Robots for volcanos – the state of the art

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ABSTRACT
This paper discusses the state-of-the-art in the area of mobile robots for outdoor applications with particular attention to extremely rough environments such as those found in volcanic and planetary exploration applications. The paper looks at the area of locomotion, manipulations, sensors, control and navigational methods that are available so that the most appropriate can be identified. The intention is therefore to present a survey paper rather than new research but the applicability of the current technology to such environments will be studied and shortcomings reported. This study is part of an EC project to develop a mobile robot that can inspect active volcano vents. Mt. Etna in Italy will be used as the primary test bed but trials at Stromboli and Montserrat (UK Antilles) are also planned.

1. INTRODUCTION

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.

Such reasons together with recent advances in robotics have inspired a new EC project named ROBOVOLC with the aim of building a robot for volcanic exploration whose activities started on March 2000. The partnerships includes two Universities and two industrial organisations stated above and two research organisations who provide the expertise in vulcanology: Istituto Internazionale di Vulcanologia CNR, Italy and Institute de Physique du Globe de Paris, France. A more detailed description of the project with the latest updates can be found in the project WEB pages: http://www.robovolc.dees.unict.it.

A major aim for this project 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 paroxysmal phases of eruptions, which unfortunately are also the time of greatest risk for humans.

Volcanologists have identified that a robot for volcano exploration should be able to do many operations, but the most important are that it must be able to:
- approach an active volcanic vent
- collect samples of the volcanic products erupted
- collect other physical and chemical data on the eruptive processes
- survey 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. Unfortunately 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.

Fig. 1. Paroxysmal phase of Etna. Fig. 2. Example of terrain around Mt. Etna.

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 (i.e. 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 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 place. For semi-autonomous use, we intend that the robot will have the capability of deciding 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 forecasts for long-lived volcanic phenomena such as lava flow eruptions.

2. PROJECTS ON ROBOTS FOR VOLCANIC EXPLORATION

The first step of the ROBOVOLC project consisted in the analysis of the state of the art in mobile robots for rough terrain. If the 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 also the successful results of the Sojourner in the exploration of Mars, many new robots have been designed for planetary exploration. In many cases such robots have been tested on volcanic surfaces, due to the fact that there are strong similarities with planetary terrain.

In the following subsections three big projects concerning a legged, a wheeled and a flying robot adopted in volcanic exploration are briefly reviewed, then in the next section more general considerations on the state of the art in the various technologies that are needed will be presented.

2.1 Dante II

Dante II is an multi-legged frame walking robot that was designed by NASA and Carnegie Mellon University to investigate five volcanoes and help test robotic technology for NASA [1-4]. The robot is a frameworker with eight pantographic legs arranged in two groups of four, on inner and outer frames. Dante II is connected by a tension-controlled tether to maintain stability and to allow rappelling on steep slopes [5].

In 1994 Dante II was adopted to explore the 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 teleoperated control. The legged robot travelled one-quarter of its 165-m descent autonomously, relying only on onboard 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 was adopted to measure the gas composition of several large fumarole vents. [2]. 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 the case in missions to other planets. This also gave NASA the opportunity to determine what improvements are needed for future robotic missions.

2.2 Marsokhod

The Marsokhod rover is an all terrain vehicle developed by the Mobile Vehicle Engineering Institute (VNIITransmash) in Russia for planetary exploration [7]. 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 produce 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 of up to 45°. The autonomy of operation with batteries is about 6 hours.
The Marsokhod robot even if designed for Mars explorations has been extensively tested in volcanic surfaces such as in Kamchatka, Russia in 1993, in the Amboy crater test in California in 1994 and the Kilauea Volcano test in Hawaii in 1995. Kilauea Volcano was selected primarily for its great diversity of geologic features similar to those expected on Mars and the Moon [6].

2.3 Yamaha Helicopter

Yamaha motors has been recently involved in a project for the surveillance of the Mt. Usu Volcano in the Hokkaido area of Japan. For this purpose a special version of the unmanned helicopter RMAX has been developed. In particular due to the long distance of operation an autonomous flight system has been produced and the cruise autonomy of the helicopter was increased to 4km. In April 2000 the helicopter, equipped with four CCD cameras, was successfully adopted to perform several surveillance missions with the objective of observing the hazards caused by volcanic sediment and debris flow.[8]

3. STATE OF THE ART IN THE VARIOUS TECHNOLOGIES

3.1 Mode of Locomotion

3.1.1 Wheeled

There is a huge number of examples of wheeled mobile robots developed in the last decades. However in this section only machines specifically designed for rough environments will be briefly classified and described. Most of these machines have six legs in order to obtain more static and dynamic stability.

