ROBOVOLC: Remote Inspection for Volcanoes

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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 areas of locomotion, manipulation systems, sensors, control and navigational methods that are currently available so that the most appropriate can be identified. A design criteria for the proposed ROBOVOLC robot is presented by considering the environment to be faced and the tasks involved for exploration studies.

1. Introduction

Ancient populations suffered huge damage that eruptions caused to their towns and lands and many human lives were often lost. As a result, some people began to venture near to active volcanic vents in order to understand volcanic phenomena and 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.

With these aspects in mind together with recent advances in robotics, a new EC project named ROBOVOLC has been proposed. This has as its aim to build a robot for volcanic exploration. The partnership includes two Universities, two industrial companies and two volcanology research organisations. More details about the project with the latest updates can be found in the project's web pages: http://www.robovolc.dees.unict.it.

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 sophisticated locomotion capabilities to allow it 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 and navigational system (i.e. laser ranging) will be useful for both driving and measurement purposes. Finally an efficient data link will be required to operate the rover and to download the collected data.

Fig.1. Paroxismal phase of Etna.

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 terrains. If the attention is concentrated on recent projects with the specific objective of volcanic exploration only a few systems have been developed. In the following subsections three projects concerning legged, wheeled and flying robot that has then adopted in volcanic exploration are discussed.

2.1 Dante II

Dante II is a multi-legged frame walking robot that was designed by NASA and Carnegie Mellon University to investigate live volcanoes and help test robotic technology for NASA [1-4]. The robot is a framewalker 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]. 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 Marsokhod robot was designed for Mars explorations but it has been extensively tested on 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. The 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 have developed an unmanned helicopter Rmax for surveillance of the Mount Usu Volcano in the Hokkaido area of Japan. 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

3.1 Locomotion

3.1.1 Wheeled

There are a huge number of examples of wheeled mobile robots developed in the last decade. A common feature of many wheeled robots is the fact that they possess a passively articulated frame that allows them to easily adapt to the surface irregularities. In this 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 and long duration missions [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. Individual propulsion drive units reside inside each wheel.

Shrimp is a wheeled rover developed by EPEL, Lusanne (Switzerland) for planetary explorations [10]. 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 it to adapt purely passively to the terrain. Moreover, Shrimp shows excellent off-road capabilities of overcoming rocks and obstacles even with a frontal inclination of 40°.

Sojourner, Rocky 7, 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 [11]. Rocky 7 is an improvement of the Sojourner designed to expand its capabilities while increasing the range of operations [12-15].

Other important vehicles to be considered are the MUSES (four-wheeled nanorover developed by NASA laboratory and JPL for the exploration of asteroid surfaces [16]) and commercial vehicles such as the HOBO of Kentree in Ireland [17].

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 include the CMU Helicopter [18], the Asrt [19], the Cypher by Sikorsky Aircraft [20], the Camcopter [21] and the Arod [22].

However, from the point of view of the ROBOVOLC project, it should be taken into consideration that many of these UAVs do not work suitably at high altitude (Mount Etna's height is 3300m), are sensitive to strong wind conditions, have no resistance to the impact of even small rocks and sometimes require well-trained operators. Flying robots are therefore not felt to be suitable for the ROBOVOLC Project.

3.1.3 Hybrid

Hybrid robots are machines that integrate both wheels and legs in order to obtain a compromise between the capabilities of legged machines (adaptability to very rough terrain) and wheeled machines (speed, autonomy, stability). Among the examples of such kind of robots is the Chariot [23](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 [24] (with two front legs and two rear wheels, and the Workpartner with four wheels, each one mounted at the end of a leg) [25].

3.1.4 Legged and hopping

This section presents a brief summary on the legged and hopping machines that have been produced over recent years. These can be grouped 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 Massachussetts 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 environment [26]. 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 [27]. 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 [28-29]. A number of six-legged robots have been developed using ideas from nature, such as insects, and have incorporated a number of sensors and neural control methodologies. These include Ioan (ULB, Belgium), Ambler and Daedalus (Carnegie Mellon), Rest (CSIC-IAI, Sain), Mecant (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. Another eight-legged pipe climbing robot has been developed by Dr Neubauer of Siemens AG, Munich.

3.1.5 Tracked

Tracked machines have had a long history in comparison to legged machines and many machines have been commercialised. For example, the Hobot tracked vehicles produced by Kentree [17] have been used for anti-terrorist measures in over 30 countries. The machine weighs 185 Kg and is powered by DC motors. Other machines are also available (Imp and Brat). A variety of tracked machines for construction applications are also widely available, these include JCB machines. R&D is still an active area for tracked machines. In addition, there are a variety of military vehicles with tracks, including armoured vehicles, tanks, etc.

