A Robotic System for Volcano Exploration

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1. Introduction

Robovolc: "A Robot for Volcano Exploration" is the name of a project funded by the European Commission, whose activities started in 2000. The main purpose of the ROBOVOLC project has been the development and trial of an automatic robotic system to explore and perform measurements in a volcanic environment. The robot, shown in Fig.1, has been realized to minimize the risk for volcanologists who are involved in work close to volcanic vents during eruptive phenomena. The robot is capable of moving on very rough and unstructured terrain thanks to its six independently actuated wheels and to its articulated chassis; sampling lava rocks and gas using its SCARA manipulator; collecting measures of the explored environment using the onboard video camera, the IR camera, the still camera and the radar Doppler. Details on the projects are reported and updated on the web pages: http://www.robovolc.diees.unict.it

The project has required both robotic and volcanology expertises. The involved partners have a recognised know-how in Europe as regards Service robotics both for academic (Università degli Studi di Catania, Italy and University of Leeds, UK) and industrial aspects (BAE Systems, UK and Robosoft, France). The two research institutes involved (Istituto Nazionale di Geofisica e Vulcanologia, Italy and Institute de Physique du Globe de Paris, France) are among the most important research institutes on volcanology in Europe.

Figure 1. The Robovolc system in operation

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The project required the complementary expertises that these partners together offered and that can not be found in a single country. The problem of volcano monitoring and forecasting is a large problem and is common to more than one European country which emphasises the need for pan-European co-operation in the RTD.

The realized robot is a useful tool to help volcanologists increasing their knowledge on volcanic activities especially during dangerous active phases. In this way the safety of people employed in collecting such a kind of measurement will considerably improve. Historically many scientists studying eruptions from unsafe places suffered serious injuries. Due to both the unpredictable timing and to the magnitude of volcanic phenomena, several volcanologists still die surveying eruptions.

The improvement in the working conditions for volcanologists that are directly involved in monitoring dangerous eruptive activity will enhance the systematic study of these phenomena for which many measurement data are not yet available. Another important aspect to be considered concerns the improvement in the anticipatory capability of the volcanic activity by way of continuous updating during eruptive phenomena, also when they become very dangerous for volcanologists. This could improve volcanic risk assessment contributing to an integrated risk management system for obtaining an almost real-time early warning, useful to Civil Protection authorities to inform and protect citizen from dangerous volcanic eruption consequences. This will lead to huge savings in potential losses caused by damage to buildings, land, equipment, livestock and injury to humans. From this point of view the Robovolc robot will contribute to achieve a very important social objective of the Community: the improving of the safety, and in general the quality of life, of the people living around active volcanoes located in the European countries. In volcanology the measurement and sampling processes in the proximity of active eruptive vents are fundamental. The most important kinds of measurement are: magmatic gas geochemistry, physical modelling of magma degassing, and stability assessment of the craters and domes:

Magmatic gas geochemistry: due to the rapid mixing between the gas released by the magma and atmosphere it is quite difficult to make accurate measurements of the quantity of some gas species produced by volcanoes that are abundant also in the atmosphere. In particular the CO_2 released during eruptions could contribute significantly to the global warming of the planet. Accurate measurement of this gas during eruptions of basaltic magma, in which it is more abundant, will help to better discriminate natural and human activity contributions of the CO_2 increase in the atmosphere.

Physical modelling of magma degassing: dynamics of the gas bubbles that rise up in the magma and disrupt at the surface drives all eruptions. Its modelling depends on the geophysical data collected close to the disrupting surface where the bubbles burst. This process is very frequent in active craters of the basaltic volcanoes where explosive activity is produced. Unfortunately it observation and measurement is often prevented by the funnel shaped geometry of the volcanic vents, so a very close approach with specific instrumentation (stereo cameras, Doppler-radar, etc.) is necessary to collect these data.

Stability assessment of the craters and domes: active volcanic crater and dome structures are subject to a rapid growth during an eruption and often collapse under their own weight and due to endogenous forces. Dome collapses produce very dangerous pyroclastic flows and surges. Crater collapses block the erupting vent and can produce large explosions due to gas overpressures inside. The measurement of the instability of craters and domes is hence very useful to forecast dangerous eruptive phenomena,

however due to the unpredictability of these collapses fieldwork it is not possible without a robot.
The purpose of the project ROBOVOLC was then to build a vehicle capable to approach an active volcanic vent and to perform several kind of measurement keeping the operators at a safe distance. ROBOVOLC can be considered as a system constituted by two main parts: the rover and the measurement systems. The development of the rover involved a careful analysis of the requirements and of the environmental conditions. Volcanic terrain is one of the worst outdoor environments that can be found for a robot: rocks, steep slopes, very fine ash sand, snow, high temperatures close to the vents and sometimes, due to the high altitudes, very low temperatures. Moreover operations often must be carried out without a direct view of the system by the operators. The measurement system also required a great research effort in developing suitable instruments. Most of the operations to be performed by the robot were previously performed directly by a human operator on-site and consequently most of commercial instruments are not automatic.

In section 2 of this chapter some previous projects concerning robots used for volcano exploration are reported. In the next sections a description of the different phases of the project will be shown. In particular in section 3 some preliminary activities to understand the requirements and the specifications of the system are presented. Then a description of the designed and built sub-systems is reported. In Section 5 some details on the localisation sub-system are presented and finally in Section 4 some considerations on the field trials and results obtained are given.

2. Previous Projects on Robots for Volcanoes

In known, published literature, there is only one example of a robot specifically developed for volcano exploration, *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 (Bares & Wettergreen,1999). The robot is a frame-walker 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. 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 fumaroles vents. 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. There are instead several examples of robot that have been designed for planetary exploration and that have been tested on volcanic sites (Guccione et al., 2000). In fact there are many similarities between volcanic terrain and many planetary sites. It is important to observe that not one of these robots has been totally developed in an EC country. An important example that can be cited is the *Marsokhod Planetary Rover*. The Marsokhod rover is an all terrain vehicle developed by the Mobile Vehicle Engineering Institute (VNIITransmash) in Russia for planetary exploration (Kemurdjian et al., 1992). 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.

Finally, as an example of flying vehicles tested on volcanic environments, a *Yamaha RMAX helicopter* 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 (Yamaha, 2000).

3. Preliminary Activities

The lessons learnt from these previous machines and the advances made in robotic have been directly applied to the ROBOVOLC robot. The major innovations are in the mechanical structure and materials (lightweight, dust proof, heat and impact resistant), locomotion systems (intelligent control, robust traction for the harsh and unstructured environment), guidance (environmental mapping, intelligent path-planning, autonomous decision making) and sensors (integration of a variety of sensors for robust localization and environment reconstruction, an effective user interface). Several preliminary technical visits to volcanic sites (Etna, Stromboli and Vulcano) were organised and detailed discussions were carried out with the volcanologists, in order to investigate the requirements of the system. It was immediately apparent that the extremely rough and difficult volcanic terrain required the development of specific solutions.

Figure 2. Examples of terrain found in volcanic environment

Ground surface change, varying from rough lava to rocky surfaces or sandy slopes, occur typically in a short distance. Then it was decided to concentrate our attention on specific kinds of missions that could be accomplished by the robot on specific types of terrain. A system capable to be useful in all of the possible situations exceeds current robotic capabilities.
Some prototypes of robots were also built in this phase of the project, also to explore the capabilities of different locomotion architectures. For example the WHEELEG robot (Fig. 3a) is a hybrid locomotion robot composed by two front pneumatic legs and two rear wheels (Guccione & Muscato, 2003), (Lacagnina et al., 2003). The M6 robot (Fig. 3b) is a six independently actuated wheels robot with a very articulated chassis (Lacagnina et al., 2002). The P6W robot (Fig. 4a) is a 1:4 scale prototype of the Robovolc rover that is used also to test the traction capability of Robovolc in laboratory, with a high degree of repeatability (Caltabiano & Muscato, 2002), (Caltabiano et al., 2004a).
In order to measure volcanic terrain features a four wheel probe was built. This cart, shown in Fig. 4b, was manually driven into quiescent craters, to simulate possible paths taken by a robot inside the craters. The probe carried the following instrumentation: a GPS, encoders in both wheels, a video camera, temperature, humidity and pressure sensors (Azad et al., 2001).

