Development and Field Testing of UAV-based Sampling Devices for Obtaining Volcanic Products

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***Abstract*—When an active volcano erupts, a restricted area is typically imposed around the crater of the volcano to protect people from volcanic phenomena. On the other hand, it is important to make observations inside the restricted area, to initiate alarms and make evacuation plans. Therefore, research and development of unmanned volcano exploration robots have been carried out all over the world. However, although ash sampling in restricted areas is an urgent necessity, there is no quick sampling method. Therefore, in this study, we aim to realize a sample-return system that uses a multi-rotor unmanned aerial vehicle (UAV) for obtaining volcanic products. In this paper, we introduce two sampling devices that we developed, and report results of indoor sampling experiments and outdoor field tests.**

I. Introduction

When an active volcano erupts, volcanic phenomena (e.g. large and small volcanic cinder, ash fall, pyroclastic flow, debris flow, mud flow, lava flow and volcanic gas) occur [1]. To protect people from these phenomena, a restricted area is typically imposed around the crater of the volcano. On the other hand, it is important to make observations inside the restricted area to initiate alarms and make evacuation plans. For this purpose, fixed cameras and sensor equipment have recently been set up near the craters of active volcanoes. However, this preparation is insufficient. For example, in 1990, almost all of the sensor equipment malfunctioned because of the eruptions of Mt. Unzen-Fugen. Moreover, a new crater sometimes appears in an unexpected place.

Therefore, research and development of unmanned volcano exploration robots have been carried out all over the world. Representative robots are the eight-legged robots, Dante and Dante II, developed at Carnegie Mellon University [2], [3]. Dante explored Mt. Erebus in 1992, and Dante II explored Mt. Spurr in 1994, both successfully. In Europe, a wheel robot called ROBOVOLC was developed by European robotics research group that is centered on Italian researchers, and test operations were performed with the robot in Mt. Etna and Mt. Vulcano [4]. In Japan, Taniguchi et al. developed a volcano observation robot, called MOVE, for scientific observation in restricted areas [5]. It was based on an unmanned construction machine. In our group, a small-sized volcano exploration robot, called CLOVER, was developed [6]. One of the features of the robot is that it is able to be carried by a small multi-rotor unmanned aerial vehicle (UAV). The main purpose of the above robots is to enter hazard areas by using their locomotion mechanisms, and to obtain information by using their sensors.

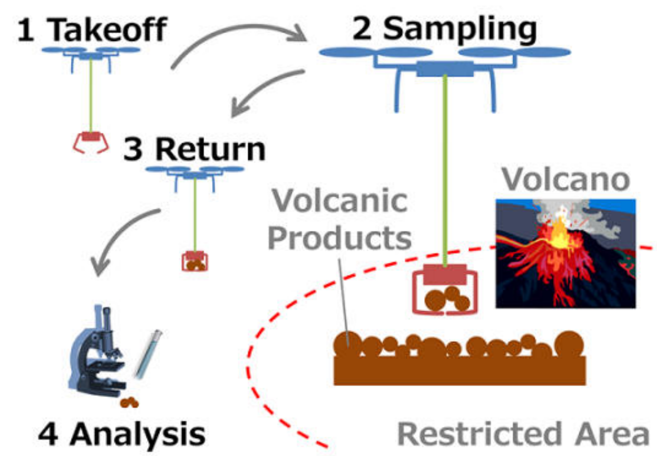


Fig. 1. Sample-return scenario of volcanic products inside restricted areas

On the other hand, debris flow prediction is an important mission for volcanic disaster response. This phenomenon, which is caused by rainfall, has the potential to cause large disasters at the foot of the volcano, even outside the restricted area. For accurate prediction of such debris flow, it is said that ash sampling and analysis are very important. Moreover, sampling and analyzing volcanic products in the early stage of eruption are related to predicting the transition of volcanic activity. This is because the volcanic products contain ingredients that originated directly from magma [7]. As mentioned above, it is an urgent necessity to conduct ash sampling in restricted areas. However, with our current technologies, there is no systematic device for sampling volcanic products quickly. Therefore, in this research, we aim to realize a sample-return system that uses a multi-rotor UAV for obtaining volcanic products inside restricted areas. Our scenario for sample-return is as follows:

