Volcanic Environments

Robots for Exploration and Measurement

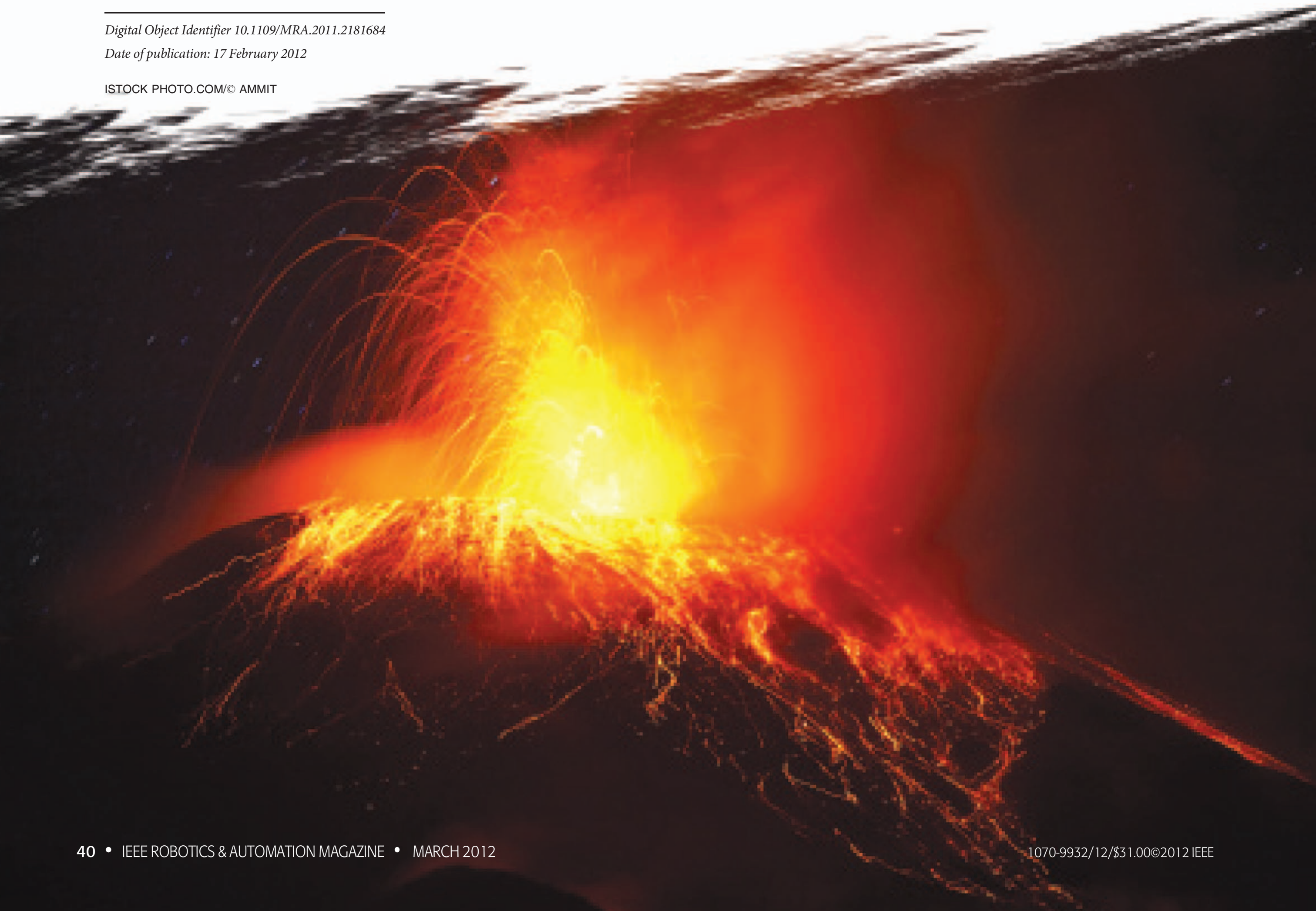
By G. Muscato, F. Bonaccorso, L. Cantelli, D. Longo, and C.D. Melita

The study of volcanic activity is important from a scientific point of view as it allows for a better understanding of one of the most spectacular geological phenomena and of the working principles that are at the basis of geophysics. Furthermore, there are numerous events that directly result from volcanic eruptions and that affect many populations. Therefore, improving the prediction methods of eruptive phenomena would be of great benefit. There are more than 1,500 potentially active volcanoes in the world, and roughly 10% of the world's population live in areas directly threatened by volcanoes. In all of these areas, volcanoes have a strong influence on many day-to-day activities. The eruption of Eyjafjallajökull in Iceland in April 2010 caused the cancellation of more than 100,000 European flights and, consequently, left more than 10 million passengers stranded. Each year, on a graver note, many regions in the world are destroyed or heavily damaged by lava or pyroclastic flows, in some cases, resulting in numbers of casualties that could have been avoided with the improvement of early warning systems.

Most of the measurements necessary for a comprehensive analysis of what is taking place inside a volcano should be

Digital Object Identifier 10.1109/MRA.2011.2181684
Date of publication: 17 February 2012

ISTOCK PHOTO.COM/© AMMIT



1070-9932/12/$31.00©2012 IEEE

taken in the proximity of the craters. Moreover, the best period to perform such measurement campaigns is before or during an eruption. By comparing data before and after an eruption, it is possible to better understand the best precursors, thus allowing for a more precise prediction of the activity. Understanding the intensity and duration of lava flow enables volcanologists to decide whether the population of a specific area needs to be evacuated or if lava deviation measures have to be performed. Also, the knowledge of when and how a plume of volcanic ash will be emitted is useful for the advanced planning of route modifications, and if need be, flight cancellations; thereby, this information can help reduce inconvenience and discomfort to passengers.