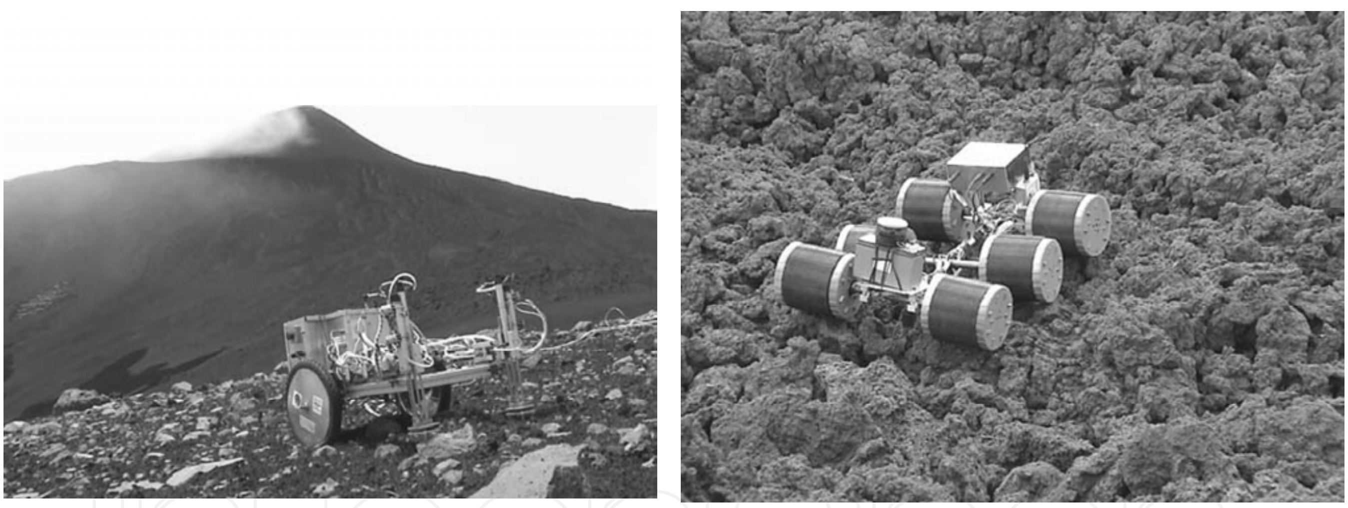


Figure 3. The Wheeleg and the M6

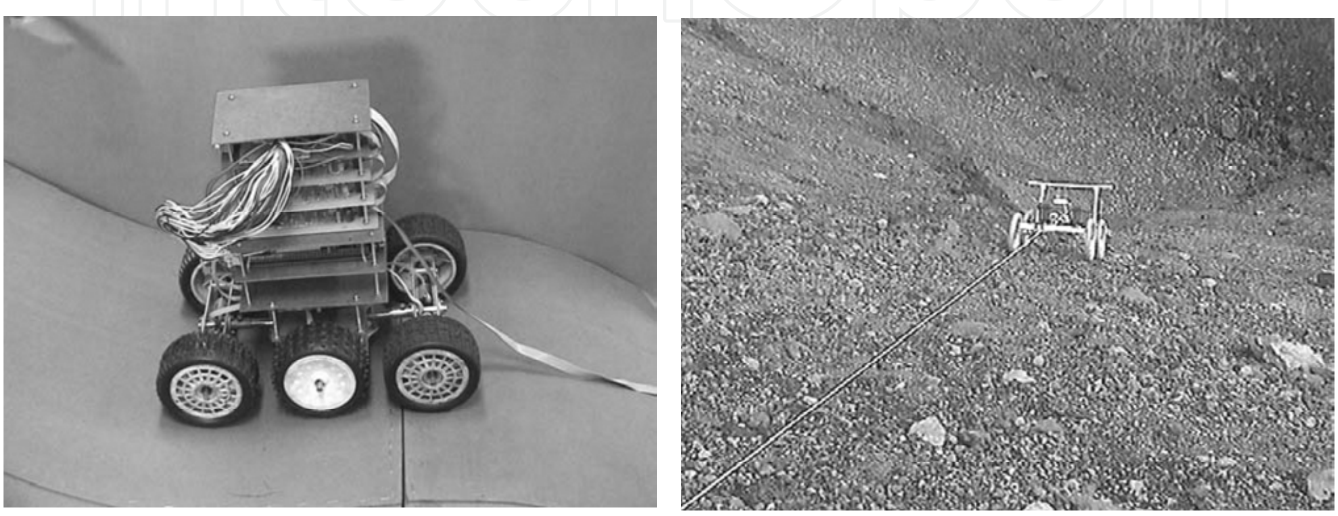


Figure 4. The P6W and the four wheel probe

Following a careful examination of all the measured data and several meetings and discussions performed jointly by the volcanologists and the robotic technology providers, the requirements and the specifications of the Robovolc systems were stated. A typical mission was divided into different phases:

- Transportation of all the equipment from the laboratory into a safe place close to the volcanic vent named base station;
- Settling of the instrumentation on the robot and of the control console;
- Teleoperation of the robot to reach the site of interest;
- Measurements of volcanic parameters;
- Teleoperation of the robot the way back to the base station;
- Transportation of all the equipment into the laboratory.

The specification of the system required a modular robot with each module of limited dimensions and weight, in order to be transported by no more than 5 people in case of problems. The maximum slope was limited to 30° to guarantee a good stability margin and to avoid the use of cables that could limit the range of operations of the system. The distance required to reach the sites of interest from a safe place was estimated to be less than 2km, with half of the path in rough terrain. Once the site is reached the phase of measurement could last several hours, with the robot to be put in a low consumption mode.

Figure 5. Transportation of the ROBOVOLC in the volcano Etna

4. The ROBOVOLC System

A picture of the final ROBOVOLC system is reported in Fig. 6. The system can be divided in several different subsystems, as shown in the diagram of Fig. 7, that will be described in the following subsections.

