Paper: Rb*--**-****:**

Recent Trends and Issues of Volcanic Disaster Response with Mobile Robots

Keiji Nagatani

Graduate School of Engineering, Tohoku University
6-6-01, Aramaki-Aoba, Aoba-ku, Sendai, 980-8579, Japan E-mail: keiji@ieee.org
[Received 00/00/00; accepted 00/00/00]

Typically, volcanic eruptions cause heavy damage in its vicinity area, and the eruption often continues for years. During this period, a restricted area is set up in the vicinity of the crater, in order to the safety of people. Therefore, it is important for mitigation of volcanic disaster to realize observation of the eruption and mudslide-control construction based on teleoperation-type robotic technology. To promote development of such technologies, various types of volcano exploration robots have been researched and developed in Japan and overseas. With regard to volcanic observations, this paper presents conventional methods for volcanic teleoperated observation, and discusses technical issues and research topics for the future technologies, particularly, mobile robotics and flying robotics. With regard to mudslide-control construction, the paper describes the teleoperated construction system that has been developing at Fugen-dake of Mount Unzen, and discusses technical problems in current unmanned construction system to be solved in the near future.

Keywords: volcanic eruption, teleoperated robot, unmanned aerial vehicle, unmanned ground vehicle

1. Introduction

1.1. Background

The tsunami that accompanied the Great East Japan Earthquake on March 11, 2011, with a magnitude of 9.0 on the Richter scale, caused unprecedented destruction mainly along the east coast of the Tohoku region. Although, as of June 2012, earthquake activities in the Tohoku region appear to be subsiding, there are indications of seismic energy continuing to build up in the Kanto region and the Nankai trough because of subduction of oceanic plates. Therefore, Japan should continue to be prepared for major earthquakes.

On the other hand, around the time of the 869 Teikan Earthquake, which is considered to have many similarities with the Great East Japan Earthquake, major eruptions occurred at Mount Fuji and Mount Chokai. Since 1900, when earthquake magnitude measurements began, every earthquake of magnitude 9 or greater has been accompanied by volcanic eruptions without exception. (The M9.0 Kamchatka Earthquake in 1952 was accompanied by eruptions of two volcanoes including the Karpinsky Volcano; the M9.5 Great Chilean earthquake in 1960, by eruptions of Cordon Caulle and two other volcanoes; the M9.2 Alaska earthquake in 1964, by eruptions of Trident and Redoubt Volcanoes; and the M9.2 Great Sumatra-Andaman earthquake in 2004, by eruptions of Talang, Marapi, and Kerinci.) Furthermore, many studies have been published on the causal relationship between major earthquakes and volcanic irregularities [1]. Based on the above, there is a high probability of a volcanic eruption occurring in Japan within a few years of the Great East Japan Earthquake.

1.2. Classification of volcanic disasters

The phenomena accompanying volcanic eruptions that could cause great damage include volcanic cinders and ash fall, pyroclastic flows, lava flows, snowmelt-type volcanic mudflows, debris flows, and release of volcanic gases. A pyroclastic flow is a phenomenon in which high-temperature lava debris and a mixture of volcanic ash and gas flow down the volcano's slope at high speed (as high as 180 km/h). On June 3, 1991, the pyroclastic flow accompanying the eruption of Fugen-dake of Mount Unzen caused a pyroclastic surge (heated air) that killed 43 people. A photograph of Fugen-dake taken in November 1991 after the pyroclastic and debris flows is shown in Fig. 1 [3]. Although it is not possible to stop a pyroclastic flow, the damage to human lives can be circumvented if its occurrence is predicted. Debris flow, on the other hand, occurs when rain washes down the volcanic lapillus and ash that were deposited on a slope, causing great damage to downstream areas. For instance, the city of Shimabara suffered great damage from the debris flows caused by the eruption of Fugen-dake. When a volcano covered in snow erupts, larger damage may occur from snowmelt-type volcanic mudflows, in which the snow melted by the volcanic eruption, washes down the debris. Human casualties caused by debris flows and snowmelt-type volcanic mudflows can also be prevented if their occurrence can be predicted. Furthermore, property damage to houses, etc., can be reduced by constructing mudslide control dams in areas that are likely to experience debris flows.

