechanical robustness.

Platform Power supply Unit (PSU)

The chosen power supply solution employs lead acid batteries, however to extend mission duration a hybrid Internal Combustion (IC) engine has been designed and manufactured. The optimum mode of operation would be to use the IC generator in combination with the batteries, as a back up and recharge system. This arrangement would greatly extend mission duration and enhance the capability of the system.

Computer infrastructure

The infrastructure design is based on the utilisation of general purpose embedded computer boards, with a combination of COTS and bespoke software running on these platforms. The various tasks are distributed over three PC104 based computers located in the rover. The distribution of the Robovolc systems across three computers was chosen because it increases the reliability of the individual components. This is particularly true for rover motion control, with one PC dedicated to motion control, this reduces the likelihood that a failure in one of the other systems will result in the rover being unable to move.
The three PC's and their tasks are allocated as follows :

- Rover PC (Linux OS): Rover motion, Low-Speed Communications, Traction control, Navigation control, Rover motion sensors
- Manipulator PC (Linux OS) : Manipulator motion,
- Science PC (Windows OS): Video inputs & switching, Localisation, Gas analyser, Geophysical sensors

The motion controllers selected are RoboSoft RMPC-555. These motor controllers are to be used for both Rover and Manipulator motion and are interfaced to the PCs through a CAN network.

Tele-operation sensors

The tele-operation of the robot on volcanic terrain is not a trivial task (see Fig. 8), since all the wheels should be observed and a good view of the frontal area is also fundamental. Consequently four fixed cameras have been installed on each side of the rover and a camera with zoom capability is mounted on the pan/tilt turret. Also during tele-operation in active volcanic areas the use of an infrared camera will help avoid hazardous hot regions. Information from the inclinometers is also available to the operator to maintain the stability of the rover.

5.6 Science package

The Science package can be decomposed into three main subsystems: the Manipulator, the Pan-tilt turret and the gas sampling system.(Details described in D4.fin).

5.6.1 The manipulator

A 5 degree of freedom SCARA manipulator has been specifically designed for the Robovolc system. Fig. 9 shows the manipulator mounted on the rover. The manipulator will be adopted to collect samples of rocks, to drop and pick up instruments at specific locations and to collect gas samples in the proximity of fumaroles. It's actuators are DC motors with encoders for position feedback. A three-finger gripper, shown in Fig. 10, has been designed with force sensors to pick up rocks with a maximum diameter of 15 cm.

5.6.2 Pan/Tilt turret

On the Pan/tilt turret (Also visible in Fig. 9)the following sensors are installed: a digital video-camera recorder, a high resolution still-image camera, a video-camera, an infrared camera and a Doppler radar for gas speed measurement. The user can orient the turret and can tele-operate all the installed sensors.

Fig. 8: Test of the platform in rough terrain

Fig. 9: The complete final system.

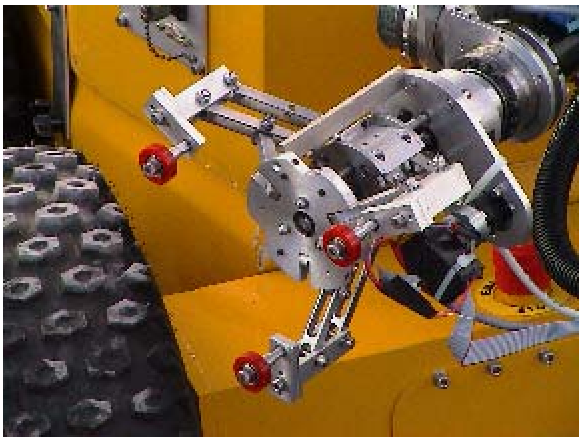

Fig. 10. Close up of the gripper.

5.6.3 Gas sampling system

Gas sampling is the most important measurement to be carried out by the robot. The analysis of the gas ejected from volcanic vents is one of the main indicators of volcanic activity. The main problems with this operation are: sampling gas that reach temperatures above 600°C ; the presence of extremely corrosive acid components; and the avoidance of gas mixing with the surrounding atmosphere resulting in corrupted samples.

To perform precise sampling a new system has been specifically designed for the Robovolc project. The system is composed of:

A probe for sampling the gas: This probe is comprises a small diameter titanium tube 1.5 m long, with a thermocouple on its tip and an Oxygen sensor. These two sensors will be used to assess the quality of the samples to be taken. The probe is also equipped with a thermal control system with the purpose cooling the gas temperature below 200°C to allow the gas to flow through flexible Teflon pipes. At the same time the temperature must also be maintained over 120°C to avoid water condensation that can corrupt the measurements.

A gas collection system: this system is made of teflon pipes, a set of valves, pumps, dryer and condensers to initially clean the circuit and to collect the gas samples in two bottles, when the samples are assesses to be reliable. A CO_2 sensor and several termocouples are also included in the circuit.

A set of gas sampling bottles: at the top of these bottles a high degree of vacuum is maintained, while the bottom of each bottle is filled with NaOH. When the valves in the bottom of the bottle are opened the gas sample will enter the bottles.

A tele-operated control system will allow the sequence of operations for sampling and measurement to be controlled.

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6. Test Campaign 3-14 September 2002

Venue: INGV Nicolosi, Catania, Italy and Pizzi Deneri observatory.

6.1 Attendees

1. UNICT : Giovanni Muscato, Salvatore Guccione (3-6), Domenico Longo (2-12) Michele Prestifilippo (11), Giuseppe Davide Bruno, Daniele Caltabiano, Vincenzo Sacco, Yuri Ciardo.

2. INGV : Mauro Coltelli, Emilio Pecora (5-13) , Antonio Cristaldi.

3. IPGP: Francoise Guillon, Pierre Briole (9-11).

4. UNI-PO: Exit from project.

5. PORTECH: Exit from project.

6. ROBOSOFT: Antonella Semerano (12), Pierre Pomiers (9-14) , Benoit Rameix (9-14)

7. BAE SYSTEMS: Glen Callow, Richard Alexander, Dave Gough.

8. UNIVLEEDS: Gurvinder S. Virk (12-14), Patrick Sim.

6.2 Introduction

6.2.1 Monday 2 September 2002

Arrival of : G. Callow, R. Alexander, D. Gough (BAESYSTEMS), P. Sim (UNIVLEEDS), F. Guillon (IPGP). Arrival of First robot prototype. Welcome dinner and arrangement of agenda for the next days.

6.2.2 Tuesday 3 September 2002

Arrival of ROBOVOLC robot. Setting up the Laboratory at the INGV Nicolosi.
Unpacking and testing of both robots. Locomotion test in the lab.

6.2.3 Wednesday 4 September 2002

Preliminary integration test and laboratory test.
Test of locomotion.
Test of Radio LAN.
Test of sensor interfaces (pan tilt, and videocamera).

6.2.4 Thursday 5 September 2002

First field trial at Pizzi Deneri with the First prototype. The first prototype is a simpler version of the final system that has been adopted to perform test on navigation and traction.
Traction and locomotion tests in volcanic environment.

Navigation tests with DGPS and with Laser scanner.

Fig. 11Locomotion and Navigation test with the first prototype.

Fig. 12 DGPS reference station and Pizzi Deneri observatory (INGV)

6.2.5 Friday 6 September 2002

Integration of localization system in the ROBOVOLC prototype.
Integration of sensor system in the ROBOVOLC prototype.
Test of localization.

Test of navigation of the First prototype.

Integration of the user interface with the ROBOVOLC system
Integration of the gas sampling system with the ROBOVOLC system.

6.2.6 Monday 9 September 2002

Test of Localisation system
Arrival of Pierre Pomiers and, Benoit Rameix (ROBOSOFT).
Arrival of manipulator
Mechanical and Electrical integration of the manipulator, test of manipulator.

6.2.7 Tuesday 10 September 2002

Mechanical and Electrical integration of the Manipulator
Software integration of the manipulator and of the traction system

Navigation trials at Torre del Filosofo (Etna) with the First prototype

Fig. 13 Localization trials in laboratory and integration of manipulator and sensors

6.2.8 Wednesday 11 September 2002

Laboratory tests of the ROBOVOLC prototype
Arrival of A. Semerano (ROBOSOFT) and G.S. Virk (UNIVLEEDS)
10 ROBOVOLC meeting
Departure of A. Semerano

6.2.9 Thursday 12 September 2002

Trials of the ROBOVOLC prototype in volcanic terrain
Test of manipulator, test of pan/tilt

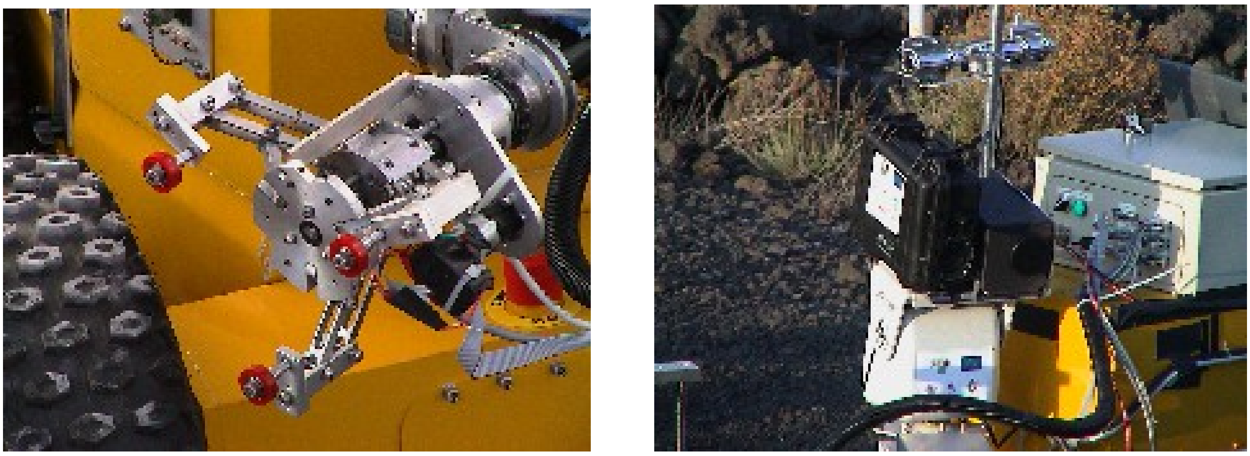


Fig. 14 Gripper and pan-tilt with Digital videocamera and IR camera

Fig. 15 Trials of the complete system on volcanic surfaces

Fig. 16 Transportation of the system

6.2.10 Friday 13 September 2002

Trials of ROBOVOLC prototype at Piano delle concazze
Test of locomotion capabilities on rock and sand areas.
Test of radio lan, test of video transmitter.