In this article, we present some research activities performed in the Robotic Laboratory of the Dipartimento di Ingegneria Elettrica Elettronica e Informatica (DIEEI) at the University of Catania, Italy, concerning the adoption of robots for measuring volcanic activity. Catania is located in southern Italy on the Island of Sicily and is situated at the base of Mt. Etna, Europe's largest active volcano. Etna has been responsible for a number of big eruptions that have destroyed or seriously damaged constructions, roads, and at times villages, shutdown airport activity in the area, and on some occasions, killed irresponsible tourists. In light of these situations, we began to closely cooperate with researchers of the Istituto Nazionale di Geofisica e Vulcanologia (INGV, the Italian Institute of Geophysics and Volcanology) and have since built several robot prototypes.

Interestingly, one of the first examples of robotic makers was the mythological God Hephaestus (whose ancient Roman name was Vulcano). In the Homer epic poem "The Odyssey," Hephaestus is cited as the builder of some mechanical helpers for his workshop, which, according to myth, was situated inside Etna. In our laboratory, situated at Etna's base, we are, in a way, continuing this old tradition of combining the robotics with the study of volcanoes.

Importance of Robots for Measurements in Volcanoes

The main goal of using robotic systems for volcanoes is to reduce the level of risk involved for volcanologists who are working too closely to volcanic vents during eruptive phenomena. The scenes that follow a volcanic eruption can lead to some of the worst possible conditions on earth: flows of lava, pyroclastic flows of hot mud, precipitation of big and hot stones, and earthquakes with terrain fractures are some of the typical events that take place in the areas surrounding the craters. In the last few decades, several volcanologists have misinterpreted signs indicating imminent eruptions and have thus lost their lives during volcanic explorations. Consequently, volcanologists should take precise safety precautions to avoid dangerous areas, but from another point of view, their quest for information and data often pushes them to put themselves in situations of high risk. Therefore, one possible instrument that can allow them to take measurements in dangerous situations without risking their lives is a robot. This innovation in volcanic risk assessment is going to be part of an integrated risk management system, which will obtain an almost real-time early warning that, in turn, will allow Civil Protection authorities to protect citizens from eruption catastrophes.

Our research activity did not only deal with robotics; we needed to collaborate with several groups of volcanologists about the best ways to solve related problems. In some cases, the requirements were too complex or expensive, and in others, simple solutions—not exciting from a robotic-research point of view—were possible. Our goal is not to simply design and build a new and original robot but, instead, to realize suitable instruments for volcanologists.

Many types of measurements can be useful for research regarding volcanic activity, but we have identified the most important ones, and they are discussed here.

Visual

Visual measurement is capable of getting pictures and videos within immediate proximity to the craters so as to better understand the evolution of an eruption. Active volcanic craters and dome structures are usually subject to rapid changes and often collapse under their own weight or as a result of endogenous forces. These collapses can produce dangerous pyroclastic flows or block erupting vents, leading to the presence of high-pressure gas, which can thus cause explosions. Hence, the visual measurement of craters and domes is particularly useful in predicting dangerous eruptions.

Thermal Images

Thermal images allow volcanologists to better understand the behavior and the evolution of an eruption, giving further information with respect to traditional visual images. Infrared (IR) cameras are widely adopted and are necessary instruments to be carried onboard a robot. Moreover, a thermal camera can also serve to read the temperature of the path where the robot is going to move in order for it to avoid riding over fumaroles or on recent lava flow, which can thus destroy the system.

Gas Analysis and Sampling

The analysis of the gas ejected from volcanic vents is one of the main indicators of volcanic activity. Gas emission comes from inside the volcano, and its composition shows the happenings in the depths of the earth. However, the emitted gas is at a high temperature and quickly mixes with the atmosphere, thus changing its original composition. As a result, a collecting system must be capable of gathering or analyzing gas close to the vents. Although there are remote systems that permit analyzing the nature of the gas through spectral or similar analysis, only a direct measurement can give a precise data concerning the gas composition.

Several environmental constraints must be taken into account in the developmental phase of a robotic system that is to be adopted in volcanic areas.

Terrain

The terrain on top of a volcano is one of the hardest and heterogeneous: hard rocks, very fine ash, steep slopes, snow and ice, and large fractures are typical, and, consequently, a single system cannot be capable of coping with all of these situations.

Temperatures, Gases, and Weather Conditions

Temperatures in the proximity of volcanic vents or of lava flows can be enormously high. The melted lava is in fact at a temperature of more than 1,000 °C. However, it should be observed that, by adopting ad hoc designed probes to perform measurements, the robot does not need to stay close to the lava, so a protective shield can be enough to protect it. Protective gear is also needed because volcanic gases are full of sulfur and can be highly corrosive to metal parts. Another key issue is that weather conditions at such high altitudes can rapidly change, and temperatures can be very low with strong winds. During eruptions, rock precipitation can occur. In one mission in June 2000 on Mt. Etna, we experienced such a storm with rocks ejected from the craters weighing about more than 1 kg and covering a distance of about 4 km (Figure 1).

Other Projects Concerning Robots and Volcanoes

The interest in robotics applied to volcanology is still not widespread, probably, because of the technical difficulties involved in developing robots suitable for harsh environments and because of the lack of substantial economic resources as those that are available to the military or space sectors [1].

Among the few robots devoted to volcanoes, Dante II is probably the one that deserves the most recognition. This robot was designed by Carnegie-Mellon University in a project funded by National Aeronautics and Space Administration (NASA) to perform measurements in live volcanoes and to further develop robotic technologies in rough environments [2]. The robot was an eight-legged frame walker, with the pantographic legs arranged in two groups of four. Dante II also moved by means of a tension-controlled tether to improve its stability and to allow for rappelling on steep slopes [3], [4]. The most important field trial put to this robot was performed in 1994 on Mt. Spurr in Alaska. The robot was driven for more than five days inside the volcano crater using both autonomous and teleoperated control. The mission was successful; however, while climbing out of the crater, Dante II lost stability and fell on its side, thus ending the mission and requiring the help of a helicopter to recover it [5].