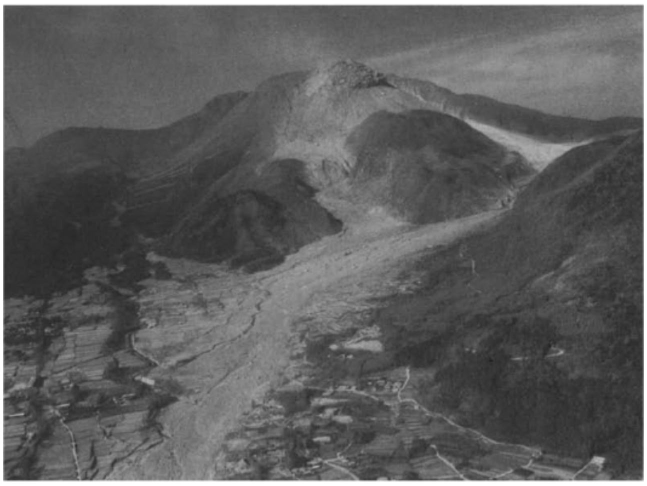

Fig. 1. Volcano disaster at Fugen-dake of Mount Unzen (from [3])

Fig. 2. Flight of autonomous helicopter, Yamaha R-Max, at Mount Usu (from [4])

1.3. Objective of this paper

As shown in the above, volcanic eruptions often cause great damage and the eruptions tend to continue for extended periods. Thus, the use of teleoperation-type robotic technology to deal with volcanic eruptions becomes important. This paper reviews how robotic technology has been applied in the past to deal with the various types of volcanic disasters, and discusses future applications of them.

2. Past response projects against volcanic disasters

As stated in section 1, volcanic eruptions can cause great damage to areas in its vicinity because of volcanic cinders and ash fall, pyroclastic flows, lava flows, snowmelt-type volcanic mudflows, debris flows, and the release of volcanic gases. Since it is not possible to prevent the volcanic eruption itself, it is essential to monitor the volcano's activities and undertake mudslide-control construction to prevent or reduce human damage. However, during an eruption, humans are restricted from entering dangerous zones, which are established according to the degree of the eruption. For instance, when a level 3 eruption occurs at Mount Asama, humans are prohibited from entering an area with a 4 km radius centered at the crater. Even after the eruption has subsided, humans are basically restricted from entering areas where the possibility of debris flows exists. It is therefore essential to monitor the situation in the restricted areas remotely and conduct unmanned mudslide-control construction.

In resent approaches for volcanic observation, monitoring cameras have been set up in volcanic craters that have the possibility of erupting, and wire sensors or mountain-stream monitoring cameras have been set up in areas that are subject to debris flows. These measures ensure that the occurrence of a disaster can be detected during periods of intensified volcanic activities. When Fugen-dake of Mount Unzen erupted, however, many of the preinstalled sensors were damaged by the eruption and failed to function properly. Furthermore, since it is difficult to predict the locations of craters and lava domes (which can give rise to pyroclastic flows) before they are created, the currently installed monitoring cameras may be inadequate when an eruption occurs.

To deal with these situations, the use of GPS-navigated unmanned helicopters are highly expected for volcanic monitoring. When Mount Usu in Hokkaido erupted in 2000, an unmanned helicopter, equipped with GPS and a video camera, was employed to observe the land features and geological status of the vicinity of the crater. This made it possible to monitor the local eruption conditions and land feature changes from a remote location (see Fig.2). However, problems such as the limited flight time, high dependence on weather conditions, and the difficulty of fixed-pointed observations, still exist. Furthermore, such a small unmanned gasoline-engine-helicopter, used in this case, is unusable in altitudes exceeding 1,500m, because of the insufficient air supply to the gasoline engine and the decrease in lifting power due to lower atmospheric pressure.

