2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 25-29, 2020, Las Vegas, NV, USA (Virtual)

Development of a Steep Slope Mobile Robot with Propulsion Adhesion *

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***Abstract*— A mobile robot that can achieve a stable attitude and locomotion on steep slopes is needed to overcome the problems of slipping and falling for automation of works on steep slopes. The conventional approaches to achieve a stable attitude and locomotion have been researched by adopting tracked wheels and multi-legged mechanisms instead of wheel mechanisms. However, these robots have limitations in term of application angles. A systematic theory for stable attitude and locomotion on steep slopes has not been established. Therefore, research on control strategies for wheeled mobile robots on steep slopes is essential. In this paper, a method to realize a stable attitude and locomotion on a steep slope for the wheeled mobile robot by using propellers for propulsion adhesion is proposed. The proposed robot can generate a large frictional force by pushing its body against the slope with a thrust force. This force prevents the robot from slipping while maneuvering on the slope. The magnitude and the direction of the thrust force is optimized using an appropriate control mechanism influencing the moment of force acting on it to avoid falling and side slipping during locomotion on steep slopes. A simulation experiment was conducted from the perspective of mechanics and dynamics to arrive at an optimal design of the mobile robot. The developed robot has four propellers to generate thrust forces and a rotation axis to control the direction of the generated thrust forces. Evaluation experiments were performed to validate the stability of the robot at a resting position and during lateral locomotion and its ability to climb over a slope. The experimental results confirmed that the proposed robot with propellers realized a steady attitude and locomotion on a slope of up to 90° by controlling the magnitude and the direction of the thrust force.**

I. Introduction

Many researches have focused on automation of work on uneven terrains. Traveling on steep slopes is an important challenge for mobile robots as they have to overcome the problem of slips and falls to function effectively. A study on the control strategy of a mobile robot is hence essential to achieve stable attitude and locomotion on a steep slope. In this study, a method to realize stable attitude and locomotion on a steep slope for a wheeled robot is proposed.

Gehring et al proposed a fundamental control strategy for a four-legged robot to achieve stability of posture on a slope [1]. A robot with six legs was shown to maintain its posture on a slope of up to 55° [2]. This six-legged robot was developed for proposed use in the maintenance of nuclear plants and for rescue during nuclear accidents. Although leg-type mobile robots show good stability on steep slopes, they required a large number of actuators and each of their legs must be controlled separately. Compared to leg-type robots, the robots with wheels and tracks have straightforward structures and control strategies. Mobile robots that use tracked wheels to increase the coefficient of friction with the ground are commonly studied to avoid slips on slopes. To improve stability on a steep slope, a mobile robot with multi tracked wheels was proposed [3]. This robot was developed as a platform for general use on an uneven terrain. It connects three single-tracked robots with a bar linkage. It is effective in stabilization over a slope, but it is limited to a slope angle of less than 35° as the friction coefficient is not determined by the contact area of the wheel. The wheel-track hybrid robot has two moving mechanisms: wheel and tracked wheel [4]. This robot adapts to different dangerous environments by using the wheel on a plane surface with low energy consumption and the tracked wheel on a slope with high stability. However, this robot climbs up to 25° and hence, it needs more improvement. Iwano et al. developed mobile robot with single-tracked wheel and realized movement on a 45° slope [5]. This robot was developed for carrying out grass cutting work on a steep slope. Grass cutting on a steep slope, for agricultural activity in mountainous terrain or side slopes of highways, is a strenuous burden for workers. Their study is remarkable as they evaluated lateral movement on slopes. The problem of side slip occurs during lateral movement on slope was overcome by controlling the wheel speeds on both upslope and downslope of a mountain independently. However, this method only worked on comparatively gentle slope angles of below 45°. At steeper slope angles, the side slip was observed to be large. The study of lateral locomotion on a steep slope is needed to improve the robustness of mobile robots, which carry out works on slopes. Moreover, it is important for work robots on slopes to consider not only side slips but also falls. When installing a robot on steep slope from the beginning and trying to perform locomotion, slipping and falling happen at the same time. Hirose et al. developed the four-legged robot called TITAN VII for the maintenance of sloped structures and grass cutting on side-slope of highways [6]. The robot needs to avoid falling down while carrying out those works and TAITAN VII does so by moving its center of gravity close to the ground, however, it could move up to 30°.

