Teleoperation of mobile robots using hybrid communication system in unreliable radio communication environments

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***Abstract*—**When an active volcano erupts, it is important to have visual images of the area to be able to forecast debris oods and /or pyroclastic ows. However, restricted zones are usually established within a radius of a few kilometers of the crater because of the direct danger to humans. Therefore, we propose an observation system based on a teleoperated mobile robot that is controlled using radio communication during volcanic activity. To evaluate the system, we conducted eld tests using a 3G cellular phone inside certain volcanoes. During the experiments, we faced several dangerous situations where the robot stopped all motion because of the weakness of the 3G signal. To solve this problem, we developed a hybrid communication system with multiple robots that employs two radio communication links. In the proposed system, each robot is controlled via 3G communication signals. However, if any of the robots lose the 3G link, the control signal is relayed by another neighboring robot using a local communication link. In this paper, we explain the system, introduce our newly designed robots, and present results of our operation tests.

KeyWords : Volcano Observation, Mobile Robot, Field Robotics, Hybrid Communication System, Teleoperated Robot

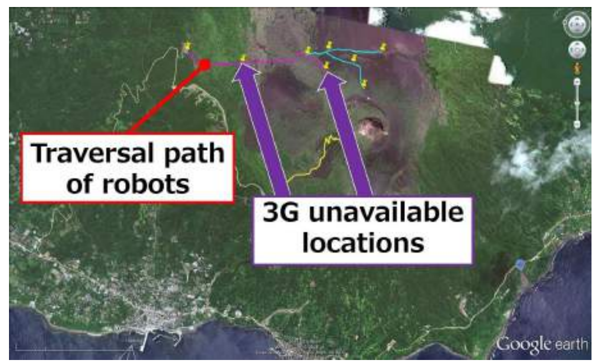

Fig. 1: Traversal path of robots and the locations at which the robots failed to communicate with the operator via the 3G network on Mt. Mihara

I. Introduction

The ability to observe the interior of active volcanoes is critical to the forecasting of potential eruptions and for planning the evacuation of inhabitants. However, restricted areas are usually established within a radius of a few kilometers of volcanic craters because of the direct danger to humans. For example, when the volcanic alert level reached 3 on Mt. Asama, a restricted area was established for a 4-km radius of the crater. In such cases, there is a commonly used method of observing the interior of the volcanoes, which involves the use of stationary cameras. However, these cameras cannot observe some locations of interest such as newly formed craters. Furthermore, they may suffer from malfunctions because of the eruptions. Therefore, there is the need to ensure continuous observation of restricted areas using teleoperating mobile robots.

Several robots have been developed to observe the interior of volcanoes via wireless communication links. ROBOVOLC [1], which is a wheeled robot, was developed by researchers who are based mainly in Italy. ROBOVOLC succeeded in exploring the Mt. Etna Volcano and the Mt. Vulcano Volcano. Similarly, Dante Ⅱ [2] was developed at the Carnegie Mellon University. Dante Ⅱ succeeded in observing the crater of Mt. Spurr. Moreover, our group developed TrackWalker [3], which is a tracked vehicle designed for exploring volcanic areas, and ELF [4], which demonstrates a high degree of traversability on the soft ground found inside volcanoes. However, these robots exhibited problems such as low energy efficiency and poor portability owing to their large size and weight. Therefore, we developed a small, lightweight mobile robot called GeoStar, and tested its teleoperation via a 3G link on Mt. Asama and Mt. Mihara. From these experiments, we con rmed that it is possible to observe volcanoes using small, teleoperating mobile robots. However, in several locations, we were unable to maintain the radio communication link with the robots because of the weak communication signal. Fig. 1 shows the path traversed by the robots on Mt. Mihara and the locations where the robots were unable to communicate with the operator via the 3G network. In such a scenario, where a robot is disconnected from the operator, he will be unable to maintain teleoperation. To solve the problem, installing redundant communication devices is one good option, and several proposals have been made for robotic applications, such as the use of mesh networks [5], hybrid communication in wireless sensor networks [6], and hybrid communication for indoor robots[7]. Based on these methods, in this research, we developed a hybrid communication system composed of different radio communication links to connect multiple robots. Then, we equipped CLOVER [8] (Compact and Lightweight

