Design and Development of a Tethered Mobile Robot to Traverse on Steep Slope based on an Analysis of its Slippage and Turnover

Keiji Nagatani[1], So Tatano[2], Keisuke Ikeda[2], Atsushi Watanabe[2], and Miwa Kuri[3]

***Abstract*— Observations of fumaroles are important in forecasting volcanic eruptions. However, such observations are dangerous for humans because of volcanic gases and high-temperature steam that surround fumaroles. In previous study, a teleoperated mobile robot was developed to realize remote observations. However, it was observed that typical mobile robots were unable to reach fumaroles on a steep cliff. Therefore, extant research focused on the development of tethered small mobile robots to tackle thsese types of challenging cliffs to observe fumaroles. This study proposes a design of a tethered mobile robot to traverse a steep slope based on the analysis of slip and turnover. A few indoor experimental studies and field experiment were performed to verify the proposed design.**

I. INTRODUCTION

It is important to accurately grasp the status of a volcano to prevent disasters caused by volcanic eruptions. Therefore, regular on-site investigations are performed in the case of volcanoes that necessitate vigilance. An important surveillance tool involves measuring gas concentration and temperature in the fumaroles to obtain information directly related to understanding the behavior of magma and water vapor in the mountains [1] [2]. Therefore, this information is indispensable for predicting eruptions. However, investigators currently perform manual surveillance. This is dangerous for humans due to the potential of inhaling toxic gases and burns caused by hot fumarolic gases. Therefore, remote surveillance is desirable from an investigation safety viewpoint.

An extant study focused on volcano surveillance around the world [3] and developed a teleoperated small-sized mobile robot to realize remote surveillance by robotic technology. In November 2015, the authors conducted the first experiment on Mt. Mihara in Izu Oshima island. The test confirmed that the small-sized robot contributed to remote surveillance with respect to fumaroles. However, a few fumaroles existed on large cliff as shown in Figure1. The robot was unable to approach the fumaroles due to the tough terrain. Thus, it is necessary to construct a new robot with traversability on steep slopes to realize remote surveillance on steep cliffs.

A typical mobile robot turns over while traveling on a steep slope. Therefore, a tethered robot pulling from the top of the slope was adopted to prevent turnover. Mechanical analysis and indoor tests using a real machine were conducted to model the tethered robot. Based on the results, suitable tether tension was examined to prevent turnover and slips. Additionally, a tension-adjusting-mechanism was implemented on the robot to traverse variations in the slope. Finally, a field test of the robot was conducted in a volcanic environment.

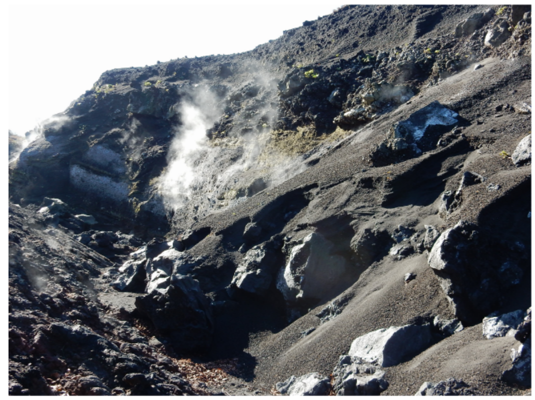

Fig. 1. Fumaroles on a cliff in Mt. Mihara in Izu Oshima island.

This study involved the modeling of a robot based on a mechanical analysis, designing a tethered robot, and reporting field experiment results.

II. RELATED WORKS

A related study used traversal methods with tether traction to achieve steep slope movement. Representative examples of tethered robots include Titan XI [4] developed by Tokyo Institute of Technology, Dante and Dante II [5] [6] developed by Carnegie Mellon University, and Cliff-bot [7], TRESSA [8], and Axel Rover [9] developed by a research group at NASA JPL.

Titan XI is a four legged tethered walking robot that maintains continuous walking with a sufficient stability margin to avoid ferroconcrete reinforcement frames covering steep slopes. Dante and Dante II are also legged mobile robots that use tether traction. The Dante II successfully performed the real exploration of volcanoes (Mt. Spurr, Alaska) in 1994, and obtained high-temperature fumarole gas samples. However, these types of legged robots typically become large and heavy, and thus it is impossible to manually transport them to the mountains. Therefore, a legged robot is unsuitable for the purposes of the current study.

