Development of Multi-D.O.F. Tracked Vehicle to Traverse Weak Slope and Climb up Rough Slope

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***Abstract*— During a volcanic activity, it is very dangerous to approach a restricted area. For this reason, robotic remote observation system would be quite useful, and it is particularly urgent for a country with a high degree of volcanic activity, such as Japan. In response to this need, our research group developed a novel multi-D.O.F. tracked vehicle, called ELF, which can conduct observation in a restricted volcanic area. The robot essentially consists of six tracks, and it has eleven actuators that change its configuration. These actuators enable the robot to assume various configurations, which increase its ability to traverse weak and rough terrains in the area around a volcano. In this research, we propose one configuration of the robot, in which the surface of the contact plane at the bottom of the track is horizontal, which is advantageous for traversing a weak slope. The feasibility of this design was verified in a field experiment on Mt. Kushigata, on the island of Izu-Oshima, and in a simulated volcanic field that was filled with pumice stones.**

Fig. 1. Quince version for volcanoes: Originally developed for rescue applications, it consists of two main tracks and four subtracks. It is equipped with a total of six mounted actuators.

Fig. 2. Novel design of tracked vehicle ELF, which consists of two main tracks and four subtracks. It is equipped with a total of eleven mounted actuators that give it a high degree of traversability on weak and uneven terrains.

I. INTRODUCTION

To prevent volcanic damage from spreading, it is very important to observe the affected area. During a volcanically active period, though, people are prohibited from setting foot in the restricted area, which is typically defined as being within several kilometers of the crater. Therefore, to observe a volcanic activity, a **robotic remote observation system** would be quite useful, and it is particularly urgent for a country with a high degree of volcanic activity, such as Japan.

In response to this need, our research group has promoted the research and development of volcanic observation robots, and has conducted a number of field experiments with a tracked vehicle designed for rescue operations, called Quince [1], and with a tracked vehicle designed for exploring volcanic areas, called TrackWalker [2]. Fig. 1 shows a photograph of the Quince tracked vehicle traversing a hill in an uphill direction. In the tests we conducted, we confirmed that these robots demonstrated better mobility performance than other conventional tracked vehicles because they had additional actuators, i.e., subtracks. At the same time, we discovered two major problems with these vehicles in such a challenging environment.

One problem was the difficulty of traversing a weak slope. A tracked vehicle typically generates downhill sideslip on such a slope, and it sometimes changes direction against the operator's will. In a field test on Mt. Koasama, Quince could not traverse a weak-30°-slope straightly, which forced the operator to repeatedly change the robot's direction.

The other problem involved the vehicle's "digging in" on a weak upslope. If the tracked vehicles begin to lose traction while climbing up such a slope, grousers that are attached to the tracks dig into the ground. This increases the apparent angle of the slope that the robot senses, until it finally gets stuck.

To address the above problems, we developed a novel design for a tracked vehicle, called **ELF**, which we intended would demonstrate a high degree of traversability on weak and uneven terrains. ELF essentially consists of two main tracks and four subtracks. It is equipped with a total of eleven degrees of freedom. Two of its actuators are for locomotion, two are for changing the configuration of each subtrack, and one is a slide joint between the two main tracks. These actuators enable the robot to assume various configurations and give it the potential to display increased traversability

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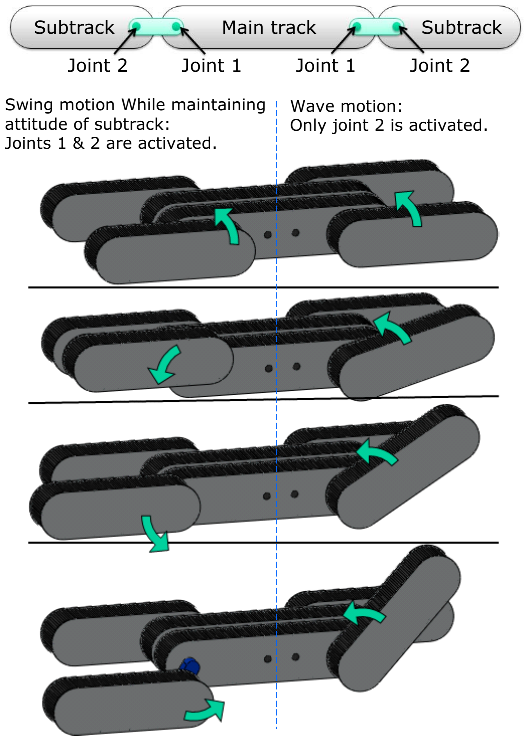

Fig. 3. Illustration of subtrack mechanism. Each subtrack is connected to the main track by a link that has two actuated joints. The link connection endows the subtracks with dexterous motion ability.

on weak and rough terrains. Fig. 2 shows an overview of the robot; the mechanism and the controller of the robot are introduced in Section II.