Figure 6. The Robovolc system

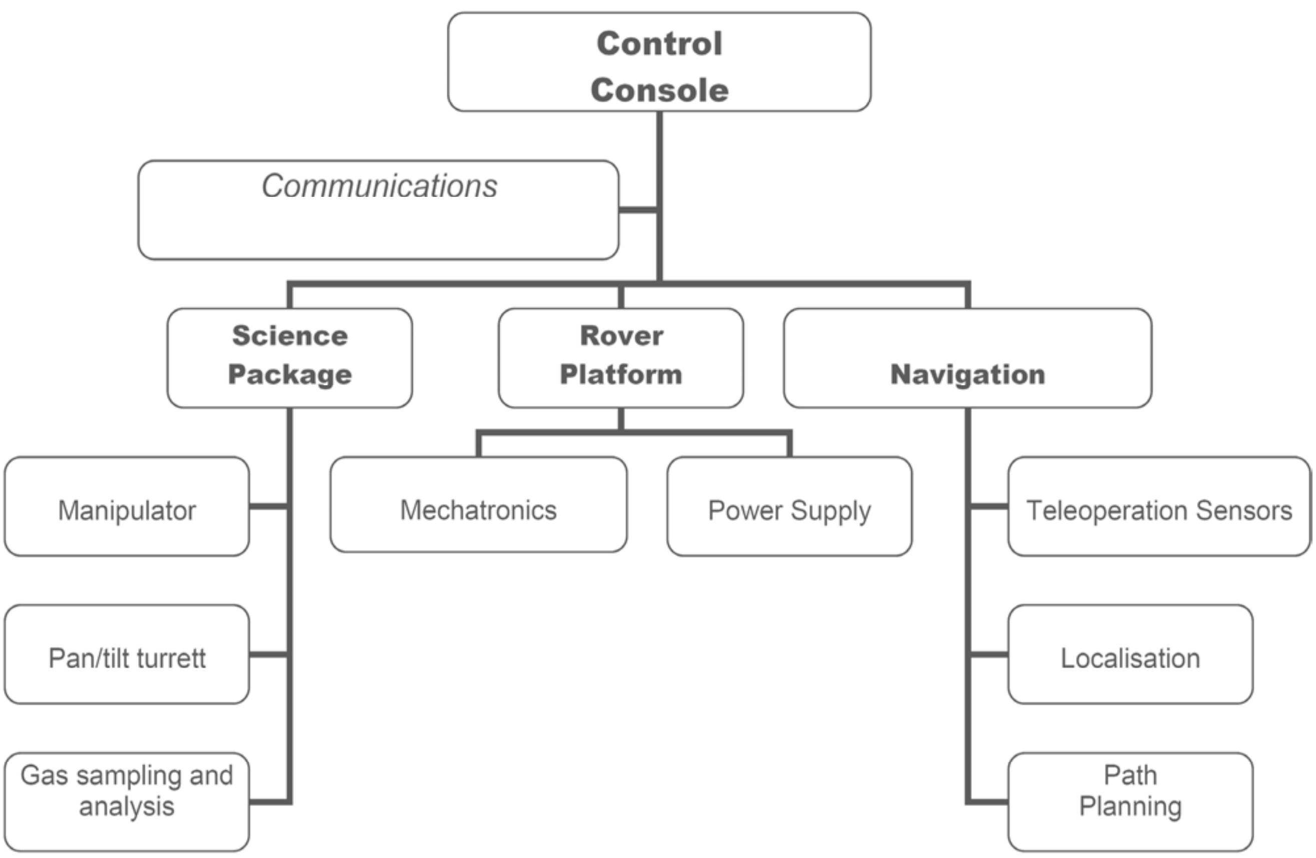


Figure 7. Block diagram of the Robovolc main sub-systems

4.1 The Rover Platform

The platform adopted 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. Six independent DC motors actuate the wheels. Three different types of wheels have been adopted to cope with sandy terrain, rocky

terrain or mixed type terrain. In Fig. 8 some drawing explaining the kinematic capabilities of this platform are reported.

The platform contains the power supply unit (PSU) constituted of 4 sealed lead acid batteries coupled to form two 24V units. The first unit is used to power the platform and the second is used to power the science package and the manipulator. These batteries are mounted in the lower part of the chassis in order to guarantee a low center of gravity and consequently increase the rover stability.

The computer infrastructure is based on the utilisation of three PC104 based computers located in the rover. The first PC is dedicated to the *Motion control* of the rover and to the *Low-speed communication* management; the second PC is for the *Manipulator control* while the third manages the *Science package*, the *Video system control* and the *Localization system*. The first two PC use a Linux operating system, while the third runs on MS Windows 2000 OS. The distribution of the Robovolc systems across three computers was chosen to increase 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 can result in the rover being unable to move. The three PC are connected into a LAN and through a high power bridge to a Wireless LAN to be interfaced to the remote Control Console.

The communications between the software modules is implemented through an RPC (Remote Procedure Call) protocol.

The motion controllers used for the control of the DC motors of the platform are RoboSoft RMPC-555. These motor controllers have been used for both Rover and Manipulator motion control and are interfaced to the PCs through respectively a serial port and a CAN BUS (Caltabiano & Muscato,2002),(Caltabiano et al., 2004a).

A traction control algorithm has been implemented to guarantee a suitable distribution of the torque among the wheels, guaranteeing at the same time low power consumption.

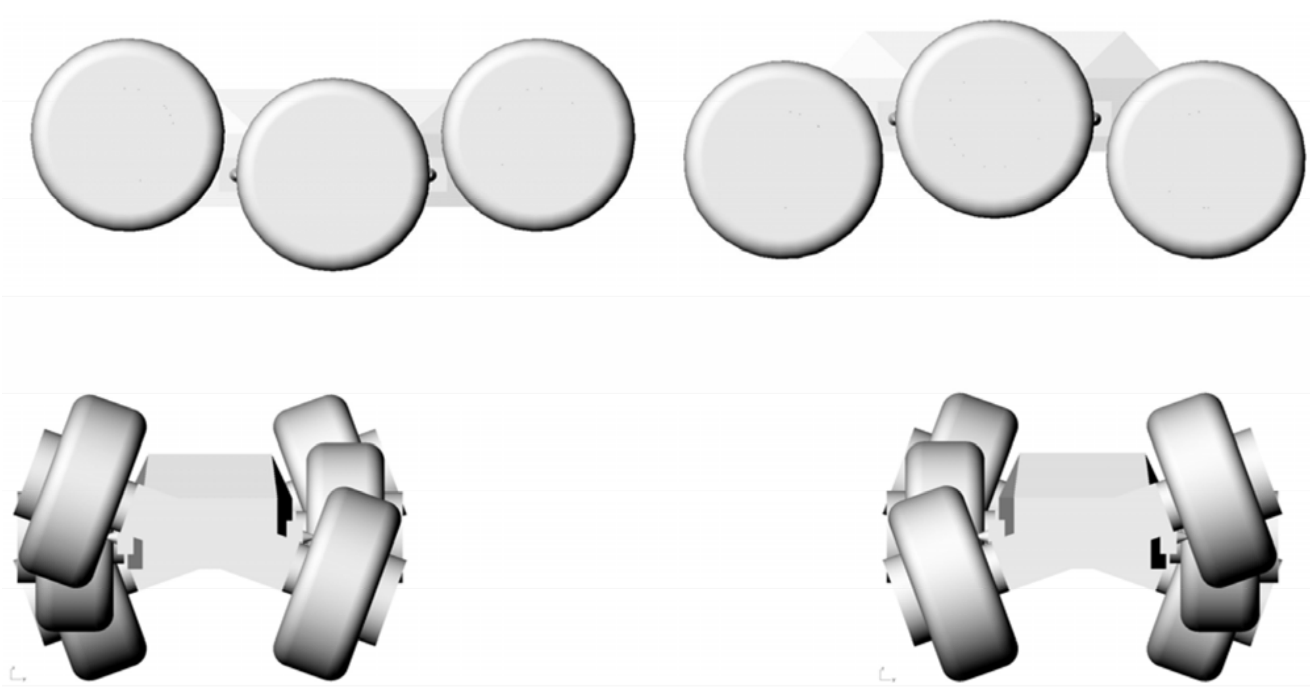


Figure 8. Articulation capabilities of the platform

4.2 The Science Package

The science package is formed by the *pan tilt turret*, the *manipulator* and the *gas sampling system*. All the electronic modules needed to control these equipments are installed within a box mounted on the rover. The pan-tilt turret can be oriented by the user in order to point the different devices to the region of interest (Fig. 9). The devices installed on this turret are a digital video-camera recorder, a high resolution still image camera, a video-camera, an infrared camera for thermal measurement, and a radar Doppler for lava and gas-jet speed measurement. All these devices have been installed within weather and shock proof sealed containers.

Figure 9. Detail of the pan-tilt turret

The manipulator, shown in operation in Fig. 10, has been designed specifically for the Robovolc system. This is of SCARA type with 5 degrees of freedoms plus a gripper, all actuated by DC motors. The manipulator is adopted to collect samples of rocks, by using a three finger gripper, or to drop and pick instruments into the field or to collect gases in the proximity of fumaroles. This gripper has a force sensor to measure and control the grasping strength.

