Volcanic Ash Observation in Active Volcano Areas using Teleoperated Mobile Robots

– Introduction to Our Robotic-Volcano-Observation Project and Field Experiments –

Keiji Nagatani, Ken Akiyama, Genki Yamauchi,
Hikaru Otsuka, Takuma Nakamura,
Seiga Kiribayashi, Kazuya Yoshida
Tohoku University
Aramaki-Aoba, Aoba-ku, Sendai, Japan
Email: keiji@ieee.org

Yasushi Hada
Kogakuin University
1-24-2, Nishi-shinjuku,
Shinjuku, Tokyo, Japan
Email: had@cc.kogakuin.ac.jp

Shini'chi Yuta
Shibaura Institute of Technology
3-7-5, Toyosu, Koto-ku,
Tokyo, Japan
Email: yuta.shinichi@gmail.com

Kenichi Fujino
Public Works Research Institute
1-6, Minamihara,
Tsukuba, Japan
Email: fujino@pwri.go.jp

Tomoyuki Izu
Enroute Co., Ltd.
1-3-29, Ureshino, Fujimino,
Saitama, Japan
Email: izu@enroute.co.jp

Randy Mackay
Japan Drones Co., Ltd.
1019-396, Karuizawa, Kita-Saku-gun,
Nagano, Japan
Email: rmackay9@japandrones.com

***Abstract*—Observation of an active volcano is very important to determine a strategy for estimating its eruptive activity and providing residents with an evacuation warning. However, it is too dangerous for humans to install cameras during eruptive activity to determine the status of a volcano. Furthermore, permanently installed cameras might be damaged by eruptions, and craters can emerge in unanticipated positions. To handle this situation, we proposed robotic observations in a volcanic area after an eruption using a multi-rotor UAV (unmanned aerial vehicle) and a small ground robot. Field experiments are effective at promoting this type of research and development. Therefore, we performed several field experiments at Mt. Asama. In this paper, we introduce our robotic observation project, and report on the field experiments conducted with teleoperated mobile robots in October 2012 at Mt. Asama.**

I. INTRODUCTION

Once a volcano erupts, it typically takes a long time (2-3 years) before the end of its activity. During this activity, it has the potential to cause damage to neighboring environments from volcanic cinders, molten rock, pyroclastic flow, and debris flood. To protect the lives of inhabitants, volcano observation is a very important task.

Fig. 1. A bird's eye view of Mt. Asama (Nov. 2011)

Mt. Asama is one of the active volcanoes in Japan, and a debris flood from it caused catastrophic disaster in Kamahara village on August 5, 1783. The death toll rose to 477 (approximately 84% of the population of the village). The volcanic activity started in April 1783, but the people of the village never anticipated this disaster. If there had been a remote observation system for the volcano, the villagers could have been successfully evacuated. Mt. Asama is still an active volcano (the last eruption was in 2009), and it has a profound effect on the capital of Japan because the mountain is at only 100 km from Tokyo. The current status of Mt. Asama is level 1, which means the area within 500 m from the crater is restricted (Fig.1). Some cameras are installed in and around the crater, and a continuous observation system is now in place. However, during an eruption, permanently installed cameras may be damaged, and craters can emerge in unanticipated positions. In addition, the restricted area must be expanded, which makes it impossible to install new cameras using human labor. In the case of a level-3 eruption of Mt. Asama, the size of the restricted area encompasses a 4 km radius.

In such an environment, it is very important to obtain visual information from restricted areas, within a radius of several kilometers. Therefore, to observe volcanic activity, **a robotic remote observation system** is very useful, and such technology development must be an urgent concern for countries with high volcanic activity such as Japan.