TRESSA is a four wheel mobile robot that is towed by two tethers. A key feature of this robot is the presence of two tethers to realize high stability on a steep slope. Based on

[1]New Industry Creation Hatchery Center, Tohoku University, 6-6-10, Aramaki-Aoba, Aoba-ku, Sendai, 980-8579, Japan

[2]The graduate school of engineering, Tohoku University, 6-6-10, Aramaki-Aoba, Aoba-ku, Sendai, 980-8579, Japan

[3]International Research Institute of Disaster Science, Tohoku University, 468-1, Aramaki-Aoba, Aoba-ku, Sendai, 980-0845, Japan

the mechanism, the robot successfully traverses steep slopes and is used to scientifically investigate fjord topography. However, the configuration of the robot is complicated since the robot uses two tethers, and the installation of the robot is time consuming. Furthermore, a target volcanic environment is typically half-pipe shape because of gully erosion, and two tethers system are not effective.

Axel Rover is a two-wheel mobile robot that uses tether traction. This simple robot demonstrated high traversal performance in steep cliff environments. However, its locomotion is composed of two wheels, and this leads to difficulties in turning and crossing motions on a slope. The purpose of the present study involves precisely approaching a target hole, and thus the fore-mentioned mechanism is unsuitable.

A compact robot with a lightweight airframe that can be manually carried with ease in a mountain is required to conduct a fumarolic hole survey on a steep slope of a volcano. Additionally, the robot should be easy to install. However, it was difficult to meet the fore-mentioned requirements in previous studies.

Hence, the target robot used in the present study is a four wheeled single tethered robot that can turn and cross a steep slope. Furthermore, the adoption of a single tether can reduce the size and weight of the system.

III. SLOPE TRAVERSAL OF MOBILE ROBOTS WITH A TETHER

A. The Proposed Method

Robots can turn over and slip in a volcanic environment. This is because the environment consists of weak soil or gravel and typically involves a steep slope. A mobile robot can explore a wider range of volcanoes by overcoming the dual problems of turnover and slippage.

In order to ensure that the robot is stationary on a slope, it is necessary to counteract the effect of gravity that acts to induce slippage and turnover on a slope. A tether can be attached to the robot to induce tether tension that forces gravity inducing slippage and turnover and amplifies the ground contact force with respect to the slope. This allows the robot to remain on and traverse a steep slope.

However, there is a paucity of studies that focus on tether tension control by considering turnover and slippage of a tether robot. Therefore, in this study, single tether tension control is discussed by considering the turnover and slippage of a four wheel mobile robot "CLOVER" [10] to realize transversing of a slope.

Figure 2 shows a compact 4-wheel mobile robot that is termed as "Tethered CLOVER", which mounts a pillar for tether fixing. A stand is installed on the upper part of the pillar to mount a weight to change its center of gravity. A mechanical analysis and experiments are performed with the prototype robot to ensure the practical use of this type of a compact robot in volcanic environments. The weight of the robot corresponds to 4 kg with respect to manual transport, and the size is shown in Figure 2.

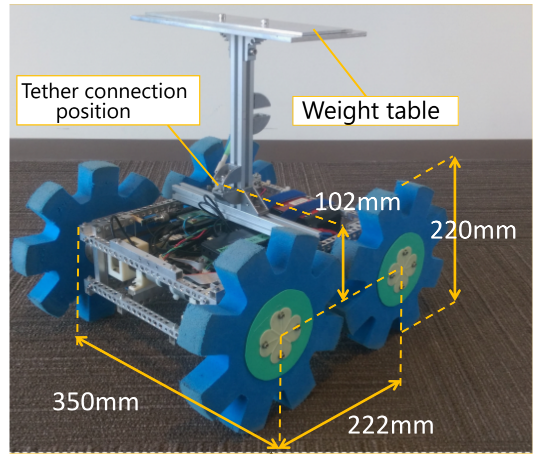

Fig. 2. Tethered CLOVER

B. Mechanical Analysis

Tether tension applied to a robot can prevent slippage and turnover on a slope. The value of the tether tension corresponds to the lower limit value to prevent slippage and turnover, and conversely the upper limit value of the tether tension causes the fore-mentioned phenomena. Therefore, the suitable range for the tether tension is initially calculated from the mechanical analysis of the modeled mobile robot.