Gas sampling is the most important measurement to be carried out by the Robovolc system, since the analysis of gas ejected from a volcano is one of the main indicator of its internal activity. The main problems with this operation are: sampling gas that reaches 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. A system has been specifically designed for the Robovolc system composed of a titanium probe with a thermal control system, and a gas collection and analysis system. The main problem was to design all the systems to be teleoperated, since most of the equipment was originally designed to be carried on site by human operators. This fact required also the adoption of a series of additional video-cameras to monitor all the sequence of operations.

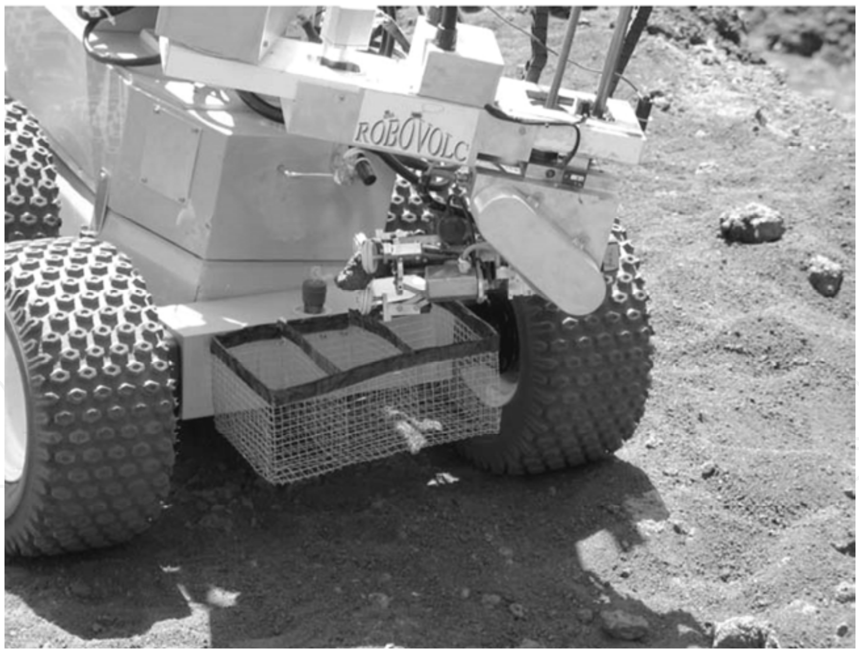


Figure 10. The SCARA manipulator picking a rock

4.3 The Control Console

The Control console had to satisfy two main requirements: to be user friendly, in order to allow the volcanologists to operate the system, and to be rapidly and easily installable on site (Fig. 11). The control console is mainly composed by two LCD monitors and two laptop PCs. The first monitor is connected to a camera on the pan-tilt turret of the science package, while the image of the second monitor can be selected from all the other cameras and the IR-camera. The first PC is to manage the teleoperations of the rover and of the arm, while the second allows operating the science package instruments. In this way a first operator can drive the robot, while a second can, at the same time, conduct the scientific measurements. The control of the robot is accomplished by two joysticks and touch-screen/mouse inputs. Ergonomic considerations have been taken in account in the design of the interface since a mission can be several hours in duration, so the employment of graphics and customisable GUI (graphic user interface) was intended to reduce the eye-strain involved in understanding the various information displayed in the screens (Sim et al., 2004).

4.4 Communication System

The communication system is composed mainly by two subsystems, used for transmitting respectively binary and video data. The first subsystem is based on a redundancy apparatus using both a standard high-power wireless LAN interface, for most of the data exchanged at a high data rate (10Mbps) and a pair of low speed radio modems (100kbps), for critical tele-operation purpose when the wireless communications fails. In fact the wireless LAN interface does not work properly when the robot is out of the line of sight; in this case the radio modems restore the communication with the control console.
The video links are guaranteed by two pairs of video receiver and transmitter, the first pair is used to transmit the video signal of the frontal video camera mounted on the pan/tilt turret while two 8 channels switches are used to connect all the other video signals to the other video link. The video source can be selected by the operator from the control console.

Another communication subsystem is the radio-link that connect the base GPS with the rover GPS for the transmission of the differential signals. Also this link works properly only if the antennas are in the line of sight, when the signal is lost the rover GPS act as a single GPS, hence with a lower accuracy.

Figure 11. The Control Console installed on a pick-up vehicle

4.5 Navigation System

Most of the operations of Robovolc are handled by a human operator, so that the system is tele-operated, however since the connection link cannot be guaranteed for all the situations and in order to increase system reliability and to decrease the effort of the operators in long duration mission, a limited amount of autonomy was included in the system. For teleoperations five fixed and two mobile video cameras are adopted. Four of the fixed cameras view each side of the robot, while the fifth is in front of the robot to help the teleoperations of the arm. Another camera is mounted on the manipulator wrist and is used to help pick and place operations, while a last camera with zoom capabilities is on the pan-tilt turret and is adopted to examine far and close terrains in front of the robot. The user if needed can switch the monitor to the IR-camera view, thus allowing to avoid the robot to move on very hot surfaces.
As regard autonomous navigation this is based on a hierarchical structure that models the cognitive process employed in human navigation. This is implemented into four layers: *long range planning* to define the map based way-point map of the robot; the *short range path planning* that manages the navigation of the robot between the waypoints; *the instant path planning* that decides the direction of the robot on the basis of the short range layer inputs and on the terrain data. Finally the motion control layer translates these commands into control commands for the motion control boards.
In order to guarantee a precise positioning of the robot a reliable localisation system was needed. Some details of this localisation system are described in the next section.

5. Localisation System

Localization is a major task in mobile robotic for outdoor environment. 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. A block diagram is reported in Fig. 12. The main sensor adopted for localisation is a DGPS (Ashtec model Z-Xtreme) based on a Real Time Kinematic Differential GPS (RTKDGPS) with an optimum position accuracy lower than one centimetre. However the precision of the DGPS in some situation can be drastically reduced. 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.
In order to avoid such problems several data fusion algorithms have been designed to improve the accuracy of localisation data from the DGPS by merging it with inputs from other sensors. The sensors inputs include odometry data from the wheels encoders, rate of turn from gyroscopes and the attitude of the robot measured by an inclinometer (Longo et al., 2002).