There have been some research projects on volcano exploration using mobile robotic technology. The most famous project was the "Dante project," which used a walking mechanism with multiple legs [1]. This mechanism provided good traversability performance on rough terrain, and several field experiments were conducted to prove its reliability. However, the disadvantages of the system were that it was very heavy and slow. After the eruption of Mt. Unzen in Japan in 1990, unmanned construction machines were used for building mudslide-control dams to prevent damage from debris flow [2]. This system could be applied to remote observation, but the system is also very heavy. In Europe, there was a large project called ROBOVOLC that was designed to help scientists in the exploration of volcanoes [3] [4]. It explored MountEtna during September 2002. For its locomotion, the robot used six wheels, and it seemed to have difficulty exploring steep and weak slopes.

On the other hand, a UAV (unmanned aerial vehicle) has a good potential for use in volcanic observation, and Yamaha's UAV was used practically for the observation of Mt. Usu in 2000 [5]. This UAV obtained environmental information in restricted areas, which proved the usefulness of a UAV system for volcanic observation. However, their UAV used a gasoline engine, which could not work at elevations above 1000 m because of the decreased oxygen density at high altitudes. Because some active volcanoes in Japan are located at high altitudes, such as Mt. Asama, this system cannot be directly applied to them. Recently, researches on electric-powered multi-rotor UAVs have become popular globally, and battery performance is rapidly being improved. This type of UAV does not have a problem with low oxygen density, and there have been some actual flight achievements by electric-powered multi-rotor UAVs at very high altitudes (such as 6,200 m above sea level.)

Considering the situation mentioned above, our research group proposed robotic observations in volcanic areas after eruptions using a multi-rotor UAV and a small ground robot. The idea is that the small robot is transported and deployed by the multi-rotor UAV to obtain visual information about volcanic ash.

To promote research and development projects to realize the above robotic observation, field experiments are effective and essential. Therefore, we performed several field experiments in actual volcanic areas.

In this paper, we introduce the problems and solutions to realize the robotic observation and report on our experimental results at Mt. Asama.

II. EXPLORATION SCENARIO

To realize accurate debris flood forecasting, observation of volcanic ash in restricted areas is very important. This requires many kinds of information about the volcanic ash, but the most important information is the ash thickness and a close-up shot of the ash. To measure ash thickness, we assume that the target environment has poles, and we have photographs of the poles before an eruption. Then, after we take pictures of the poles following an eruption, we can precisely estimate the ash thickness by comparing the two photographs. Thus, the minimum requirement for the robotic observation mission is to obtain visual information in restricted areas.

Therefore, we determined that the aim of our robotic observation system was to transport mobile cameras on a slope surface in a restricted area for active volcanoes.

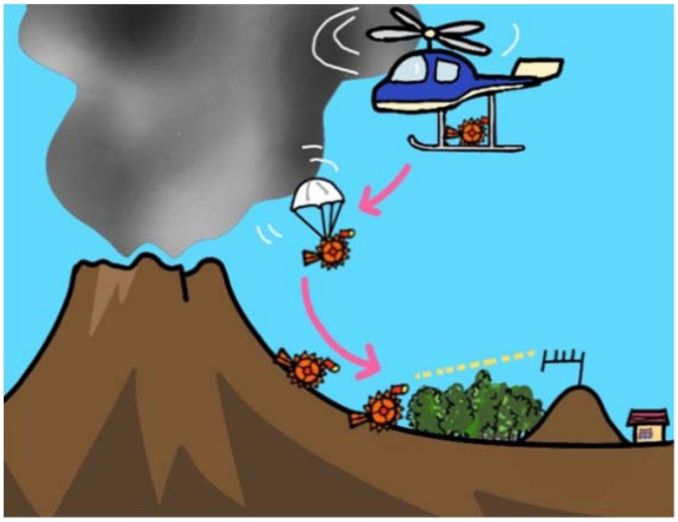


Fig. 2. Conceptual image of robotic observation using UAV and small robot.

A multi-rotor UAV has the advantage of mobility in a volcanic environment because of its ability to fly at high altitudes. However, the flight duration of a UAV is limited, and it is difficult to capture a close-up shot of volcanic ash from the air. On the other hand, a ground robot has the advantage of being able to operate for a relatively long time. In a case where the robot is equipped with solar battery panels, its period of activity can be greatly extended. However, the typical locomotion ability of such a robot is insufficient, and it takes a long time and much power for traversing restricted areas.