To traverse a weak slope, we propose one configuration of the robot, in which the surface of the contact plane at the bottom of the track is horizontal, not parallel to the slope surface. This advantageous configuration enables it to traverse a weak slope, and the effectiveness of this configuration was confirmed by a number of experimental results. This confirmation, which is the main topic of this paper, is presented in Section III.

II. Development of multi-D.O.F. tracked vehicle

A. Mechanisms

The novel design of the tracked vehicle ELF consists of two main tracks and four subtracks. The vehicle is slightly larger than the Quince robot (see Fig. 1) because its total length is a maximum of 1490 mm (its length changes according to the configuration of the subtracks). The specifications of the robot are listed in Table I. Each subtrack is connected to one of the main tracks by a link that has two actuated joints at both edges. The rotation of one joint permits only a wave motion of the subtrack, and the synchronized rotation of two joints permits a swinging motion of the subtrack, while maintaining its attitude. Therefore, the robot has eight degrees of freedom that enable it to form various configurations of subtracks. Fig. 3 shows a graphical illustration of the motion of the subtracks.

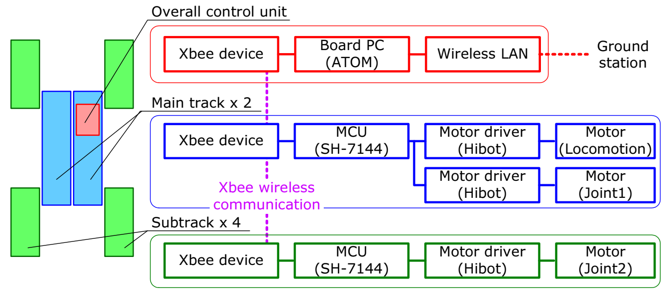

Fig. 4. Configuration of ELF's controller. It consists of two main track modules, four subtrack modules, and one overall control unit mounted on one of the main tracks.

Each main track has a locomotion actuator, and the power source of each subtrack's locomotion is transferred from one of the main tracks via a synchronous belt. In addition, one slide joint is mounted between the two main tracks.

The robot has a total of eleven degrees of freedom, which is the origin of the name ELF, which means "eleven" in German. The surface of the track is equipped with flat grousers with heights of 5 cm that are set at 12 cm intervals, to improve ELF's traversability on weak ground.

B. Configuration of controller

In this mechanism, each subtrack joint can be rotated in unlimited directions, which makes it difficult to concentrate the power source and control functions in a single module, electrically. Therefore, in this robot, each track contains batteries (IDX), a microcontroller (SH-7144), and a wireless communication device (Xbee). The motion of the entire robot is created by the coordinated motion of the main tracks and subtracks, which are commanded by the overall control unit (PC-ATOM board) located at the top of the main track and by communication with a ground station via wireless LAN. In case of simple experiments, the control unit is removed from the robot, and a standard laptop PC with Xbee device commands each track via the Xbee wireless communication, directly. Fig.4 shows the basic configuration of the ELF's controller.

C. Related works on other mechanisms

There have been a number of research projects involving volcano exploration using mobile robots. The most famous of

TABLE I

Specifications of ELF.

Entire body	
Size (L × W × H)	max 1490 × 630 × 236 mm
Weight	48.0 kg
Main track	
Size (L × W × H)	669 × 120 × 136 mm
Sprocket axis distance	533 mm
Weight	10.8 kg
Subtrack	
Size (L × W × H)	452 × 120 × 136 mm
Sprocket axis distance	330 mm
Weight	6.6 kg

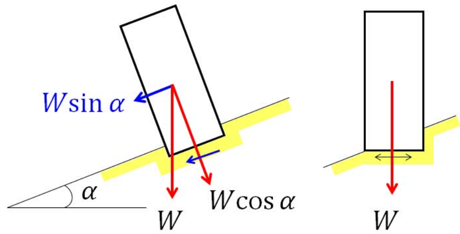

Fig. 5. Reducing sideslip based on configuration of contact surface. The figure on the left-hand side shows the normal contact configuration, whose contact surface is parallel to the slope. The figure on the right-hand side shows a horizontal contact configuration.