1) A multi-rotor UAV that hangs a sampling device takes off from outside the restricted area. (Fig. 1-1)
2) When the UAV parks over the destination inside the restricted area, the sampling device touches down and obtains samples of volcanic products. (Fig. 1-2)
3) After completion of the sampling, the UAV lifts the sampling device and returns to the takeoff point. (Fig. 1-3)
4) The samples of volcanic products are analyzed in the laboratory. (Fig. 1-4)

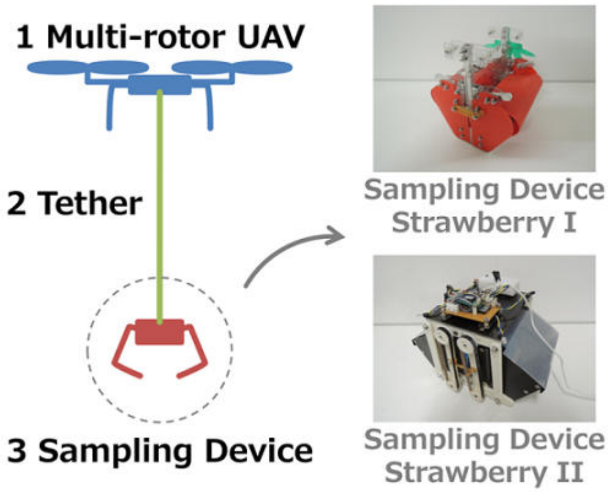


Fig. 2. Configuration of sample-return system using multi-rotor UAV for obtaining volcanic products inside restricted areas

This system consists of three elements: (1) a multi-rotor UAV (Fig. 2-1) to move between the outside and inside of the restricted area, (2) the tether (Fig. 2-2) to hang the sampling device from the multi-rotor UAV, and (3) the sampling device (Fig. 2-3) to obtain volcanic products. Therefore, in this study, we developed sampling devices to realize this system. In this paper, we introduce two sampling devices that we developed and report results of sampling experiments and field tests of the two devices.

II. Sampling Device: Strawberry I

At the beginning of this study, a passive-type sampling device called Strawberry I was developed as a prototype (referred to as the SB-1 in the rest of this document).

A. Structure and Principle of Operation

The structure and the specifications of SB-1 are shown in Fig. 3 and Tab. I. As shown in Fig. 3, the connecting part of SB-1 can move along the slider. The shovels are attached to the shaft of the connecting part, and they can maintain an open state by fixing the rods of the shovels with the locking part. The shape of the mouth of the sheaves is simply flat for easy-to-make.

When SB-1 touches down and the locking part is released, it obtains samples of volcanic products by closing the shovels with the tensile force of the elastic band. A detailed sequence of the sampling operation is as follows:

1) SB-1, which is in the open state, is lowered. (Fig. 4-1)
2) The grounding part of SB-1 touches down. (Fig. 4-2)
3) The rods of the shovels are removed from the locking part by the shock of landing. (Fig. 4-3)
4) The shovels are closed by the tensile force of the elastic band (closed state), and SB-1 obtains samples of volcanic products. (Fig. 4-4,5)