Under these limitations, we decided to combine the advantages of both a UAV and a ground robot to enable robotic observation in restricted areas of active volcanoes. The idea is to follow this procedure.

1) The wheeled small ground robot is transported to the top of the slope by multi-rotor UAV.
2) The UAV releases the ground robot.
3) The robot is navigated to some pre defined check-points.
4) The robot obtains visual information about the volcanic ash.

A conceptual image of the observation procedure is shown in Fig.2. An advantage of this approach is that the ground robot can stay longer time (more than 2 hours) and observe ashes much closer than UAVs.

III. PROBLEMS AND SOLUTIONS

To realize the mission described in the previous section, we are required to solve some technical problems. In this section, we would like to introduce the problems and solutions for our robotic observation system.

A. Flying Ability of UAVs

As mentioned in section I, a gasoline-engine-UAV cannot be applied under high-altitude conditions. There are two problems: low atmospheric pressure and low oxygen density.

Initially, we assumed that the first problem, low atmospheric pressure, was the biggest problem. According to the

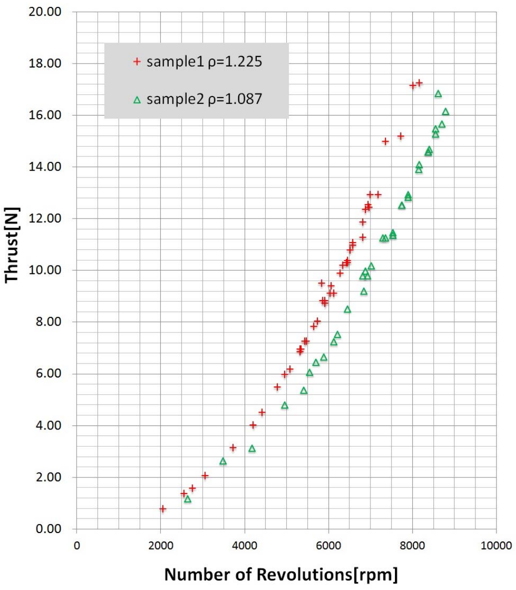


Fig. 3. Single rotor experiment result: Relationship between rpm and thrust at different elevations. The green triangles indicate the data at elevations of 1,140 m, and the red-plus-marks indicate the data at elevations of 470 m.

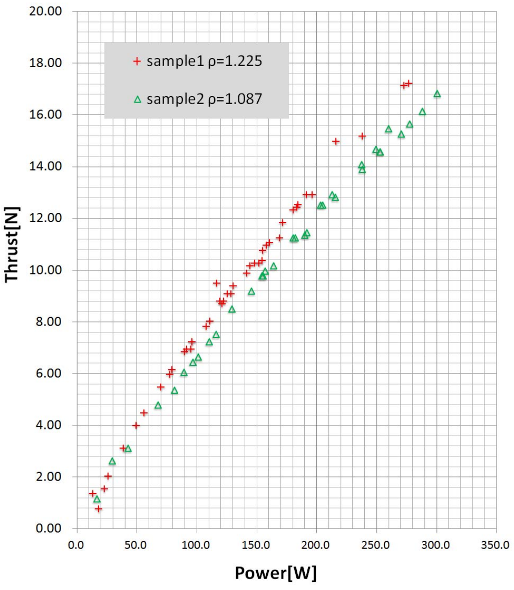


Fig. 4. Single rotor experiment result: Relationship between power consumption and thrust at different elevations. The green triangles indicate the data at elevations of 1,140 m, and the red-plus-marks indicate the data at elevations of 470 m.

rotary wing lifting theory in aeronautical engineering, the thrust of a wing is proportional to the dynamic pressure [6]:

$$T = C_t \times \rho n^2 D^4 \tag{1}$$

$$\rho n^2 D^4 \propto 1/2 \rho V^2, \tag{2}$$

where T denotes the thrust, C_t is the thrust coefficient, ρ is the mainstream density, n is the rotational frequency of a rotor, D is the radius of the rotor, and V is the mainstream flow velocity. The right side of equation (2) indicates the dynamic pressure. The atmospheric pressure at elevations of 1,140 m is approximately 90% of the pressure at elevations of 470 m. According to these equations, an additional 12% thrust would be required to facilitate the flight of a UAV at elevations of approximately 1,200 m.