3.2 Manipulations

An effective manipulator system is needed to allow the machine to perform complex tasks that are normally carried out by volcanologists.

Following the formulation of the volcanologists' requirements, it is apparent that the manipulator needed must satisfy the following specifications:

1. Anthropomorphic type
2. As light weight as possible but with a payload capacity of approximately 5 Kg.
3. A long reach capability >500 mm.
4. "Reasonable" repeatability and accuracy (order of cm).

3.3 Mechanics

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 their 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. It is expected 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.

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

3.4 Sensors

To assist the volcanologists to operate the vehicle and to perform more extended analysis of the volcanic environment, there are three types of sensors that need to be considered, namely:

1. Specific sensors for physical data collecting such as gas analysis, temperature measurement, etc.
2. Modelling of the environment to determine the volcanic vent's morphology and topography.
3. Vehicle localisation to determine the precise position of the vehicle in the environment.

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. A video camera is needed for texture in this application.

4. Navigation

Navigational tasks for a mobile robot are clearly important as this involves addressing the problems of localisation, direction in which to move to reach the target, determining the environmental situation and to finding the optimum path to follow [30]. 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. [31].

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. Differential GPS can achieve far better resolution and can have an accuracy of 1mm to 1cm [4, 32]. 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 barcodes and beacons. Detection is much easier with artificial landmarks, which are designed for optimal contrast [33, 34] and many are based on computer vision. Other methods that can be used include line navigation [35] and map-based methods (where the map is either pre-stored or created in an on-line manner) [36, 37].

5. Autonomy

Autonomy is the capability of a mobile robot, which allows it to 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 a procedure to carry out, planing paths to move along, avoiding obstacles, object recognition, effective manipulation, etc [38]. Considering the environmental conditions, it is more appropriate to consider a semi-autonomous system for the ROBOVOLC project where the machine to be designed has some autonomous capabilities and some functions are tele-operated.

6. Proposed Outline Specifications

Design specifications for the ROBOVOLC robot is an important part of the project, and need to be done carefully. The technical requirements for the robot are quite stringent but the choice for the final design will not only be based on technical issues but must also take into account cost implications. The tasks that the robot needs to perform are:

1. Gas sampling and on-site measurements.
2. Lava and tephra sampling.
3. To leave and collect instruments around the active vents.
4. To carry out topographic and morphologic measurements.
5. To carry out physical measurements, e.g. ground accelerations.
6. Remote transmission of high definition images of the volcano.

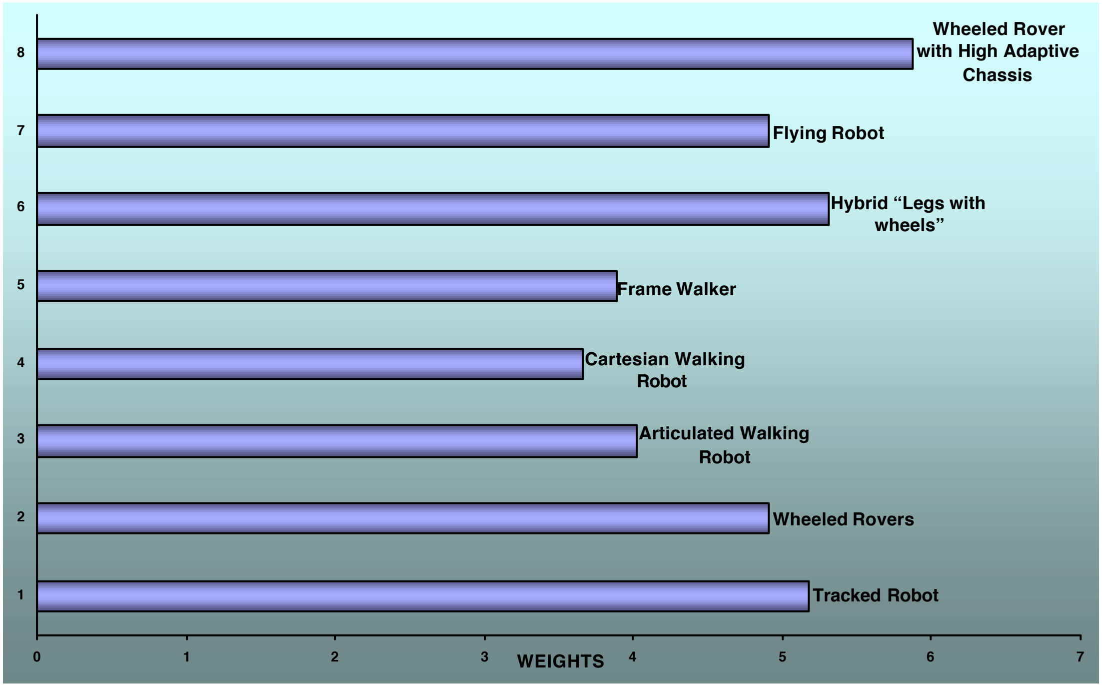

Table 1: Evaluation result for the suitability of various locomotion methods for ROBOVOLC robot.