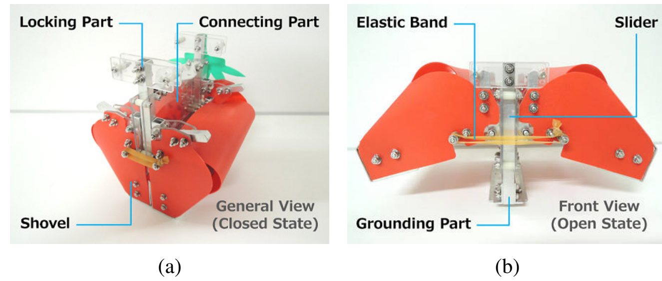


Fig. 3. Structure of Strawberry I

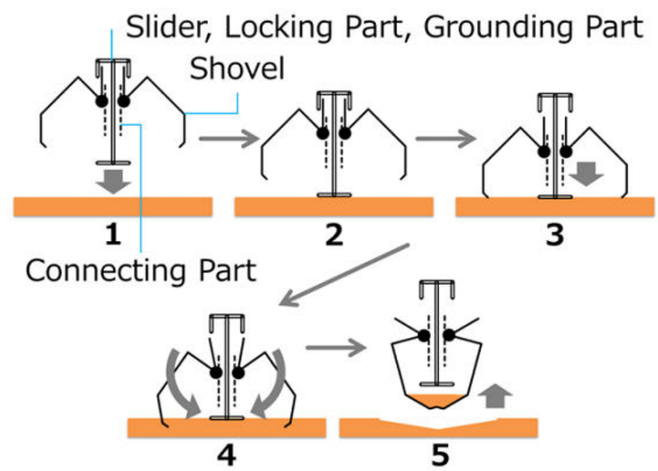


Fig. 4. Sequence of Operation of Strawberry I for obtaining volcanic products inside restricted areas

B. Sampling Experiments and Field Tests

To verify the validity of SB-1, we first carried out sampling experiments of SB-1 on simulated fields of sand and gravel in our laboratory.

According to the experiments, which were repeated three times, the average sampling amounts were 123 g of sand and 7 g (4.7 pieces) of gravel. As a result of the experiments, it was seen that SB-1 was suitable to obtain samples of small particles, even though the structure of SB-1 was very simple. However, when SB-1 obtained sand, it leaked from the mouth of shovels. To solve this issue, we must improve the mouth of shovels.

Secondly, we carried out field tests of SB-1 at Mt. Koasama on September 30, 2013. Fig. 5 shows the actual field test conditions. SB-1 was hung from a multi-rotor UAV (Zion EX460, made by enRoute Co., Ltd.) with a 5 m tether, and

TABLE I. Specifications of Strawberry I

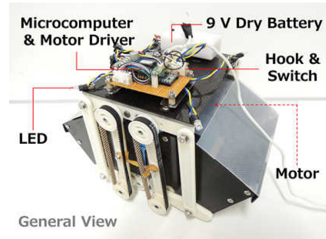
size [mm]	155 × 160 × 175
weight [g]	570
maximum tension [N]	8

Fig. 5. Field test conditions for Strawberry I at Mt. Koasama on September 30, 2013

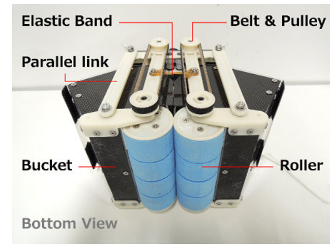
(a) Particle Size : Large

(b) Particle Size : Small

Fig. 6. Comparison of field test results of Strawberry I



(a)



(b)

Fig. 7. Structure of Strawberry II

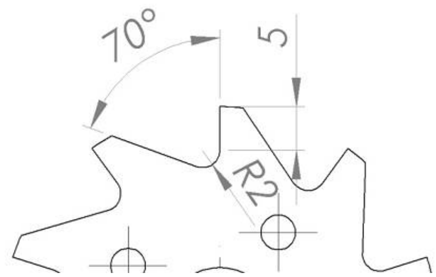


Fig. 8. Shape of grooves of Strawberry II

we conducted sampling operation with manual control of the UAV at several dozen meters away from the takeoff point.

As a result of these field tests, the sample-return motion of volcanic products was successfully demonstrated using this system. As shown in Fig. 6, the tendency of the results was almost the same as the results of our indoor sampling experiments. In addition, the following issues were uncovered by the field tests:

1) It was difficult for SB-1 to obtain volcanic products consisting of large particles (over 30 mm).
2) In the case that SB-1 fails to obtain a sample, it closes and cannot repeat the sampling motion.
3) Sometimes, when the UAV takes off, the connecting part slides down because of the shock of lifting up. Then SB-1 closes and cannot conduct the sampling motion .
4) Manual control of the UAV to touch down SB-1 is very difficult for an operator.

III. Sampling Device: Strawberry II

To solve the above issues, we developed a roller-type sampling device, called Strawberry II (hereafter referred to as SB-2), as a second prototype.

