Tethered dual-wheeled robot for exploration of volcanic fumaroles on steep slopes

Keiji Nagatani and Masaki Momii

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Abstract The observation of volcanoes is critical in the estimation of volcanic activities and disaster prevention. Volcanic gas from fumaroles is an effective target for these observations. This is because the gas is highly mobile and quickly transmits underground information to the surface. However, as typical volcanic gas is high temperature and contains toxic chemical components, the manned observation of volcanic fumaroles is dangerous. Therefore, in this research, the authors propose an improved version of the dual-wheeled robot to obtain volcanic information from around fumaroles. This robot has a passive tether-guide module to improve its turning range on a slope, which enables the robot to change its traversal direction independent of the tether direction; thus, it has improved turning motion, diagonal traversal motion, and crossing motion on a steep slope. Indoor and field experiments proved the validity of these mechanisms. The lessons learned from these field experiments are also discussed.

1 Introduction

Japan is a volcanic country with 111 active volcanoes, which is about 7% of all the active volcanoes in the world. Volcanic eruptions cause serious damage to surrounding environments and societies, and consideration to evacuation methods based on eruption levels is essential. The Japan Meteorological Agency has designated 50 out of 111 active volcanoes as constantly observed volcanoes that require a thorough monitoring and observation system for volcano disaster prevention. In these volcanoes, volcano observation facilities, such as seismographs, inclinometers, air

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vibrometers, GNSS observation devices, surveillance cameras have been installed to capture the precursors of the eruption and appropriately issue eruption alerts. Such monitoring is conducted 24 hours a day.

On the other hand, periodic manned volcano observation is also performed by the Meteorological Agency and academic institutions. Volcanic gas is highly mobile and quickly transmits underground (magma) information to the surface. Therefore, analysis of the chemical composition and measurement of the emission amount of the volcanic gas can act as clues that reveal the status of the magma and volcano. However, because volcanic gas is typically of high temperature and contains toxic chemical components, the manned observation of volcanic fumaroles is dangerous. Therefore, the development of a robot that substitutes humans for the performance of these tasks is expected. Additionally, some fumaroles exist in depressions and steep slopes, thus, it is difficult for typical wheeled robots and tracked vehicles to reach them. Therefore, in the ex-research, the authors' group has developed a lightweight four-wheeled mobile robot with a tether to investigate volcanic fumaroles on steep slopes [1]. The robot performed well on steep slope traversal using a tether. However, in field tests in volcanic environments, the robot occasionally tipped over. As a result, it has been found that the operation of such robots in real volcanic environments is difficult. Robots, for this purpose, are required to have more reliable and robust locomotion while maintaining their lightness. In this research, to meet the above requirements, a steep-slope mobile robot is proposed for the investigation of fumaroles. Additionally, experimental results in volcanic fields proved the advantages of the proposed robot.

2 Related work

In related works, tethered mobile robots have been used to traverse a steep slope. Dante and Dante II, developed by Carnegie Mellon University, were early tethered robots aimed at moving in extreme environments with eight legs. In 1994, Dante II succeeded in surveying the crater of a snow-covered volcano [2]. TRESSA, made by NASA JPL, was a four-wheeled mobile robot that used two tethers and achieved more stable traversability than one using a single tether [3]. However, some problems were reported. Because two tethers were used, contact between the tethers occurred on the slope, which caused unstable motion of the robot. Furthermore, the tether encountered the ground and wore out because a tether pulling device was not built into the robot. Axel rover, also developed by NASA JPL, was a dual-wheeled mobile robot with a built-in tether traction device that performed excellently when it was made to traverse rough slopes. [4]. Furthermore, DuAxel rover system, which connected two Axel rovers serially, was a tethered robot system that did not require the installation of anchors. Instead, one Axel rover acted as an anchor for the other rover.

However, because the direction of the rover was restricted by tether pulling, the authors conclude that the turning motion on a slope was difficult, and that its moving range was limited. The system of Moonraker and Tetris, developed by Yoshida's lab, were based on the same concept [5].