We conducted thrust measurement experiments with a single rotor and an electric motor under high-altitude conditions and identified that the atmospheric pressure at elevations of 1,140 m was approximately 80% of the pressure at the elevations of 470 m for the same rotational velocity. This result is shown in Fig.3. The decreasing ratio was slightly larger than that calculated by the equations above.

Practically, in the case of electric motors, less electricity is required to generate the same rotational velocity at a low atmospheric pressure than at sea level. This is because of the lower air resistance. Therefore, comparatively, a low atmospheric pressure condition is not a serious disadvantage for such electric motor systems. Fig.4 shows a graph of the relationship between the electric power consumption and the thrust. The decrease was approximately 10% at 150 W, which was smaller than the decrease shown in Fig.3.

The second problem, low oxygen density, is the most serious problem for a gasoline-engine-UAV. In particular, it is difficult for a gasoline-engine to obtain stable thrust in the case of a pressure change. This can be solved by replacing the power source, from a gasoline engine to electric motors. However, in the latter case, the battery weight is the problem. Currently, the energy storage per battery unit weight is smaller than that of the gasoline. However, we expect a rapid improvement in batteries.

B. GPS navigation and altitude control of multi-rotor UAV

To realize the scenario shown in section 2, two basic functions are required for a multi-rotor UAV: GPS navigation and altitude control. Because the target point of a multi-rotor UAV is typically far from the operator, the UAV should be navigated automatically. In addition, a robust altitude control is very important because the total weight of the UAV changes after releasing the small robot. Both functions were solved by Arducopter, the GNU Lesser GPL software for the Arduino microcontroller on a multi-rotor UAV [7]. It includes a motor controller, IMU-based stabilizer, barometer-based altitude holder, and GPS autopilot software. Fig.5 shows a display of the GPS-based way point navigation in the ArduCopter software package. This software has been examined globally using various multi-rotor UAVs.

C. Locomotion ability of small robot

We believe that traversing volcanic environment is the most difficult task for a ground robot locomotion mechanism because of the steepness of the slope, roughness of the terrain, and weakness of the ground. To achieve this task, we have conducted research activities to obtain high traversability on such a ground [8][9]. However, the weight of the small robot carried by a multi-rotor UAV is limited, because it is difficult for the UAV to compensate for the increased payload. Additionally, high locomotion traversability for a ground robot


APM Planner 1.0.0 Build 1.0.4173.36295 By Michael Oborne

ArduPilotMega · COM46 · 115200

Distance: 0.5663 Km
Prev: 367.69 m

1. Connect
2. Read WP's if you need to.
3. Ensure your Home location and ALT is set
4. Click on the map to start adding WP's

Mouse Location
Lat 37.87082211
Long -122.3200714
Alt 0

GoogleSatellite
Status: loaded tiles

Home Location
Lat 37.87127945
Long -122.3175930
Alt 100

WP Radius 30 · Loiter Radius 45 · Default Alt 100 · ☐ Absolute Alt · ☑ Hold default Alt · ☐ Verify Height

	Command	Delay	Alt	Lat	Long	Lock GE	Delete	Up	Down
▸ 2	WAYPOINT	I need ...	100	37.8721433	-122.3179471	☑	X		
3	WAYPOINT	I need ...	100	37.8724651	-122.3166704	☑	X		
4	WAYPOINT	I need ...	100	37.8716352	-122.3160160	☑	X		

Fig. 5. Screenshot of GPS-based way point navigation based on ArduCopter software package. (http://code.google.com/p/arducopter/)