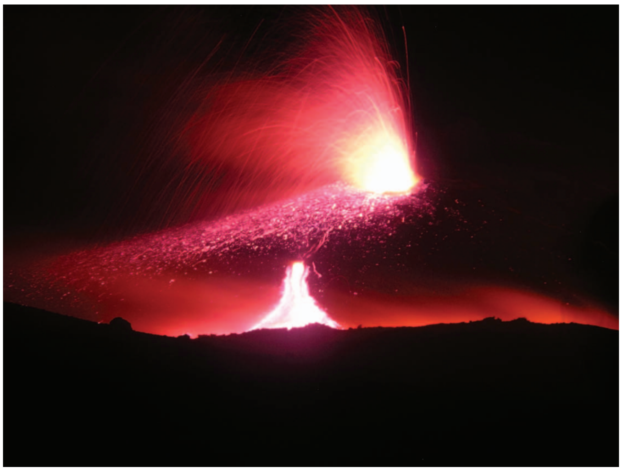


Figure 1. Mt. Etna Crater during an eruption. (Photo courtesy of G. Giudice, INGV.)

Many other ground robots that have been designed for planetary exploration have often been tested in volcanic sites because of the striking similarities between volcanic terrains and many planetary sites.

An important example is the Marsokhod rover, an all-terrain vehicle developed by the Mobile Vehicle Engineering Institute (VNIITransmash) in Russia for Mars exploration [6]. The Marsokhod robot has been extensively tested in volcanic environments, such as in Kamchatka, Russia (1993), Amboy Crater in California (1994), and Kilauea Volcano in Hawaii (1995). The last one was selected primarily for its great diversity of geological features similar to those experienced on Mars and Moon.

Aerial exploration can be another valuable way to get useful information in volcanic areas. Scientific literature is rich of civil applications of unmanned aerial vehicles (UAVs) [7]. However, only a few experiments done on volcanic-exploration surveillance exist. In April 2000, a Yamaha RMAX helicopter was adopted for the surveillance of Mt. Usu Volcano in the Hokkaido region of Japan. Because of the large distances of operation, an autonomous flight system was developed with cruise autonomy of 4 km. The helicopter, equipped with four charge-coupled device (CCD) cameras, was successfully adopted for performing several surveillance missions observing the hazards caused by volcanic sediment and debris flow [8]. The helicopter was also integrated with a gas detection meter to measure densities of volcanic gas in Mt. Oyama on Miyake-jima Island in February 2001.

In 2004, the U.S. Geological Survey made a single 20-min test flight above Mt. St. Helens; however, no publication concerning the achieved results is available. Similarly, Aerosonde [9], together with JPL, announced a project dealing with the adoption of UAV for monitoring volcanic plume in 2003, but no results have been presented. A Silver Fox UAV by Advanced Ceramics Research [10], equipped with thermal imaging payload, has been deployed to monitor seismic activity at Mt. St. Helens in Vancouver, Washington.

The DIEM Aerospace Division, Università di Bologna, Italy, carried out a test campaign over the Island of Stromboli in October 2004 to demonstrate the feasibility of an unmanned aircraft system (UAS) for volcano monitoring [11]. In 2007, Scottish physicist Andrew McGonigle made some measurements of volcanic carbon dioxide with a small, remotely operated helicopter [12] and, in 2008, won the Rolex Award for adopting a larger helicopter for the analysis of gases on volcanoes.

Most volcanoes can be found underwater, as approximately 71% of the Earth's surface is covered by water. In recent years, the interest in the exploration of underwater volcanoes has also increased, and several research groups have adopted underwater robots to survey the depths of oceans, such is the case of the Autonomous Benthic Explorer (ABE), a robotic underwater vehicle used for exploring the ocean to depths of 4,500 m. This robot has been used by geologists to locate, map, and photograph many deep-sea hydrothermal vent sites and volcanoes [13].

In 2010, the National Oceanography Centre (NOC) in Southampton piloted the underwater vehicle known as HyBIS at a depth of 5,000 m to film the Black Smokers in the Cayman Trough in the Caribbean [14].

Figure 2. A view of Mt. Etna's central crater.

Robots Developed at the University of Catania

In 1999, following preliminary discussions with volcanologists of INGV and about previous research activities carried out together on data processing, we decided to start prototyping robots for volcanic exploration. Many technical visits to volcanic sites (Etna, Stromboli, and Vulcano) were needed, and several meetings were organized to agree upon the requirements. It was immediately clear that the terrain was extremely rough and challenging and that a single system capable of being used in all of the possible conditions exceeded current robotic capabilities. In Figure 2, a typical scenario is shown.

Figure 3. Our prototype robots for volcanic exploration: (a) Wheeleg in action on Mt. Etna, (b) M6 on volcanic terrain, (c) P6W robot, and (d) U-Go robot during a teleoperated outdoor test on the island of Vulcano.

Our group developed several types of ground robotic vehicles to experiment different traction strategies, control, localization and navigation algorithms, and measurement systems (Figure 3). Since the payload needed to carry all the needed instrumentation was rather high, the adoption of UAVs was initially excluded because it was considered useful for specific missions only.

Table 1 summarizes the main ground-prototype robots developed, their most important features, and several references where the interested reader could find more details on each system. With the exception of U-Go, which was mainly adopted as a mule for several volcanic missions, all other robots were prototypes developed just to test locomotion architectures or traction strategies that were useful to the improvement of ROBOVOLC system.

In 2005, we also started a research line for the development of UAVs for volcanic inspections. In particular, the Volcan Project was initiated in cooperation with INGV, with the aim of building an autonomous flying system able to perform gas analysis and sampling and the visual monitoring of volcanic areas. More details concerning this case could be found in [28] and [29].

ROBOVOLC

ROBOVOLC was the original name of a research project that was initially funded by the European Commission from 2000 to 2003. The partnerships included two universities (Università degli Studi di Catania, Italy, and the University of Leeds, United Kingdom), two industrial organizations (Robosoft, France, and BAE Systems, United Kingdom), and two research organizations that provided their expertise in volcanology and cartography: INGV, Italy, and the Institute de Physique du Globe de Paris, France. A more detailed description of the project with the latest updates can be found at the project Web site [21] and in [22] and [23].