The motion of a robot on the slope can be classified into the following three types: climbing or descending slope, crossing, and turning. For purposes of simplicity, two-dimensional climbing or descending slope motion is modeled and analyzed in the study.

C. Introduction of Climbing/descending Model

A vertical climbing/descending model of the robot is shown in Figure 3. The robot's weight corresponds to M, and the slope angle corresponds to θ. The tether fixed at the top of the slope applies a tension T to the robot with an angle θ_T.

The normal forces from the ground correspond to R_1 for the rear wheel and R_2 for the front wheel. The speed of the robot is assumed as sufficiently slow, and thus the inertia force due to acceleration can be ignored. The motion of the robot is influenced by the maximum value of the force F that is caused by driving force of the wheel.

The midpoint of the front and rear wheel axes corresponds to the origin. With respect to the dimensions of the robot, the horizontal and vertical directions of the coordinates are represented by w_i and h_i, respectively, and the subscript i denotes the size of each part. The midpoint of the front and rear wheel axes corresponds to the origin.

The sizes in the horizontal and vertical directions are represented by w_i and h_i, respectively, and the suffix i represents a type of robot size. Based on the notation, (w_G, h_G) represents the center of gravity, $(\pm w_r, h_r)$ represent wheel ground points, and (-w_l, h_l) represents tether fixation.

In the following calculations, traversal direction of the robot corresponds to the x axis, and the direction perpendicular to the slope corresponds to the z axis.

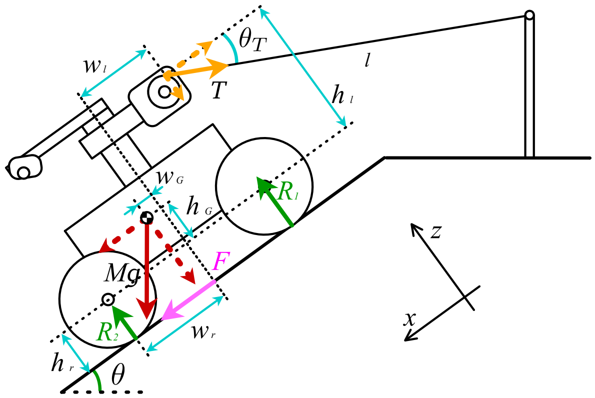

Fig. 3. Vertical Climbing/descending Model

D. Analysis in the Stationary State

Initially, the balance of force applied to the robot is considered with respect to the stationary state as follows:

$$x \quad direction: \ |Mg\sin\theta - T\cos\theta_T| = \mu(R_1 + R_2) \quad (1)$$

$$z \quad direction: \ Mg\cos\theta + T\sin\theta_T = R_1 + R_2, \quad (2)$$

where μ denotes the static friction coefficient with the ground. The tether tension works to cancel gravity in direction x and to amplify gravity in direction z.

1) Tether Tension to Prevent Slippage: The power balance in the x axis collapses when the robot slips on the slope. The equation of power balance for T is organized, and the upper and lower limit values of the tether tension T_{Slip} to prevent slip are represented as follows:

$$T_{\text{Slip max}} = \frac{\sin\theta + \mu\cos\theta}{\cos\theta_T - \mu\sin\theta_T} Mg \quad (3)$$

$$T_{\text{Slip min}} = \frac{\sin\theta - \mu\cos\theta}{\cos\theta_T + \mu\sin\theta_T} Mg, \quad (4)$$

where $T_{\text{S}_\text{m}\text{ax}}$ and $T_{\text{S}_\text{m}\text{in}}$ denote the upper limits and lower limits, respectively of tether tension to prevent slippage, and μ denotes the coefficient of static friction.

2) Tether Tension to Prevent Turnover: A wheel detaches from the surface when the robot begins turning over on the slope, and the normal force of the wheels becomes zero. The rear wheel rises in a case in which the tether tension is low, and R_1 becomes zero. Conversely, the front wheel rises in a case in which the tether tension is high , and R_2 becomes zero.

The fore-mentioned conditions are assigned to the balance condition of robot's moment, and thus the upper and lower limits of tether tension T_{Fall} to prevent turnover can be expressed as follows:

$$T_{\text{F\_max}} = \frac{(h_r + h_G)\sin\theta + (w_r + w_G)\cos\theta}{(w_l - w_r)\sin\theta_T + (h_r + h_l)\cos\theta_T} Mg \quad (5)$$

$$T_{\text{F}_\text{m}\text{in}} = \frac{(h_r + h_G)\sin\theta + (-w_r + w_G)\cos\theta}{(w_l + w_r)\sin\theta_T + (h_r + h_l)\cos\theta_T} Mg, \quad (6)$$

where $T_{\text{F}_\text{m}\text{ax}}$ and $T_{\text{F}_\text{m}\text{in}}$ denote the upper limits and lower limits, respectively, of tether tension to prevent turnover.