Meanwhile, test operations have been carried out with rough-terrain mobile robots to explore eruption sites via surface travel. In the United States, Carnegie Mellon University has conducted volcanic explorations using the rough-terrain mobile robots, Dante and Dante II [8]. This eight-legged walking robot was used to explore the crater of Mount Spurr while it was attached to a tether cable. In Europe, a wheeled volcano exploration robot was constructed by the Italian-led RoboVolc Project, and tested at Mount Etna and Vulcano Island [9]. While these explorations have demonstrated that it is possible to conduct volcanic explorations using mobile robotic technologies, they have not yet achieved practicality in terms of being prepared for an upcoming eruption. In Japan, Tohoku University has developed a teleoperated robot called the Mobile Observatory for Volcanic Eruption (MOVE) (see Fig.3) [10]. This robot was constructed by modifying a

Fig. 3. Volcano observation robot "MOVE"

Fig. 4. Unmanned construction system at Fugen-dake of Mount Unzen

radio-controlled power shovel, and was equipped with observational instruments, allowing it to carry out various scientific observations during volcanic eruptions. It is no longer in active service because of issues such as the increased maintenance costs caused by aging.

With regard to mud-control construction, test construction based on teleoperation of construction machines was conducted for the first time in Japan during the eruption of Fugen-dake of Mount Unzen, which began in 1990 [5]. Specifically, the first construction was teleoperated from a distance about 100 m, under a transient temperature up to 100 degrees centigrade and 100% humidity. It consisted of an emergency gravel removal operation and construction of sediment-retaining basins after a debris flow had occurred, and involved the crushing of gravel with sizes of 2—3 m. Subsequently, unmanned construction has been established as a practical construction method, and was continued at Fugen-dake to construct mud-control dams (see Fig.4). It was also employed to construct sediment-retaining basins at Mount Usu, which erupted in 2000, and carry out floor consolidation in the preparatory stage of building a mud-control dam on Miyake Island, which also erupted in 2000. These and other major construction projects in Japan that have so far been undertaken using unmanned construction technology are outlined in reference [6]. Unmanned construction technology was also used for debris removal at the Fukushima Daiichi Nuclear Power Station, the site of a hydrogen explosion following the Great East Japan Earthquake in 2011. Unmanned construction has been incorporated into the Information-Oriented Construction Promotion Strategy (July 31, 2008), drawn up by the Ministry of Land, Infrastructure, Transport and Tourism. This policy makes information-oriented construction technology generally available and encourages the development of practical applications of the unmanned construction technology [7]. In the policy, information and communication technology is introduced into unmanned construction, whereby CAD data, GPS, inertial measurement unit, etc., are utilized to carry out unmanned construction with high accuracy. This area is expected to be continuously developed and improved in the near future.

3. Expected robotic technologies in volcanic environments

With regard to mud-control construction to reduce the damage caused by volcanic disasters, there is a requirement to expand the current teleoperation technologies to enable rapid constructions. With regard to disaster prediction, the following tasks are expected to carry out:

1. Mobile observation of high-altitude volcanoes
2. Fixed-point volcanic observation at an arbitrary location
3. Amount measurement of volcanic ash and sample return to predict debris flow

To realize these technological goals, it is necessary for technology that can be (1) deployed over an extended area, (2) equipped with environmental resistance, and (3) suitable for teleoperation. In the following sections, promising teleoperation technologies for construction equipment are described, which include mobile robot technology, flying robot technology, and the elementary technologies for both of them.