A. Structure and Principle of operation

The structure and specifications of SB-2 are shown in Fig. 7 and Tab. II. The rollers and buckets can be moved from side to side, and these motions are restricted by elastic bands between them. A small motor is connected to the rollers via belts and pulleys to rotate them actively. The shape of the grooves of the rollers is determined by the trade-off between the depth of grooves and angle of it, as shown in Fig. 8.

A feature of the SB-2 is that the rotation of the rollers shaves the surface of the ground, and gathers volcanic products into the buckets. A detailed sequence of the sampling operation of SB-2 is as follows:

1) SB-2 is lowered. (Fig. 9-1)
2) After SB-2 lands on the ground, the roller's rotation begins. (Fig. 9-2)
3) The rotation of the rollers shaves the surface of the ground. (Fig. 9-3)
4) Volcanic products are gathered in the buckets by the rotation of the rollers. (Fig. 9-4)

The rotation of the rollers is controlled by a small microcontroller and a motor driver to prevent a false operation at the takeoff point. The switch for the rollers is located at the hook of the tether to judge whether the tether is loaded or not. Therefore, when the SB-2 is in the air, the tether is loaded and under tension, and the switch remains OFF. When the SB-2 is on the ground, the tether is unloaded and not under tension, and the switch is ON for the rotation of the rollers.

TABLE II. Specifications of Strawberry II

size [mm]	180 × 240 × 170
weight [g]	770
roller diameter [mm]	ϕ 50
roller material	hard : polyethylene foam soft : polyurethane foam
motor	NC-153901G ZJP1/256 (Citizen Chiba Precision Co.)
minimum tension [N]	3

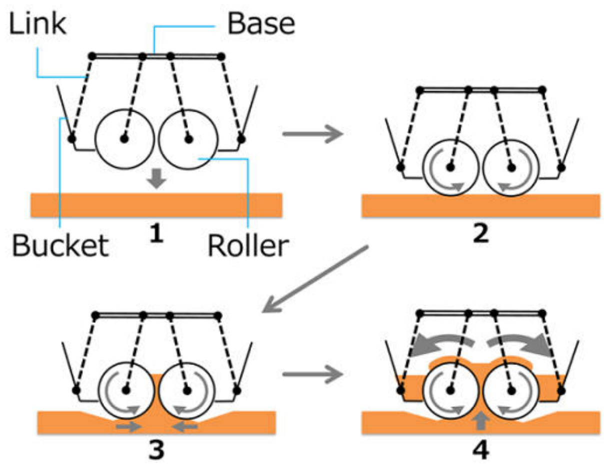


Fig. 9. Sequence of Operation of Strawberry II for obtaining volcanic products inside restricted areas

B. Sampling Experiments

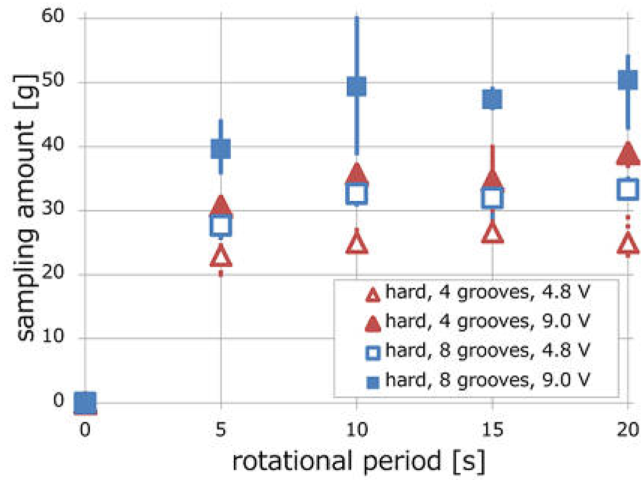
To verify the validity of SB-2, we first carried out sampling experiments with SB-2 on simulated fields of sand and gravel in our laboratory. In these experiments, we changed the voltage of the motor, the number of grooves of the rollers, the material of the rollers, and the rotational period, as shown in Tab. III.