A common feature of many wheeled robots is the fact that they possess a passively articulated frame that allows to easily adapt them to the surface irregularities. To these category belongs the robots NOMAD, MARSOKHOD, SHRIMP, SOJOURNER, ROCKY 7, FIDO and ATHENA.

NOMAD was developed by JPL to demonstrate and evaluate robotic systems capable of long distance, long duration mission [9]. This four-wheeled robot features a transforming chassis that can expand or compact by driving two pairs of four-bar linkages with two electric motors, one on each side of the robot. Moreover Nomad has two floating side frames that supports and deploys two wheels. Individual propulsion drive units reside inside each wheel. In the past 3 years, Nomad has completed three very successful missions, one in the Atacama desert and two in Antarctica. The latest of these has led to the first meteorite discovery by a robot [9–12].

SHRIMP is a wheeled rover developed by EPFL Lusanne (Switzerland) for planetary explorations [13]. It is a six-wheeled rover, with one wheel in the front mounted on an articulated fork, one wheel in the rear directly connected to the body of the rover and two wheels mounted on two lateral bogies. The only actuators are the motorised wheels allowing to adapt purely passively to the terrain. The rover is able to overcome steps that are twice its wheel diameter and can climb regular stairs. Moreover, Shrimp shows excellent off-road capabilities of overcoming rocks and obstacles even with a frontal inclination of 40°.

Sojourner, Rocky7, Fido and Athena robots are four similar robotic roving vehicles with six-wheeled chassis and a rocker-bogie system. Sojourner, developed by JPL, was the first robotic autonomous vehicle sent to Mars in July 1997 [14]. Rocky 7 is an improvement of the Sojourner designed to expand its capabilities while increasing the range of operations [15–18].
Fido is a larger version equipped with a 5 degrees of freedom instrument arm on which three science instruments are mounted at the end effector location [19].

Other important vehicles to be considered are the MUSES (four-wheeled nanorover developed by NASA laboratory and JPL for the exploration of asteroid surfaces [20]) and commercial vehicles such as the HOBO of Kentree in Ireland [21].

3.1.2 Flying
Unmanned Aerial Vehicle (UAV) is a research field with a great interest both for commercial and for military applications. There are many different kinds of vehicles designed and many research groups are working to build completely autonomous vehicles able to reach a given location without teleoperation. A classification can be done between Helicopters, Airships and Aeroplanes. Projects involving helicopter vehicles includes the CMU Helicopter [22], the ASRT [23], the CYPHER by Sikorsky Aircraft [24], the CAMCOPTER [25], the AROD [26]. Airship research projects include the AURORA adopting an Airspeed Airship [27] and SASS LITE of Bosch Aerospace [28]. Projects on small autonomous aeroplanes include the Aerosemic [29], the Global Hawk [30], the MUAV [31], the VINDICATOR [32], and many other not mentioned here for space reasons.

However from the point of view of the ROBOVOLC project it should be taken into consideration that many of these UAV do not work suitably at high altitude (Mt Etna height is 3300m), are sensible to strong wind conditions, have no resistance to the impact of even small rocks and sometimes require well-trained operators.

3.1.3 Hybrid
Hybrid robots are machines that integrate both wheels and legs in order to obtain a compromise between the capabilities of totally legged machines (adaptability to very rough terrain) and totally wheeled machines (speed, autonony, stability). Among the examples of such a kind of robots there is the CHARIOT [33](with two wheels and four legs, the big drive wheels are located on each side of the body while there are two legs on each end), the WHEELEG [34] with two front legs and two rear wheels and the WORKPARTNER with four wheels each one mounted at the end of one leg [35].

3.1.4 Legged and hopping
This section presents brief summary on the legged and hopping machines that have been produced over recent years. These can be group in many ways such as application, type of actuation or number of legs. For convenience we describe the machines by leg number and start with one-legged machines as several such machines have been developed. Clearly these can only move by hopping from one place to the other. The first such machine was developed by Marc Raibert at Massachusetts Institute of Technology. Several one-legged hoppers have been subsequently developed at MIT and elsewhere, e.g. MacGill.