Fig. 17 Trials of the vehicle on hard lava surface (3000m altitude) at Piano delle concazze ETNA.

6.2.11 Saturday 14 September 2002

Final trials of ROBOVOLC prototype
Test of gas sampling probe on the arm (Fig. 18).
Final meeting.
Packing all material.

ì

Fig. 18 Test of the gas sampling probe

6.2.12 Sunday 15 September 2002

Departure of all people

7. Trial of Radio Doppler, Etna 20 December 2002

Venue: Torre del Filosofo (Nicolosi), Italy

7.1 Attendees

1. UNICT : Giovanni Muscato, Salvatore Guccione, Giacomo Spampinato.

2. INGV : Mauro Coltelli.

7.2 Introduction

This technical visit was performed during the December 2002-January 2003 eruption to test the capabilities of the radar doppler to perform measurement of gas speed and of lava flow speed.
The site was reached by using an Helicopter of the Italian Civil Protection. A portable test system was designed to perform such measurements.

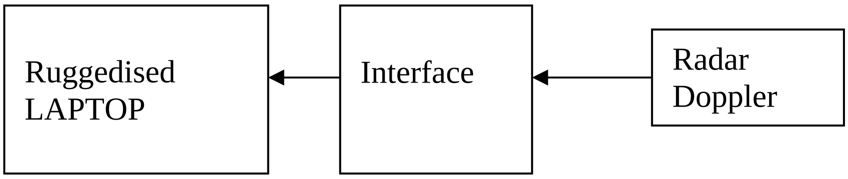


Fig. 19. Block diagram of the test system designed

However both the measurement were unsuccessful. The radar doppler had not the required power to be able to measure gas jet speed, while the minimum measurable speed of 1mph was too high to allow the measurement of lava flow speed.
Further investigation will be performed to find a different sensor more suitable for this kind of measurements.

8. Test campaign Nicolosi, 30 June 2003 – 4 July 2003

Venue: INGV, Nicolosi, Italy

8.1 Attendees

3. UNICT : Giovanni Muscato, Salvatore Guccione, Domenico Longo.
4. INGV : Mauro Coltelli, Antonio Cristaldi, Michele Prestifilippo, Daniele Caltabiano, Luciano Cantelli, Giacomo Spampinato.
5. IPGP: Pierre Briole, Nicolas Houlie, Marcello de Michele.
6. UNI-PO: Exit from project.
7. PORTECH: Exit from project.
8. ROBOSOFT: Aida Goumbele, apologies from Dominique Touya
9. BAE SYSTEMS: Tim White, Richard Alexander.
10. UNIVLEEDS: Gurvinder S. Virk, Patrick Sim.

EC: Apologies from Prof. M. Bergamasco and Dr. M. Verdese.

8.2 Introduction

This second test campaign included the review meeting and a press conference to demonstrate the capabilities of the Robovolc system to the public.

Each of the Robovolc subsystems was tested during the review and the results are summarised in the following sections.

8.3 Result of the tests

8.3.1 Communications

The communication system consists of a long-range Wireless LAN that allows all the computers inside the rover (Rover PC, Manipulator PC, Science PC) to be interfaced with the Console PC. A low-speed serial modem as backup is connected to recover situations when the wireless communications fail. No problems have been observed with the wireless LAN during the trials. A video/transmitter and receiver connects all the video equipment on the rover to the base station. The input of the transmitter is connected to a remotely operated switch to select a video channel at a time. Initially the transmission were received in Black and white. Following a small modification of the transmitter and receiver the problem has been solved and the video transmitter worked well.
The other communication system was the connection between the base DGPS and the rover DGPS for the transmission of the differential signals. This transmission has generated sometimes some problems and the differential signals in some trials was not received. The problems was mainly due to the high power of the transmitter that during trials performed in a

short distance caused some problems in the receiver. When the trials have been performed in longer distance the problem was no more observed.

8.3.2 Console Hardware

The console hardware consists of two ruggedised laptop PC connected in a LAN to the wireless LAN receiver. The first laptop is devoted to the teleoperation of the rover and of the manipulator through a graphical interface and two joysticks. The second laptop is devoted to the teleoperations of the science package. A video monitor is connected to the video receiver to show the video signals coming from the rover. A protective carry case host the rover laptop, the joystick the video monitor, the wireless lan receiver and the lan switch. Some improvement should be done in the assembly of all the subsystems in the protective case to speed-up the set-up of the system on the field.

8.3.3 Console PSU

All the equipment in the Console are powered by using a 1kW 220V Internal combustion generator. No problems have been observed in the adoption of this system.

8.3.4 HMI

The HMI allow to teleoperate the rover by using the joystick. Some modifications have been suggested and implemented during the trials to allow to change the speed of the rover.

The HMI allow also to teleoperate the manipulator in different modalities by using the joystick. The teleoperation allowed during the trials to remotely control the arm to collect samples of rocks.

8.3.5 Science Package

Consists of:

- Pan tilt: The Pan-tilt allow to orientate the following sensors mounted on it: Infrared camera, videocamera, videorecorder camera, High resolution still image camera.
- IR camera: teleoperated in most of the setting and operation allow to view thermal map of the environment and to shoot thermal images stored in a flash memory card on-board.
- Videocamera: telecontrolled in most of the operation allows to telecontrol the system in most of the operations.
- Videorecorder camera: Allows to record on a DV tape the images. Most of the main operations (on/off, record, zoom in/out) can be teleoperated.
- High resolution still image camera: Allows to store HR images into a Compact flash. The teleoperations consists in the shooting of the images and the download of the images.
- Gas sampling system: It has not been tested during this trial and will be tested in the next trial campaign.
- DGPS: The DGPS is adopted to sample the position of the rover to reconstruct terrain deformations.

8.3.6 Manipulator

The manipulator movement has been tested successfully. The arm was capable to collect sample of rocks and put them inside a basket through teleoperation. Some improvement are needed in the protection of the manipulator from dust and rain. Moreover to avoid damages of the manipulator during transportation some locking system, to be adopted when the system is not in use, should be installed.

8.3.7 Navigation

The navigation system has been tested by using teleoperation. Several cameras have been installed to view front and rear of the rover and on the gripper to help during rock picking.
Autonomous navigation was not tested and will be tested during the next test campaign.

8.3.8 Platform Mechatronics

The rover has been tested on sandy terrain and in more hard surfaces. During the test on the sand some problem in the traction of the rover occurred. These problems have been almost solved by using a different type of tyres, moreover during the next test campaign a different low level control system will be adopted to improve the traction control of the rover.

8.3.9 Platform PSU

The two groups of batteries gave the system the needed autonomy to fulfil the requirements.
An additional charger should be adopted to allow to recharge in parallel both groups of batteries.

8.3.10 Platform Infrastructure

No problems have been observed in the platform infrastructures.

8.3.11 Tele-operation Sensors

A video camera with zoom was installed on the pan/tilt, four fixed cameras have been installed to view the four corners of the rover and two extra fixed cameras have been used to view the manipulator. The cameras are connected to a remotely controlled video switch to select one channel to be remotely transmitted to the base station. The position and orientation of the fixed cameras can be adapted each time to each specific mission.

8.4 Field trials

Three different environments have been selected for the trials:

8.4.1 28 June 2003.

Trials on soft sand. Traction control is required. Extra tyres needs to be tested. Test of manipulator in picking rocks performed successfully. Test of teleoperations performed successfully. Test of sensors for science performed successfully.

8.4.2 1 July 2003.

The rover has been successfully teleoperated to move inside one the crater of the eruption Dec 2002-Jan 2003. Traction performing successfully on rocky terrain. Manipulator test and sensor for science test not performed since battery not fully charged and voltage going down rapidly. Test of different tyres on sand terrain performed successfully.

8.4.3 2 July 2003

Press conference. Demonstration on volcanic environment performed successfully, showing teleoperation, sensors for science and gripping of rocks.

8.4.4 4 July 2003.

Test of gas sampling system performed at INGV labs. The system has been tested to simulate a gas sampling procedure inside a gas fumarole.

Fig. 20 1st July. The robot moving inside one the crater of the eruption Dec 2002-Jan 2003.

Fig. 21 Manipulator and pan-tilt turret

Fig. 22 Picking a rock sample

Fig. 23 Change of tyre type

Fig. 24 Transportation on test site

Fig. 25Test of different tyre type

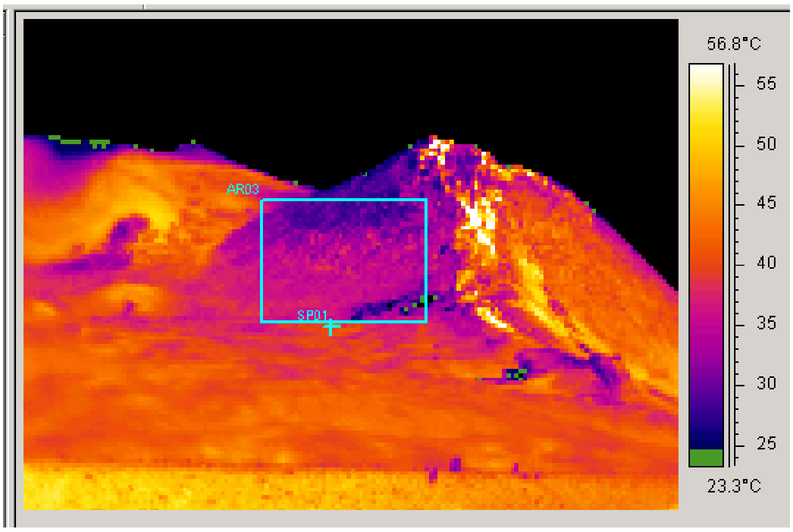


Fig. 26 Thermal image of the S.E. crater done by the robot with the IR camera

9. Nicolosi, 10 August 2003 – 14 August 2003

9.1 Attendees

1. UNICT : Giovanni Muscato, Salvatore Guccione, Domenico Longo.

2. INGV : Antonio Cristaldi, Michele Prestifilippo, Daniele Caltabiano, Luciano Cantelli, Giacomo Spampinato, Emilio Pecora.

3. IPGP: .

4. UNI-PO: Exit from project.

5. PORTECH: Exit from project.

6. ROBOSOFT: Benoit Rameix, Pierre Pomiers

7. BAE SYSTEMS: Richard Alexander.

8. UNIVLEEDS: Vincenzo Sacco.

9.2 Introduction

The purpose of this trials was to integrate into the rover the new traction control system and to test it. MPC555 boards have been installed inside the robot for the low level control of the speed of the robot, thus allowing individual control of the speed of each wheel.
The system has been tested in the INGV laboratory of Nicolosi and has shown considerable improvement.