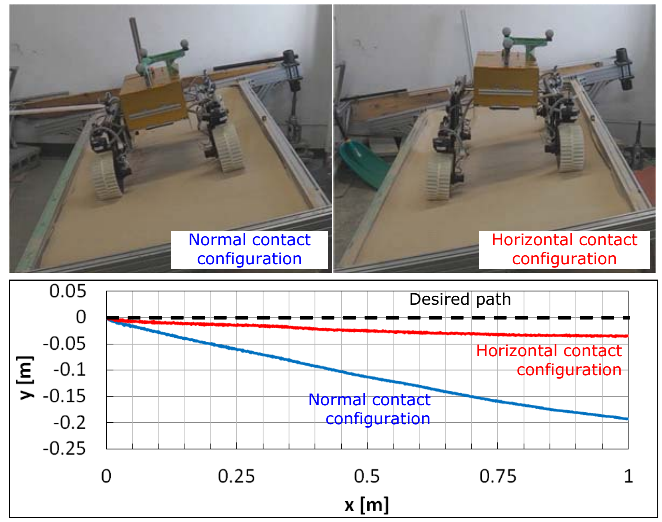

Fig. 6. Experimental results of traversing a slope by wheeled mobile robot. The photographs on top show the experimental set-up, and the graph below presents a comparison between different configurations of the robot.

these exploration robots was “Dante,” a legged-mechanism that proved its reliability in exploring several volcanic fields. A legged mechanism, however, has the disadvantage of slowness. To improve the locomotion speed of legged mechanisms, leg-wheel locomotion mechanisms have been proposed [3] [4]; these are hybrid systems that improve locomotion by changing the locomotion mode according to the environment. Another approach to traversing rough terrain is track mechanisms. To improve traversability, sub-track mechanisms have also been proposed [1] [5], and in this regard, our group proposed a surface-contact-type locomotion mechanism called TrackWalker, which offers an improved locomotion ability on weak soil [2]. The mechanism proposed in this paper is a type of improved version of the TrackWalker. Recently, Prof. Hirose’s group developed a track-changeable quadruped walking robot [6]. This is another approach to increasing a robot’s locomotion ability, but it is apparently difficult to realize equalization of the load distribution of the tracks on weak soil.

III. Improved traversability on weak slope for multi-D.O.F. tracked vehicle

A. Sideslip reduction method

To traverse a weak slope, one of the greatest challenges is downhill sideslip. To reduce this slip, To reduce this slip, Prof. Wettergreen suggested that the posture of the robot should be controlled to remain vertical with respect to gravity [7]. In our research group, we confirmed this suggestion empirically using our wheeled mobile robot and proposed a mechanical model of sideslip based on terramechanics theory [8]. It can be intuitively understood that the horizontal contact configuration shown in Fig. 5 (on the right-hand side) has less sideslip than the normal contact configuration (on the left-hand side), whose contact surface is parallel to the slope. The reason for this is that in the configuration on the left, there is no constraint of the contact plane along the surface of the slope, whereas there is such a constraint in the configuration on the left.

Fig. 6 shows the results of a simple indoor experiment that employed different contact configurations of the wheeled mobile robot. The blue line shows the trajectory of the robot in the normal contact configuration, and the red line shows its trajectory in the horizontal contact configuration. The results verified that the contact plane should be set horizontally when traversing a weak slope.

In this research, we applied the above idea to our multi-D.O.F. tracked vehicle. As mentioned earlier, the proposed robot has the capability of swinging its subtracks while maintaining its attitude. It also has a slide joint between the main tracks. As a result, the configuration of the tracks can be changed to adapt to the target slope angle, while maintaining the horizontality of the contact surface of the track. Fig. 7 shows an example of a slope traversal configuration of ELF, which can navigate on slopes with angles of up to 25°.