Biped research has received considerable interest and Japan has a major R&D programme where the aim is to produce a human-friendly system that can interact with humans in their everyday environments. The most advanced of these is the Honda biped P3 system which can demonstrate a number of complex operations such as going up and down stairs, turning, etc.[36].

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Only one three-legged machine has been developed to the authors' knowledge. This is the Robinspec magnetic climbing machine developed at the University of Catania [37]. The machine is able to work on ferrous surfaces for remote inspection.

There are numerous examples of four-legged systems and Germany has a major R&D programme in this area. The most advanced four-legged system that has been developed to date is probably Sony's pet robot, AIBO [38]. Sony has invested major effort in developing the AIBO robot through an extensive network of universities across the world. The universities have been developing different aspects of the system, ranging from sensing, mechanical design, actuation, autonomy, etc., and the system developed has now been commercialised with considerable success. Over 40,000 units have been sold for $2,500 each and there is now an annual soccer playing competition where each team comprises four AIBO robots that have to play a game of football against another team of four AIBO robots [39].

A number of six-legged robots mainly developed using ideas from nature such as insects and has incorporated a number of sensors and neural control methodologies. These include Ioan (ULB, Belgium), Ambier and Daedalus (Carnegie Mellon), Rest (CSIC-IAI, Spain), Mecat (Helsinki University of Technology, Finland), Forest Walking Machine (Plustech, Finland) and Hercules (Robosoft and LRP, France).

Only one seven-legged machine has been identified - this is the Walking Beam machine developed by Lockheed Martin, USA for NASA.

Several eight-legged machines have been developed based again on biological thinking, such as spiders and crabs. The main machines identified are Robug III and Robug IV developed by University of Portsmouth and Portech respectively. Both are pneumatically powered and can walk and climb. Robug IV is an extension of the Robug III thinking to a smaller, more compact format with much more emphasis on modularity. The overall design has been much more refined and more advanced than the thinking adopted in Robug III. Another eight-legged pipe climbing robot has been developed by Professor Lawitzky of Siemens AG, Munich. The eight legs allow the machine to support itself and climb up by pushing against the wall.

3.1.5 Tracked

Tracked machines have had a long history in comparison to legged machines and many machines have been commercialised. Hence there are many robust designs that have proved themselves in practical situations. For example, the Hobot tracked vehicles produced by Kentree [21] have been used for anti-terrorist measures in over 30 countries. The machine weights 185 Kg and is powered by DC motors. Others machines are also available (IMP and Brat). A variety of tracked machines for construction applications are also widely available. These include JCB machines are widely available. R&D is still an active area for tracked machines. For example, Sourny is developmental three-segmented tracked machine from Tokyo Institute of Technology designed for creeping into the debris after natural disasters like earthquakes. In addition, there are a variety of military vehicles with tracks. These include armoured vehicles, tanks, etc.

3.2 Manipulations

Aiming to assist the volcanologists to perform more extended analysis of the volcano environment in safe conditions, the ROBOVOLC partners have established that a manipulator arm is to be mass-produced close to active volcanoes.

At present, the customer requires a custom design.

Following the manipulators needs:
- Anthropomorphic
- As light as possible
- A long reach
- "Reasons unknown"

Initial studies have led to the following characteristics:
- Most suitable for off-the-shelf assembly (can also be produced in-house)
- The main requirements are:
  - Few synchros
  - Customised mountings
  - The whole machine is to be cost-effective.

![Fig. 3.1.5](image)

If the customer's requirements are

1. Off-the-shelf requirement

2. One type of manipulator

3. Hydraulics and electronics

4. The electron usually costs £10,000.

Cost is to be kept as low as possible.
arm is to be mounted on the robotic platform. The most extended use of the manipulator arm is to pick and place environmental sensors and to collect lava and gas samples from zones close to active vents.

At present, the consortium is assessing whether an off-the-shelf manipulator can be used or if a custom design is more adequate for achieving the required functionality.

Following the formulation of the volcanologists’ requirements, it is apparent that the manipulators needed must satisfy the following specifications:
- Anthropomorphic type
- As light weight as possible (less than 55 Kg.) but with capacity to carry a payload of approximately 10 Kg.
- A long reach capability >500 mm.
- “Reasonable” repeatability and accuracy (order of cm).