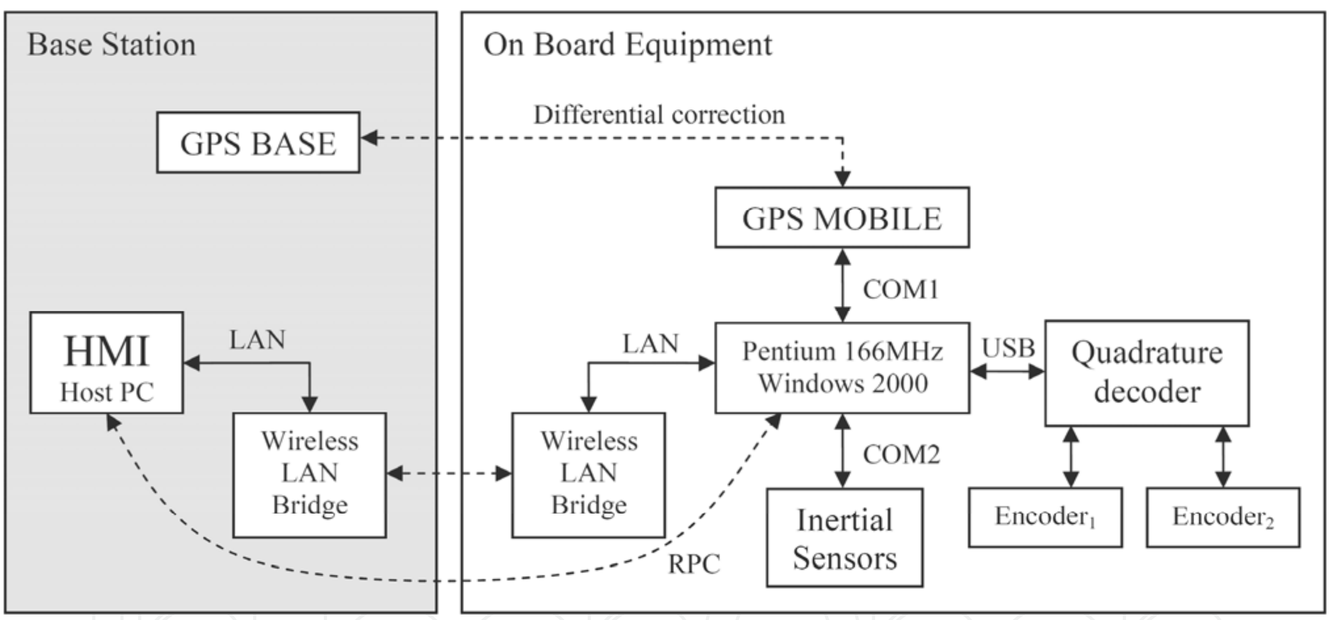


Figure 12. Block diagram of the Localisation system

5.1 Self Calibrating Extended Kalman Filter

This section presents one of the localization algorithms, called “Self Calibrating Extended Kalman Filter” (EKFSC), which has been developed for Robovolc. The EKFSC algorithm uses an EKF to fuse DGPS and encoder data in order to calculate the robot position and to estimate the parameters of the robot model (Caltabiano et al., 2004b).
Odometry is based on the assumption that measures of wheels movements can be translated into measures of the vehicle motion using the kinematic model of the robot. This assumption is only of limited value, because there are several reasons bringing inaccuracies in the odometry. The main causes of error sources in odometry are: wheels slipping, uncertainty in the odometry parameters (wheels radii and wheelbase), misalignment of the wheels and finite encoder resolution and sampling frequency.
The error sources related with the encoders, most of the time, can be neglected due to the excellent resolution of the encoders and to the high sampling frequency. If the robot is well

assembled, the misalignment of the wheels is also negligible compared to the other sources of error. The errors caused by the wheels slipping cannot be estimated by the encoders and hence can not be compensated. On the other hand the error caused by the uncertainty on the odometry parameters could be reduced if a good calibration is performed (Borenstein and Feng, 1996).
Calibration is the problem of estimating the parameters of the robot model from sensors measures. This estimation is sometimes very difficult for various reasons: the pressure of tires can change during the time; furthermore the effective wheelbase depends on the terrain where the robot is moving; In our specific application, different kind of tires can be mounted on Robovolc, depending on the environment where the robot has to move (rocky or sandy terrain), hence affecting the measures of the wheels diameter and wheelbase; therefore the calibration of the robot parameters is periodically required.
In practical robotic applications, the odometry parameters are identified in a dedicated phase and then they are no more calibrated. Most of the researches, in fact, use an absolute sensor like a Laser Scanner or a GPS to compensate the accumulated errors caused by dead reckoning (Martinelli et al., 2003), (Foxlin, 2002). Unfortunately, using wrong parameters, the robot can get lost very quickly, if for some reason the measure from an absolute sensor is not available. For example a big rock or a building can reduce the number of visible satellites of a GPS.
The EKFSC is a solution to the Simultaneous Localization and Auto-Calibration (SLAC) problem using an Augmented Kalman Filter (AKF): the state vector has been augmented with the odometry parameters; moreover an odometric filter model is used in the *Predict phase* of the EKF, while the *Update phase* uses the GPS data asynchronously.
The EKFSC localization algorithm relies on an Extended Kalman Filter where the predictive phase, calculated using the odometry measures, computes at high frequency the expected position and orientation of the robot and the update phase corrects these estimations at a lower frequency using the GPS measures. The odometry parameters are considered as state variables in the EKF hence they are estimated together with the localization variables. The details of this algorithms are reported in the paper (Caltabiano et al., 2004b), where a comparison with the UMBmark calibration procedure is also reported (Borenstein and Feng, 1996).

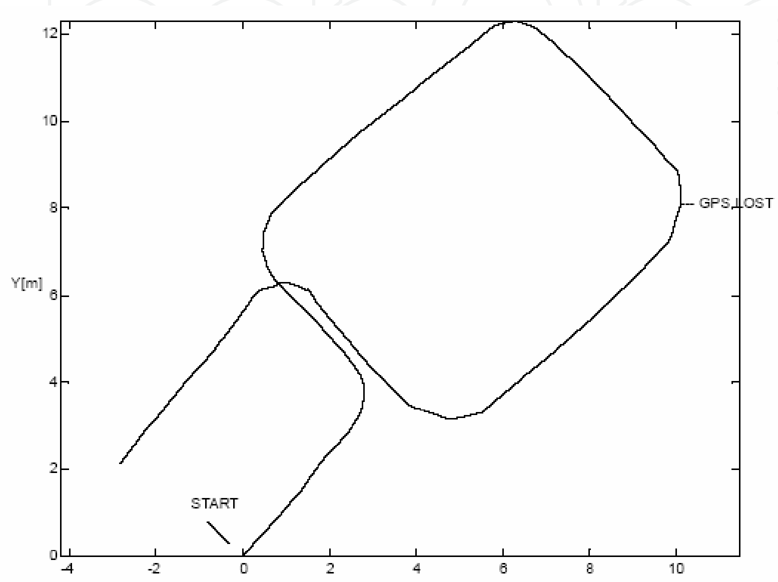


Figure 13. Robot trajectory adopted for testing the EKFSC localization algorithm

In order to test the presented algorithm several trials have been realized with Robovolc. The odometry parameters of Robovolc, measured directly on the robot are: Wheels radius: *R1*=0.21m, *R2*=0.21m, Wheelbase: *L*=0.82m, while the EKF algorithms are initialized with the wrong parameters: *R1(0)*=0.20m, *R2(0)*=0.20m, *L(0)*=0.69m. The robot moves along the trajectory shown in Fig. 13. During this trial, DGPS data have been really accurate, so the above trajectory has been reconstructed using only this sensor. A GPS failure has been simulated at time t=90s and is indicated in the image as *GPS LOST*, hence in the rest of the trajectory the GPS measures are not available for the localization algorithm.