E. Analysis with Respect to Considering Movement

The above discussion of tether tension discussion corresponds to the stationary state of the robot. When the robot moves on the slope, the wheel traction applies a driving force to the ground, and the forwarding force F acts on the robot as a reaction force. The F corresponds to the force derived from the friction force. Therefore, F_{max}, which corresponds to the maximum value of F, is assumed as proportional to the contact force F_z as follows:

$$F_{\text{max}} = \mu f_z. \quad (7)$$

The moment force caused by F_{max} leads to a change in the suitable range of the tether tension to prevent turnover when the robot moves. In the cases of both climbing and descending, the range can be calculated as follows:

$$T_{\text{FD\_max}} = \frac{(h_r + h_G)\sin\theta + (w_r - \mu z_G + w_G)\cos\theta}{(w_l - w_r + \mu z_G)\sin\theta_T + (h_r + h_l)\cos\theta_T} Mg, \quad (8)$$

$$T_{\text{FD\_min}} = \frac{(h_r + h_G)\sin\theta + (-w_r - \mu z_G + w_G)\cos\theta}{(w_l + w_r + \mu z_G)\sin\theta_T + (h_r + h_l)\cos\theta_T} Mg, \quad (9)$$

$$T_{\text{FU\_max}} = \frac{(h_r + h_G)\sin\theta + (w_r + \mu z_G + w_G)\cos\theta}{(w_l - w_r - \mu z_G)\sin\theta_T + (h_r + h_l)\cos\theta_T} Mg, \quad (10)$$

$$T_{\text{FU\_min}} = \frac{(h_r + h_G)\sin\theta + (-w_r + \mu z_G + w_G)\cos\theta}{(w_l + w_r - \mu z_G)\sin\theta_T + (h_r + h_l)\cos\theta_T} Mg, \quad (11)$$

where $T_{FD\_max/min}$ denotes maximum/minimum tether tension in the case in which the robot moves downward, and $T_{FU\_max/min}$ denotes maximum/minimum tether tension in the case in which the robot moves upward.

IV. MODEL-BASED ROBOT DESIGN

A. Stability Evaluation of the Tethered Robot

The stability of the tethered robot can be evaluated based on the suitable range of the tether tension derived in the previous section.

Figures 4-6 show the relationship between the slope angle and the suitable tether tension range. In each graph, the blue region represents a suitable tether tension range that does not cause slippage. In this study, this region is termed as a "stable zone to prevent slippage". The upper limit $T_{\text{S\_max}}$ and lower limit $T_{\text{S\_min}}$ are calculated based on equations (3) and (4), respectively. The red region in Figure 4 represents a suitable tether tension range that does not cause turnover when the robot does not move. The upper limit $T_{\text{F\_max}}$ and lower limit $T_{\text{F\_min}}$ are calculated by equations (5) and (6), respectively. The red region in Figure 5 represents a suitable tether tension range that does not cause turnover when the robot moves upward. The upper limit $T_{\text{FU\_max}}$ and lower limit $T_{\text{FU\_min}}$ are calculated by equations (10) and (11), respectively. Figure 6 represents a suitable tether tension range that does not generate turnover when the robot moves downward. The upper limit $T_{\text{FD\_max}}$ and lower limits $T_{\text{FD\_min}}$ are calculated by equations (8) and (9), respectively. In this study, the red regions are termed as a "stable zone to prevent turnover". The robot parameters shown in Figure 2 are used in the above calculations. Additionally, the static friction coefficient is set as $\mu = 0.505$. The parameter is

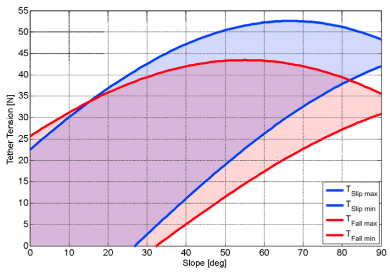

Fig. 4. The relationship between the slope angle and the suitable tether tension range in the case in which the robot remains on the slope.