Initial studies have indicated that existing commercial manipulators can meet most of these characteristics. In particular we can conclude the following:
- Most systems are either pedagogical (poor lifting capacity) or are meant for specific industrial applications (product testing, material handling, machine loading and assembling, welding, etc.). In both cases system accuracy is very high (order of 0.001 mm) leading to high cost.
- The majorities are fixed systems, either to the ground and/or ceiling and are not customised for mobile platforms.
- Few systems exist for onboard platforms primarily target for tele-operated nuclear and/or de-mining applications (Fig. 3, Fig. 4).

![Fig. 3: TSR202 tracked](image1)
![Fig. 4: EAG2: medium-size wheeled](image2)

If the commercially available mobile manipulators are able to meet ROBOVOLC’s requirements, tele-operation is felt to be the best way of carrying out the tasks. A survey on the off-the-shelf tele-operational manipulator systems has been carried out. This has revealed the following:
- two types exists: electric and hydraulic.
- Hydraulic manipulators types have larger lifting capacities (over 100 Kg.) and are themselves heavy. In addition they are usually the most expensive.
- The electric arms are mainly of the master/slave type. The “slave” component is usually customised for mobile applications and has limited payload capacities (from 1 to 10 Kg), much lighter weight (<50 kg.) and have a repeatability accuracy of ≈1 mm.
- Cost is usually less than half the hydraulic system cost.
- Both electric and hydraulic systems can be made for nuclear and/or acid applications.
3.3 Mechanics
As already stated, the design of the ROBOVOLC platform will need to address a broad range of problems in order to culminate in a reliable, robust and effective “tool” for the observation and measurement of the required volcanic phenomena. The primary requirement is clearly the ability to traverse the wide variety of rough terrain. It is anticipated that the final design will be a trade-off between ability to negotiate terrain, travelling speed and the energy consumed.

Preliminary investigations have indicated that a hybrid design using legs and wheels could be suitable but may be difficult to control. A wheeled machine with good suspension capability for each wheel or some form of “walking” capability may be a good compromise. The actual platform design has not been finalised at this time, but several concepts are being analysed for suitability.

The mechanical design philosophy for the ROBOVOLC project is being developed from studying the user requirements and the current state of the art in robotics. Experience from previous robotic deployments into volcanic craters and for planetary exploration such as Dante II [2] and the Marsokhod robot [7], have been used in the thinking of the consortium. High power-to-weight ratios, over designing, maximising modularity and system redundancy have been the most important issues raised by the initial studies. We expect that the robot will encounter situations that were not exactly predicted. Past experience has also shown that integration of the robot sub-system modules can cause major stresses to the components. However high power/weight ratio and over design in conjunction with other elements will ensure that the robot can withstand and overcome these situations successfully and remain mechanically intact. This does not negate the proper design procedures involving simulation and model testing.

The concept of mechanical modularity will be an important feature in the design for several reasons. The ability to modify the robot to suit different mission profiles will provide efficient use of the platform. The capacity to reconfigure/remove unwanted modules will allow greater flexibility, for example increasing the rock sample carrying capacity or more fuel to extend the duration of the mission. It would also be possible to make available different modules to suit different terrain structures thus allowing the robot to extend its capabilities without unduly increasing the overall size and weight.

The issue of system redundancy will be addressed to ensure that the mechanical system is capable of recovering from failures without the total loss of the robot. The obvious hazards of the environment include the potential of damage from flying debris and other threats. As well as mechanical robustness and redundancy will mitigate these threats to give a reasonable level of confidence that the robot will survive most situations presented.

3.4 Sensors
To assist the volcanologists to operate the vehicle and to perform more extended analysis of the volcano’s environment there are three types of sensors that need to be considered, namely:
- Specific sensors for physical data collecting such as gas analysis, temperature measurement, etc.
- Modelling of the environment to determine the volcanic vent’s morphology and topography.
- Vehicle localisation to determine the precise position of the vehicle in the environment.

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The environment modelling is expected to be carried out using experience from previous R&D projects. The use of scanning optical Lasers and video 3D reconstruction systems could be used. Two examples of systems that could be used are the sensor from Riegli that was specifically designed for the acquisition of three dimensional images. In this system a rotating mirror directs the internal laser rangefinder's transmit beam over a precise angular pattern. The resulting range measurements comprise a very accurate three dimensional representation of the scene. The texture of the image is directly extracted from the reflectance of the beam.

In such a case, no need to use an extra video camera. Another very accurate system is the AccuRange Line Scanner from Acuity research that can be used with the AccuRange 4000 (an optical distance measurement sensor) to scan and collect distance data over a full circle.