The experimental results are shown in Fig. 10. As a result of these experiments, the higher the applied voltage is, the higher the sample quantity becomes. This means that high rotational speed contributes to the amount of sampled material. In terms of the rotational period, the amount of gravel that is sampled grows proportionally to the rotational period until 20 s. On the other hand, the amount of sand sampled converges in approximately 10 s. The reason is that the sand flows out from the gaps between the roller and the bucket after 10 s. In addition, the sampling amount grows proportionally with the number of grooves on the rollers, and the soft material rollers are better for gathering gravel than the hard rollers.

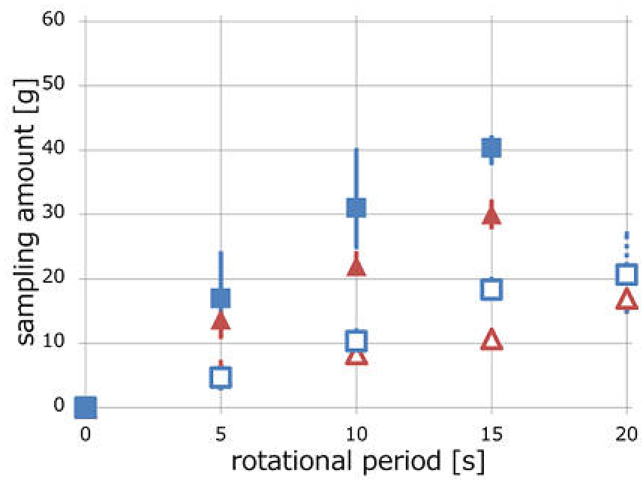
Moreover, the rollers were sometimes stopped by clogging of gravels between the roller and the bucket. When the sampling amount increased, the number of times of this phenomenon increased. Typically, when the rotational period is over 20 s in the case of applied voltage = 9 V, the rollers were stopped before the end of rotational period. Therefore, the results of this experiment were not plotted in fig. 9. To solve this issue, it is necessary to have a partition between the roller and the bucket, suitable size of a bucket, and the system that detects the situation of the rollers.

TABLE III. EXPERIMENTAL CONDITIONS OF STRAWBERRY II

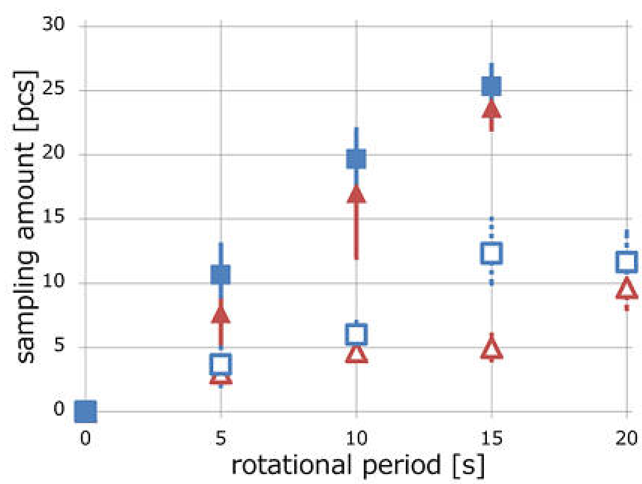
voltage [V]	4.8, 9.0
number of grooves of rollers [pcs]	0, 2, 4, 6, 8, 10
material of rollers	hard: polyethylene foam soft: polyurethane foam
rotational period [s]	5, 10, 15, 20



(a) Weight of Sand



(b) Weight of Gravel



(c) Number of Pieces of Gravel

Fig. 10. Examples of experimental results of Strawberry II in indoor sampling experiment

Fig. 11. Field test conditions for Strawberry II at bank of Hirose River on April 8, 2014

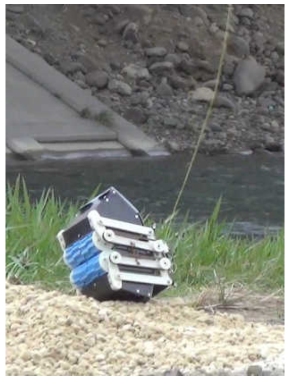


Fig. 12. Tipping over of Strawberry II

C. Field Tests

We carried out field tests of SB-2 at the bank of the Hirose River on April 8, 2014. Fig. 11 shows the actual field test conditions. SB-2 was hung from a multi-rotor UAV (Zion PG560, made by enRoute Co., Ltd.) with a 3 m tether. We conducted sampling operations with manual control of the UAV at 10 m away from the takeoff point. A 9 V dry battery was used as the power source for the rotation of rollers, because it is lightweight and easily obtainable. The rollers had 10 grooves, their material was hard, and their rotational period was set at 10 s.