The main result of the project was the design, realization, and testing of the ROBOVOLC platform, as shown in Figure 4. Since the conclusion of the project, the robot has been continuously updated and tested and is a powerful tool for the investigation of the adoption of robotics in volcanology.

The Mechanical Platform

ROBOVOLC uses a six-wheeled system with an articulated chassis. Its dimensions are $W \times L \times H = 80$ cm $\times$ 130 cm $\times$ 180 cm, and its total weight is 350 kg. The robot is skid steering since it is able to rotate by using the different speeds of the wheels on the right side as well as those on the left. The wheels are actuated by using six independent dc motors, and three different types of tires can be chosen depending on the expected soil. Several tests, also performed on the previously exposed prototypes, have shown that an articulated chassis satisfies all requirements and guarantees an adequate mechanical robustness. The front and rear axles of the robot have two possible movements: a rotation along the longitudinal axis of the robot, which is only passive, and a second rotation along the lateral axes (parallel to the rotation axis of the central wheels), which can be actively controlled by means of two electric motors. Figure 5 reveals a typical situation on a rocky terrain where the chassis' capability of adapting to the terrain is fundamental. Traction control algorithms have been developed and tested to maximize the robot's traction capabilities in different situations [18]–[20].

Power supply is guaranteed by means of four sealed lead-acid batteries, coupled to form two 24-V units. The autonomy of the system in typical working conditions has been tested to be 2 h, while the distances that can be covered are in the order of 3 km.

Control Hardware Architecture

The actual version of the robot is equipped with three PC boards to manage the wheel speed and traction control, the

Table 1. Ground-prototype robots for volcanic exploration developed at the University of Catania.

	Wheeleg	M6	P6W	U-Go
Locomotion	Two front legs (pneumatic) and two rear wheels (dc motors)	Six wheels independently actuated by a stepper motors inside each wheel	Six wheels independently actuated by independent dc motors	Rubber tracks (dc motors)
Main features	Hybrid locomotion architectures	Highly adaptive chassis: each pair of wheels is jointed to the other with a prismatic and rotational joint with variable stiffness	Smaller scale prototype of the ROBOVOLC system for traction control strategies test, field-programmable gate array (FPGA)-based low-level control architecture	Two control modalities: teleoperated and autonomous, 200-kg payload
Dimensions $W \times L \times H$ (cm)	66 × 111 × 40	71 × 75 × 15	20 × 30 × 20	70 × 120 × 110
Weight (kg)	25	10	3	250
References	[15], [16]	[17]	[18]–[20]	[25], [26]

science sensor package, and the navigation and localization system. Another axis control board is devoted to the control of the manipulator arm. All these systems are interconnected by an Ethernet LAN and are interfaced with a remote base station for mission supervision and teleoperations through a wireless radio link.

Navigation and Localization System

In most situations, the robot can be teleoperated by human operators on the base station located at a safe distance from dangerous sites. However, since distances can reach several kilometers, it can be difficult to recognize the terrain by means of video cameras onboard the robot; likewise, in some cases, the radio link signal can be broken. Therefore, the ability of the robot to move autonomously is crucial. With this in mind, a precise localization and navigation module was installed following the initial development of ROBOVOLC [24].

The navigation and localization system of ROBOVOLC has recently been renewed by adopting an architecture similar to the one installed in the U-Go robot. By using a modular hardware and software architecture, we can easily exchange the two robotic platforms by maintaining the same programming environment and hardware components.

The navigation onboard sensor suite is composed of

- stereo camera (Videre, STH-MDCS3-VAR)
- attitude and heading reference system (AHRS) (X-Sens MTi)
- laser range finder (LRF) (SICK LMS200) ultrasound sonars (Devantech SRF08)
- global navigation satellite system (GNSS) receiver (Ashtech ZXtreme)
- encoders on each wheel.

The integration of the information coming from all the sensing devices is fused to both reconstruct the terrain morphology and implement a localization and obstacle avoidance algorithm.

The localization is based on an extended Kalman filter (EKF) fusing GNSS, AHRS, and odometer data that allows volcanologists to accurately estimate the robot's position and heading. Stereo cameras are used both to detect the presence of obstacles in the mission path and to recognize and define drivable surfaces in the proximity of the robot [25], [26]. Obstacles are also detected with an LRF and US-Sonar.

The control electronics have been designed to provide two different control modalities: teleoperated and autonomous. During teleoperations, a remote user, using a joystick, can send simple, direct commands to the robot. In an autonomous mode, the robot is able to follow a planned trajectory, avoiding obstacles and finding a suitable, traversable path. The planned trajectory is formed by a sequence of waypoints the robot has to move on.

The architecture of the onboard software has been developed in a layered fashion to further improve system modularity and uses the Microsoft Robotics Developer Studio (MRDS) tool [27]. This environment allows for high-level visual programming, while all the lower level behaviors can be coded using the programming language C#. In Figure 6, a block diagram of the developed architecture is shown.

Figure 4. ROBOVOLC in action on top of Mt. Etna (the southeast crater is in the background).

First of all, data from navigation sensors are processed by the EKF to evaluate the robot's state. Following this step, the navigation algorithm deals with generating the control references for the robot.

Among the different navigation algorithms that were tested, the well-known potential field method (PFM) [30] has been chosen. PFM allows motion control and obstacle avoidance to be performed simultaneously without losing the main navigation task. For instance, waypoints act on the robot as attractive forces, while LRF and Sonars act with only repulsive forces. Computer vision information, which comes from the processing of the stereo camera images, is transformed into virtual forces as well, suitable to be used for the PFM.

The Science Sensor Package

The science package mounted on ROBOVOLC comprises a pan-tilt turret, a manipulator, and a gas sampling system. Mounted on the pan-tilt turret, shown in Figure 7, is a video camera with recorder, a high-resolution, still-image camera, another video camera for teleoperations, an IR camera for

Figure 5. ROBOVOLC in action on rocky terrain.