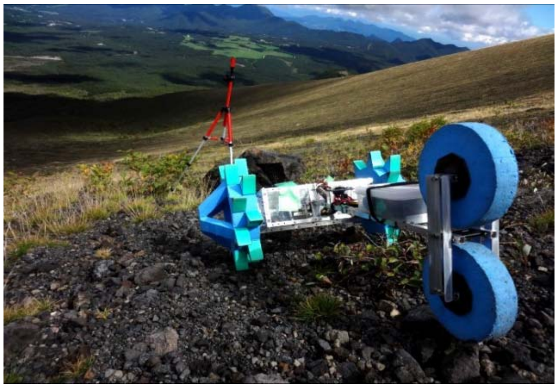


Fig. 6. Photograph of GeoStar-II on Mt. Asama (Oct.24, 2012).

requires a large locomotion mechanism, e.g., wheels with large diameters.

To solve this problem, we chose a ground robot with a smaller wheel diameter for deployment at the top of volcano slopes. The idea is that it is difficult for small robots to climb up, but not very difficult to climb (or tumble) down the slopes. To survive the impact of hitting the ground, the robot should be able to endure the impact of falling from several meters. In addition, to compensate for the tipping, the top and bottom of the robot should be symmetrical.

D. Communication

A significant issue in teleoperation in a large-scale environment is communication. Typically, high-frequency radio transmission, such as on the 2.4 GHz bandwidth, is required to send smooth dynamic images via wireless communication. However, the communication quality cannot be assured when using high-frequency radio waves in uneven environments such as volcanoes, because the diffraction phenomenon of electric waves decreases with the wavelength. When a communications blackout occurs, the robot can no longer be teleoperated.

In Japan, the bandwidth around 200 MHz, which is known as the public broadband, has attracted attention for application during in emergencies. Our project also considered the use of this bandwidth. However, the current commercial devices are too large to carry small ground robots and multi-rotor UAVs.

Therefore, we tentatively chose a modem connection via a cellphone signal, Docomo FOMA (800 MHz). Officially, the target environments at Mt. Asama are out of service areas. However, practically, we confirmed beforehand that almost all of the areas had good reception. Furthermore, if a volcano erupts and no base station exists around the target, a mobile base station can be deployed by the cellphone company.

IV. FIELD EXPERIMENTS AT MT. ASAMA

To proceed with our volcano ash observation scenario, we conducted field experiments at Mt. Asama to confirm some elemental functions on October 22-24, 2012.

A. Teleoperation of small robot, GeoStar-II

We implemented the vision-based teleoperation of a small ground robot, GeoStar-II, using a cellphone signal. An overview of this robot is shown in Fig.6 at elevations of approximately 2,000 m at Mt. Asama. The robot is 800 mm in length, 600 mm in width, and 300 mm in height, and the front wheels are 300 mm in diameter. The total weight is less than 2.7 kg. The top and bottom of the robot are symmetrical, and the navigation view for the operator can be inverted upside down. The robot mounts a camera (BSW20KM11BK, Buffalo) at the front for navigation, a gyroscope (MPU6050, InvenSense) to obtain its posture, and one small GPS module (LS20031, LOCOSYS Tech.) to obtain its global location. The GPS module is originally for cellular phone, and the accuracy is about 10 m.

The operator was located at the Rokuri-Gahara parking area, 3 km away from the robot. We placed six dummy poles to measure volcanic ash on the surface of the mountain slope at elevations from 2,100 m to 1,900 m. The robot was initially placed at an elevation of approximately 2,100 m, and the mission was to locate the 5 poles (50-100 m interval between poles) using the mounted camera. In Fig.6, one of the poles is located in front of the robot.