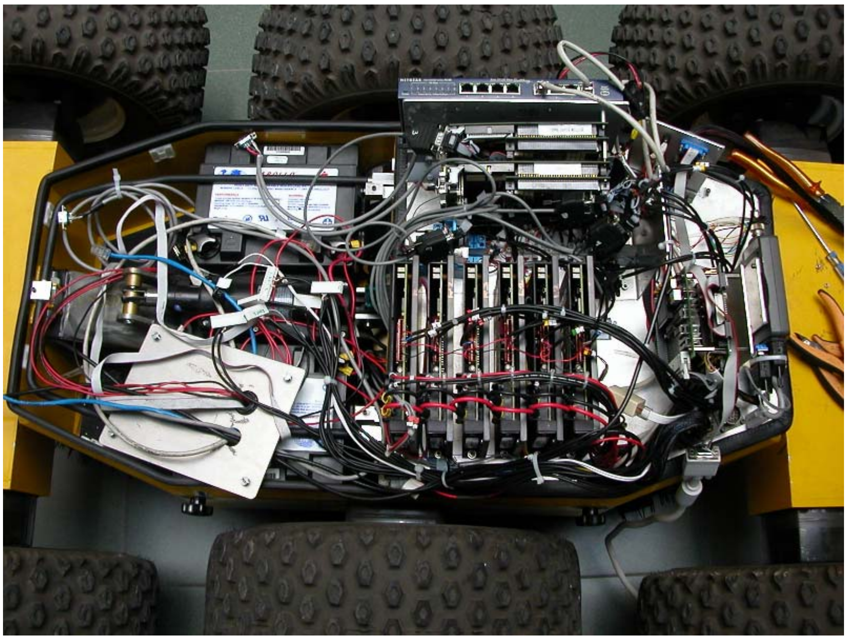


Fig. 27 Internal view of the robot with then new low level control boards installed

Fig. 28 Traction control test at INGV laboratory in Nicolosi

Fig. 29 Climbing capability test at INGV laboratory in Nicolosi

10. Nicolosi, 18 August 2003 – 23 August 2003

10.1 Attendees

1. UNICT : Giovanni Muscato, Salvatore Guccione, Francesco Russo.
2. INGV : Antonio Cristaldi, Daniele Caltabiano, Luciano Cantelli, Giacomo Spampinato, Emilio Pecora.
3. IPGP: .
4. UNI-PO: Exit from project.
5. PORTECH: Exit from project.
6. ROBOSOFT: .
7. BAE SYSTEMS: .
8. UNIVLEEDS: Vincenzo Sacco.

10.2 Introduction

During this period extensive test on the localisation system were performed. The details are reported in the deliverable D7.fin.

The localization algorithm is a key factor in semi-autonomous mobile robots in outdoor environment. A fail on the localization algorithm can compromise the mission outcomes and might drive the robot in critical places.

The navigation system of Robovolc requires an estimation of the absolute position and orientation of the robot with the following characteristics:

- Reliability even if no absolute correction is available for short periods.
- Availability of new samples with a frequency higher than 10 Hz.

Fusing of some dead-reckoning sensors with some absolute sensors can lead to the desired requirements.

Actually dead-reckoning sensors, like encoders, can give a good estimation of relative movements with a very high frequency (e.g. 1 KHz) but their accuracy decreases with time due to wheel slippage, sensors biases or not exact knowledge of the robot model.

A Differential GPS (DGPS) system can give very precise measures of the position but it can not estimate the orientation of the robot, moreover its estimations can become really unreliable if large obstacles (like big rocks in the mountain or tall buildings in the city) reduce the number of visible satellites or the differential correction of the other receiver is lost, finally its sampling frequency is generally low (e.g. 1 Hz).

For this reason it has been chosen to use an Extended Kalman Filter (EKF) that, fusing the measurements of both kind of sensors, can collect the qualities of all the sensors and obtain fast and accurate measures; in fact the GPS compensate the uncertainty of the dead reckoning sensors while the latter permit to have estimations at high frequencies.

Detailed description of the localisation system is described in the deliverable D7.fin. In the following a short summary of the results obtained during these trials is reported.

10.3 Summary of results

10.3.1 Test of the EKF_3 algorithm.

This algorithm allow a faster recovery of the initial orientation of the system with respect to a classical EKF by using an estimation of the orientation measure. In the following figures the small circles are proportional to the variance of the measures.

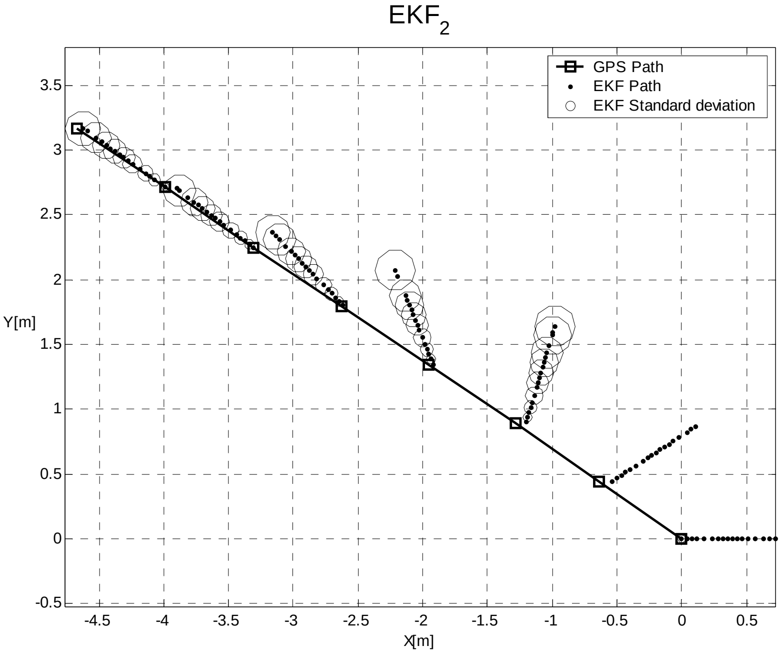


Fig. 30 Transient of the EKF_2 algorithms of the Robovolc tests.

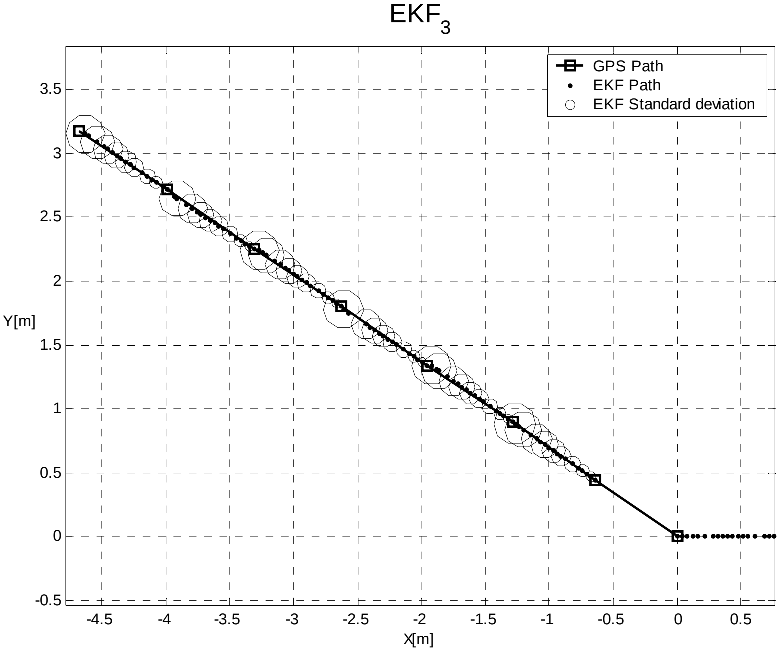


Fig. 31 Transient of the EKF_3 algorithms of the Robovolc tests.

10.3.2 Self calibration of kinematic parameters.

The EKF relies both on the DGPS system and the odometry sensors, if for a while the DGPS system is not reliable (due to multi-path effect or insufficient number of visible satellites or loss of the differential correction) the algorithm must be able to produce good estimation of the position and orientation of the robot and allow the user to move the robot to a safer place.

The quality of these estimations depend strongly on the parameters of the model, hence find the right parameters is very important and allow longer movements without the GPS.

A self calibrating procedure based on an Extended Kalman Filter with augmented state has been developed and tested.

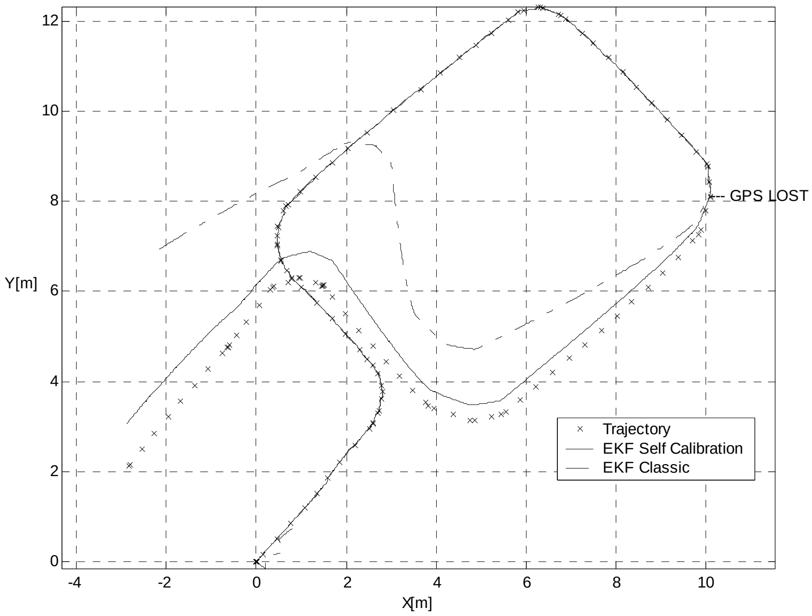


Fig. 32 Comparison between the estimated trajectories obtained with the standard EKF and the EKF$_{SC}$ during the Robovolc tests.

11. Nicolosi, 25 August 2003 – 29 August 2003

11.1 Attendees

1. UNICT : Giovanni Muscato, Salvatore Guccione, Francesco Russo, Domenico Longo.

2. INGV : Antonio Cristaldi, Daniele Caltabiano, Luciano Cantelli, Giacomo Spampinato, Emilio Pecora, Mauro Coltelli.

3. IPGP: .

4. UNI-PO: Exit from project.

5. PORTECH: Exit from project.

6. ROBOSOFT: Benoit Rameix.

7. BAE SYSTEMS: .

8. UNIVLEEDS: Vincenzo Sacco, Patrick Sim.

11.2 Introduction

The purpose of this test period was to integrate the arm manipulator into the system with the last modifications performed, to validate the traction control system on volcanic environment, to test teleoperation of the system and to perform further test of the sensor for science sub-system.