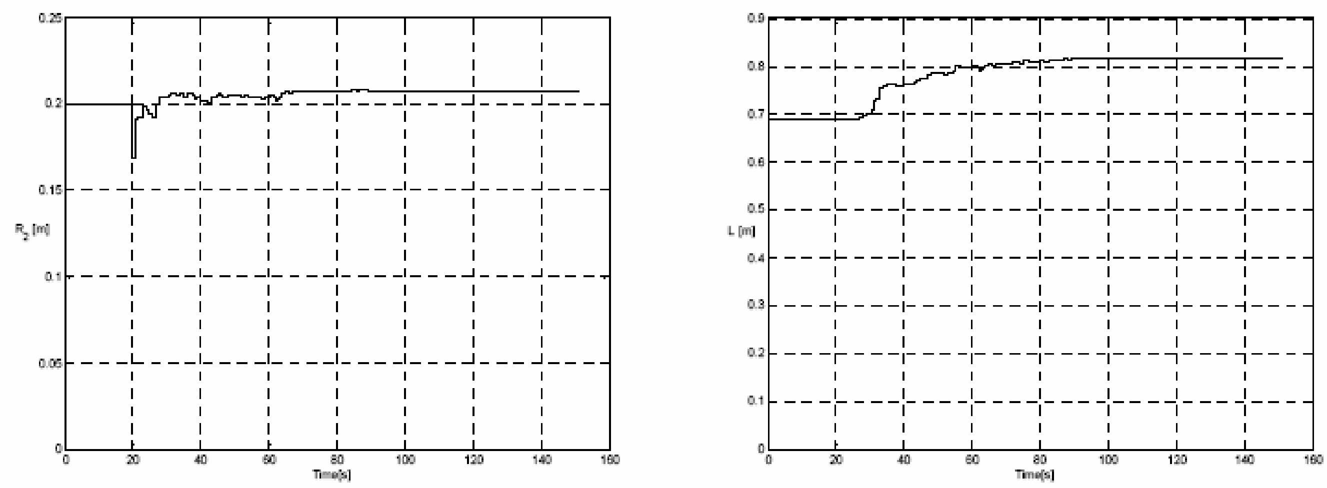


Figure 14. Estimation of *R1* and of *L*

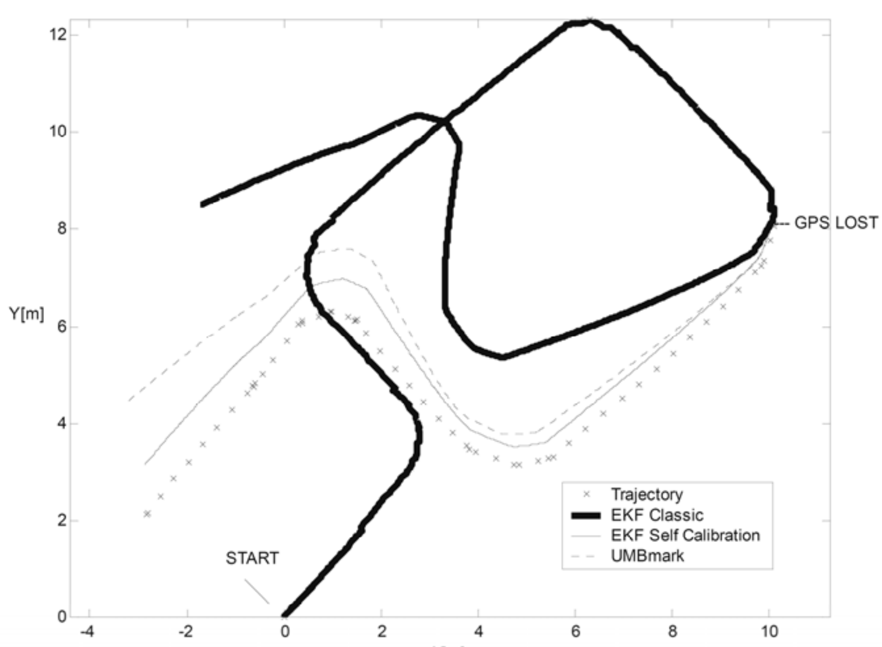


Figure 15. Comparison between EKFSC and EKFClassic and an EKF calibrated via the UMBmark procedure

When the robot was moving along the trajectory, the odometry parameters have been estimated as shown in Fig. 8 and 9. Fig. 14 shows the estimation of *R1* and of *L*. The estimated final value are *R1(90)*=0.209m and *L(90)*=0.816m. Similar results have been obtained for *R2*, the estimated final value is *R2(90)*=0.208m.

Fig. 15 shows the comparison between the EKFSC the EKFClassic and an EKF calibrated via the UMBmark procedure in the reconstruction of the test trajectory

The EKFClassic brings to really poor results when the GPS is not available and the parameters are not calibrated. On the contrary the trajectory reconstructed, using the EKFSC algorithm, is very close to the real one and is much better than those obtained by using the UMBmark calibration.

5.2 Orientation Estimator

Another localisation algorithm that was implemented and tested on the Robovolc platform is a modified Kalman filter that includes an orientation estimator. Magnetic compasses are the most classical absolute orientation sensors. However, the precision that can be obtained is usually low (0.1°) and they can be strongly affected by external disturbances. When an extra magnetic field is present (i.e. motors, electrical equipment or magnetic rocks), the precision of the compass can be very poor. The rocks in volcano environments are often magnetic hence compass provides very unreliable measures. Moreover, no estimation of the standard deviation of the measurements is usually given by the sensor. For all these reasons using a compass on volcano environments is not recommended.

This problem is particularly important when the robot is moving following a rotation. In this case due to the skid-steering system, the precision of the odometry to compute the orientation is very low and a classical EKF converge to the true orientation very slowly. The absolute orientation can be obtained, instead, helping the EKF by using two consecutive GPS measures. The adopted localization algorithm is a classical Extended Kalman Filter where the predictive phase, calculated using the odometry measures, computes at high frequency the expected position and orientation of the robot and the update phase corrects these estimations at a lower frequency using the GPS measures (Fig. 16). Moreover the measurement vector contains both the position and the orientation of the robot; the latter is obtained through an algorithm using the information contained in two consecutive GPS measures (Caltabiano & Muscato, 2003).

In order to verify the speed-up of the EKF3 algorithm, it has been compared with the classical EKF2 algorithm.

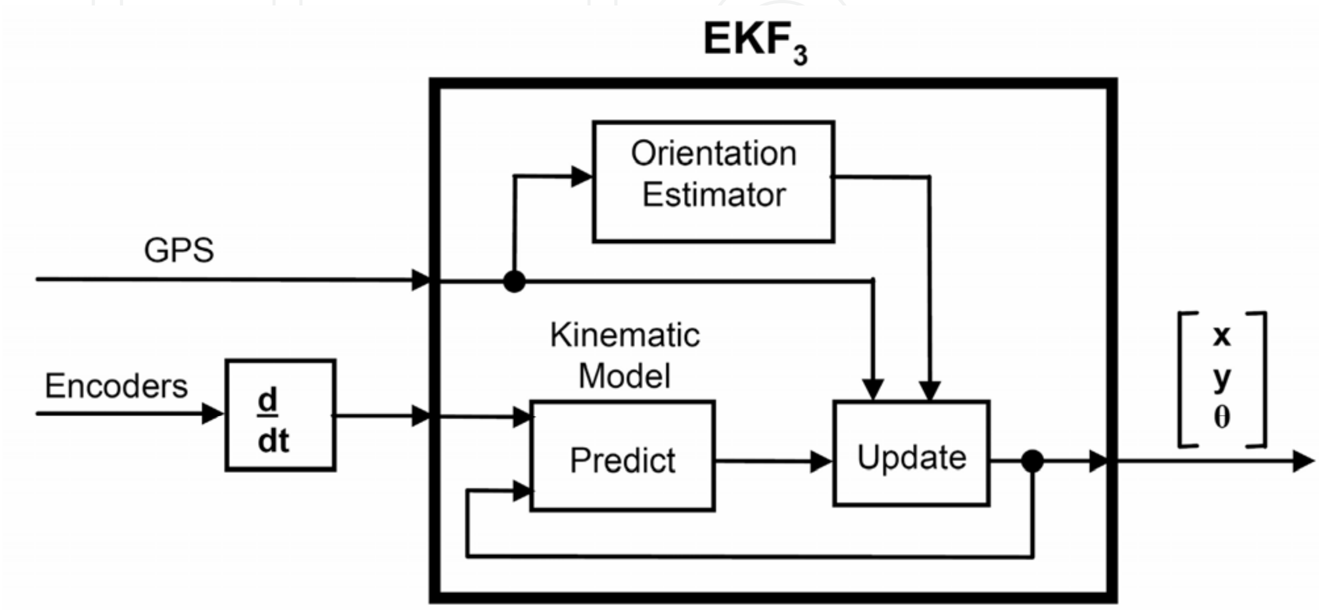


Figure 16. Scheme of the EKF3 localisation algorithm

It has been assumed that: the robot moves toward North-West with an average speed of 0.81 m/s; the GPS has a sampling frequency of 1 Hz; the Encoders are sampled at 20 Hz; the initial orientation of the EKF algorithm is the East. The EKF2 algorithm output is given in Fig. 17a, where the square boxes correspond to the GPS measures (sampled at 1Hz) connected with a solid line, the small points are the EKF output (sampled at 20Hz) while its standard deviation is represented with circles.
In order to obtain clear images, the standard deviation circles are plotted at half rate (10Hz) and for diameters below half a meter. Fig. 17b refers to the EKF3 algorithm. As it can be observed from these results the transient passed from 5 seconds (4 m of path) obtained with the classical EKF2 algorithm to 1 second (70 cm) obtained with the EKF3. In our application 4m of path with an uncertain direction could represent the difference between falling inside a crater and following the right trajectory.