3.1. Teleoperation technology for construction equipment

As stated in the previous section, research and development of unmanned construction technology are being

Fig. 5. Recent teleoperation room for unmanned construction

carried out under the Information-Oriented Construction Promotion Strategy, so that it is becoming increasingly possible to carry out highly advanced mud-control construction and civil engineering work from remote locations. For example, teleoperation tests from large distances (50 km) using fiber optic cables were succeeded in, recently. There is a concern, however, regarding the shortage of high skill operators. They are required to have abilities to (1) operate construction equipment, (2) visualize the conditions at the site from two-dimensional image data (display), and (3) operate in a time-delayed environment. The layout of a current operating room is shown in Fig.5. In order to deal with this shortage of skilled operators, research and development have been carried out in teleoperation assist technologies for low skill operators. For example, there are operator-assist studies on the use of a head-mounted display as the three-dimensional visual display of the site environment. Recently, real-time kinematic GPS technology has been used to realize functions that have been demonstrated to successfully reduce the operator's workload, such as height adjustment of the bulldozer's blade, and operational guidance for backhoes. In futures, further efforts are required in order to improve the human interface, such as methods to accurately obtain the information at the construction site, to improve teleoperation technology in an environment with communication delays, and to develop assist functions that reduce the operator's workload.

3.2. Flying robot technology

The autonomous flying robot currently being applied in disaster response efforts is a modified version of a medium-sized radio-controlled helicopter with a gasoline engine (see Fig. 2). This model has a relatively large payload, and can endure long flights depending on the amount of gasoline carried on board. However, it cannot fly at altitudes above 1,000 m because of the reduced lift caused by the lower air density, and the reduction of thrust due to insufficient air supply to the engine at high altitudes. Unfortunately, volcanoes where eruption activities are feared to occur often have a high altitude, such as Mount Asama with an altitude of 2,568 m, and the currently active Shinmoe Dake with an altitude of 1,420 m. Furthermore, those flights are impossible during ash falls. Although recent engine improvements are reported to have made flights at about 1,500 m possible, further technological development is required. Research and development must also be extended to explorations using electrically powered motor helicopters, and mobile observations by autonomous fixed-wing flying robots.

3.3. Mobile robot technology

Since autonomous helicopters are unsuitable for fixed-point observations in a volcanic environment or volcanic ash measurements for disaster prediction, there is a requirement of rough-terrain mobile robots that travel on the surface. While there are several issues that require to be resolved, a major one is the technology for traversal on rough terrain that consists of soft irregular soil and loose rocks.

Traversability over rough terrain, particularly the ability to maneuver around obstacles, depends much on the robot's size, so a large robot is preferable. For instance, Dante II [8], which was used for volcanic exploration, was quite large and heavy, with dimensions of 3.7 m $\times$ 2.3 m $\times$ 3.7 m and a weight of 770 kg. Unmanned construction equipment is basically construction equipment, and therefore also weighs several hundred kilograms. From the point of view of portability and transportation energy efficiency, however, smaller exploration robots are preferred. Therefore, the team jointly formed by Tohoku University and Chiba Institute of Technology has been engaged in a study to improve the traversal performance of rough-terrain mobile robots for use in volcanic explorations, employing the modified chassis of a small rescue robot. Currently, a rough-terrain traversal test using a small robot (weighing 20—40 kg) is underway at Mount Asama and other sites, with high expectations for future applications [15].

Additionally, research and development on designs that combine a small, mobile ground robot and a flying robot are also being developed [14]. In this study, a small, lightweight mobile ground robot is carried by an electric multicopter and set down at the specified site. The mobile ground robot is then teleoperated to explore the restricted areas. Figure 6 shows a small mobile ground robot being lowered to the ground by a tether from a flying robot, taken during a field test conducted in October 2013. The field test verified the possibility of observation mission when combining a small mobile ground robot and a flying robot.