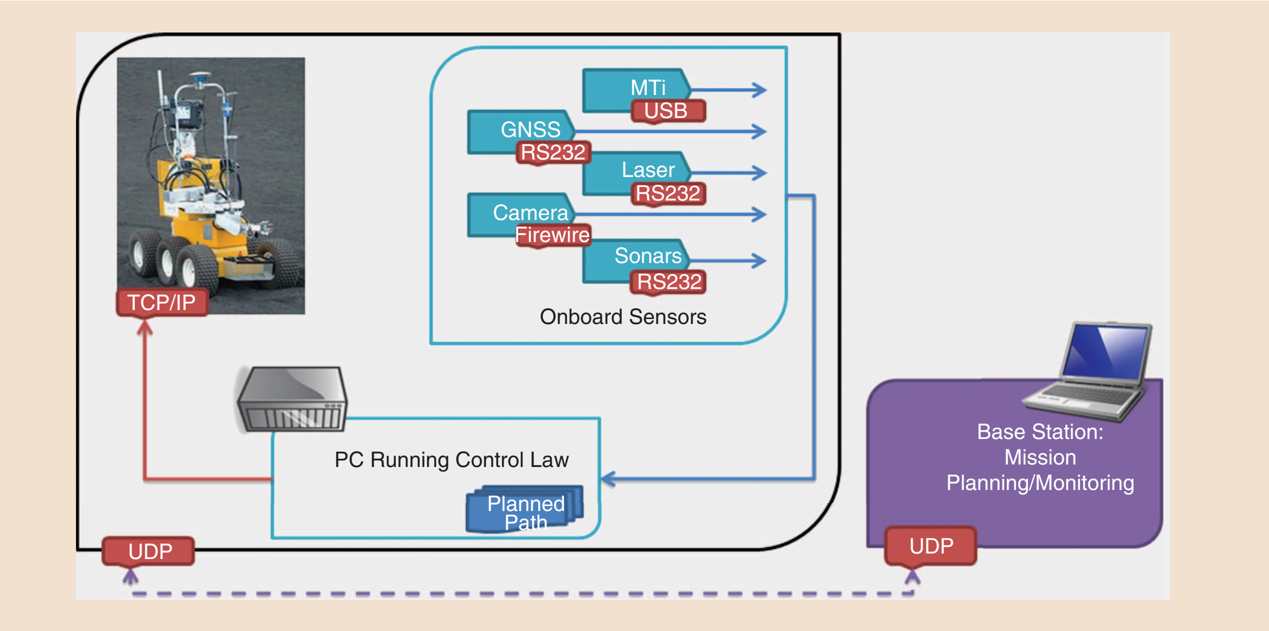


Figure 6. Navigation system control architecture.

thermal measurements, and a Doppler radar for lava and gas-jet speed measurements. All these devices have been installed inside weather and shock-proof sealed containers and can be oriented by moving the pan-tilt turret.

The manipulator arm, shown in action in Figure 8, designed and built by ROBOSOFT, is of SCARA type with five degrees of freedom plus a special three-finger gripper that is used to collect samples of rocks or to drop and pick up instruments in the field. By changing the end effector, the manipulator can be used to collect gases in the proximity of volcanic fumaroles.

The gas sampling system, specifically designed for ROBOVOLC, is composed of several subsystems. Volcanic gas is ejected at temperatures above 600 °C and could contain corrosive acidic components. For these reasons, we have adopted a titanium probe with a thermocouple and an oxygen sensor on its tip. These sensors enable volcanologists to assess the quality of samples before starting the collecting procedure. A temperature control system on the probe is also mounted to maintain the gas temperature between 120 and 200 °C. Low temperatures may cause water condensation that can corrupt the measurements while higher temperatures are dangerous for the flexible pipes that connect the probe to the collection system. A gas collection system mounted on the manipulator arm and made of Teflon pipes, valves, pumps, a dryer, and a condenser (Figure 7) is adopted to save the gas samples in two glass bottles. All the operations are also telecontrolled by using the measurements from several other thermocouples, a CO_2 sensor, and a camera.

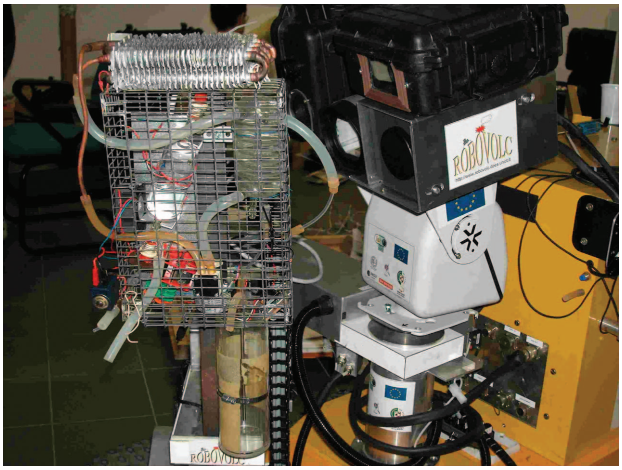


Figure 7. The gas sampling system on the left and the pan-tilt turret on the right.

A precise real-time kinematic–differential global positioning system (RTK–DGPS) was also installed with a dual purpose. As explained previously, the precise localization is adopted by the navigation module as a GNSS to better control the motion of the robot. This DGPS is also used as a scientific instrument to detect ground deformations. Nowadays, volcanologists often adopt both static and kinematic DGPS receivers to evaluate deformations [31]. In particular, crossover error analysis can be performed by computing the discrepancies in height determinations, which are computed at the intersections of independent tracks covered by the robot [32]. In this way, vertical deformations can be detected or the thickness of deposits between one epoch and another can be measured.

Field Results

Several tests of the ROBOVOLC platform have been performed on Mt. Etna since 2002 [22]. In the summer of 2003, the rover was successfully teleoperated to move inside one of the still hot craters created by the December 2002–January 2003 eruption. Since then, ROBOVOLC has been continuously maintained efficient and tested in different missions.