11.2.1 27 August 2003

Trials in Nicolosi Monti Rossi site. Traction control test with different type of tyres and with the traction control system.

11.2.2 28 August 2003

Trials of the gas sampling system. A complete simulation of a gas sampling operation in the laboratory was performed (Details reported in Section 12).

Fig. 33Test of the gas sampling system

11.2.3 29 August 2003

Trials on Etna on the base of the Laghetto crater (January 2002 eruption). Test of the manipulator, test of the user interface.

Fig. 34 Picture of the 2002 crater taken by the robot.

Fig. 35. 29 August 2003 : from the left : P.Sim, G. Spampinato, S. Guccione, E. Pecora, M.Coltelli, G. Muscato, G. Giudice, L. Cantelli, V. Sacco, D. Caltabiano.

12. Test of gas analysis and sampling system

(Prepared by Gaetano Giudice and Salvatore Giammanco (INGV))

12.1 Vulcano island 11 April 2003

During the mission of 11 April 2003 at Vulcano Island the materials and sensors to be used for the geochemical system on RoboVolc have been tested.

The titanium probe designed for the project has been used. The probe is 1.5 m long, with internal diameter of 4 mm. It is heated externally with a heating element of total power of about 100 W, so as to keep the fumarolic gases inside the probe at a temperature higher than 100 °C. This in order to avoid both the condensation of steam and the chemical and isotopic fractionation of gases.

The tests to verify the correct operation of the system have been carried out at the Spiaggia di Levante beach on Vulcano, near the Mud Pool. The sampling system for the fumarolic gases was made of an inverted pyrex funnel placed into the ground to a depth of about 20 cm and then connected with the titanium probe.

The absence of air in the sampling system has been verified using a infrared spectrophotometer calibrated for the determination of CO_2.

Fig. 36: Test of gas sampling system in Vulcano island.

After this procedure a sampling pump has been activated with a flow of 0.85 l/min, the condenser has been cooled with ethylic ether and the condensed fluid has been collected in a flask.

In the second phase of the sampling the valve to the condenser has been closed; in this phase the pump has been turned off and the tap of the caustic soda bottle was slowly opened to sample the fumarolic gases according to the traditional method of Giggenbach. With this procedure two samples have been collected with a sampling time of 8-10 min for each.

In the third phase of the sampling the dry gases have been collected by turning the pump on again and opening the valve. Because of problems due to the small dimentions of the flow-through hole of the valve, which impeded the flow of gas, the valve itself has later been bypassed.

In order to compare the obtained results, samples of gas have also been collected with the traditional methods, both with alkaline bottles and with samplers for dry gases.

12.2 Results obtained

<u>Caustic soda bottles:</u> comparison of the analytical results highlighted a marked difference between the RoboVolc samples and those collected with the traditional method. Most evident are the higher

H_2 concentrations in the samples collected by the RoboVolc. This is to be ascribed almost certainly to hydrogen release by hydrolisis catalyzed by the titanium probe.

	Data	**He(ppm)**	**H2(%)**	**O2 (%)**	**N2 (%)**	**C0(ppm)**	**CH4(%)**
RoboVolc	11.04.03	27.7	61.2	0.16	33.9	10.8	4.87
Trad. Meth.	11.04.03	24.1	29.7	<l.d.	68.8	6.15	2.7

The data of dry gases (Table below) show the presence of air in the sampling system, probably due to a non perfect seal of the flask tap.

	Data	**He(ppm)**	**H2 (ppm)**	**O2 (%)**	**N2(%)**	**CH4(ppm)**	**CO2(%)**
RoboVolc	11.04.03	<l.d.	6663	11.3	46.4	594	41.7
Trad. Meth.	11.04.03	<l.d.	16800	1.51	7.59	1317	89.24

The results of the isotopic analyses on $\delta^{13}C$ in the samples collected with both methods do not show marked differences, with values of -3.6±0,1 ‰.

The obtained data allow to highlight some aspects of the sampling system that can be summarized in the following points:

1. the system comes up with our expectations. It is therefore possible to collect samples with a reliability comparable with the traditional methods of collection;
2. new materials must be tested in order to limit air contamination;
3. the titanium probe must be substituted with a new one made of iron or stainless steel, avoiding in any case zinced material;
4. the use of ether is to be discouraged due to logistic problems, to its toxicity and its flammability. We think that water can be used instead, together with a small radiator in order to disperse the heat of condensation;
5. the teflon valve must have a diameter compatible with the flow of condensed steam collected by the sampling system.

Following the test made at Vulcano, the geochemical sampling system has been improved in accord with the remarks reported.
A water radiator and a pump for the dispersion of the heat of condensation have thus been inserted.
The teflon electrovalve has been substituted by another one with a higher flow.
We used a cilindrical condenser made intentionally to grant impermeability to external air.
Furthermore, the sampling and measuring devices have been inserted into protective boxes made of metal grids; this allows to easily disperse the heat while at the same time allowing a good visibility from the outside and a reasonable protection from collisions.

The final version of the system is composed of five parts:

1. probe for gas collection
2. systems for sampling of acid gases and condensation of steam
3. system for sampling of dry gases and measurement of CO_2 content
4. device for control, data acquisition and power supply
5. probe for the determination of oxygen content

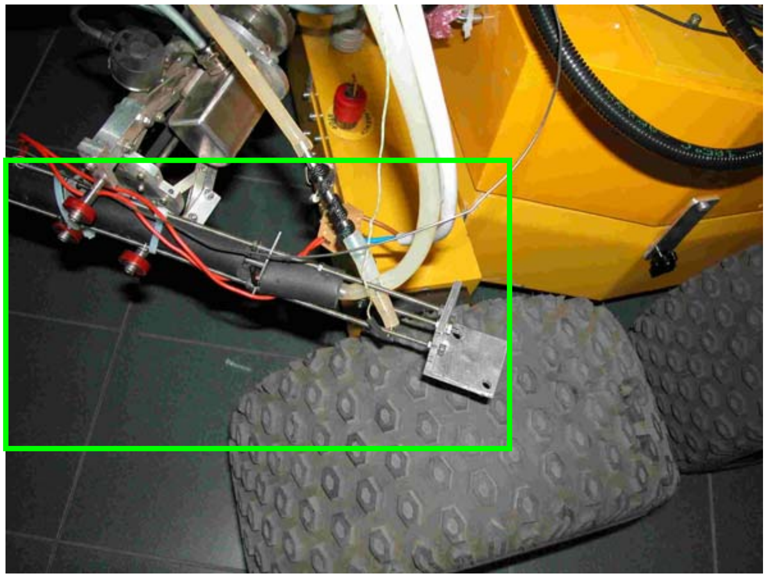


Fig. 37. Gas sampling probe.

The system for the control of and power supply to the samplers and sensors of the geochemical part has been cabled inside the RoboVolc, by housing block 1 on the wrist of the mechanical arm (Fig. 37). In this way it is possible to allow the rotation of the arm apart from the motion of the arm itself, so that the probe can be positioned effectively and precisely in the connection with the sampling funnel placed on the ground surface. This funnel is the part above the ground surface of a sampling pipe which is placed in the sampling site once for all by an operator. This represents an important point for volcanic surveillance, whenever it is necessary to carry out samplings repeatedly in a given site, notwithstanding the area is subject to a potential hazard for the operators.

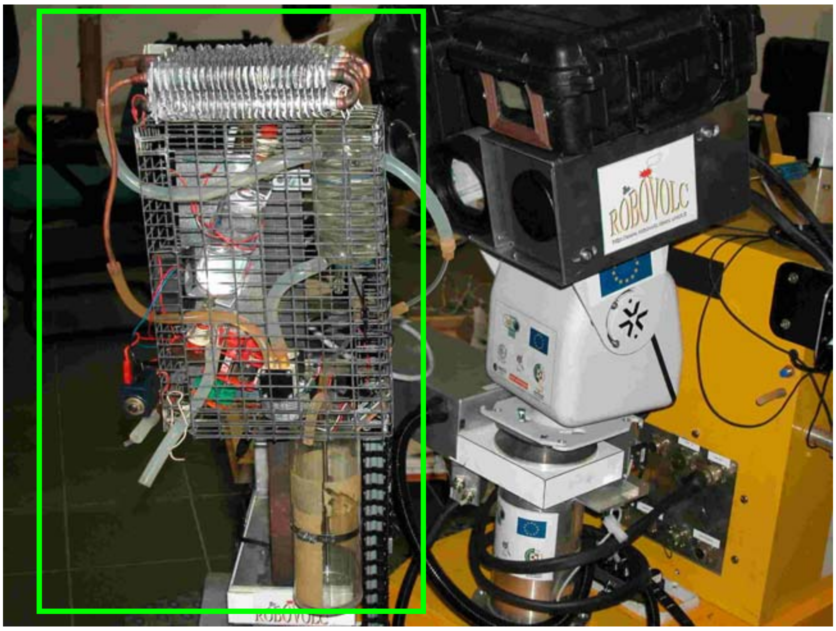


Fig. 38. System for sampling of acid gases and condensation of steam

Block 2 has been installed on the front part of the tower of the arm, so as not to impede the arm movements. This block has been directly connected with the probe end in order to collect the acid gases immediately (Fig. 38). The condensation system has been placed after the flask, inside the same container.