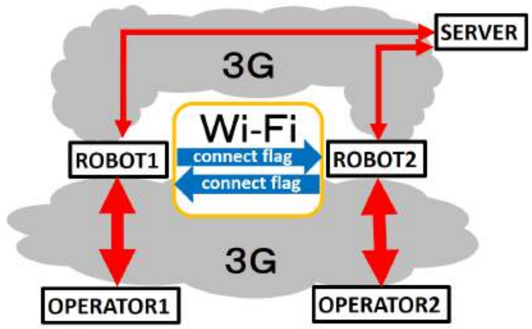

Fig. 2: Teleoperation of two robots via 3G network

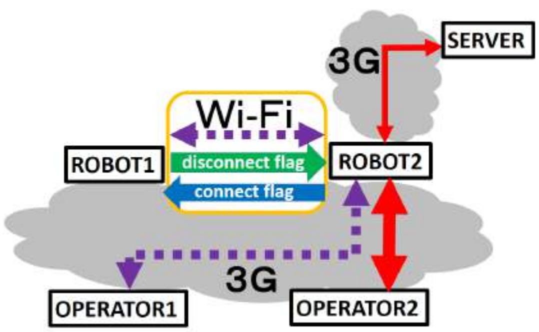

Fig. 3: Teleoperation of robots via a 3G/Wi-Fi combination

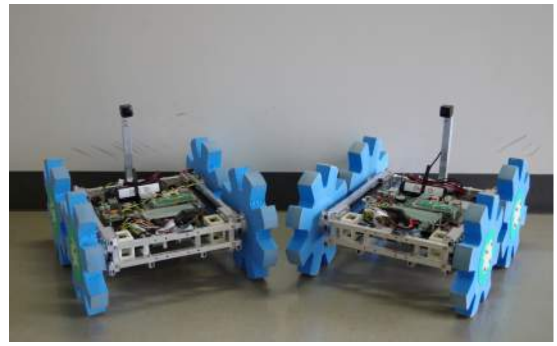

Fig. 4: Small-sized mobile robots: CLOVER

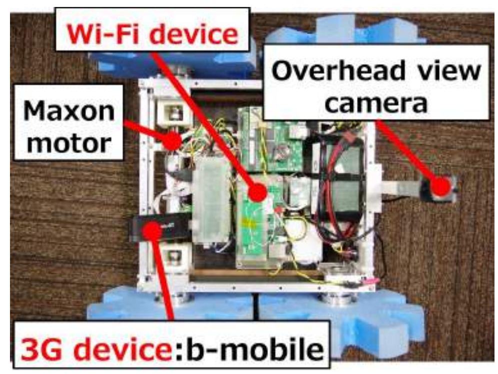

Fig. 5: Overhead view of CLOVER

teleOperation robot for Volcano ExploRation), which is a small mobile robot, with the system. After that, we veri ed the usability of the system in actual volcanoes. In this paper, we explain the architecture of our proposed hybrid communication system, introduce our new robots that were equipped with the system, and present the results of operational tests that were performed on them.

II. Teleoperation of mobile robots via a hybrid communication system

Teleoperating a robot via a normal radio communication link is not possible if the link is broken. Therefore, in this research, we developed a hybrid communication system composed of two robots and two radio communication links. One radio link is for use in a large area, even if the communication speed is slow. The other link is used for close range communication. To satisfy these conditions, we use 3G as the former and Wi-Fi (IEEE802.11g) as the latter.

A. Implementation of hybrid communication system

In this section, we describe details of the method used to realize the hybrid communication system. Here, we refer to OPERATOR1, OPERATOR2, ROBOT1, and ROBOT2 as OP1, OP2, R1, and R2, respectively. Using the 3G link, OP1 and OP2 connect to R1 and R2, respectively. The robots contact each other via Wi-Fi (Fig. 2) to share information such as images from their cameras.

In the case where both R1 and R2 can use 3G (Fig. 2), the operators can teleoperate their respective robots directly via the 3G link. The robots send data (a connect ag) to each other to indicate that they each are still communicating with their respective operators. When a robot receives the connect ag, it can only be controlled by its own operator. However, in the case where OP1 cannot communicate with R1 via 3G (Fig. 3), R1 sends data (a disconnect ag) to R2 via Wi-Fi to indicate that it cannot communicate with OP1 via 3G. When R2 receives the disconnect ag, it connects with R1 via Wi-Fi and becomes a relay station between OP1 and R1. Likewise, when R2 cannot communicate with OP2 via 3G, communication can be re-established with OP2 via R1.

Moreover, in this system, robots can communicate with a server via the 3G link to check whether they are still able to communicate with their respective operators.