Traction tests such as those represented in Figures 2 and 5 have been performed on rocky terrains. The rover demonstrated good traction capabilities on rough surfaces and easily coped with rocky obstacles of more than 40 cm in diameter and with 30-cm ground fissures. Also, traction tests using different types of tires on sandy terrains have been successfully executed on the base of the Laghetto Crater (January 2002 eruption) as well as on surfaces with slopes of 30°. Research activities concerning the localization system and the calibration of robot-model parameters were also performed [24].

Scientific Data Collected

As previously mentioned, the robot was designed to execute tasks and take measurements much like a volcanologist, thus reducing the associated risks. Therefore, the acquired measurements show no particular differences with respect to those that can be obtained manually. Moreover, most of the trial tests of the system were performed in situations with low risk, since during the development and tuning phase, the close presence of technicians was necessary. However, eruptions in most situations happen without any forewarning and, in some cases, are extremely dangerous or occur on terrains that are very difficult for the robot too. As a result, even if the robot was tested many times on a volcano, the number of trials during a real eruption was very low.

In the following section, we give a critical review for each measurement executed by the different sensors.

Video Camera Images

Images that are broadcast live from the high-definition video camera enable volcanologists to observe in detail the area of inspection and, during eruptions, provide a close view of the phenomena. The image stabilizer on the camera improves the quality of the images also while the robot is moving.

Video camera images of lava rivers, as the one captured in Figure 9, were also adopted to estimate the amount of lava flow through an algorithm based on image-flow processing.

Infrared Camera Images

The IR camera provides thermal images of the volcanic ground. Such images can also serve to prevent the robot from moving over very hot areas, detect high-temperature magmatic gas sources such as fumaroles, sample gases, identify rocks with temperatures higher than the surroundings, and collect fresh volcanic product. In addition, the camera can furnish thermal maps of specific areas of the crater floor, which are useful for the detection of volcanic activity. In Figure 10, a picture of Etna's southeast (SE) crater, viewed from the IR camera onboard the robot, is shown.

DGPS Data

Because of the high accuracy of the DGPS receiver in post-processing mode and because of the capability of remotely controlling the robot trajectory in real time, it was possible to perform repeated surveys almost exactly following the same path as in the previous ones. The relative coordinates of each path were then examined using the methods of node crossing [32]. The difference in elevation of the trajectories at the nodes can estimate the vertical deformation of the volcano with a typical accuracy of 5–10 cm.

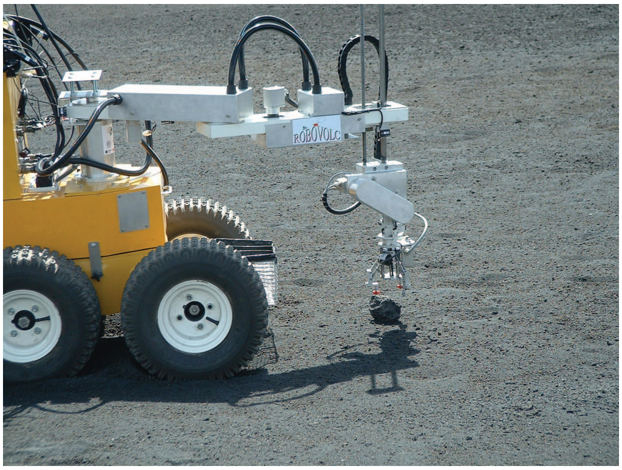


Figure 8. Rock sampling with the ROBOVOLC manipulator.

Still-Image Camera and Stereo Images

Still images collected with the camera, combined with the accurate positioning provided by the DGPS, were useful to quantitatively assess two-dimensional or three-dimensional surface changes of a nonaccessible target, such as an active crater. The system can work with or without ground control points located in the images. The accuracy achievable with the actual instruments can detect only relatively large deformations (20 cm) or morphological changes when the robot is at a safe distance (1 km). However, this is enough for the monitoring of an active crater as Etna's SE Crater in recent years has shown. The potential of this technique is still largely underused, and significant progress is possible in the future.

Figure 9. Example image of hot lava flow on Mt. Etna taken by ROBOVOLC in October 2004.

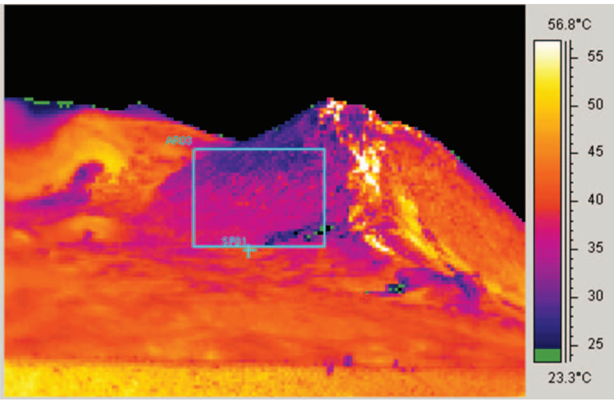


Figure 10. The Etna SE Crater viewed from the IR camera onboard ROBOVOLC. Clearer zones indicate higher temperatures.

Gas Sampling and Analysis

During several tests performed in the laboratory and on the Island of Vulcano, the sampling system showed results comparable with those obtained by using the typical manual sampling procedure performed by volcanologists. From these performed tests, it can be concluded that the sampling system designed for ROBOVOLC is able to provide reliable chemical and isotopic data on the fumarolic gases of interest for volcano monitoring. However, as yet, it has not been possible to test the system onboard the robot while on a real volcano.

Doppler Radar

Doppler radar speed sensors were theoretically able to measure lava and fumaroles' gas speed. Nevertheless, during several tests performed on flowing lava and gas on Etna, the first sensor we installed did not perform the requested measures. This was mainly due to the low speed of lava flow and the low radar backscattering of volcanic gas and particles produced during the explosive activity. A new Doppler radar speed sensor with better performance was then set up. With this sensor, it was possible to measure lava speed; however, it needed to be precisely located with respect to the lava river, and the obtained measurements required some further filtering and processing to be adopted. The processing of video images was then considered more reliable for the measurement of lava speed, and the Doppler radar was not therefore installed.