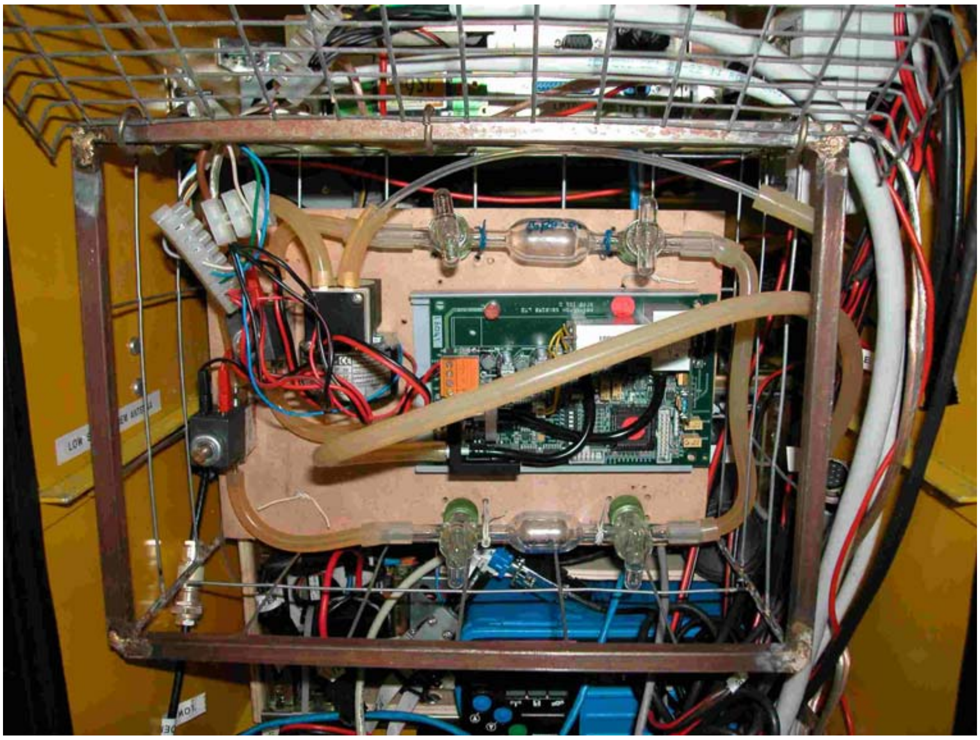


Fig. 39. System for sampling of dry gases and measurement of CO_2 content.

Block 3 has been placed inside the robot, immediately behind the door.

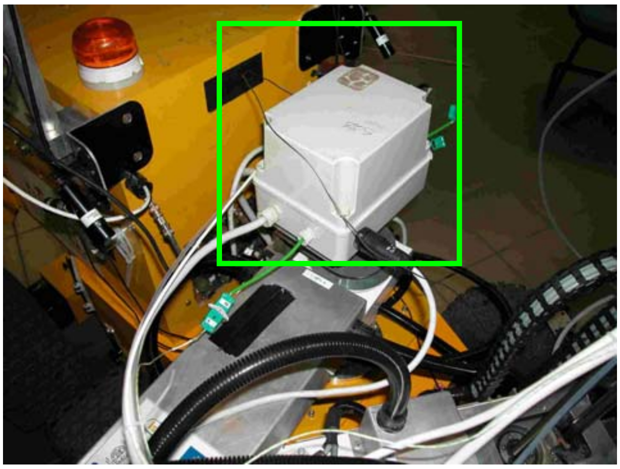


Fig. 40. Device for control, data acquisition and power supply.

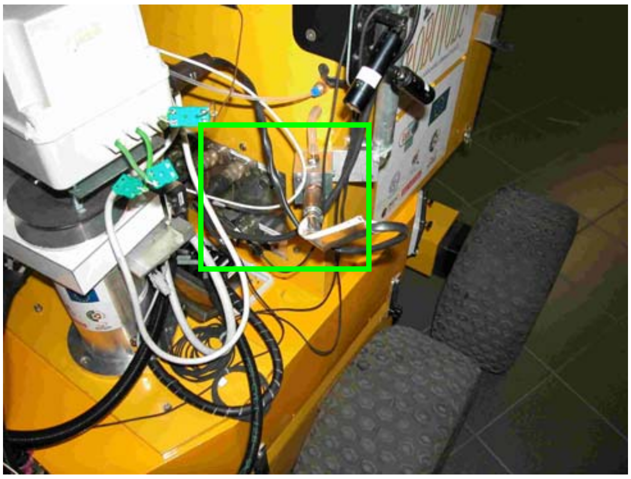


Fig. 41. Oxygen sensor.

Both block 4 and block 5 have been placed outside the robot, on its top. The oxygen sensor of block 5, because it reaches high temperature values during its operation, is the last segment of the gas transport system inside the robot, and is located immediately before the gas exhaust.

Fig. 42. Test of gas sampling procedure in laboratory.

Several manoeuvring tests have been carried out in the laboratory to check the positioning of the probe in the sampling funnel, and the results were satisfactory.

12.3 Conclusions

After the field tests made on the island of Vulcano and the consequent technical improvements adopted, it can be concluded that the sampling system designed for the RoboVolc is able to provide reliable chemical and isotopic data on the fumarolic gases of interest for volcanic surveillance. The system in itself is sufficiently versatile and precise to carry out the gas sampling, provided that a funnel has been previously placed and left constantly in the sampling site. This will allow to reach the primary goal of the project, that is to minimize the exposition of the volcanologists in areas with high volcanic hazard and at the same time to get significant data to be used for volcanic surveillance. Further field tests are necessary to better test the system in its actual version and will be performed in the next period following the end of the project.

13. Validation of Requirements for Functional Blocks

The following sections enumerate the requirements for each of the functional blocks that were listed in the Deliverable D3.2A System specification and Concept definition. In each section the requirements identified in Table 1 and Table 2 are enumerated, expanded and interpreted for each functional block.

13.1 Communications

The communication system consists of a long-range Wireless LAN that allows all the computers inside the rover (Rover PC, Manipulator PC, Science PC) to be interfaced with the Console PC. Since the wireless LAN adopt IEEE 802 standard, most of the specifications are satisfied by this standard.
A low-speed serial modem as backup is connected to recover situations when the wireless communications fail. A video/transmitter and receiver connects all the video equipment on the rover to the base station. The input of the transmitter is connected to a remotely operated switch to select a video channel at a time. The other communication system is the connection between the base DGPS and the rover DGPS for the transmission of the differential signals.

From Table 1 it can be seen that requirements D1, I2, K, L1 and L4 cumulatively apply to this functional unit. These are expanded and interpreted below.

D1, the communications system shall:	**Achievement**
1. Be robust for normal handling and deployment.	*Achieved*
2. Retain some minimal operating characteristic without line of sight.	*Achieved*
3. Operate in environment with scattered low obstacles, e.g. boulders <1m high.	*Achieved*
4. Operate in prevalent meteorological conditions, e.g. rain, mist, light-snow, wind to force 5.	*Achieved*
5. Operate reliably for periods of up to 24 hours.	*Achieved*
6. Fail gracefully and recover automatically.	*Achieved*

I2, the communications system:	**Achievement**
7. Shall operate over a range of up to 6 km from base station to rover.	*Achieved*
8. Should support full-duplex communication.	*Achieved*
9. May use a communications relay where line of site is not possible.	*Achieved*
10. May reduce bandwidth availability with range.	*Acieved*
11. Shall retain some minimal operating characteristic over the full range.	*Achieved*
12. Shall allow control signals priority with respect to data signals.	*Achieved*
13. May require repositioning of the robot platform to achieve full bandwidth.	*YES*
14. May require special “radio communications agency” licensing to achieve the full requirements.	*YES*

J3: the communication system components located on the platform:	**Achievement**

15. Shall operate from one or more 0V, 24V, 12V, -12V, and 5V unfiltered power buses.	*Achieved*
16. Shall support two modes of operation, a fully active state and a low-power state that may be software selected.	*Not achieved(See*Note A*)*
17. Shall consume less than 1W when in the low-power state.	*Achieved*
18. Shall consume less than 20W when in the active state.	*Achieved*
K, L1, L4, the communications system:	
19. Shall provide the bandwidth for communications from the console hardware to the platform.	*Achieved*
20. Should provide a minimum bandwidth for tele-operation functions (64Kbit/s).	*Achieved*
21. Shall provide a sufficiently low latency for tele-operation (0.5s).	*Achieved*
22. May allocate bandwidth to subsystems as a function of task.	*Not achieved (See* Note A*)*
23. May change bandwidth as a function of the environment but shall provide a minimum bandwidth of 9.6Kbits/s available under all environmental conditions.	*Achieved*
24. May use multiple radio channels/bands to achieve bandwidth and range.	*Achieved*
25. Will have a maximum bandwidth of less than 11 Mbits/s.	*Achieved*

Note A : The bandwith of the system and the power of transmission is automatically decided by the wireless LAN in a transparent way with respect to the user. When the specification were written such devices were not so common.

13.2 Console HW

From Table 1 it can be seen that requirements D1, J3, K, L1, L4 cumulatively apply to this functional unit. These are expanded and interpreted below.

D1, the console HW system:	**Achievement**
1. Shall be robust for normal handling and deployment.	*Achieved*
2. Shall be portable and self contained.	*Achieved*
3. Shall operate in a dusty outdoor environment.	*Achieved*
4. Shall operate in a 3G vibration environment.	*Achieved*
5. Shall operate reliably for periods of up to 24 hours.	*Achieved*
6. May operate in moderate meteorological conditions, e.g. light rain, mist, wind to force 5.	*Achieved*
7. Shall have thermal and reliability characteristics such that it is possible to operate it for periods of up to 24 hours.	*Achieved*
8. Should be constructed using robust low-cost COTS hardware and software where possible (Gnu Public licence software desirable).	*Achieved*

J3, the console HW system:	**Achievement**
9. Shall have a power consumption characteristic compatible with up to 24 hours operation from the console PSU when operating from an external AC or 12V DC supply.	*Achieved*
10. Shall have a power consumption characteristic compatible with up to 2 hours operation from the console PSU when operating from an internal power supply.	*Achieved*

L1, L4, the console HW system:	**Achievement**
11. Shall provide a visual display to support tele-operation and the HMI.	*Achieved*
12. Shall provide a haptic interface to support tele-operation and the HMI.	*Achieved*

13.3 Console PSU

From Table 1 it can be seen that requirements D1 and J3 cumulatively apply to this functional unit. These are expanded and interpreted below.

D1, the console PSU system:	**Achievement**
1. Shall be robust for normal handling and deployment.	*Achieved*
2. Shall be portable and self contained.	*Achieved*
3. Shall operate reliably for periods of up to 24 hours.	*Achieved*
4. Shall operate in a dusty outdoor environment.	*Achieved*
5. May operate in moderate meteorological conditions, e.g. light rain, mist, wind to force 5.	*Achieved*
6. Shall have a means of powering down the console and PSU to a safe state.	*Achieved*

J3, the console PSU system:	**Achievement**
7. Shall offer three modes of operation: (i) connection to an external AC supply, (ii) connection to an external 12V automotive 'cigar-lighter' supply, and (iii) an internal battery supply.	*Achieved* *(*Note B*)*
8. When connected to an external supply this shall recharge the internal batteries in a period of less than 2 hours.	*Achieved*
9. Shall operate to supply the Console HW with power for periods of 24 hours when connected to an external power source.	*Achieved*
10. May operate to supply the console HW hours form internal batteries for periods of up to 2 hours.	*Achieved*

Note B: The adoption of internal batteries has never been tested.

13.4 HMI

See UNIVLEEDS report in Annex.

13.5 Science package

From Table 1 it can be seen that requirements A1, A3, B, C, D1-D3, E, F, J3, K, L2, and L3 cumulatively apply to this functional unit. These are expanded and interpreted below.