VolcanoBot, developed by NASA JPL, was a tether-traction type dual-wheeled mobile robot for mapping craters. The robot could be controlled by teleoperation using the connected tether, and succeeded in observing the insides of crater crevices that humans cannot enter. TReX, developed by the University of Toronto, was a tethered four-wheeled mobile robot aimed at mapping steep slope environments [6]. Because this robot could arbitrarily change its traversal direction independent of its tether direction, it had a wider range of movement on the slope in comparison to other robots, such as legged or dual-wheeled robots. However, because the number of wheels is more than that for others, the wheels' diameter should be smaller than other robots, and its traversability on rough terrain tends to be reduced.

In this study, the authors focus on mechanisms of dual-wheeled robots, such as Axel rovers, to retain traversability on rough terrains.

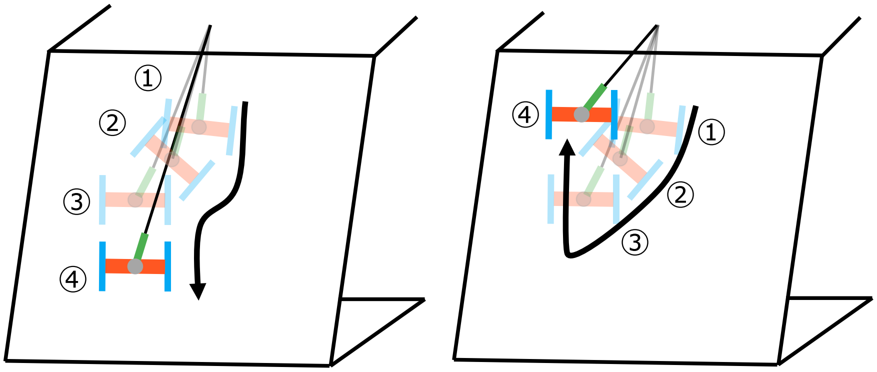
3 System design of a steep slope traversal robot

3.1 Proposal of passive tether guide module

This research focuses on the dual-wheeled robot. It has better traversal performance than others because it can mount large wheels. One problem is that its steering performance is limited on a slope. In this research, the authors propose an improved version of the dual-wheeled robot to solve this problem. A feature of this robot is that it has a passive tether-guide module to extend its turning range on a slope. The module, which includes a tether guide and tether traction mechanism, is connected passively to the robot. This improves its turning motion, diagonal traversal motion, and crossing motion on a slope, as shown in Fig. 1. Additionally, as shown in Fig.2, the proposed mechanism exhibits good turning motion performance when compared to a four-wheeled robot (TReX), and it traverses rough terrain with performance similar to that of a single-tether dual-wheeled robot (Axel). In the following subsections, the proposed steep slope traversal method and development of a prototype are discussed.

3.2 Steep slope traversal method

When a robot moves to an arbitrary goal point on a slope, it is necessary to extend its tether length, while keeping its front directed at the goal point and simultaneously rotating its wheels so that it does not slip. To realize this motion, it is necessary to coordinate the control of the wheels and the tether traction mechanism. If the wheel rotation does not match the tether delivery, the robot may slip and tip over, causing



(a) Traversing / diagonal motion (b) Traversing motion

Fig. 1 Method using tether guide rotation mechanism

failure to reach the goal position. In addition, both mechanisms may provide a large load to each other, and the robot itself may be damaged. In this research, to satisfy the above requirement, speed control is applied to the tether traction mechanism, and torque control is applied to the driving wheels. By generating a constant tension T_{bias} from the driving wheels to the tether tension, the wheels rotate while maintaining tether tension when the tether is put in and out. Thus, coordinated control of both the wheels and the tether traction mechanism is realized. In addition, to realize stable steering control of the robot on rough terrains, the control amount T_{diff}, calculated by PD controller for azimuth angle is introduced. By using T_{bias} and T_{diff}, the reference torque of the wheels (T_R, T_L) are determined using the following equations:

$$T_R = T_{bias} + T_{diff} \tag{1}$$

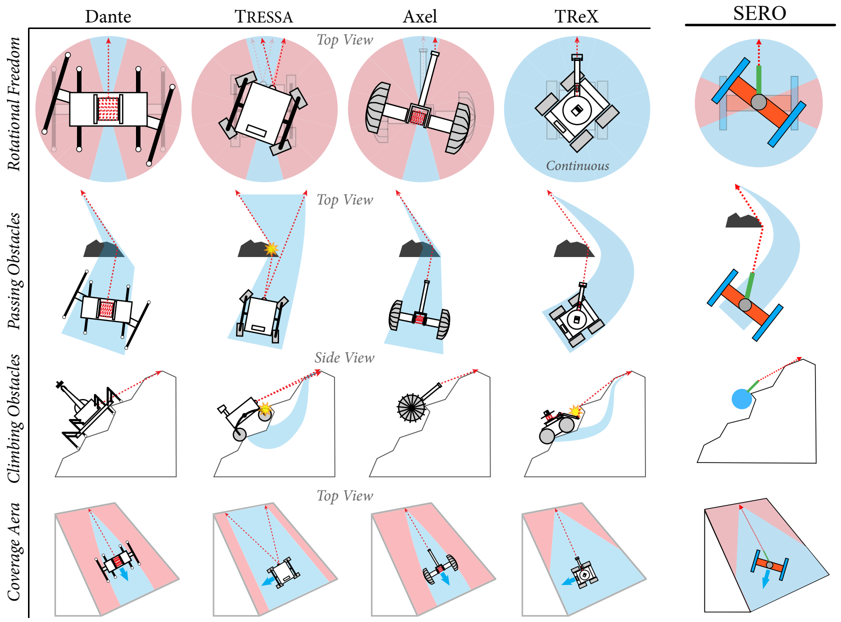
$$T_L = T_{bias} - T_{diff}, \tag{2}$$

where

$$T_{diff} = K_p e(t) + K_d \frac{de(t)}{dt} \tag{3}$$

$$e(t) = \psi_{measured} - \psi_{target}. \tag{4}$$

(See Fig.3 also.)



(a) Conventional tethered mobile robots

(b) Tethered dual-wheel mobile robot with a passive tether guide module.

Fig. 2 Comparison among tethered mobile robots. The (a) part is quoted from the literature [7], and the (b) part is the authors' proposal.

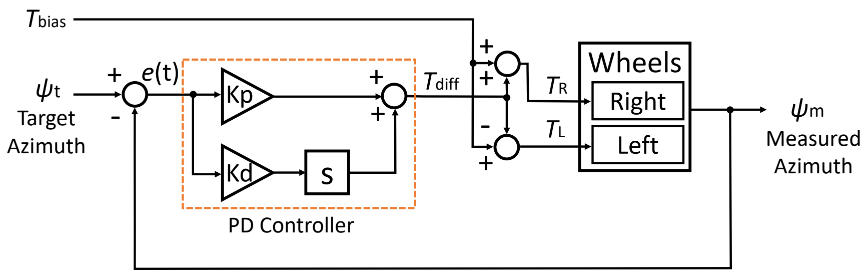


Fig. 3 Wheel torque controller

3.3 Development of Steep slope Exploration RObot with dual Wheels

Based on the previous sub-sections, the authors developed a prototype of the dual-wheeled robot for steep slope traversal, called Steep slope Exploration RObot with