As the result of these field tests, the system was successful in performing a sample-return motion. However, in the field tests, the sampling amount was less than the results of the indoor sampling experiment in our laboratory, as shown in Tab. IV. The reason was that the 9 V dry battery could not apply enough electric current. In addition, during its sampling motion, we observed that SB-2 moved on the ground. The reason of the unanticipated motion was that the links were not synchronous.

When SB-2 touched down on the inclined ground, it sometimes tipped over, as shown in Fig. 12. The reason was that the center of gravity of SB-2 was high. In this field test, we observed tipping over situation. However, in the real operation, we cannot check it because the UAV and the sampling device conduct sampling farther away. Therefore, it requires detection mechanism of its tipping over. Moreover, we observed that the tether and SB-2 were swung largely while the UAV moved. This swing affects not only the flight of UAV, but also a possibility of tipping over of SB-2. To solve this issue, the tether winding mechanism and the swing reduction control is necessary.

TABLE IV. FIELD TEST RESULTS FOR STRAWBERRY II

	outdoors (field test)				indoors (experiment)
	1st	2nd	3rd	avg.	avg.
number of pieces of gravel [pcs]	2	12	7	7	24.67

IV. CONCLUSION

In this study, we developed two sampling devices with different methods for conducting sample-return missions in volcanic restricted areas. In addition, we carried out sampling experiments in our laboratory and in outdoor fields, clarified features of the sampling devices, and verified the usefulness of these sample-return systems.

In the future, we will continue to research and develop SB-2, conduct sampling experiments, and elucidate key technologies to increase the sample quantity. Moreover, we will develop the tether winding mechanism and conduct an autonomous sample-return mission using GPS.

REFERENCES

[1] S. Nakada, T. Fujii, *Preliminary Report on the Activity at Unzen Volcano (Japan), November 1990-November 1991: Dacite Lava Domes and Pyroclastic Flows*, Journal of Volcanology and Geothermal Research (1993)

[2] D. Wettergreen, C. Thorpe and R. Whittaker, *Exploring Mount Erebus by Walking Robot*, International Conference of Intelligent Autonomous Systems (1993)

[3] J. E. Bares, D. S. Wettergreen, *Dante II: Technical Description, Results, and Lessons Learned*, International Journal of Robotics Research (1999)

[4] G. Muscato, D. Caltabiano, S. Guccione, D. Longo, M. Coltelli, A. Cristaldi, E. Pecora, V. Sacco, P. Sim, G.S. Virk, et al., *Robovolc: A Robot for Volcano Exploration Result of First Test Campaign*, Industrial Robot: An International Journal (2003)

[5] A. Yokoo, M. Ichihara, A. Goto, H. Taniguchi, *Atmospheric Pressure Waves in the Field of Volcanology*, Shock Waves (2006)

[6] K. Nagatani, K. Akiyama, G. Yamauchi, H. Otsuka, T. Nakamura, S. Kiribayashi, K. Yoshida, et al., *Volcanic Ash Observation in Active Volcano Areas using Teleoperated Mobile Robots - Introduction to Our Robotic-Volcano-Observation Project and Field Experiments -*, 2013 IEEE International Workshop on Safety, Security and Rescue Robotics (2013)

[7] K. Watanabe, T. Danhara, K. Watanabe, K. Terai, T. Yamashita, *Juvenile Volcanic Glass Erupted Before the Appearance of the 1991 Lava Dome, Unzen Volcano, Kyushu, Japan*, Journal of Volcanology and Geothermal Research (1999)