The Science package consists of:

- Pan tilt: The Pan-tilt allow to orientate the following sensors mounted on it: Infrared camera, videocamera, videorecorder camera, High resolution still image camera.
- IR camera: teleoperated in most of the setting and operation allow to view thermal map of the environment and to shoot thermal images stored in a flash memory card on-board.

- ☐ Videocamera: telecontrolled in most of the operation allows to telecontrol the system in most of the operations.
- ☐ Videorecorder camera: Allows to record on a DV tape the images. Most of the main operations (on/off, record, zoom in/out) can be teleoperated.
- ☐ High resolution still image camera: Allows to store HR images into a Compact flash. The teleoperations consists in the shooting of the images and the download of the images.
- ☐ Gas sampling system: It has not been tested during this trial and will be tested in the next trial campaign.
- ☐ DGPS: The DGPS is adopted to sample the position of the rover to reconstruct terrain deformations.

A1-A3, B the Science Package:	**Achievement**
1. Shall have a fixed mass of less than 15kg.	*Achieved*
2. Shall have a payload of samples or additional modular science sensors of up to 20kg (30kg).	*Achieved*
3. Shall occupy a volume on top of the platform that shall be constrained by the overall system spatial limits for transport of the robot platform (1.7m long , 1.2m wide, 0.8m height) and the needs for the swept volume of the manipulator arm.	*Achieved*

D1, D2, D3, E the Science Package:	**Achievement**
4. Shall be robust for normal handling and deployment.	*Achieved*
5. Shall have a modular design such that different sensors/instruments are implemented independently so that they may be interchanged for different missions. Further, these modules shall be removable from the platform for transportation and shall be easily replaced on the platform with a small toolkit in less than 15 minutes effort assuming one technician.	*Achieved*
6. Shall operate in a dusty outdoor environment.	*Achieved*
7. Shall not leak fluids or gasses. Any fluids or gasses required for the operation of the science package shall be either: (i) non-flammable, or (ii) stored in such a manner as to mitigate against the risk of ignition and fire. All fluids, high pressure gasses or low-pressure gasses shall be stored in containers meeting the required safety standards.	*Achieved*
8. Shall operate following transport in a 3G vibration environment.	*Achieved*
9. Should operate in moderate meteorological conditions, e.g. light rain, mist, wind to force 5.	*Achieved*
10. Shall have thermal and reliability characteristics such that it is possible to operate it for periods of up to 24 hours.	*Achieved*
11. Should be constructed using robust low-cost COTS hardware and software where possible (Gnu Public licence software desirable).	*Achieved*
12. Shall have a means both in hardware and software of shutting down to a safe state.	*Achieved*
13. Shall be robust against the prevailing volcanic atmospheric environment found in the region of vents etc.	*Achieved*
14. Shall be able to operate in an ambient temperature of 0-40^{o}C.	*Achieved*
15. Shall be able to operate with contact temperatures of up to 100^{o}C.	*Achieved*
16. Shall be robust against impact from falling small rocks.	*Achieved*

17. Exposed components should survive impact from falling small rocks of mass 1kg or size 0.2m (d).	*Partially Achieved* (Note C)

Note C: Further protection will be required to protect exposed devices mounted on the pan-tilt.

F, the science package in combination with the platform mechatronics, platform PSU, platform infrastructure, manipulator, and tele-operation sensors shall be statically stable on a slope of 40^o in the specified reference position it has been estimated that this require the combined cog to be located below a height of 0.71m. *Achieved*

K, the science package shall not require more than 2Mbits/s for control of experiments and data logging. *Achieved*

J3, the science package:	**Achievement**
18. Shall operate from one or more 0V, 24V, 12V, -12V, and +5V unfiltered power buses	*Achieved*
19. Shall support two modes of operation, a fully active state and a low-power state that may be software selected.	*Achieved*
20. Shall consume less than 10W when in the low-power state.	*Achieved*
21. Shall consume less than 100W when in the active state.	*Achieved*

L2, L3 the Science Package shall incorporate a DGPS sensor whose accuracy is better than 10cm after a TBD integration period. *Achieved*

13.5.1 Details of Science Package

The follow list represent the mandatory list of experimental agreed from the Partners, suggested form the Volcanologist.

- Video collecting (VC)
- Still images collecting (SIC)
- Gas analysis and sampling(GAS)
- Lava and tephra sampling (LTS)
- Temperature imagery and measurement (TIM)
- Gas and particle speed measurement (GPSM)
- Terrain reconstruction (TR)

All these experiments have been be verified in laboratory, in different action planned form each partner involved.
List of "commands" needed to tele-operate each sensor.

Video collecting (VC)	
Mandatory :	
ON/OFF of the camera.	*Achieved*
Control of Pan/tilt	*Achieved*
Remote transmission of (low-res) analog video signal	*Achieved*
REC-ON REC-OFF	*Achieved*
ZOOM IN/OUT	*Achieved*
Optional :	
Tape/Camera status	*Achieved*

Rewind of tape and playback	*Achieved*
Remote transmission of digital (high-res) video data	*Not Achieved*
Other camera setting (autofocus, shutter time, etc.)	*Partially achieved*

Still images collecting (SIC)	
Mandatory :	
ON/OFF of the camera	*Achieved*
Control of Pan/tilt camera for teleoperations	*Achieved*
Shooting	*Achieved*
Remote transmission of (low res) analog video signal	*Achieved (*Note D*)*
Optional :	
Camera status	*Achieved*
Camera settings (Exposure time,…)	*Achieved*
Download of digital image	*Achieved*

Note D: Achieved through an aligned video camera.

Gas analysis and sampling(GAS)	
Mandatory	
Control of manipulator (single axis/ cartesian with probe maintained parallel, playback of recorded trajectories)	*Achieved*
Control of Pan/tilt camera for teleoperations	*Achieved*
ON/OFF of pump	*Achieved*
ON/OFF of N servovalves (TBD)	*Achieved*
Getting data from O2 sensor	*Achieved*
Getting data from CO2 sensor	*Achieved*
Getting data from 5 thermocouples	*Achieved*
Optional	
Recording of sequences of operations	*Achieved*

Lava and tephra sampling (LTS)	
Mandatory	
Control of manipulator (single axis/ cartesian/ playback of recorded trajectories i.e.*put object in basket n*)	*Achieved*
Coming back to the precise basket and recording of storage position and corresponding robot position	*Achieved*
Control of Pan/Tilt camera for teleoperations	*Achieved*
Force control of gripper	*Achieved*
Optional	
Autonomous sampling	*Partially achieved*

Temperature imagery and measurement (TIM)	
Mandatory	
Control of pan/tilt camera for location of measurement zone	*Achieved*

Transmission of analog image	*Achieved*
All commands for the camera will be through a proprietary LABVIEW interface, installed on the sensor computer and remotely controlled	*Achieved (*Note E*)*

Note E: The adoption of Labview reduced too much the speed of the teleoperations, so it was specifically designed and implemented an interface between the IR camera and the User interface.

Gas and particle speed measurement (GPSM)	
Mandatory	
Control of pan/tilt camera for location of measurement zone	*Achieved*
Transmission of speed value	*Achieved*

Terrain reconstruction (TR)	
DGPS	
Mandatory	
Navigation capable to playback trajectories	*Not Achieved (See UNIVLEEDS Navigation report in annex)*
GPS are autonomous	*Achieved*
Optional	
GPS status	*Achieved*
Send/receive commands to GPS	*Achieved*
Stereo imagery	
Mandatory	
Position the robot in some precise location	*Achieved*
Move the pan tilt to horizontal position	*Achieved*
Optional	
Reconstruct the terrain	*Partially achieved*

13.6 Manipulator

From Table 1 it can be seen that requirements A1-A3,C , D1-D3, E, F, J3, and K cumulatively apply to this functional unit. These are expanded and interpreted below.

The manipulator:

1. shall allow sensors to be placed on, or picked up from, the ground surrounding the robot platform. This function is predicated on the correct end effector being attached to the manipulator arm.	*Achieved*
2. shall allow rock samples of mass ≤ 2kg to be picked up from the ground surrounding the robot platform and placed in a suitable receptacle on the platform. This function is predicated on the correct end effector being attached to the manipulator arm.	*Achieved*
3. shall allow the gas sensing probe to be placed in vents with probe tip placement to better than 1mm. This function is predicated on the correct end effector being attached to the manipulator arm.	*Achieved*

A1-A3, C the manipulator:	
4. Shall have a mass of less than 50kg.	*Achieved*
5. Shall occupy, in some specified transport configuration, a volume	*Achieved*

on top of the platform that shall be constrained by the overall system spatial limits for transport of the robot platform (1.7m long , 1.2m wide, 0.8m height) and the needs for locating the science package instruments.	

D1, D2, D3, E the Manipulator:	
6. Arm motion shall be controlled in such a manner so as not to damage other components of the robot platform.	*Achieved*
7. Shall be robust for normal handling and deployment.	*Achieved*
8. Shall have a modular design where these modules shall be removable from the platform for transportation and shall be easily replaced on the platform with a small toolkit in less than 15 minutes effort assuming one technician.	*Achieved*
9. Shall operate in a dusty outdoor environment.	*Partially achieved (*Note F*)*
10. Shall not leak fluids or gasses. Any fluids or gasses required for the operation of the manipulator shall be either: (i) non-flammable, or (ii) stored in such a manner as to mitigate against the risk of ignition and fire. All fluids, high pressure gasses or low-pressure gasses shall be stored in containers meeting the required safety standards.	*Achieved*
11. Shall operate following transport in a 3G vibration environment.	*Achieved (*Note G*)*
12. Should operate in moderate meteorological conditions, e.g. light rain, mist, wind to force 5.	*Achieved*
13. Shall have thermal and reliability characteristics such that it is possible to operate it for periods of up to 24 hours.	*Achieved*
14. Should be constructed using robust low-cost COTS hardware and software where possible (Gnu Public licence software desirable).	*Achieved*
15. Shall have a means both in hardware and software of shutting down to a safe state.	*Achieved*
16. Shall be robust against the prevailing volcanic atmospheric environment found in the region of vents etc.	*Partially Achieved (*Note F*)*
17. Shall be able to operate in an ambient temperature of 0-40^{o}C.	*Achieved*
18. Shall be able to operate with gripper contact temperatures of up to 100^{o}C.	*Achieved*
19. Shall be able to operate with gas-sampling probe tip temperatures of up to 350^{o}C.	*Achieved*
20. Exposed components shall be robust against impact from falling small rocks.	*Achieved*
21. Exposed components should survive impact from falling small rocks of mass 1kg or size 0.2m (d).	*Partially achieved(*Note F*)*

Note F: Further protection to some joint is required for continuous operations in volcanic environment.