III. Development of CLOVER equipped with a hybrid communication system

In this research, we developed CLOVER 4 and 5 to teleoperate two robots via a hybrid communication system. CLOVER is a small, lightweight wheeled mobile robot. Fig. 4 shows a photograph of CLOVER 4 and 5, and Fig. 5 shows an overhead view of CLOVER. CLOVER's speci cations are presented in Table I. CLOVER has a length of 400 mm, width of 350 mm, height of 300 mm, and weight of 4.0 kg. With respect to its networking equipment, CLOVER is equipped with a B-mobile (WM320 made by Nihontushin Co.), which is a 3G device, and a 2.4-GHz wireless device (FXE2000 made

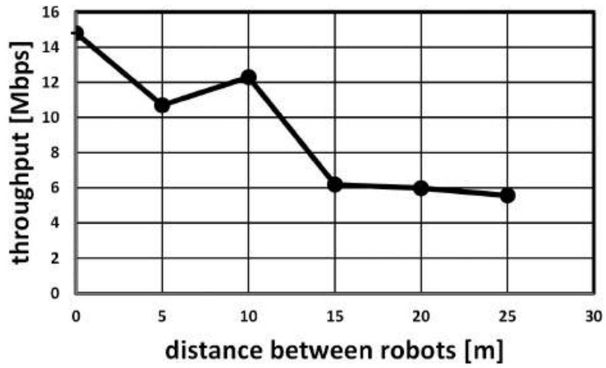

Fig. 6: Communication throughput between robots

by CONTEC Co.), which is a Wi-Fi device equipped with a chip antenna. Further, CLOVER is equipped with a camera (CY-RC70KD made by Panasonic Co.) to enable it to look down on itself. For the control system, CLOVER is equipped with an embedded PC (Armadillo-810 made by Atmark Co.), a motor controller (SH2/7144), two wheel motors (REmax-24 12V made by Maxon Co.), and a motor driver (3-Axes DC Power Module made by HiBot Co.). CLOVER is also equipped with a lithium ferrite battery (LiFePO4, 13. 2 V, 2300 mAh made by A123 Co.).

IV. Operation test

A. Measurement of Wi-Fi range

In the proposed system, one of the most important factors is the range of the wireless devices. To measure the range of the Wi-Fi devices used by two robots, we connected a PC to each of the 2.4-GHz wireless devices equipped with chip antennas on the robots, and we measured the communication range and throughput by sending ping packets from one robot to the other. This test was conducted in an outdoor at eld on the Aobayama Campus of the Tohoku University. Fig. 6 shows the results of the communication experiment. We found that for a distance exceeding 25 m, the robots were unable to ping each other in outdoor at terrain. The throughput was 5.98 Mbps for a distance of 25 m between robots. We con rmed that with our system, the hybrid communication system can be operated normally up to a distance of 25 m between robots.

TABLE I: CLOVER's speci cation

Length	400 mm
Width	350 mm
Height	300 mm
Weight	4.0 kg
3G device	B-mobile WM320
Wi-Fi device	Contec FXE2000
Camera	Panasonic CY-RC70KD
PC	Atmark Armadillo-810
Motor controller	SH2/7144
Motor	Maxon REmax-24 12V
Motor driver	HiBot 3-Axes DCPower Module
Battery	A123 LiFePO4

Fig. 7: Before (left) and after (right) covering the 3G device with aluminium

B. Time delay when switching connection paths between robots and operators

There is usually a limited amount of time within which a volcanic observation mission needs to perform using mobile robots. However, in our proposed hybrid communication system, after a robot checks the communication status with a server to determine whether it can communicate with the operator, the robot switches communication paths. This switch takes a nite time to be e ffected. To determine the effect of this time on the mission, we tested scenarios (1) and (2) below, and measured the switching time of the connection for each case.

(1) Switching from 3G-only communication (Fig. 2) to a combination of 3G and Wi-Fi communication (Fig. 3).
(2) Switching from a combination of 3G and Wi-Fi communication to 3G-only communication.

We tested each scenario ve times and found the average of the results for these tests. In the tests, we covered the antenna of the 3G device with aluminum to disconnect the 3G line (Fig. 7). Moreover, we monitored the connection switching via a simple application (Fig. 8) showing the communication paths in real time.

Table II lists the results. In experiment (1), it took about 10 s to switch between connections after the 3G link was disconnected. In experiment (2), it took about 5 s to switch between connections after communication recovery. From our results, (1) takes more time than (2). However, both of them had sufficiently high speed not to prevent operation.