Rock Collecting

The collection of rocks during the trial tests on Mt. Etna performed with the manipulator arm using its three-finger gripper proved to have effective results. The gripper was able to collect samples from the eruptive activity of interest for volcanologists and store up to three samples in a basket located in front of the robot platform, thus avoiding the mingling of samples collected at different sites. These activities, in part, were performed autonomously, with a high degree of efficiency, to reduce the amount of time the robot would be in dangerous sites.

Analysis of the volcanic products emitted by ongoing volcanic activity and collected close to active vents allowed us to reach the primary goal of the project, which was to minimize volcanologists' exposure to areas with high volcanic hazards. At the same time, we wanted to get significant data to be used for volcanic monitoring, in particular, during an unrest crisis of dormant volcanoes.

Conclusions

The adoption of robotics in volcanology is still in its infancy, since only few prototypes have been realized, and most of the research activity needs further investigation and resources. Despite this, robots have shown to be quite useful for environmental measurements and, in general, for taking measurements in dangerous locations.

The performed research activity in the development of robots for volcanic measurement and exploration allowed us to better understand and solve problems related to the adoption of robots in extreme environments, as well as in other contexts such as search and rescue along with operations in other hazardous situations and areas.

From our experience, we believe that robots used to obtain scientific data will help to further increase the quality and quantity of information needed for a clearer understanding of volcanoes and also serve to reduce risks for volcanologists.

The Volcan UAV, the U-Go robot, and the ROBOVOLC system are maintained operative and are now useful tools for the volcanologists of INGV, being used each year in several missions, both to perform measurements and to further develop robotic strategies.

Acknowledgments

The authors acknowledge the work performed by all the partners of the ROBOVOLC Project. Particularly, they also thank M. Coltelli, G. Giudice, S. Gurrieri, and G. Puglisi of INGV, the past Ph.D. students S. Guccione, M. Prestifilippo, G. Spampinato, D. Caltabiano, S. Sessa, and A. Pennisi, and the entire master's students who have greatly contributed to achieving the obtained results.

References

[1] S. Guccione, G. Muscato, G. Nunnari, G. S. Virk, A. K. M. Azad, A. Semerano, M. Ghrissi, T. White, and C. Glazebrook, "Robots for volcanos: The state of the art," in *Proc. 3rd Int. Conf. Climbing and Walking Robots (CLAWAR)*, Madrid, Spain, Oct. 2–4, 2000, pp. 777–788.

[2] D. Wettergreen, H. Pangels, and J. Bares, "Behaviour based gait execution for the DANTE II walking robot," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems: Human Robot Interaction and Cooperative Robots*, 1995, vol. 3, pp. 274–279.

[3] D. Apostolopoulos and J. Bares, "Locomotion configuration of a robust rappelling robot," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems: Human Robot Interaction and Cooperative Robots*, 1995, vol. 3, pp. 280–284.

[4] M. Krishna, J. Bares, and E. Mutschler, "Tethering system design for Dante II," in *Proc. 1997 IEEE Int. Conf. Robotics and Automation*, vol. 2, pp. 1100–1105.

[5] J. Bares and D. Wettergreen, "Dante II: Technical description, results and lessons learned," *Int. J. Robot. Res.*, vol. 18, no. 7, pp. 621–649, July 1999.

[6] A. Kemurdjian, V. Gromov, V. Mishkinyuk, V. Kucherenko, and P. Sologub, "Small Marsokhod configuration," in *Proc. IEEE Int. Conf. Robotics and Automation*, Nice, France, 1992, pp. 165–168.

[7] K. P. Valavanis, Ed., *Advances in Unmanned Aerial Vehicles, State of the Art and the Road to Autonomy* (Series: Intelligent Systems, Control and Automation: Science and Engineering), vol. 33. Berlin: Springer-Verlag, 2007.

[8] A. Sato, "Research, development and civil application of an autonomous, unmanned helicopter," in *Proc. 57th American Helicopter Society Int. Forum*, Washington, DC, 2001.

[9] G. J. Holland, P. J. Webster, J. A. Curry, G. Tyrrell, D. Gauntlett, G. Brett, J. Becker, R. Hoag, and W. Vaglienti, "The Aerosonde robotic aircraft: A new paradigm for environmental observations," *Bull. Amer. Meteorol. Soc.*, vol. 82, no. 5, pp. 889–901, 2001.

[10] M. C. L. Patterson, A. Mulligan, J. Douglas, J. Robinson, L. Wardell, and J. S. Pallister, "Volcano surveillance by ACR Silver Fox," in *Proc. American Institute of Aeronautics and Astronautics (AIAA) Infotech., Aerospace*, Arlington, VA, Sept. 26–29, 2005, Paper 6954.

[11] G. Saggiani, F. Persiani, A. Ceruti, P. Tortora, E. Troiani, F. Giuletti, S. Amici, M. Buongiorno, G. Distefano, G. Bentini, M. Bianconi, A. Cerutti, A. Nubile, S. Sugliani, M. Chiarini, G. Pennestri, S. Petrini, and D. Pieri, "A UAV system for observing volcanoes and natural hazards," in *Proc. American Geophysical Union, Fall Meeting*, Dec. 2007, abstract GC11B-05.

[12] A. J. S. McGonigle, A. Aiuppa, G. Giudice, G. Tamburello, A. J. Hodson, and S. Gurrieri, "Unmanned aerial vehicle measurements of volcanic carbon dioxide fluxes," *Geophys. Res. Lett.*, vol. 35, pp. L06303–L06307, 2008.