Note G: During transportation the manipulator needs to be securely fixed to avoid damage.

F, the manipulator:	
22. Shall, in combination with the platform PSU, platform mechatronics, platform infrastructure, science package and tele-operation sensors shall be statically stable on a slope of 40^o in the specified reference position it has been estimated that this require the	*Achieved*

combined cog to be located below a height of 0.71m.	
23. Arm motion shall be controlled in such a manner so as not to overbalance the robot platform at angles below the critical angle described above.	*Achieved*

K, the manipulator shall not require more than 4.25Kbits/s (full duplex) for control of the manipulator. *Achieved*

J3, the manipulator:	
24. Shall operate from one or more 0V, 24V, 12V, -12V, and +5V unfiltered power buses.	*Achieved*
25. Shall support two modes of operation, a fully active state and a low-power state that may be software selected.	*Partially achieved(*Note H*)*
26. Should consume 0W when in the low-power state.	*Achieved*
27. Shall consume less than 200W when in the active state.	*Achieved*

Note H: The selection to low power mode is performed by using two manually actuated switches one for the computer and the other for the arm control system. This could be easily substituted by remote controlled relays.

13.7 Navigation

See UNIVLEEDS report in Annex

13.8 Platform Mechatronics

From Table 1 it can be seen that requirements A1-A3,B ,C, D1-D3, E, F, G, H1-H4, I1, J1-J5, K, L1 and L4 cumulatively apply to this functional unit. These are expanded and interpreted below.

A1-A3, B, C, the platform mechatronics:	
1. Shall have a mass of less than 180kg.	*Achieved*
2. Shall be able to carry a payload of up to 30kg mix of samples or modular sensors.	*Achieved*
3. Shall be able to carry a 50kg manipulator.	*Achieved*
4. Shall be able to carry a 15kg fixed science package.	*Achieved*
5. Shall be able to incorporate a 50kg PSU.	*Achieved*
6. Shall be able to carry 10kg tele-operation sensors.	*Achieved*
7. Shall be able to carry 10kg of platform infrastructure.	*Achieved*
8. Shall occupy a volume when combined with the manipulator arm and science package that shall be constrained by the overall system spatial limits for transport of the robot platform (1.7m long , 1.2m wide, 0.8m height) and the needs for the swept volume of the manipulator arm.	*Achieved*
9. Shall supply a total internal volume greater than 0.075m^3 to contain the platform PSU, platform infrastructure, and tele-operation sensors.	*Achieved*

D1, D2, D3, E the platform mechatronics:	
10. Shall be robust for normal handling and deployment.	*Achieved*
11. Shall make provision for lifting-eyes or carriage under-slung on a helicopter.	*Achieved*
12. Shall operate in a dusty outdoor environment.	*Achieved*
13. Shall support modular mechanical interfaces for the platform PSU,	*Achieved*

manipulator and science package components such that these can individually be removed/replaced on the platform for transportation using a small toolkit in less than 15 minutes effort assuming one technician.	
14. Shall not leak fluids or gasses. Any fluids or gasses required for the operation of the platform mechatronics shall be either: (i) non-flammable, or (ii) stored in such a manner as to mitigate against the risk of ignition and fire. All fluids, high pressure gasses or low-pressure gasses shall be stored in containers meeting the required safety standards.	*Achieved*
15. Shall operate following transport in a 3G vibration environment.	*Achieved*
16. Should operate in moderate meteorological conditions, e.g. light rain, mist, wind to force 5.	*Achieved*
17. Shall have thermal and reliability characteristics such that it is possible to operate it for periods of up to 24 hours.	*Achieved*
18. Should be constructed using robust low-cost COTS hardware where possible.	*Achieved*
19. Shall have a means in hardware of shutting down to a safe state.	*Achieved*
20. Shall be robust against the prevailing volcanic atmospheric environment found in the region of vents etc.	*Achieved*
21. Shall be able to operate in an ambient temperature of 0-40^{o}C.	*Achieved*
22. Shall be able to operate with contact temperatures of up to 100^{o}C.	*Achieved*
23. Exposed components shall be robust against impact from falling small rocks.	*Achieved*
24. Exposed components should survive impact from falling small rocks of mass 1kg or size 0.2m (d).	*Achieved*

F, G, the platform mechatronics:	
25. Shall, in combination with the platform PSU, platform infrastructure, manipulator, science package and tele-operation sensors, be statically stable on a slope of 40^o in the specified reference position. It has been estimated that this require the combined cog to be located below a height of 0.71m. Additional it has been estimated that the requirement for stability implies that friction coefficient of the surface and wheel is constrained to be greater than 0.84.	*Achieved*
26. Shall, using power supplied with the platform PSU, be able to climb a slope of 30^o with the manipulator, platform infrastructure, platform PSU and tele-operations sensors fitted.	*Achieved*
27. Should, using power supplied with the platform PSU, be able to cross a slope of 35^o with the manipulator, platform infrastructure, platform PSU and tele-operations sensors fitted.	*Partially Achieved*

H1 – H4 the platform mechatronics:	
28. Shall, with the manipulator, platform infrastructure, platform PSU and tele-operations sensors fitted, be able to negotiate an obstacle with a vertical profile of height 0.2m (0.3m)	*Achieved*
29. Shall, with the manipulator, platform infrastructure, platform PSU and tele-operations sensors fitted, be able to negotiate an obstacle with a spherical profile of height 0.4m.	*Achieved*
30. Shall, with the manipulator, platform infrastructure, platform	*Achieved*

PSU and tele-operations sensors fitted, be able to negotiate a fissure of width 0.3m.	
31. Shall, with the manipulator, platform infrastructure, platform PSU and tele-operations sensors fitted, be able to negotiate an obstacle with a step-profile of height 0.2m and width 0.2m.	*Achieved*
32. Should be able to pass over a rock with diameter 0.2m	

I1, J1-J5: the platform mechatronics:	
33. Shall operate from one or more 0V, 24V, 12V, -12V, and 5V unfiltered power buses.	*Achieved*
34. Shall, using power supplied from the platform PSU, be able to achieve a operating range of up to 1 km with the manipulator, platform infrastructure, platform PSU and tele-operations sensors fitted.	*Achieved*
35. Shall, using power supplied from the platform PSU, be able to achieve continuous operation for up to 1.5 hours with the manipulator, platform infrastructure, platform PSU and tele-operations sensors fitted.	*Achieved*
36. Shall use control algorithms which protect the motors, drive-amplifiers etc. from excessive motion demands.	*Achieved*
37. Shall be able to deal with transit with a 50% rough 50% flat characteristic.	*Achieved*
38. Shall support two modes of operation, a fully active state and a low-power state that may be software selected.	*Achieved*
39. Should consume 0W when in the low-power state.	*Achieved*
40. Shall consume less than 1KW when in the active state.	*Achieved*

L1, L4 : the platform mechatronics:	
41. Shall provide the means of transporting the science package and manipulator as demanded by the navigation functional block.	*Achieved*
42. Shall provide control algorithms and associated SW for controlling its components such that demands from the navigation functional block for position changes from (X_1,Y_1,Z_1) to (X_2,Y_2,Z_2) may be effected.	*Achieved*
43. Shall provide an indication of a failure/problem while a demanded manoeuvre is executed.	*Achieved*

13.9 Platform PSU

From Table 1 it can be seen that requirements A1, C, D1-D3, F, I1, J1-J5 cumulatively apply to this functional unit. These are expanded and interpreted below.

A1, C, the platform PSU	
1. Shall have a mass of less than 50kg.	*Achieved*
2. Shall occupy a volume of less than 0.03m^3.	*Achieved*
D1, D2, D3 the platform PSU	
3. Shall be robust for normal handling and deployment.	*Achieved*
4. Shall operate in a dusty outdoor environment.	*Achieved*
5. Shall have a modular design where these modules shall be removable from the platform for transportation and shall be easily	*Partially achieved* (Note I)

replaced on the platform with a small toolkit in less than 15 minutes effort assuming one technician.	
6. Shall not leak fluids or gasses. Any fluids or gasses required for the operation of the platform mechatronics shall be either: (i) non-flammable, or (ii) stored in such a manner as to mitigate against the risk of ignition and fire. All fluids, high pressure gasses or low-pressure gasses shall be stored in containers meeting the required safety standards.	*Achieved*
7. Shall operate following transport in a 3G vibration environment.	*Achieved*
8. Shall operate reliably for periods of up to 24 hours. This may include intermittent periods of different internal modes of supply.	*Achieved*
9. Should operate in moderate meteorological conditions, e.g. light rain, mist, wind to force 5.	*Achieved*
10. Shall have thermal and reliability characteristics such that it is possible to operate it for periods of up to 24 hours.	*Achieved*
11. Should be constructed using robust low-cost COTS hardware where possible.	*Achieved*
12. Shall have a means in hardware of shutting down to a safe state.	*Achieved*
13. Shall be robust against the prevailing volcanic atmospheric environment found in the region of vents etc.	*Achieved*
14. Shall be able to operate in an ambient temperature of 0-40^{o}C.	*Achieved*
15. Shall be able to operate with contact temperatures of up to 100^{o}C.	*Achieved*
16. Exposed components shall be robust against impact from falling small rocks.	*Achieved*
17. Exposed components should survive impact from falling small rocks of mass 1kg or size 0.2m (d).	*Achieved*

Note I : Change of batteries requires the opening of the chassis and consequently the manipulator and the science package must be previously unmounted. These operation requires 1 hour operations.

F, the platform PSU shall, in combination with the platform mechatronics, platform infrastructure, manipulator, science package and tele-operation sensors, be statically stable on a slope of 40^{o} in the specified reference position It has been estimated that this require the combined cog to be located below a height of 0.71m. *Achieved*

I1, J1-J5: the platform PSU:	
18. Shall supply 0V, 24V, 12V, -12V, and 5V unfiltered (and unregulated) power buses with current capability TBA/TBD.	*Achieved*
19. May require periods of platform power-down to achieve the mission duration.	*Achieved*
20. Shall allow the use of a 12V power-supply tether for battery charging and for conservation of internal power during some portions of the transit to the trials area.	*Achieved*
21. Shall provide an electrical output signal giving an estimate of battery condition.	*Achieved*
22. May require to augment battery operation with an internal-combustion generator to achieve the mission duration. Periods during a mission may be required where such a generator is used for battery charging.	*Achieved*
23. Shall, as a minimum, be able to supply 6MJ of electrical energy.	*Achieved*

24. Shall, as a minimum, be able to supply 1.4KW for short periods and 750W for extended periods.	*Achieved*

13.10 Platform Infrastructure

From Table 1 it can be seen that requirements A1, C, D1-D3, F, J3, K, L1 and L4 cumulatively apply to this functional unit. These are expanded and interpreted below.