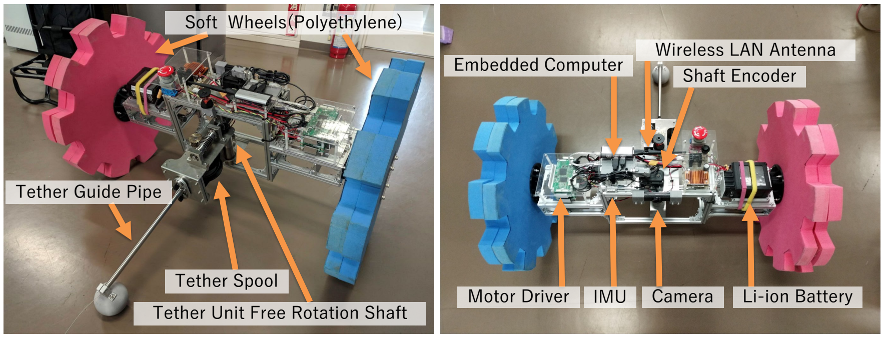


Fig. 4 An overview of SEROW

dual Wheels (SEROW), as shown in Figs.4 and 5. The specification of the robot is presented in Table 1. The tether-guide module includes a winch mechanism. By connecting the module to the body via bearings, free rotation of the module is realized. The guide module can rotate ±50°, and the winch is integrated into the module. The total length of the tether is 20 m. Additionally, the winch drives the tether through a worm gear. With the self-locking function of the worm mechanism, when the motor of the robot is not driven, it can keep its position on the slope without consuming electric power.

Soft wheels made of polyethylene with a diameter of 500 mm and width of 60 mm are used as for the robot to enhance its traversability on rough terrain. Each wheel also mounts ten grousers whose depths are 50 mm each. In addition, by designing the distance between its tires to be wider than the shoulder width of a typical human, it is easy to carry in a backpack. The robot weighs a total of 13 kg and is light enough for humans to carry across long distances.

Table 1 System Specifications

Dimension	750 x 830 x 500 mm (L x W x H)
Mass	13 kg
Power	Li-ion 23.1V 5.5Ah
Computer	Raspberry Pi 3 B
IMU	MPU9250 (RT-USB-9axisIMU2)
Motor Driver	T-frog TF-2MD3-R6
Wheel Motor	Maxon DCX26L GB KL18V
Winch Motor	Maxon DCX32L GB KL 18V
Tether	ϕ1mm 30m SUS304

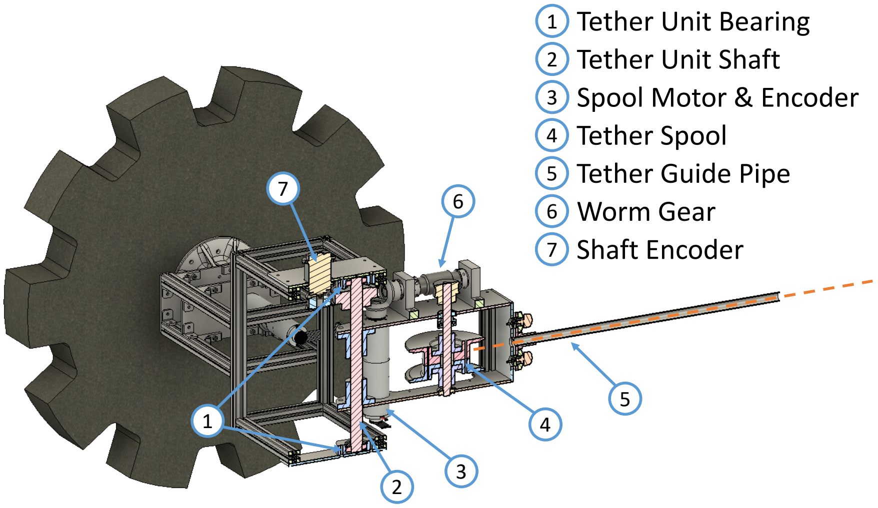


Fig. 5 Cut view of SEROW

3.4 *Evaluation of the passive tether-guide module*

An evaluation test was conducted to confirm whether the tethered dual-wheeled mobile robot improved its turning capability on steep slopes with the use of its passive tether-guide module. For this test, simulated slopes made of veneers with variable inclination were used. The tether was fixed to the upper part of the slope via a pulley. To evaluate the usefulness of the passive tether-guide module, two conditions were set: (1) the module was fixed and, (2) the module moved passively. The experimental procedure of the test is as following:

1. Set the robot horizontally on the slope,
2. Apply reverse torque to the right and left wheels, and then measure the turning angle of the robot, continuously.
3. Increase the torque until the wheels slip occurs.
4. Conduct each measurement test and increase the slope angle from 20° to 80° in 20° increments.