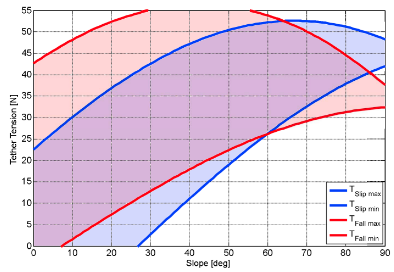

Fig. 5. The relationship between the slope angle and the suitable tether tension range in the case in which the robot moves upwards on the slope.

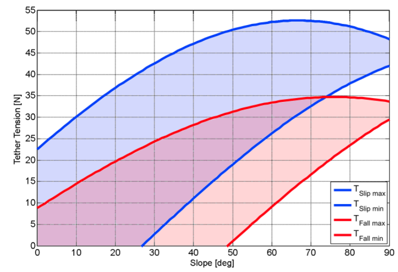

Fig. 6. The relationship between the slope angle and the suitable tether tension range in the case in which the robot moves downwards on the slope.

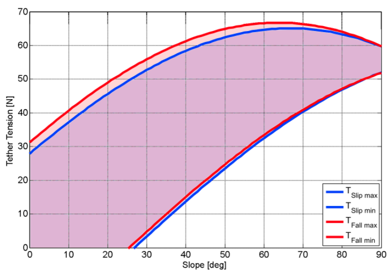

Fig. 7. The relationship between the slope angle and the suitable tether tension range in the case in which the remodeled robot remains on the slope.

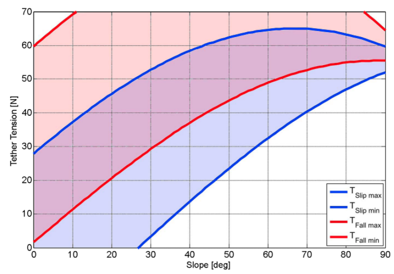

Fig. 8. The relationship between the slope angle and the suitable tether tension range in the case in which the remodeled robot moves upwards on the slope.

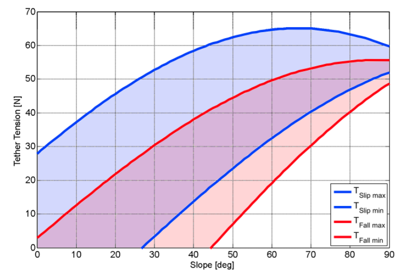

Fig. 9. The relationship between the slope angle and the suitable tether tension range in the case in which the remodeled robot moves downwards on the slope.

measured by an indoor experiment as shown in the next section.

As shown in Figure 4, a tether tension exists to prevent both slippage and turnover up to the slope angle of 80 degrees at which both stable zones overlap. However, as shown in Figure 6, the region in which the stable zones overlap decreases up to 70 degrees when the robot moves downward to the slope. Additionally, as shown in Figure 5, the region in which the stable zones overlap decreases up to 60 degrees in the case in which the robot moves upward to the slope. The fore-mentioned discussions indicate that it is not possible for the robot to remain on extreme slopes such as a slope exceeding 80 degrees.

B. *Robot Design to Increase Stability*

In order to expand a traversal region of the robot, it is necessary for the "stable zone to prevent slippage" to overlap the "stable zone to prevent turnover" in the wide region to the maximum possible extent. The "stable zone to prevent slippage" depends on the weight of the robot.

Conversely, as shown equations (5)-(11), "the stable zone to prevent turnover" depends on the concentrated moment M_T caused by the tether tension. The influence of M_T can be minimized by decreasing the distance between the tether fixing point and the center of gravity. Therefore, 1 kg weight is added to the top of the robot, and the height change of the center of gravity is aligned to the tether fixing point. The calculation results are shown in Figures 7 - 9. Based on the addition of weight to the robot, the overlapping region of stable zones increased significantly, and the tension that can traverse a slope of 90 degrees exists in the case in which the robot moves forward/backward. This implies that the choice of the center of gravity is important for traversal on a steep slope.

V. INDOOR EXPERIMENTS

A. *Experimental Conditions*

A few indoor experiments were conducted with a self-made slope simulator to evaluate the calculation results discussed in the previous section. Figure 10 shows the appearance and dimensions of the simulator. It consists of an angle changeable slope, a tether, and the developed traction apparatus. The traction apparatus can apply any tension to the tether with a torque controlled motor. The apparatus is fixed at the simulator basement. A pulley installed at the slope-top is used to realize the towing simulation of the robot from the cliff-top. The target robot is the same as that in the analysis as shown in Figure 2.