This scanner consists of a balanced, rotating mirror and motor with position encoder, and mounting hardware for use with the AccuRange 4000. This sensor is coupled to the high speed interface for data collecting. For complete environment acquisition, this sensor must be mounted on the pan-tilt unit. A video camera is needed for texture in this case.

In any case the real time 3D reconstruction could be considered using these kind of sensors.

3.5 Navigation

Navigational tasks for a mobile robot are clearly important as this involves addressing the problems of localisation, direction to move to reach the target, determining the environmental situation and to finding the optimum path to follow [40]. Generally speaking, there are two main methods for determining the robot's position, namely relative and absolute positioning. Relative positioning involves odometry that uses encoders to measure wheel rotation, steering information and inertial navigation via gyroscopes and accelerometers. Absolute positioning involves using beacons (active or passive) and global positioning systems (GPS), natural and artificial landmark recognition, natural landmark recognition and model matching methods.

[41].

For relative positioning systems, sensor data can be scaled by a known factor to obtain the actual position of the machine. This method is an important part of a mobile robot navigation system and can provide good short-term accurate predictions through high sampling rates with minimum cost. However, the fundamental idea of relative positioning for longer time horizons leads to poor accuracy because of accumulation of the error [42]. Active beacon-based methods are the most common as they can provide accurate positioning information with minimal processing (see for example [43]). Active beacon systems have been proven in practice, and there are several commercial systems available that use lasers, infrared and ultrasonic transducers and which can derive the robot's location via triangulation of the received beacon signals. For more technical information of these system refer to [44] for localisation using laser and passive reflectors and [45] for transponders system.

Global positioning systems can also be used for finding the absolute 3D location using trilateration techniques based on time of flight for uniquely coded spread-spectrum radio signals transmitted by satellites. The method is conceptually simple but many factors need to be considered during the system design phase. These include time synchronisation between individual satellites and the GPS receivers, precise real-time location of the satellites' positions, accurate measurement of signal propagation times and ensuring sufficient signal-to-noise ratios for reliable operation in the presence of interference and possible jamming.

Also, due to security reasons, small errors in timing and satellite positions have been deliberately introduced for commercial applications of GPS and this leads to positional...
accuracies of around 2 to 3 meters. Differential GPS can achieve far better and can have an accuracy of 1mm to 1cm range [4][53].

Landmarks (natural or artificial) are distinct features that a robot can recognise for the purposes of localisation. Natural landmarks are clearly objects or features that normally exist in the environment whereas artificial ones are special markers placed at known locations in the environment with the sole purpose to enabling robot navigation. Different kinds of artificial landmarks include patterns or marks, retro-reflective beacons and beacons. Detection is much easier with artificial landmarks, which are designed for optimal contrast [47], [48] and many are based on computer vision. Other methods that can be used include line navigation [49] and map-based methods (where map is either pre-stored or created in an on-line manner) [50], [51].

3.6 Autonomy

Autonomy is the capability of a mobile robot, which allows it make decisions in an independent manner according to the particular perceived situation that the robot “finds” itself in. To have full autonomy in non-structured environments the robot should be equipped with suitably smart systems that are able to perform all the operations that the machine has to carry out. These include prioritising tasks, selecting procedure to carry out, plan paths to move along, avoid obstacles, object recognition, effective manipulation, etc [52]. Unfortunately full autonomy is not yet possible and there is still much to learn as to how such systems can be realised for robust designs that can operate in hazardous and dynamic environments such as those found on volcanoes. It seems therefore more appropriate to consider a semi-autonomous system for the Robovolc project where the machine to be designed has some autonomous functions and some tele-operated functions. A suitable block diagram for the machine could be along that shown in Figure 5 where decision support systems need to be designed to allow the autonomous and tele-operated features to be carried out.

![Figure 5: Block diagram for navigation and task performing structure for the mobile robot.](image-url)
4. CONCLUSIONS
The paper has presented a summary of a comprehensive state of the art that has been carried out by the ROBOVOLC consortium. The focus of the project is to design a mobile robot that is able to explore and conduct measurement in a volcanic environment. The requirements for this machine have been formulated by volcanologists, the state of the art of the robotic area has been collected by robotic researchers and initial design considerations have been drafted by industrial machine manufacturers. The project is in its early phase and progress on it will be reported as the machine is developed, but it is hoped that the final machine will offer volcanologists a useful tool that can remove the danger that they have to currently face when collecting vital data from active vents during paroxismal activity.

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