3.5 *Results of the experimental test*

Table 2 presents the comparison result based on the presence of the passive module. Additionally, Fig. 6 shows the experimental scenes for the case when the slope angle is 60° and absolute value of the torque is 15 Nm. From the results, it is seen that when the passive tether-guide module is a passive connection, the robot turns more

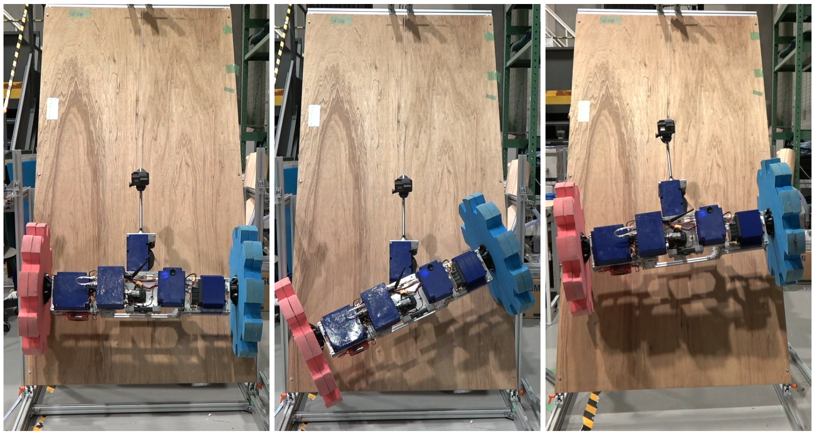

(a) Initial pose (b) The module was in passive (c) The module was fixed.

Fig. 6 Experimental scenes based on the presence of the passive module when the slope angle is 60° and absolute value of the wheel torque is 15 Nm.

than 40° in all tests. On the other hand, when the tether guide module was fixed to the robot, it did not succeed in achieving a turning motion over 40°. Furthermore, the maximum turning angle decreased with an increase in the slope inclination. Based on the above, it was confirmed that the passive tether-guide module improves the turning capability of the robot on steep slopes.

4 Field experiments

4.1 Steep slope traversal

To evaluate the traversal performance of the robot on steep slopes, field experiments were conducted on 6 different kinds of slopes, as shown in Fig. 7. In these field

Table 2 Comparison result based on the presence of the passive module.

Slope angle [°]	Maximum steering angle [°]	
	Passive module	Fixed module
20	over 40	33.1
40	over 40	14.4
60	over 40	8.4
80	over 40	4.5

Some plants and gravels
(5cm maximum) are on the slope

Huge rocks are on the slope

Lower half is pyroclastic flow deposit,
upper half is sediment deposited

Pyroclastic flow deposit

Scoria

Scoria, huge rocks, gravels

Fig. 7 Target fields

experiments, the robot was made to go up and down different steep slopes and we checked whether it succeeded or not.

The procedure for all field experiments is as follows.

1. First, an anchor is installed at the top of the slope, and the end of the tether is fixed with a carabiner.
2. The operator controls the robot from a position where the robot can be visually recognized.

3. The operator descends the robot to the deepest part of the slope while avoiding obstacles on the slope.
4. The operator ascends the robot to the initial position.

The test environment and test results for each field are presented in Table 3. The results indicate that the robot succeeded in traversing all slopes. However, for a small number of cases, a failure of wireless communication may have occurred, resulting in situations where the robot could not be controlled. Failures in Exp.3 and Exp.6, as seen in Table3, were caused by the failure of wireless communication.