B. Field experiment

To confirm the above idea, we conducted a field experiment with ELF, shown in the previous section. The target environment was a slope on Mt. Kushigata, on the island of Izu-Oshima, in Japan. The surface of the slope was covered with weak soil, which is called scoria. The slope angle was about 30°. The velocities of both tracks were controlled at 12 cm/s, and the navigation distance was 10 m. We tested two configurations of the subtracks: the normal contact configuration, whose contact surface is parallel to the slope, and the proposed configuration, whose contact surface is horizontal. Three trials were conducted using the same configuration, and the robot’s trajectory was recorded by the surveying equipment, Total Station, GPT-8200, produced by TOPCON Co. Ltd.

C. Discussion of field experiment

Fig. 8 is photograph that shows a composite of experimental scenes that are superimposed upon one another. In the photograph, it is obvious that in case of the normal contact configuration, the robot generated a higher degree of sideslip than it did with the horizontal contact configuration. Fig. 9 shows a 3D graph of the trajectories of the robot, which shows the same tendency for each configuration. At a point

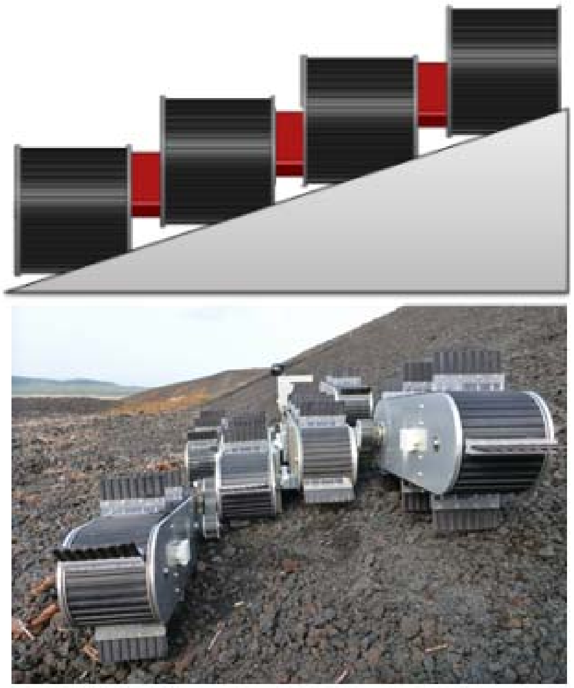

Fig. 7. Slope traversal configuration of ELF. The upper figure shows a front-view conceptual diagram of ELF in a horizontal contact configuration on a slope. The lower figure is a photograph of ELF in the same configuration.

7 m from the starting point, the error was 2.7 m in case of the normal contact configuration, and this error was reduced by 58% in the horizontal contact configuration.

However, the error ratio was still high in the case of the proposed configuration. To confirm the reason for this high ratio, we plotted the direction of the robot's movement at every location, as shown in Fig. 10. In this graph, the lateral axis indicates the x position of the robot, and the longitudinal axis indicates the direction of the robot's movement, which is defined as follows:

$$\tan^{-1}(\frac{dy}{dx}) \tag{1}$$

where dx denotes the velocity toward the x axis, and dy the velocity toward the y axis. We would note that the direction of movement is not the same as the slip angle, as defined in equation (4), because there is no guarantee that sideslip always generates the dy.

As shown in this graph, in the case of the horizontal contact configuration, shown in blue colors, the direction of movement converged at around -15°. We presumed that sideslip stopped when the orientation of the robot became -15°. On the other hand, in the case of the normal contact configuration, shown in red colors, the direction of the robot could change in a downhill direction at any time. It thus appears that sideslip occurred continuously.

D. Additional orientation controller

According to the results of the field experiment, the error ratio was still high in the case of the proposed configuration of the robot because there was no function to adjust the robot's orientation. To address this problem, an orientation controller should be added for the traversal motion. Such control can be realized by creating a gap in the locomotion velocities of both main tracks. The left and right track velocities, v_l and v_r, are set using the following:

$$v_l = v + c\psi \tag{2}$$
$$v_r = v - c\psi, \tag{3}$$

where v denotes the reference velocity, c is the coefficient value, and ψ is the yaw angle obtained by the IMU (MPU6050, Invensense.)