C. Comparison of usability in different communication paths

We anticipated that the communication speeds for both scenarios (3G only and 3G/Wi-Fi combined) are similar because the Wi-Fi speed is high enough. Therefore, to determine whether there is a difference in the ability to control the robots

TABLE II: Comparison of switching time for connection between robots

	3G only → 3G/Wi-Fi [s]	**3G/Wi-Fi → 3G only [s]**
1	11	5
2	9	6
3	10	6
4	10	5
5	11	4
Average	10	5

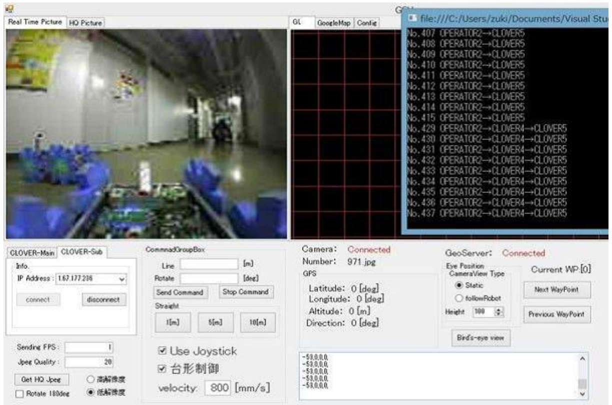

Fig. 8: Image taken from a robot's camera and application showing communication paths on the operation screen

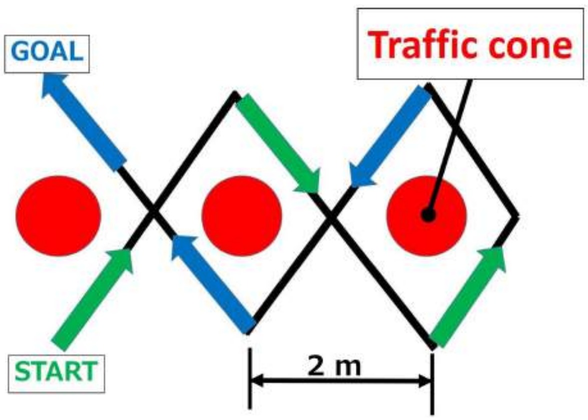

Fig. 9: Traversal course of robots

when using different communication paths, we performed experiments in which the operators controlled the robots using each of the two communication paths. We made a course that is about 15-m long (Fig. 9). Then, we performed an experiment in which three operators teleoperated robots from start to nish using different communication paths, and we measured the time taken.

Table III lists the results of our experiment. The difference in the average time taken to teleoperate the robots via 3G only and 3G/Wi-Fi was 5 s. That is, it was about 4 percent of the entire time devoted to teleoperation. We found that the control in different communication paths was similar. Therefore, it is possible to use the proposed system in actual volcanoes without the operator's work being hindered.

D. Field tests in an active volcano

We performed experiments using this hybrid communication system on a slope 1700 m above sea level on Mt. Asama. We tested the teleoperation of the robots via the 3G link several times, and found that the 3G signal was lost in certain locations. Therefore, in one of these locations, we tested the hybrid communication system to determine the suitability of the system. Fig. 10 shows CLOVER 4 and 5 using the hybrid

Fig. 10: Robots traveling on Mt.Asama

communication system while traveling on a slope on Mt. Asama. In this test, each operator drove CLOVER 4 and 5 from the mountaintop towards the base of the mountain. CLOVER4 remained in the lead, and they maintained a sufficient distance to ensure normal operation of the system.

After CLOVER4 had travelled about 100 m from the starting point, the 3G signal was lost. About 10 s later, the communication path changed. Then, the operator of CLOVER4 was able to teleoperate CLOVER4 via CLOVER5 using the 3G/Wi-Fi hybrid link. After CLOVER4 had travelled a few meters, it recovered the 3G signal. Then, the operator of CLOVER4 resumed teleoperating it directly via the 3G link only, and CLOVER4 continued to travel. From these results, we have shown that the system can be used in actual volcanoes.

V. Conclusion

In this research, we developed a hybrid communication system that is based on two operators and two robots to overcome problems caused by an unreliable radio communication link. Then, we developed two small mobile robots that are able to travel inside volcanoes, and which were equipped with the hybrid system. We also measured the range of the Wi-Fi system under normal conditions. We then conducted an experiment in which we changed the communication paths of the system to measure the switching time, and to determine the suitability of the system for different communication paths. We found that there was no signi cant di fference in the usability for the different communication paths. Moreover, we performed an experiment using the system on the slopes of Mt. Asama. The results showed that the system can be used to teleoperate robots that are inside actual volcanoes. In the future, we will perform experiments inside other volcanoes,

TABLE III: Comparison of total time of teleoperation of robots

	3G only [s]	**3G/Wi-Fi [s]**
Operator1	83	87
Operator2	71	79
Operator3	85	90
Average	80	85

and will continue to improve the system using different types of robots, such as larger mobile robots and unmanned aerial vehicles (UAVs).

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