4.2 Experiment of observation scenario

In the Izu-Oshima field, a scenario experiment, the simulated investigation of a volcanic fumarole, was conducted. The target field includes some volcanic fumaroles, thus, some sensors, such as a gas detection sensor and temperature sensor, were mounted on the robot to obtain environmental information through teleoperation. The sensors mounted on the robot are shown in Fig.8.

As a result of the experiment, the robot successfully approached the vicinity of the fumarolic pores, as shown in Fig.9. Unfortunately, it failed to directly measure the gas through its gas-sensor.

4.3 Lessons learned

In this section, the lessons learned from the field experiment are discussed.

1. Portability: For this experiment, one of the authors carried the robot and other experimental materials, which totaled to over 20 kg. The elevation difference was 100 m and total distance was 4 km. The total weight should be reduced in actual surveys. Additionally, the proposed robot has a shape in which a tether guide pipe protrudes significantly from the robot body; therefore, it is dangerous for a person to carry it. Hence, such projections need to be designed to be easily removable, and SEROW has such a design.

Table 3 Field experiments

	Location	Date	Average angle of slope [°]	Number of successes / attempts
Exp.1	Asama-Yama	Oct. 2018	30	3/3
Exp.2	Asama-Yama	Oct. 2018	30	2/2
Exp.3	Asama-Yama	Oct. 2018	70	2/3
Exp.4	Asama-Yama	Oct. 2018	70	3/3
Exp.5	Izu-Oshima	Nov. 2018	40-70	2/2
Exp.6	Izu-Oshima	Nov. 2018	40-70	2/3

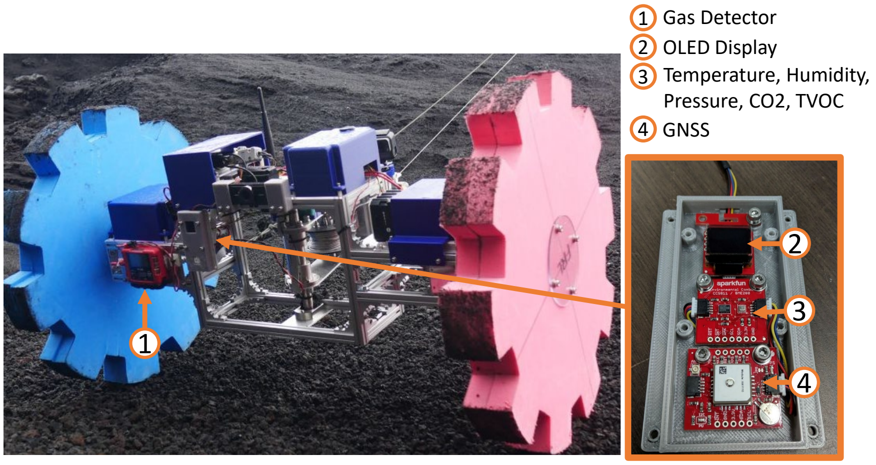


Fig. 8 Sensor configuration on the target robot

2. Tether: There was no breakage of the tether throughout the experiment. However, there was some damage. Particularly, the tether near the anchor was strongly rubbed on the ground and sometimes damaged. Soils in volcanic environments are often sharp and prone to damaging the tether. Therefore, the resistance to cutting is as important as the load capacity when selecting a tether.
3. Communication: In some tests, communication failure occurred because the wireless LAN access point was installed in the wrong position. As a result, it was necessary to manually retrieve robots that could not be maneuvered on the slope in the middle of testing. To prevent such problems, for a tethered robot, communication speed and stability can be improved by using the tether itself as a wired communication cable. In the current implementation, however, the metal tether was used to make it thin as much as possible. In addition, it requires to prepare a device that forcibly winds up the tether and recovers the robot if it becomes impossible to maneuver.
4. Controllability: In all experiments, the operator maneuvered the robot from a position where the robot could be seen directly. This was because it was difficult to maneuver with a wide-angle camera (view angle 120°) mounted in front of the robot. However, for actual operations, this problem must be solved because it is necessary to operate in a state where the robot cannot be seen. For example, laser-range-sensor-based mapping, a camera system installed at the end of the telescopic rod, or video streaming captured from an unmanned aerial vehicle are considered.
5. Passive tether-guide module: One of the features of the SEROW's mechanism is a passive tether-guide module. It enables the improvement of turning motion of the tethered robot. Actually, in the experiment 6, observation scenario, the robot finally approached to the vicinity of the fumarolic pores as shown in Fig.10. It