A1, C the platform infrastructure:	
1. Shall have a mass of <10Kg.	*Achieved*
2. Shall occupy a volume of less than $0.02m^3$.	*Achieved*

D1, D2, D3, the platform infrastructure:	
3. Shall be robust for normal handling and deployment.	*Achieved*
4. Shall have a modular design so that its components can be easily removed/replaced for maintenance.	*Achieved*
5. Shall operate in a dusty outdoor environment.	*Achieved*
6. Shall operate following transport in a 3G vibration environment.	*Achieved*
7. Shall operate reliably for periods of up to 24 hours.	*Achieved*
8. Should operate in moderate meteorological conditions, e.g. light rain, mist, wind to force 5.	*Achieved*
9. Shall have thermal and reliability characteristics such that it is possible to operate it for periods of up to 24 hours.	*Achieved*
10. Should be constructed using robust low-cost COTS hardware and software where possible (Gnu Public licence software desirable).	*Achieved*
11. Shall have a means both in hardware and software of shutting down to a safe state.	*Achieved*
12. Shall be robust against the prevailing volcanic atmospheric environment found in the region of vents etc.	*Achieved*
13. Shall be able to operate in an ambient temperature of 0-40^{o}C.	*Achieved*
14. Shall be implemented using COTS hardware/software where possible.	*Achieved*
15. Shall use commercially available (Gnu Public Licence software desirable) SW development tools and languages.	*Achieved*

F, the platform infrastructure in combination with the platform mechatronics, platform PSU, science package, manipulator, and tele-operation sensors shall be statically stable on a slope of 40^o in the specified reference position. It has been estimated that this require the combined COG to be located below a height of 0.71m. *Achieved*

L1, L4, K, The platform infrastructure:	
16. Shall support modular electrical and logical interfaces for the platform PSU, manipulator and science package conponents such that these can individually be removed/replaced on the platform for transportation using a small toolkit in less than 15 minutes effort assuming one technician.	*Achieved*
17. Shall provide internal logical/electrical communications interfaces	*Achieved*

to allow the platform mechatronics, science package, manipulator and tele-operation sensors to be controlled.	
18. Shall provide internal logical/electrical communications interfaces to allow the platform mechatronics, science package, manipulator and tele-operation sensors to be monitored.	*Achieved*
19. Shall provide routing of communications to/from the HMI/console to the appropriate functional blocks on the platform.	*Achieved*
20. May allocate bandwidth on any internal communications as a function of priority.	*Achieved*
21. Shall provide CPU resource for the navigation and platform mechatronics functional blocks.	*Achieved*
22. May allocate storage for the logging of results from the science package.	*Achieved*
.	
J3, the platform infrastructure:	
23. Shall operate from one or more 0V, 24V, 12V, -12V, and 5V unfiltered power buses.	*Achieved*
24. Shall support two modes of operation, a fully active state and a low-power state that may be software selected.	*Achieved*
25. Shall consume less than 10W when in the low-power state.	*Achieved*
26. Shall consume less than 80W when in the active state.	*Achieved*

13.11Tele-operation sensors

From Table 1 it can be seen that requirements A1, C, D1-D3, F, J3, K, L1 and L4 cumulatively apply to this functional unit. These are expanded and interpreted below.

A1, C, the tele-operation sensors:	
1. Shall have a mass of <10Kg.	*Achieved*
2. Shall occupy a volume of less than 0.01m^3.	*Achieved*

D1, D2, D3 the tele-operation sensors:	
3. Shall be robust for normal handling and deployment.	*Achieved*
4. Shall operate in a dusty outdoor environment.	*Achieved*
5. Shall operate following transport in a 3G vibration environment.	*Achieved*
6. Should operate in moderate meteorological conditions, e.g. light rain, mist, wind to force 5.	*Achieved*
7. Shall have thermal and reliability characteristics such that it is possible to operate it for periods of up to 24 hours.	*Achieved*
8. Should be constructed using robust low-cost COTS hardware/software where possible.	*Achieved*
9. Shall have a means in hardware of shutting down to a safe state.	*Achieved*
10. Shall be robust against the prevailing volcanic atmospheric environment found in the region of vents etc.	*Achieved*
11. Shall be able to operate in an ambient temperature of 0-40^{o}C.	*Achieved*
12. Exposed components shall be robust against impact from falling small rocks.	*Achieved*
13. Exposed components should survive impact from falling small rocks of mass 1kg or size 0.2m (d).	*Partially Achieved* *(*Note J*)*

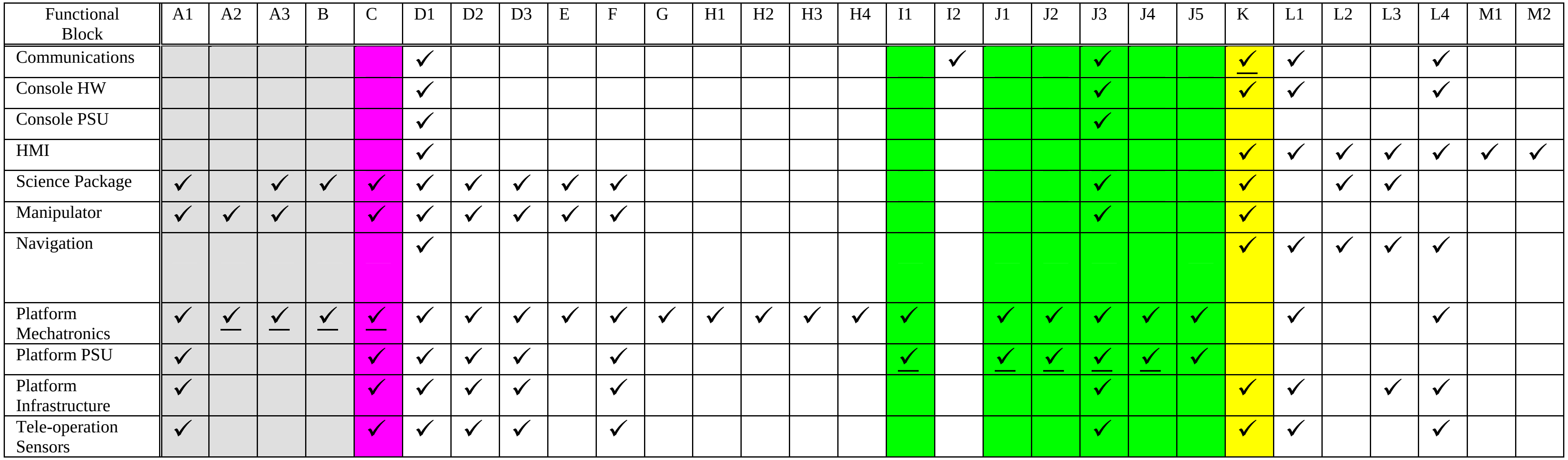
Note J: Some cameras could be destroyed from the impact of rocks.

F, the tele-operation sensors shall, in combination with the platform mechatronics, platform infrastructure, manipulator, science package and tele-operation sensors, be statically stable on a slope of 40^o in the specified reference position. It has been estimated that this require the combined cog to be located below a height of 0.71m. *Achieved*

J3: the tele-operation sensors:	
1. Shall operate from one or more 0V, 24V, 12V, -12V, and 5V unfiltered power buses.	*Achieved*
2. Shall support two modes of operation, a fully active state and a low-power state that may be software selected.	*Achieved*
3. Shall consume 0W when in the low-power state.	*Achieved*
4. Shall consume less than 20W when in the active state.	*Achieved*

K, the tele-operation sensors	
shall not require more than 2Mbits/s of downlink bandwidth.	*Achieved*
L1, L4 the tele-operation sensors:	
5. Shall provide sensor input for navigation and obstacle avoidance.	*Partially Achieved (See UNIVLEEDS report on Navigation)*
6. Shall provide a camera on the manipulator arm.	*Achieved*
7. Shall provide 360^o sensor coverage around the platform. This may be achieved through either pan-tilt units or fixed sensors.	*Achieved*
8. Shall provide sufficient resolution and frame rate for real-time control.	*Achieved*
9. Shall as a minimum provide a visual band TV type video stream (other sensor modalities are also desired).	*Achieved*
10. Shall provide as a minimum a single video output together with a means of switching between multiple sensors.	*Achieved*

Table 1: Requirements Mapping



Functional Block	A1	A2	A3	B	C	D1	D2	D3	E	F	G	H1	H2	H3	H4	I1	I2	J1	J2	J3	J4	J5	K	L1	L2	L3	L4	M1	M2
Communications						✓											✓			✓			✓	✓			✓		
Console HW						✓														✓			✓	✓			✓		
Console PSU						✓														✓									
HMI						✓																	✓	✓	✓	✓	✓	✓	✓
Science Package	✓		✓	✓	✓	✓	✓	✓	✓	✓										✓			✓		✓	✓			
Manipulator	✓	✓	✓		✓	✓	✓	✓	✓	✓										✓			✓						
Navigation						✓																	✓	✓	✓	✓	✓		
Platform Mechatronics	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓			✓		
Platform PSU	✓				✓	✓	✓	✓		✓						✓		✓	✓	✓	✓	✓							
Platform Infrastructure	✓				✓	✓	✓	✓		✓										✓			✓	✓		✓	✓		
Tele-operation Sensors	✓				✓	✓	✓	✓		✓										✓			✓	✓			✓		

Key

⬜	Mass Budget shared
🟪	Volume Budget shared
🟩	Energy budget shared
🟨	Bandwidth budget shared

Table 2: Interfaces Mapping

Functional Block	Communications	Console HW	Console PSU	HMI	Science Package	Manipulator	Navigation	Platform Mechatronics	Platform PSU	Platform Infrastructure	Tele-operation Sensors
Communications		ME L		L	EL	EL	L		E	EL	L
Console HW	ME L		ME	L							
Console PSU		ME		L							
HMI	L	L	L		L	L	L	L	L	L	L
Science Package	EL			L		ME L	L	ME L	E	EL	
Manipulator	EL			L	ME L			ME L	E	EL	
Navigation	L			L	L			L		L	L
Platform Mechatronics				L	ME L	ME L	L		ME	ME L	M
Platform PSU	E			L	E	E		ME		E	E
Platform Infrastructure	EL			L	EL	EL	L	ME L	E		EL
Tele-operation Sensors	L			L			L	M	E	EL	

Key

M	Mechanical Interface
E	Electrical Interface
L	Logical Interface