3.4. Elementary technology: power source

Construction equipment is mostly driven by diesel engines, and employs light diesel oil for fuel. While it is possible to continue operating the machine as long as the on-board fuel lasts, unmanned construction equipment must usually be returned from the construction site to a

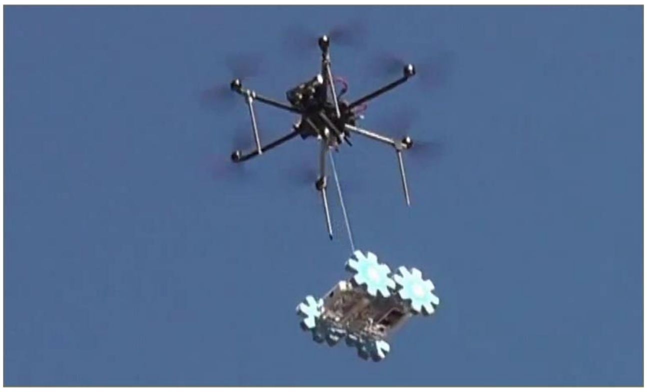

Fig. 6. Observation by flying robot and small mobile ground robot

staging area each day for maintenance. Meanwhile, autonomous flying helicopters used in disaster response are equipped with gasoline engines, and can therefore fly as long as the onboard gasoline lasts, although flight time is limited to approximately one hour.

The power source is an even greater issue in robots that are driven by electric motors. Currently, tracked mobile ground robots carry lithium-ion batteries, and can operate for 2—4 h. At this stage, the battery capacity is insufficient for such robots to carry out volcanic explorations.

In order to carry out long-term, fixed-point observations (lasting from several days to a month) for volcanic explorations, systems employing solar panels capable of generating energy at the site are considered to be important. Thus, studies are underway to consider designs such as using a mobile robot platform to travel to the observation site, then, after the robot platform has run out of internal energy, the onboard system keeps observation for an extended period using energy from the solar panel.

3.5. Elementary technology: long-distance radio communication technology

In unmanned construction system, there were reports that radio communication has been a major problem in the realization of teleoperation technology. Currently, studies are being carried out to achieve radio communication in a more stable and reliable manner. Meanwhile, GPS-based autonomous navigation without the use of continuous radio communication has been the basic approach adopted for flying robots that are in practical use. The mobile robot employed at the Fukushima Daiichi Nuclear Power Station, Quince, was teleoperated by communication over a metal cable because radio communication did not work in the reactor building [16]. In all cases mentioned in the above, communication technology is a major bottleneck for the development of these robots.

The metamaterial antenna may be a breakthrough technology with regard to radio communication [13]. Metamaterials are artificial materials engineered to have electromagnetic properties that are not found in conventional materials in nature. By using this technology, it is possible to reduce the size of the antennas. Development toward its practical usage has progressed in recent years, as evidenced by the appearance of a wireless LAN router based on this antenna technology, in the market.

A current topic with regard to radio communication is the use of the frequency band that was previously used for analog television broadcasting in Japan. Since analog broadcasting was terminated in 2011, the VHF (90—222 MHz) and UHF (710—770 MHz) bands made available. There is a proposal to secure these bands for a radio system for disaster relief/prediction and crime prevention. These frequency bands are suitable for use in radio communication with mobile units since most materials are relatively permeable to these bands.

4. Summary

In this paper, how robotic technologies have been utilized during disasters caused by volcanic eruptions, and some required technologies/applications in futures were described. Particularly, the current status and future-expectations of unmanned construction systems, flying robots, mobile robots, power sources, and radio communication technologies, were discussed. It is the author's hope that robotic technologies will continue to contribute greatly to the reduction of the magnitude of disasters caused by volcanic eruptions.

References:

[1] M.Koyama, "Mechanical Coupling between Volcanic Unrests and Large Earthquakes–A Review of Examples and Mechanisms (Japanese)", Journal of Geography, vol.111, no.2, pp.222-2322, 2002.

[2] Tsuneo OHSUMI, Hiroshi ASAHARA and Etsuro SHIMOKAWA, "INVESTIGATION OF CHARACTERISTICS WITH TEMPORAL CHANGE IN FOURIER SPECTRUM IN A FLOW CONDITION USING VIBRATION SENSORS: CASE STRUDY ALONG NOJIRI RIVER (Japanese)", in the proceedings of the 4th Domestic Symposium on landslide disaster, 2008.