(a) 0 sec.
(b) 70 sec.
(c) 140 sec.
(d) 210 sec.
(e) 280 sec.
(f) 350 sec.

Fig. 9 Experimental scene of observation scenario

was required to go up and down to move horizontally, as shown in Fig.1-(b). In case that it had no passive joint, it never succeeded in such a motion. On the other hand, it was thought that the passive joint might hind the traversal motion, particularly simple returning motion on the horizontal ground. Actually, in the beginning, one actuator was mounted at the passive joint part to fix it in case of unnecessary of passiveness. Practically, when the robot traced to the returning path straightly, the tether was always rewound, the passive joint was streight, and it never hind the desired motion. Finally, the actuator to fix the passive joint was never activated in these experiments.

6. Gas measurement: In the final test, the developed robot successfully approached the fumaroles. However, because the sensor location was not optimized, it failed to directly measure the gas. To complete gas measurement, an additional manipulation mechanism to insert the sensor head into the fumaroles may be required.

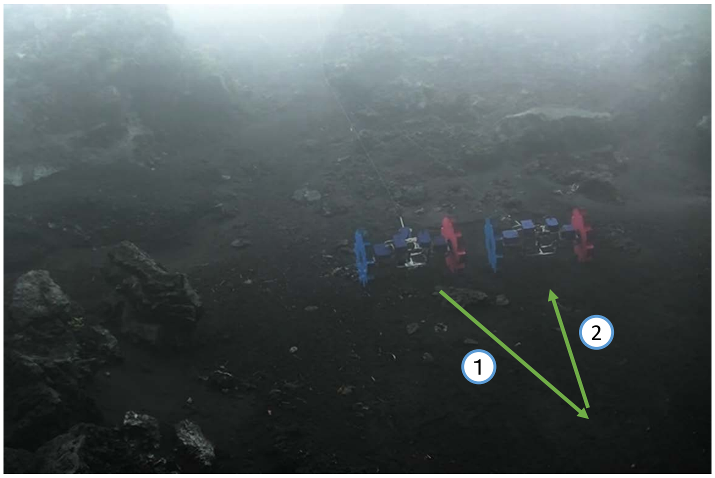


Fig. 10 Down-and-up-motion to move the robot horizontally. It proved the effectiveness of the Passive tether-guide module in a real environment.

5 Conclusions

This study aimed to develop a lightweight mobile robot for the safe investigation of volcanic fumaroles located on steep slopes. To realize the above objective, a novel dual-wheeled tethered mobile robot was proposed, which was mounted with a tether-guide rotation mechanism to enable steering motion on a steep slope. It also enabled us to change the traversal direction of the robot independent of its tether direction, which made it possible to achieve turning motion, diagonal traversal motion, and crossing motion on a steep slope. Field experiments in real volcanic environments confirmed the validity and limitations of the proposed robot. The robot can traverse up to 70° slope composed of pyroclastic flow deposits, sediment deposits, or scoria. Additionally, it can conduct a survey of volcanic fumaroles by mounting sensors. In case the wireless communication between the robot and operator PC becomes unstable due to the cliff shield on the steep slope, control of the robot also becomes unstable. Therefore, a more stable communication system is required.

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