The navigation result is shown in Fig.7, and one of the screenshots of the operator's display is shown in Fig.8. Because of the poor communication speed, the image quality and update frequency were limited. These problems led to high-stress situation for the operator, along with problems recognizing small craters that overturned the robot. Therefore, the speed of the teleoperated robot was also limited, about 5 cm/sec. To increase the reliability of the teleoperation, a better communication method is required, such as public broadband. Further, recent small and cheap GPS modules did not work properly in the target environment. We assume that this problem was caused by the high sensitivity of the GPS antenna, multi-path error of the GPS signal caused by the mountain slope, and various algorithms embedded in the GPS modules.

Even through the GPS problem and the high-stress situation for the operator, the robot found 5 poles visually within 2 hours successfully.

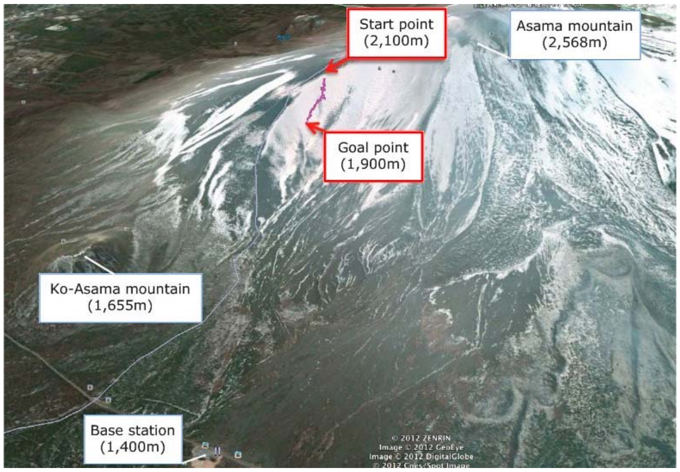
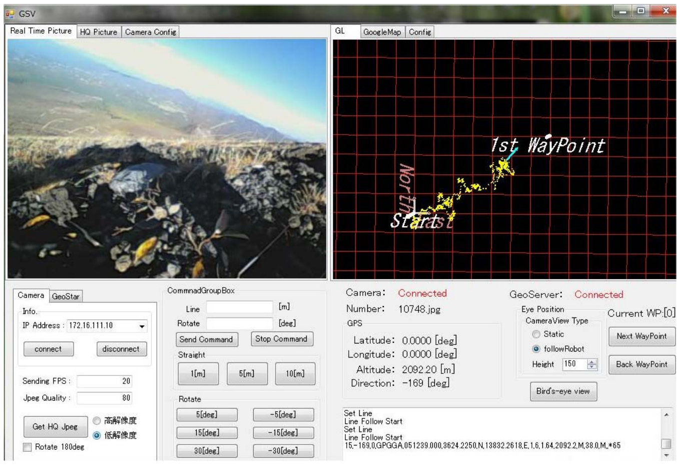


Fig. 7. Result of teleoperation experiment (Oct.24,2012).



IP Address : 172.16.111.10

Sending FPS : 20

Jpeg Quality : 80

○ 高解像度
● 低解像度

☐ Rotate 180deg

Line [m]

Rotate [deg]

Camera: Connected

Number: 10748.jpg

GPS

Latitude: 0.0000 [deg]

Longitude: 0.0000 [deg]

Altitude: 2092.20 [m]

Direction: -169 [deg]

GeoServer: Connected

Eye Position

CameraView Type

○ Static
● followRobot

Height 150

Current WP:[0]

```
Set Line
Line Follow Start
Set Line
Line Follow Start
15,-169,0,GPGGA,051239.000,3624.2250,N,13832.2618,E,1,6,1.64,2092.2,M,38.0,M,,*65
```

Fig. 8. Screenshot of operator's display (Oct.24,2012).

B. GPS navigation of multi-rotor UAV

We also confirmed the function of the GPS autopilot software for our multi-rotor UAV. The flight was conducted at the top of Mt. Koasama (1,655 m above sea level), and the UAV visited fixed way points. Typically, a strong wind blows just above a mountain ridge. We assumed a wind speed of less than 10 m/s, but the wind can be stronger. Therefore, we chose a flight path that was 30 m above the mountain ridge in this experiment.