In this experiment, the slope angle is set in the following two conditions: 60 degrees and 80 degrees. Additionally, the robot's weight is set in the following two conditions: normal weight and the case in which 1 kg weight is added to the top of the robot. In the latter condition, the center of gravity of the robot is aligned to the tether fixing point. Slope traversal tests are conducted involving the four cases.

B. *Experiment Results*

The experiment results are summarized in Figure 11. In each graph, the blue and red regions correspond to the

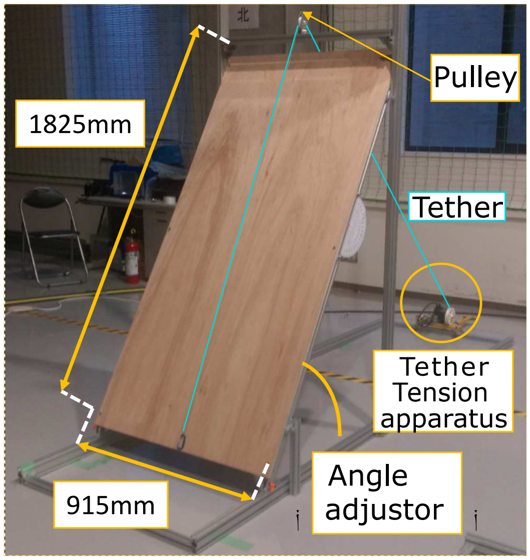

Fig. 10. An overview and dimensions of the slope simulator.

magnified analysis results described in section III. The two top graphs show the results when the robot remains on the slope, the two middle graphs show the results when the robot traverses upwards on the slope, and two bottom graphs show the results when the robot traverses downwards on the slope. The left column shows the normal robot, and the right column shows the robot with 1 kg weight placed on the top of the robot. The black circle is indicated when the robot succeeds in its expected motion. The blue cross is indicated in the case in which the robot slips downwards or upwards. The red cross is indicated in the case in which the robot falls downwards or upwards.

In the case of the normal robot, a suitable tether tension exists at a slope of 60 degrees experimentally. However, in the case of a 80 degrees slope, the robot is unable to move downwards at any tether tension. In the case of the robot with 1 kg weight, a suitable tether tension exists at slopes of both 60 and 80 degrees in the region corresponding to the overlapping of stable zones experimentally. The results indicate that the experimental results are generally consistent with results based on mechanical analysis. Additionally, the experimental results verified that the traversability of the robot improves by aligning the height of the center of gravity to the tether fixing point.

VI. ADAPTIVE TENSION CONTROL

A. Required Parameters for Suitable Tension

In case of steep slopes in natural environments, such as volcanic cliffs, the slope angle changes based on the location. Therefore, in order to maintain the traversal stability of the tethered mobile robot, tether tension should be adjusted based on the location.

The unknown parameters in Figure 3 including slope angle θ, relative tether angle to the robot θ_T, and the coefficient of static friction μ are used to calculate the suitable tether tension. Particularly, μ is very important parameter to prevent

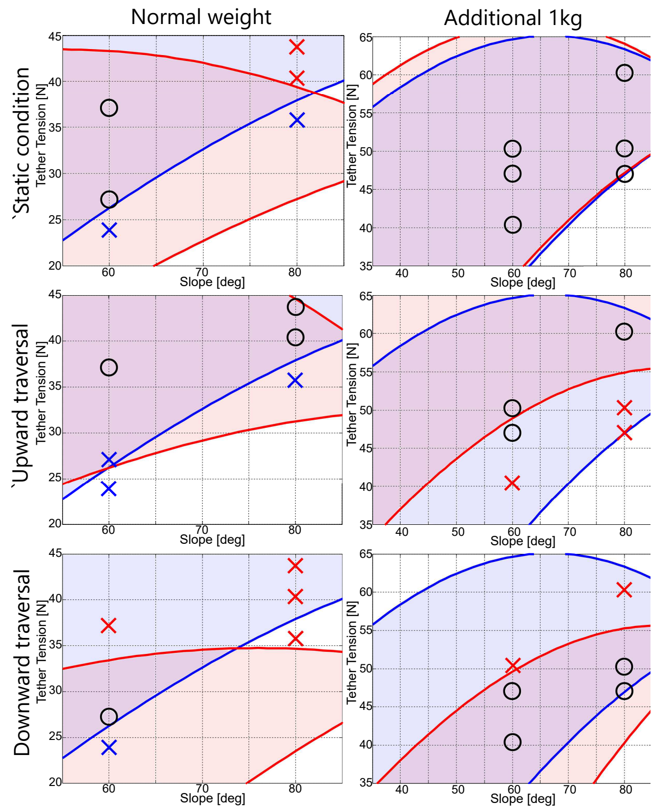

Fig. 11. Experiment results.