[13] R. Piquepaille. (2007, Dec. 21). Mapping a submarine volcano with a robot) [Online]. Available: http://www.zdnet.com/blog/emergingtech/mapping-a-submarine-volcano-with-a-robot/779

[14] (2010, Apr. 12). Robot Sub Visits World's Deepest Undersea Volcanic Vent [Online]. Available: http://www.foxnews.com/scitech/2010/04/12/robot-sub-visits-worlds-deepest-undersea-volcano/

[15] S. Guccione and G. Muscato, "Control strategies computing architectures and experimental results of the hybrid robot wheeleg," *IEEE Robot. Automat. Mag.*, vol. 10, no. 4, pp. 33–43, Dec. 2003.

[16] M. Lacagnina, G. Muscato, and R. Sinatra, "Kinematics, dynamics and control of a hybrid robot wheeleg," *J. Robot. Autonom. Syst*, vol. 45, no. 3–4, pp. 161–180, 2003.

[17] M. Lacagnina, S. Guccione, G. Muscato, and R. Sinatra, "Modelling and simulation of multibody mobile robot for volcanic environment explorations," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*, Lausanne, Switzerland, Sept. 30–Oct. 4, 2002, pp. 714–720.

[18] D. Caltabiano and G. Muscato, "A comparison between different traction methods for a field robot," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*, Lausanne, Switzerland, Sept. 30–Oct. 4, 2002, pp. 702–707.

[19] D. Caltabiano, D. Ciancitto, and G. Muscato, "Experimental results on a traction control algorithm for mobile robots in volcano environment," in *Proc. IEEE Int. Conf. Robotics and Automation*, New Orleans, LA, Apr. 2004, pp. 4375–4380.

[20] D. Caltabiano, D. Longo, and G. Muscato, "A new traction control architecture for planetary exploration robots," in *Proc. CLAWAR 8th Int. Conf. Climbing and Walking Robots*, London, U.K., Sept. 13–15, 2005, pp. 1061–1068.

[21] The Robovolc Consortium. (2001). ROBOVOLC Project Home Page [Online]. Available: http://www.robovolc.dees.unict.it.

[22] G. Muscato, D. Caltabiano, S. Guccione, D. Longo, M. Coltelli, A. Cristaldi, E. Pecora, V. Sacco, P. Sim, G. S. Virk, P. Briole, A. Semerano, and T. White, "ROBOVOLC: A robot for volcano exploration—Result of first test campaign," *Ind. Robot: An Int. J.*, vol. 30, no. 3, pp. 231–242, 2003.

[23] D. Caltabiano and G. Muscato, "A robotic system for volcano exploration," in *Cutting Edge Robotics*, R. Mayer-Scholz, Ed. Mammendorf, Germany: pIV pro literatur Verlag, July 2005, pp. 499–519.

[24] D. Caltabiano, G. Muscato, and F. Russo, "Localization and self calibration of a robot for volcano exploration," in *Proc. IEEE Int. Conf. Robotics and Automation*, New Orleans, LA, Apr. 2004, pp. 586–591.

[25] P. Aranzulla, F. Bonaccorso, C. Bruno, L. Cantelli, G. Lanteri, D. Longo, G. Muscato, A. Pennisi, and M. Prestifilippo, "An innovative autonomous outdoor vehicle based on Microsoft Robotic Studio," in *Proc. CLAWAR: 13th Int. Conf. Climbing and Walking Robots and the Support Technologies for Mobile Machines*. Nagoya, Japan: World Scientific Publishing, Aug. 31–Sept. 3, 2010. pp. 97–104.

[26] F. Bonaccorso, L. Cantelli, D. Longo, D. Melita, G. Muscato, and M. Prestifilippo, "The U-Go Robot, a multifunction rough terrain outdoor tracked vehicle for R&D on autonomous navigation algorithms," in *Proc. 5th IARP Workshop Robots for Risky Interventions and Environmental Surveillance-Maintenance*, Leuven, Belgium, June 20–22, 2011.

[27] K. Johns and T. Taylor, *Professional Microsoft Robotics Developer Studio*. New York: Wiley, 2008.

[28] G. Astuti, D. Longo, D. Melita, G. Muscato, and A. Orlando, "Hardware in the loop tuning for a volcanic gas sampling UAV," in *Advances in Unmanned Aerial Vehicles, State of the Art and the Road to Autonomy*. (Series: Intelligent Systems, Control and Automation: Science and Engineering), vol. 33, K. P. Valavanis, Ed. 2007, ch. 16, pp. 473–493.

[29] G. Astuti, G. Giudice, D. Longo, C. D. Melita, G. Muscato, and A. Orlando, "An overview of the "Volcan Project": An UAS for exploration of volcanic environments," *J. Intell. Robot. Syst.*, vol. 54, pp. 471–494, Mar. 2009.

[30] O. Kathib, "Real-time obstacle avoidance for manipulators and mobile robots," *Int. J. Robot. Res.*, vol. 5, no. 1, pp. 90–98, 1986.

[31] G. Puglisi and A. Bonforte, "Dynamics of Mt. Etna Volcano inferred from static and kinematic GPS measurements," *J. Geophys. Res.*, vol. 109, pp. B11404–B11419, 2004.

[32] P. Baldi, S. Bonvalot, P. Briole, and M. Marsella, "Digital photogrammetry and kinematic GPS applied to the monitoring of Vulcano Island, Aeolian Arc, Italy," *Geophys. J. Int.*, vol. 142, no. 3, pp. 801–811, Sept. 2000.

G. Muscato, DIEEI, Università degli Studi di Catania, Italy. E-mail: giovanni.muscato@dieei.unict.it.

F. Bonaccorso, DIEEI, Università degli Studi di Catania, Italy. E-mail: filippo.bonaccorso@dieei.unict.it.

L. Cantelli, DIEEI, Università degli Studi di Catania, Italy. E-mail: luciano.cantelli@dieei.unict.it.

D. Longo, DIEEI, Università degli Studi di Catania, Italy. E-mail: domenico.longo@dieei.unict.it.

C.D. Melita, DIEEI, Università degli Studi di Catania, Italy. E-mail: donato.melita@dieei.unict.it.