[3] Setsuya Nakada, and Toshitsugu Fujii, "Preliminary report on the activity at Unzen Volcano (Japan), November 1990-November 1991", Journal of Volcanology and Geothermal Research, 54, pp.310-333, 1993.

[4] Akira Sato. The rmax helicopter uav. Technical report, DTIC Document, 2003.

[5] Eichi Tomoda, Hajime Iwasaki, Hitoshi Okamoto, "Unmanned construction system in Akamatsu-river #9 (Japanese)", Magazine of Japan Construction Machinery and Construction, Vol.8, pp.14-20, 2010.

[6] M.Furusawa, "Innovation history of Unmanned construction system – Apprication of information - oriented construction (Japanese)", NETIS-plus, Vol.2, pp.16-23, 2011.

[7] The council for information - oriented construction promotion, "A strategy of Information-orientaed construction (Japanese)", http://www.mlit.go.jp/common/000993021.pdf

[8] John E. Bares and David S. Wettergreen, "Dante II: Technical Description, Results, and Lessons Learned", The International Journal of Robotics Research, Vol.18, No.7, pp. 621-649, 1999.

[9] Daniele Caltabiano, Danilo Ciancitto, Giovanni Muscato, "Experimental Results on a Traction Control Algorithm for Mobile Robots in Volcano Environment", Proceedings of the 2004 IEEE International Conference on Robotics 8 Automation, pp.4375-4380, 2004.

[10] Akio Goto, Hiromitsu Taniguchi, Mie Ichihara, "Development of unmanned Mobile Observatory for Volcanic Explosions "MOVE" and hurdles for its operation (Japanese)", The Journal of the Japanese Society for Planetary Sciences [You-Sei-Jin], Vol.21, No.2, pp.103-110, 2012.

[11] Keiji Nagatani, Tomoaki Yoshida, Eiji Koyanagi, et. al, “Emergency response to the nuclear accident at the Fukushima Daiichi nuclear power plants using mobile rescue robots”, Journal of Field Robotics, accepted and to be published, 2012.

[12] Keiji Nagatani, Tomoaki Yoshida, Eiji Koyanagi, et. al, “Emergency response to the nuclear accident at the Fukushima Daiichi nuclear power plants using mobile rescue robots”, Journal of Field Robotics, accepted and to be published, 2012.

[13] K.Sato, T.Nomura, S.Matsuzawa, and H.Iizuka, Metamaterial techniques for automotive applications”, PIERS proceedings, Hangzhou, China, pp.1122–1125, 2008.

[14] Keiji Nagatani, Ken Akiyama, Genki Yamauchi, Hikaru Otsuka, Takuma Nakamura, Seiga Kiribayashi, Kazuya Yoshida, Yasushi Hada, Shini’chi Yuta, Kenichi Fujino, Tomoyuki Izu, Randy Mackay, “Volcanic Ash Observation in Active Volcano Areas using Teleoperated Mobile Robots –Introduction to Our Robotic-Volcano-Observation Project and Field Experiments–, Proceedings of the 2013 IEEE Int’l Workshop on Safety, Security and Rescue Robotics, 2013.

[15] Keiji Nagatani, Hiroaki Kinoshita, Kazuya Yoshida, Kenjiro Tadakuma, Eiji Koyanagi,“Development of leg-track hybrid locomotion to traverse loose slopes and irregular terrain”,Journal of Field Robotics,Volume 28, Issue 6, pp.950-960 (2011-11)

[16] Keiji Nagatani, Seiga Kiribayashi, Yoshito Okada, Kazuki Otake, Kazuya Yoshida. Satoshi Tadokoro, Takeshi Nishimura, Tomoaki Yoshida, and Eiji Koyanagi, Mineo Fukushima and Shinji Kawatsuma,“Emergency Response to the Nuclear Accident at the Fukushima Daiichi Nuclear Power Plants using Mobile Rescue Robots”,Journal of Field Robotics Volume 30, Issue 1, pp.44-63 (2013-01)