E. Indoor experiment

To confirm the effectiveness of such a controller, the best environment would have been the same field as was shown in Section III-B. However, it was difficult to organize multiple field tests there. Therefore, we conducted an indoor experiment in a simulated volcanic field. The field was 3 m in length and 1 m in width, and it was filled with pumice stones whose bulk density was less than that found in actual volcanic fields. Thus, from the point of view of weak ground, this field presented a greater challenge for a robot than actual volcanic fields. Fig. 11 shows an overview of the field.

In this experiment, we changed the slope angle from 5° to 30° at 5° intervals. For each slope angle, two configurations of the robot-normal contact and horizontal contact-were examined, and three trials were conducted using the

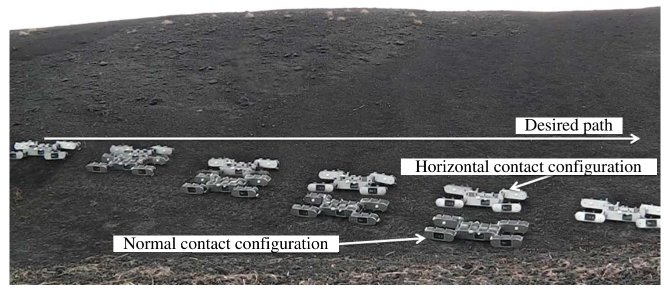

Fig. 8. Composite photograph of superimposed experimental scenes. The starting point was located to the left of the scene, and the desired direction was set in a lateral direction.

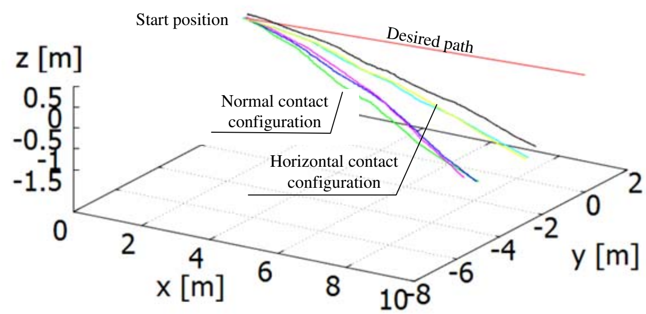

Fig. 9. 3D graph of the field experimental results.

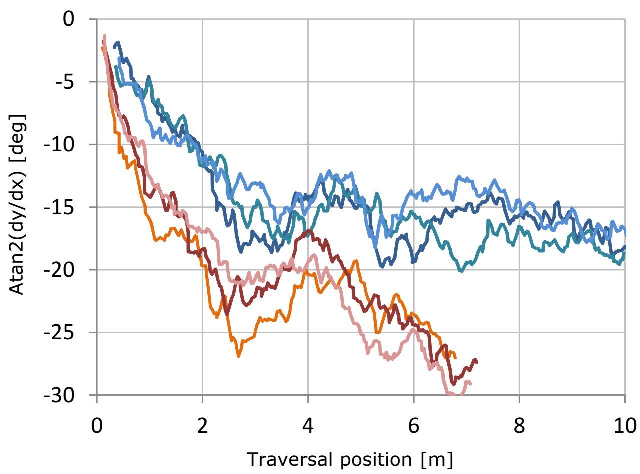

Fig. 10. Graph showing directions of movement of ELF.

Fig. 11. Simulated volcanic field covered with pumice stones. The slope angle can be changed manually using a shovel.

same configuration. Because the field was not wide enough, we applied the main tracks only, in this experiment. The locomotion velocity was set at 8 cm/s.

To evaluate the tracked vehicle's traversability on a weak slope, we adopted the slip angle evaluation given in [9]. The definition of this angle is the angle between the desired trajectory and the actual trajectory, and the slip angle β is defined by the following equation:

$$\beta = \tan^{-1} \frac{v_y}{v_x} \tag{4}$$

where v_x denotes the locomotion velocity of the robot and v_y denotes the sideslip velocity. This equation indicates that the smaller β is, the better the slope's traversability.