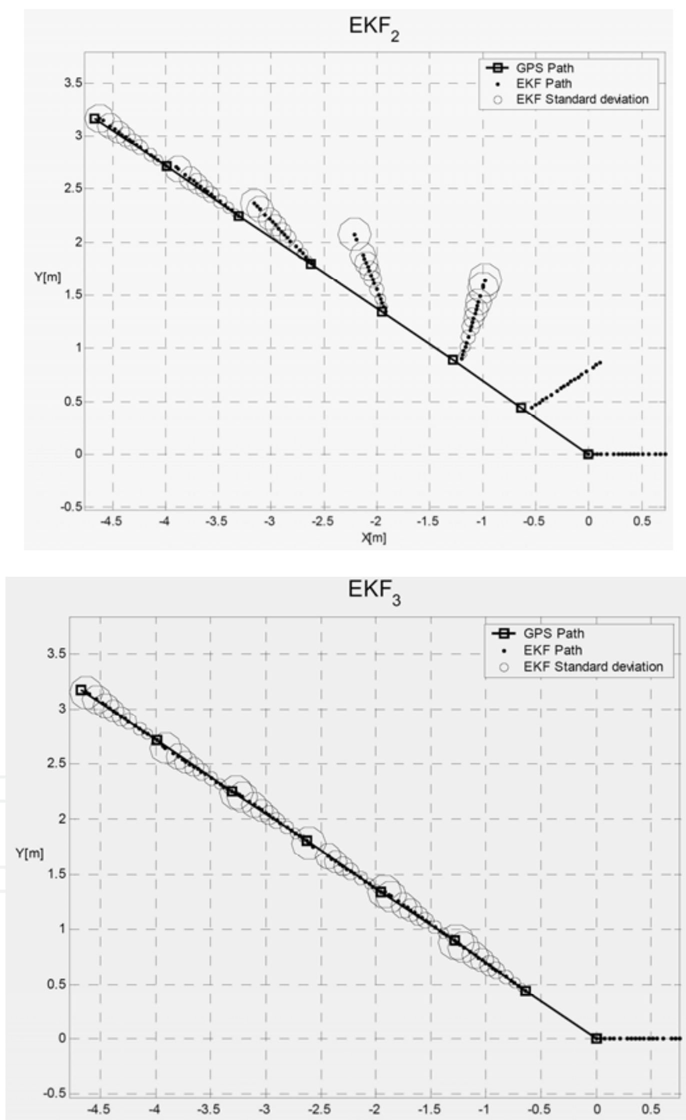


Figure 17. Transient of the EKF2 and EKF3 algorithms of the Robovolc tests

6. Trials on Mt. Etna Volcano and Final Considerations

Several tests of the Robovolc platform have been performed on the Mt. Etna Volcano in Italy where different kinds of terrain can be explored due to different types of eruptions over the years. Some pictures of the platform and of the explored environment are

reported in this section. Each of the Robovolc subsystems has been tested initially separated and then altogether in several virtual missions.
A preliminary test campaign on Etna volcano has been performed in September 2002 and has been discussed accurately in (Muscato et al., 2003).
In summer 2003, the rover has been successfully tele-operated to move inside one of the still hot craters of the eruption Dec 2002-Jan 2003. Traction tests have been performed successfully on rocky terrain (Fig. 18).
The rover demonstrated very good traction capabilities on rough surfaces. The robot easily coped with rocky obstacles of more than 40 cm in diameter and with 30 cm ground fissures. Traction tests with different tyres type on sandy environment have been performed successfully too, on the base of the *Laghetto Crater* (January 2002 eruption) (Fig. 19) also in surface with slopes of 30°.

Figure 18. Operations on rocky terrain

Figure 19. Operations on sandy terrain

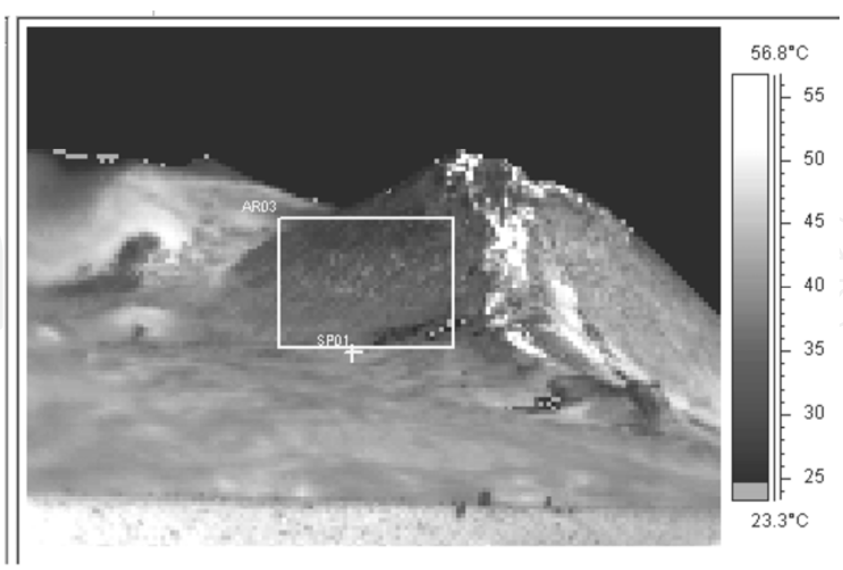


Figure 20. The Etna SE Crater viewed from the IR camera on board the robot. Clearer zones indicates higher temperatures

During the tele-operation of the robot, the entire science package has been tested: the pan-tilt turret has been oriented properly to take some pictures with the IR camera. One of the images of S.E. crater taken by the robot using the IR camera is shown in Fig. 20. Several videos have been recorded with the onboard video-camera and some navigation tests have

been performed to validate also the localization system. The manipulator has been tested in order to pick sample of rocks found in the environment.
Each trial required a great logistic effort in order to carry the robot on an altitude of about 3000m, to set-up the base station and to manage the uncountable problems encountered in all the testing phase. Fig. 21 shows the participants of this trial near the Robovolc platform.

Figure 21. Some participants to one Robovolc test campaign

7. Conclusion

The main innovation of this project is the capability to take measurements during volcanic eruptions by the development of a specific mobile robotic system for this purpose.
This robot will have a relevant impact on the mitigation of the volcanic risk both in general, since it contributes to improve knowledge about volcanic phenomena, and in particular because it is now integrated in the volcanic surveillance system to be used when the approach to active vents becomes too dangerous for human live, but information is vital for a correct forecast of dangerous eruptions. For instance, during the volcano unrest that precede a large eruption when the gas emission, thermal variation and ground deformation inside a crater or caldera, related to the ascent of new magma, give a direct information for forecasting of the approaching eruptive event; or during long-lived volcanic eruptions like large dome inflation the evaluation of the lava dome stability will significantly improve the forecasting of dome failures and pyroclastic-flow forming eruptions. The robot activity will contribute to an integrated risk management system by means of the updating, using GIS, of areas potentially threatened by catastrophic eruptions with geographical information about the volcanic products dispersion and volcanic hazard assessments to obtain an almost real-time early warning and to inform Civil Protection authorities about dangerous volcanic eruptions approaching.
The missions demonstrated the usefulness of a mobile robot in contributing to science research for volcanology. the system is now a new tool own by Istituto Nazionale di Geofisica e Vulcanologia in Sicily who are responsible for surveillance of Mt. Etna and the other Sicilian volcanoes in the Aeolian islands. The Robovolc system is ready to be used in the next active volcanic phases.