the slippage of the robot, and it changes in natural environment. However, it is difficult to measure the μ during movement of the robot. Therefore, μ is determined by referring to premeasured value with a conservative estimation, and online estimation of μ is one of our future works. In order to continuously sense θ and θ_T, the robot is remodeled as described in the following section.

B. Implementation

Figure 12 shows the remodeled tethered CLOVER. The robot mounts IMU (Inertial Measurement Unit: MPU9150, produced by InvenSense) with the Madgwick filter [11] to obtain the slope angle. A potentiometer is installed at the connection part of the tether to obtain the relative tether angle to the robot. The connection part is located at the middle of the connecting shaft between the top part (2.25kg: battery and PC are included) and the robot body (2.24kg: motors and wheels). The tether connection part is higher than the wheel diameter. Thus, the tether can tow the center of gravity without interfering with the wheels. Based on the measured θ and θ_T, the robot calculates the stable range of the tether tension continuously based on the mechanical analysis and sends the suitable tension to the tether traction apparatus via wireless communication. The robot is controlled by a bisual remote control. Furthermore, an optic camera and an infrared camera are mounted in the front region of the robot.

C. Field Experiment

In order to evaluate the remodeled tethered robot, traversal experiments were conducted in November 2016 at a cliff in Mt.Mihara, Izu-Oshima Island. Figure 12 shows an example

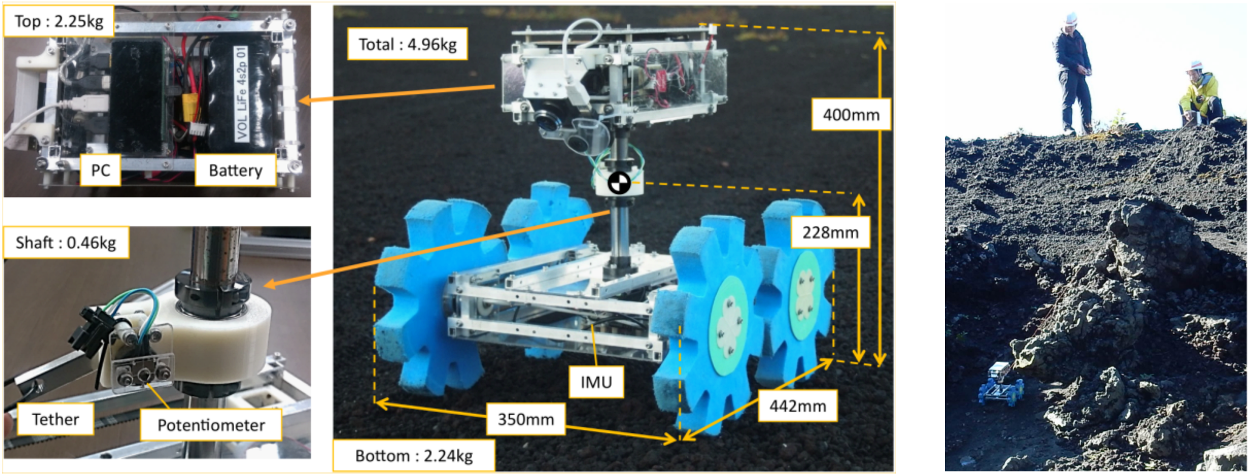

Fig. 12. Remodeled tethered CLOVER and the field experiment.

of an experimental scene on the tough cliff. In the experiments, the robot succeeded in traversing over 80 degrees of slope angle without slippage and turnover. The results indicate that adaptive tension control of the tether is effective for the traversal of tethered robots in natural environments. Additionally, the robot succeeded in measuring temperature in the fumaroles on the cliff by using an infrared camera.