Fig. 12 shows the relationship between the slope angles and slip angles for the different configurations of the robot. As seen in the figure, in both configurations, the slip angle shows a growing monotonic trend with an increase in the slope angle. However, the slip angle in the horizontal contact configuration was less than half of the angle in the normal

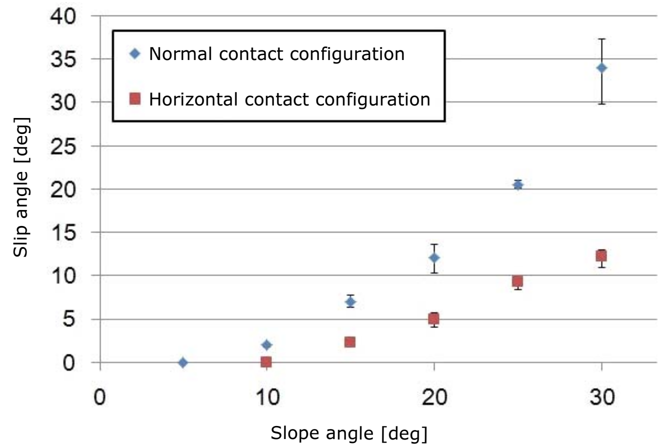

Fig. 12. Graph showing relationship between slope angles and slip angles.

configuration. Furthermore, in the case that the slope angle was 10°, a small degree of sideslip occurred in the normal contact configuration, but no sideslip was observed in the horizontal configuration.

Furthermore, a significant phenomenon was observed in the case that the slope angle was 30° in the case of the normal contact configuration, namely that the robot slipped rapidly in a downhill direction. The reason for this is that the downhill-side track was sunk into the ground, while the uphill-side track was running idle. In this situation, the robot dug into the ground on the downhill side and could not change the robot's orientation. Figure 13 (left) shows a photograph of the experiment. In the case of the horizontal contact configuration, however, such a situation was never observed. Figure 13 (right) shows stable traversal of the field.

Through the experiment, we concluded that the horizontal contact configuration offers an advantage in traversing a weak slope, and that the orientation controller contributes to the suppression of the robot's trajectory in a downhill direction.

IV. Conclusions and Future Works

In this paper, we introduced a novel multi-D.O.F. tracked vehicle, called ELF. The vehicle has eleven actuators that enable it to change its configuration for traversing weak and rough terrains in volcanic environments. One of the advantages of the robot is its high traversability on weak slopes, which can be achieved by changing the horizontal contact configuration. In this research, we confirmed the usefulness of this configuration in a number of experiments. The results of a field experiment showed that downhill sideslip was effectively suppressed, but that there was a need for the robot to be equipped with orientation control to realize straight traversal on a slope. In an indoor experiment we confirmed the advantages of both the horizontal contact configuration and the orientation control.

In this research, we confirmed only one advantage of the ELF, namely slope traversal. This one capability, though, has a hidden potential to make possible the traversal over many

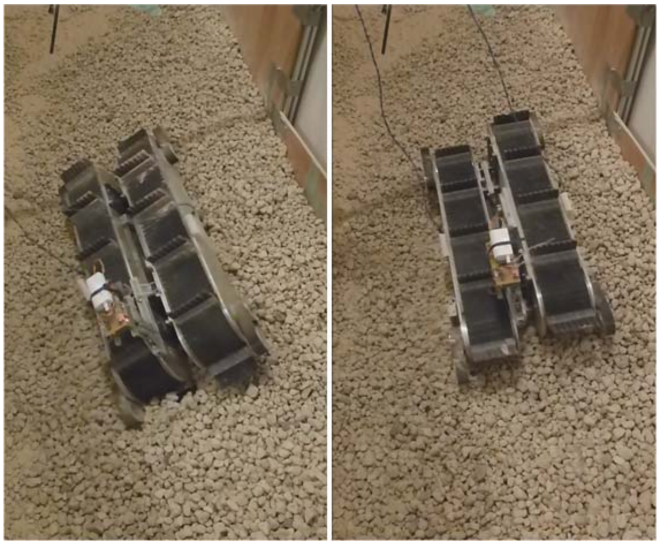

Fig. 13. Photographs of indoor experiment with slope angle of 30°. Robot in the normal contact configuration (left), and in the horizontal contact configuration (right).

types of terrains. Our future works include the realization of traversal on bumpy and weak ground. In such cases, the distribution of the vertical loads of the tracks needs to be uniform along the surface of the ground, which would require motions that have not yet been realized in conventional tracked vehicles, such as Quince. Finally, we would like to confirm the realization of such functions in volcanic fields.

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