C. Experiment to release small robot

One of the important objectives in the field experiment was to demonstrate the release mechanism of a small robot from the multi-rotor UAV. Therefore, we implemented a prototype hexa-rotor UAV, TOBI, to carry the small robot, GeoStar-mini. In this experiment, the UAV system succeeded in the tasks of carrying and releasing the small robot, as shown in Fig.9. After the release, the GeoStar-Mini was teleoperated successfully.

TOBI was a prototype carrier UAV, and the maximum flight time was limited. The robot was released by thermally cutting a nylon fishing line, and the looseness of the line resulted in unstable flight. We found that an improvement in the release mechanism was required.

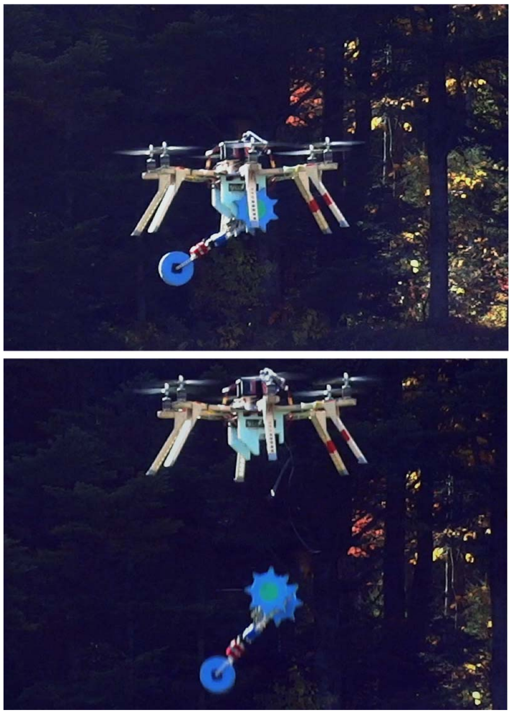


Fig. 9. Releasing small ground robot from multi-rotor UAV, TOBI (Oct.25,2012).

V. PRACTICAL SYSTEM OF MULTI-ROTOR UAV AND SMALL ROBOT

After the field experiments at Mt. Asama, we started constructing a practical model of a multi-rotor UAV and an improved small ground robot, and developing a new release mechanism.

We chose a hexa-rotor UAV, "ZionPro 800," produced by Enroute co., Ltd, as a practical carrier. This UAV has a body diameter of 800 mm. It is 300 mm in height, and the total weight is 3.8 kg, including batteries. It utilizes a 22.2 V 8000 mA/h lithium polymer battery and six 600 W motors. According to our recent estimation, a 15 min flight at elevations of approximately 2,000 m can be conducted for a 10 kg hexa-rotor UAV. The velocity of the UAV is at least 5 m/s, so it can perform a 4.5 km flight within 15 minutes in our desktop calculation. In addition, we attached a release mechanism of the ground robot to the UAV that used a servo motor instead of thermally cutting system.

To improve the traversability and the stability of the ground robot, we developed a four-wheel-drive robot called CLOVER (Compact and Light-weight teleOperation robot for Volcano ExploRation). This robot is 450 mm in length, 360 mm in width, and 220 mm in height, with a wheel diameter that is the same as the height (220 mm). The weight of the robot is 2.5 kg. Because of the limitation of the weight, the wheel size was decreased from GeoStar-II, but four-wheel-drive improved its traversability very much. The controller, GPS, and communication system are the same as those for

Fig. 10. Outdoor flying experiment in Shin-moe-dake (Mar. 11, 2013): In the left photo, the UAV (ZionPro 800) carries the ground robot (CLOVER). In the middle photo, the ground robot is released from the UAV. In the right photo, the ground robot traverses on the slope of the Naka-dake.

GeoStar-II, and it has a capability to climb up a 25° loose slope. The top and bottom of the robot are symmetrical, so there is no problem in case that it is overturned while traveling and landing.