In contrast, the robot is stuck or turns over in a few trials. The cases in which failure is observed include the following:

1) When the robot overcomes a rock or bump on the ground, then the body angle becomes close to 90 degrees. In such cases, the wheel shaves the rock or ground at times, and the ground support collapses. Finally, the robot loses the traction of its wheels.
2) When a wheel rides on a rock, then the robot turns over sideways. The model introduced in the paper did not assume any horizontal (or roll) inclination although horizontal inclinations exist in natural environments.
3) When the robot moves horizontally, a tension is generated diagonally behind the robot, and the robot turns over. The model introduced in the study only considered the lateral direction for purposes of simplicity, and did not consider such horizontal motion of the robot.

In the cases involving failure, the tether is manually extended, and the robot is recovered at the bottom of the cliff. It is necessary to overcome these phenomena for the practical use of tethered robots in these types of challenging environments.

VII. Conclusions

In this study, a tethered robot is designed and developed for remote observations of fumaroles on a steep slope in a volcanic region. A suitable tether tension is analyzed to realize a traversal of the tethered robot on a steep slope, and the validity of the analysis is confirmed by indoor experiments. Finally, an adaptive tether tension controller is installed on the robot, and its usefulness and limitations are confirmed by outdoor experiments.

Remote surveillance by a tethered robot is necessary to ensure the safety of investigators. Additionally, tethered robots can be applied to various fields such as observations of natural disasters. Therefore, it is necessary to realize the robust traversal of a tethered robot on rough and steep slopes at the earliest.

References

[1] Ryunosuke Kazahaya, Yosuke Aoki, and Hiroshi Shinohara. Budget of shallow magma plumbing system at asama volcano, japan, revealed by ground deformation and volcanic gas studies. *Journal of Geophysical Research: Solid Earth*, Vol. 120, No. 5, pp. 2961–2973, 2015.

[2] Gregory P Waite, Patricia A Nadeau, and John J Lyons. Variability in eruption style and associated very long period events at fuego volcano, guatemala. *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 4, pp. 1526–1533, 2013.

[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*, Vol. 30, No. 3, pp. 231–242, 2003.

[4] Ryuichi Hodoshima, Takahiro Doi, Yasushi Fukuda, Shigeo Hirose, Toshihito Okamoto, and Junichi Mori. Development of a quadruped walking robot titan xi for steep slope operation-step over gait to avoid concrete frames on steep slopes. *Journal of Robotics and Mechatronics*, Vol. 19, No. 1, p. 13, 2007.

[5] David Wettergreen, Chuck Thorpe, and Red Whittaker. Exploring mount erebus by walking robot. *Robotics and Autonomous Systems*, Vol. 11, No. 3-4, pp. 171–185, 1993.

[6] J.E.Bares and D.S.Wettergreen. Dante II: technical description, results, and lessons learned. *International Journal of Robotics Research*, Vol. 18, No. 7, pp. 621–649, 1999.

[7] Gale L Paulsen, Shane Farritor, Terry L Huntsberger, and Hrand Aghazarian. All terrain exploration with the cliff-bot system. In *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, pp. 721–726. IEEE, 2005.

[8] Terry Huntsberger, Ashley Stroupe, Hrand Aghazarian, Mike Garrett, Paulo Younse, and Mark Powell. Tressa: Teamed robots for exploration and science on steep areas. *Journal of Field Robotics*, Vol. 24, No. 11-12, pp. 1015–1031, 2007.

[9] Issa AD Nesnas, Jaret B Matthews, Pablo Abad-Manterola, Joel W Burdick, Jeffrey A Edlund, Jack C Morrison, Robert D Peters, Melissa M Tanner, Robert N Miyake, Benjamin S Solish, et al. Axel and duaxel rovers for the sustainable exploration of extreme terrains. *Journal of Field Robotics*, Vol. 29, No. 4, pp. 663–685, 2012.

[10] Keiji Nagatani, Kazunari Akiyama, Genki Yamauchi, Kenta Yoshida, Yasushi Hada, Shin'ichi Yuta, Tetsuya Izu, and Randy Mackay. Development and field test of teleoperated mobile robots for active volcano observation. In *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on*, pp. 1932–1937. IEEE, 2014.

[11] Sebastian OH Madgwick, Andrew JL Harrison, and Ravi Vaidyanathan. Estimation of imu and marg orientation using a gradient descent algorithm. In *Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on*, pp. 1–7. IEEE, 2011.