The expertise acquired in the development of the project and during the trial allowed the group to greatly improve the system and its reliability. On field trials have been fundamental to understand the real requirement of a system that has to operate in such hard environment and that could not be discovered by simple laboratory test.

The authors acknowledge the work performed by all the partners of the Robovolc project, more than 50 different persons were involved in the various steps of the project and their effort was fundamental for the success of the operations. Particular thank goes to each group leader M.Coltelli (INGV), P. Briole (IPGP), T. White (BAESYSTEMS), A. Semerano (Robosoft) and Prof. G.S. Virk (University of Leeds).

8. References

Azad, A.K.M.; Virk, G.S.; Qi, M; Muscato, G.; Guccione, S.; Nunnari, G.; White, T.; Glazebrook, C.; Semerano, A.; Ghrissi, M.; Briole, P. ; Faucher, C.; Coltelli, M.; Puglisi, G.; Cioni, R. & Pompilio, M. (2001). ROBOVOLC: Remote Inspection for Volcanoes, *Workshop on Autonomous artificial systems exploring hostile environments, International NAISO Congress on Information Science Innovations (ISI'2001)*, Dubai, March 18th 2001.

Bares, J.E. & Wettergreen, D.S. (1999). Dante II: Technical Description, Results and Lessons Learned, *The International Journal of Robotics Research*, pp. 621-649, July 1999.

Borenstein, J. & Feng, L. (1996). Measurement and correction of systematic odometry errors in mobile robots, *IEEE Transactions on Robotics and Automation*, Vol. 12, Issue: 6 , Dec. 1996 pp.: 869 -880.

Caltabiano, D & Muscato, G. (2002). A Comparison between different traction methods for a field robot, *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2002*, Lausanne Switzerland, Sep.30-Oct.4 2002.

Caltabiano, D & Muscato, G. (2003). A New Localization Algorithm for Mobile Robots in Outdoor Environments, *Proceedings of the 6h International Conference on Climbing and Walking Robots (CLAWAR 2003)*, 17-19 September 2003 Catania, Italy, pp 925-932.

Caltabiano, D.; Ciancitto, D. & Muscato, G. (2004a). Experimental Results on a Traction Control Algorithm for Mobile Robots in Volcano Environment, *Proceedings of the 2004 IEEE International Conference on Robotics & Automation*, New Orleans, LA, April 2004, pp. 4375-4380.

Caltabiano, D.; Muscato, G. & Russo, F. (2004b). Localization and Self Calibration of a Robot for Volcano Exploration, *Proceedings of the 2004 IEEE International Conference on Robotics & Automation*, New Orleans, LA, April 2004, pp. 586- 591.

Foxlin, E.M. (2002). Generalized Architecture for Simultaneous Localization, Auto-Calibration, and Map-building, *Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems*, EPFL, Switzerland, October 2002.

Guccione, S; Muscato, G.; Nunnari, G.; Virk, G.S.; Azad, A.K.M.; Semerano, A.; Ghrissi, M.; White, T.; Glazebrook, C. (2000). Robots for Volcanos: The State of the Art, *Proceedings of the 3rd International Conference on Climbing and Walking Robots (CLAWAR 2000)*, pp.777-788, Madrid (Spain), 2-4 October 2000.

Guccione, S. & Muscato, G. (2003), Control strategies computing architectures and experimental results of the hybrid robot Wheeleg, *IEEE Robotics and Automation Magazine*, Vol.10 No. 2, 2003. (IEEE Piscataway, USA).

Kemurdjian, A.; Gromov, V.; Mishkinyuk, V.; Kucherenko, V. & Sologub, P. (1992). Small Marsokhod Configuration, *Proceedings of the IEEE International Conference on Robotics and Automation*, Nice, France 1992.

Lacagnina, M.; Muscato, G.; Guccione, S. & Sinatra, R. (2002). Modelling and simulation of multibody mobile robot for volcanic environment explorations, *IEEE/RSJ International Conference on Intelligent Robots and System, IROS 2002*, Lausanne Switzerland, Sep.30-Oct.4 2002

Lacagnina, M.; Muscato, G. & Sinatra, R. (2003). Kinematics, Dynamics and Control of a Hybrid Robot Wheeleg, *Journal Robotics and Autonomous Systems*, (Elsevier, Oxford, UK),Vol 45, pp. 161-180, 2003.

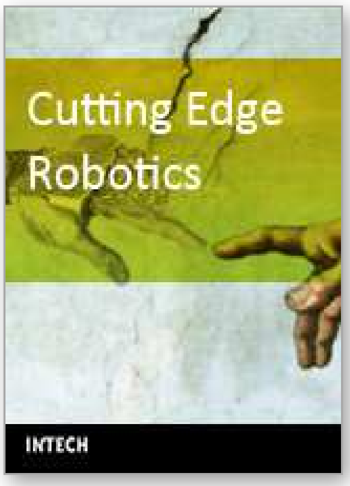
Longo, D; Muscato, G. & Sacco, V. (2002). Localization using fuzzy and Kalman filtering data fusion, *Proceedings of the 5th International Conference on Climbing and Walking Robots (CLAWAR 2002)*, 25-27 September 2002 Paris, France.

Martinelli, A.; Tomatis, N.; Tapus, A. & Siegwart, R. (2003). Simultaneous Localization and Odometry Calibration for Mobile Robot, *Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Las Vegas, Nevada, October 2003.

Muscato G.; Caltabiano, D.; Guccione, S.; Longo, D.; Coltelli, M.; Pecora, E.; Cristaldi, A.; Virk, G.S. ; Sim, P.; Sacco, V.; Briole, P.; Semerano, A. & White, T. (2003) ROBOVOLC: A Robot for Volcano Exploration Result of first test campaign, *Industrial Robots*, Vol. 30, N.3, May 2003, pp.231-242, ISSN 0143- 991X.

Sim, P.; Sacco, V. & Virk, G.S. (2004). The user interface for the Robovolc exploration robot, *Industrial Robots*, Vol. 31, N.2, pp.189-200, ISSN 0143-991X.

YAMAHA (2000) Helicopter news: http://www.yamaha-motor.co.jp/news/2000-04-24/sky-e.html



Cutting Edge Robotics

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This book is the result of inspirations and contributions from many researchers worldwide. It presents a collection of wide range research results of robotics scientific community. Various aspects of current research in robotics area are explored and discussed. The book begins with researches in robot modelling & design, in which different approaches in kinematical, dynamical and other design issues of mobile robots are discussed. Second chapter deals with various sensor systems, but the major part of the chapter is devoted to robotic vision systems. Chapter III is devoted to robot navigation and presents different navigation architectures. The chapter IV is devoted to research on adaptive and learning systems in mobile robots area. The chapter V speaks about different application areas of multi-robot systems. Other emerging field is discussed in chapter VI - the human- robot interaction. Chapter VII gives a great tutorial on legged robot systems and one research overview on design of a humanoid robot.The different examples of service robots are showed in chapter VIII. Chapter IX is oriented to industrial robots, i.e. robot manipulators. Different mechatronic systems oriented on robotics are explored in the last chapter of the book.