To confirm the reliability of the practical system, we conducted an outdoor experiment on March 11, 2013. Fig.10 shows a sequence of the experiment in Mt. Nakadake, an adjacent mountain of Mt. Shinmoe. Mt. Shinmoe is one of the active volcanoes on Kyusyu Island, Japan. It erupted in 2011, just before the Great East Japan Earthquake. In the experiment, the UAV took off at the base of Mt. Nakadake with the ground robot, and flew for about 100m horizontally (and 30m vertically) toward an inclined surface of the mountain. The flight was conducted manually, and separation signal was sent from the UAV operator. Finally, the ground robot touched down to the ground, and navigated by the ground-robot-operator toward the take-off position. After releasing the ground robot, the UAV's elevation increased a little bit because of losing body weight. However, barometer-based feedback system suppressed its rapid uplift motion.

Through the experiment, we confirmed that the UAV carried the ground robot safely, releasing mechanism of the ground robot worked well, and the ground robot went down a mountain robustly. However, we still have some issues to be solved, e.g. long range communication (more than 3 km) and automatically releasing system of the ground robot. In this experiment, the ground robot was released from 2 m above. However, in typical cases, it is difficult to enable height control on such a steep slope. We should think about the other method for landing the ground robot.

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, we introduced a scenario for robotic volcano observation, particularly the observation of ash in restricted areas. The idea is to transport a small ground robot using a multi-rotor UAV into the restricted area, and then navigate the robot downward along the volcano slope. To realize this scenario, we discussed four problems and solutions in this paper: the flying ability of a UAV, navigation method for the UAV, locomotion ability of the small robot, and communication. Then, we reported on several field experiments conducted at Mt. Asama, which confirmed the elemental technologies.

We are now planning to conduct a field experiment at Mt. Asama in August, 2013 again. The objective of this experiment is to demonstrate the reliability of our current system in an actual volcanic field to complete our proposed scenario. It is not possible to include these results in this paper, but they will be reported soon.

ACKNOWLEDGMENT

This research project is supported by the Erosion Control Engineering division of the R&D Institution of River Technology in the Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport, and Tourism. To conduct the field experiment at Mt. Asama, we had support from the Earthquake Research Institute of the University of Tokyo.

REFERENCES

[1] J.E.Bares and D.S.Wettergreen. Dante II: technical description, results, and lessons learned. *International Journal of Robotics Research*, 18(7):621–649, 1999.

[2] Tatsuo Arai. Robotics and automation in Japanese construction industries. In *Proceedings of the 22nd International Symposium on Automation and Robotics in Construction*, pages 1–5, 2005.

[3] G Muscato, D Caltabiano, S Guccione, D Longo, M Coltelli, A Cristaldi, E Pecora, V Sacco, P Sim, GS Virk, et al. Robovolc: a robot for volcano exploration result of first test campaign. *Industrial Robot: An International Journal*, 30(3):231–242, 2003.

[4] G.Muscato, F.Bonaccorso, L.Cantelli, D.Longo, and C.D.Melita. Volcanic environments: Robots for exploration and measurement. *IEEE Robotics & Automation Magazine*, 19(1):40–49, 2012.

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

[6] Hermann Glauert. *The elements of aerofoil and airscrew theory*. Cambridge University Press, 1983.

[7] Arducopter - arduino-based autopilot for mulitrotor craft, from quadcopters to traditional helis. http://code.google.com/p/arducopter/.

[8] Keiji Nagatani, Hiroaki Kinoshita, Kazuya Yoshida, Kenjiro Tadakuma, and Eiji Koyanagi. Development of leg-track hybrid locomotion to traverse loose slopes and irregular terrain. *Journal of Field Robotics*, 28(3):950–960, 2011.

[9] Masataku Sutoh, Junya Yusa, Tsuyoshi Ito, Keiji Nagatani, and Kazuya Yoshida. Traveling performance evaluation of planetary rovers on loose soil. *Journal of Field Robotics*, 29(4):648–662, 2012.