The robot needs to be robust and be able to handle the volcanic environmental conditions such as temperature, gas, terrain roughness, flying objects, etc. This modular design technique is being developed by the EC CLAWAR thematic network on climbing and walking robots and will be followed to ease the design tasks. There will be a range of sensors on-board for navigation and volcanic exploration purposes. The sensors include GPS, a laser range finder, video camera, accelerometers and gas analyser.

Considering all the tasks and constraints, general specifications for the ROBOVOLC robot have been identified. The following is a brief description of the main technical requirements for the ROBOVOLC robot effecting the selection of the platform.

- Maximum weight:- The whole system should be less than 200Kg
- Maximum overall dimensions (preferably): height- 0.8m, width- 1.2m, length- 1.7m
- Static Stability: 40^0
- Maximum slope: 35^0 (minimum is 30°)
- Maximum lateral obstacle height: 0.4m
- Maximum speed: 0.5m/s
- Maximum payload: 30kg
- Travel time for a 24 hour mission: 1.5hours

The most appropriate locomotion technique for the ROBOVOLC system was carried out by evaluating the most promising techniques by comparing their ability to satisfy certain criteria including reliability, rough terrain performance, suitable for purpose, etc. Eight techniques were evaluated, these are Tracked, Purely wheeled, Articulated and Cartesian walking robot, Frame walker, Hybrid “legs with wheels”, Flying (Fixed wing and rotary) and a high adaptive chassis. The results of the evaluation are presented in Table 1. Clearly the main contenders for the locomotion system are: Wheeled Rover with High Adaptive Chasis, Hybrid “leg with wheels” and Tracked Robot.

Functional Subsystems

A preliminary block diagram for the proposed system is shown in Figure 2. In this system the robot will be operated/monitored from a portable command system through a communication relay station. The overall system can be broken down into four primary functional subsystems, viz, platform, communications, communication relay station and portable command system.

These can then be further broken down into sub-subsystems which can be further studied to adopt appropriate designs.

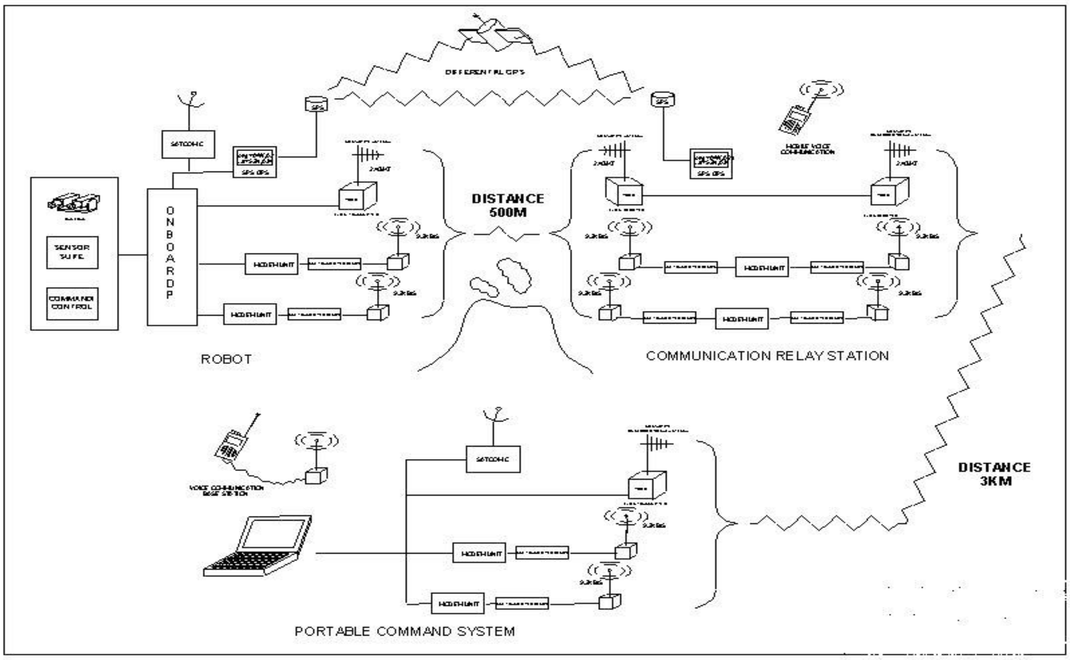

Figure 2: Preliminary system block diagram.

7. 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 measurements 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 the 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.

8. Acknowledgements

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