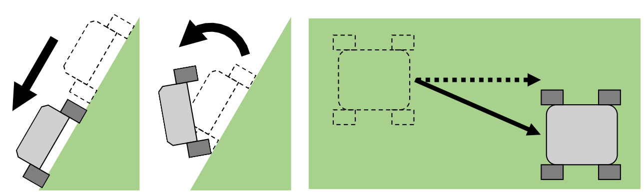

Figure 1 Types of problem faced by mobile robots on a steep slope

* Research supported by JSPS KAKENHI Grant Number 17K00360.

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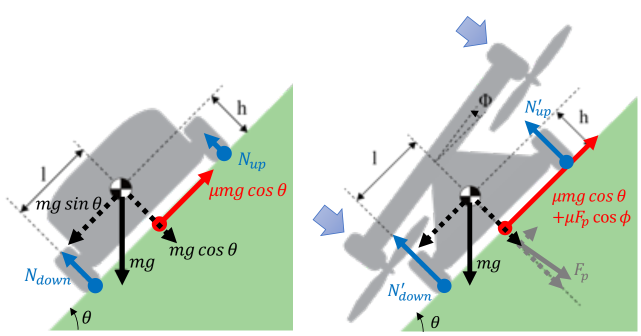
As mentioned above, the improvement of frictional force on steep slopes by focusing only on the friction coefficient, and considering the number of contact points and area is limited. A different approach considering another dimension is necessary. In the field of wall climbing robots, many adhesion methods were proposed such as those using suction [7], magnets [8], gripping equipment [9], biomimetic materials [10], [11], guide rails, and propulsion [12]-[16]. A comparison of these methods suggests that adhesion is limited by the material of the surface. However, the propulsion adhesion method can be applied to all shapes and materials of the surface and it can manage heavier payloads. VertiGo was proposed and developed by Beardsley et al. [12]. This robot presses the wall by the thrust of two propellers and moves on the wall using motor-driven wheels. Similarly, Myeong et al. used the thrust of a quadcopter to press against a wall and realized movement on a wall by using a motor [13]. Ioi et al. developed a robot equipped with a gimbal with two degrees of freedom and a contra-rotating propeller at the center of the robot [14]. The thrust of the propeller mechanism is used as the lift and the body is pressed against the wall to achieve movement on the wall. Alkalla et al. developed a robot that inspects concrete walls with contra-rotating propeller to attachment to the wall and realizes movement on both vertical and curved walls using motor driven wheels [15], [16].

The adhesion by using propulsion is effective for slope robots. However, certain important considerations are required while designing a robot for a steep slope than for vertical ascent: the robot needs to prevent slips, falls, and side slips (Fig. 1). Therefore, the control of robot's propulsion and wheels according to the slope angle is essential as the required outputs are simultaneously changing with the slope angles. The normal forces applied to the wheels on the upslope and downslope sides are significantly different on steep slopes. The ensuing unbalance should be improved for accurate locomotion on steep slopes. Therefore, the development of a slope robot based on modifying conditions of slip, fall, and side slip will enable in realizing applications in s maintenance and grass cutting on a steep slope regardless of the slope angle.

In this paper, the design of a four-wheel mobile robot with four propellers to achieve an attitude that is stable and robust while maneuvering to overcome steep slopes is presented. The contribution of this paper is to reveal the detailed analysis of robot's locomotion along a lateral direction on a steep slope. The design and development of the mobile robot with the ability for lateral movement on steep slopes based on the control of the magnitude and direction of thrust, load balance applied to each wheel, and moment acting on the robot is described. We validate the design based on propulsion adhesion for a mobile robot on a steep slope through simulations and experiments. Stable locomotion without side slips are realized by the developed robot.



(a) Normal robot (b) Proposed robot

Figure 2 Force diagram of mobile robot on slope

II. Proposed Method

This paper describes the design of a mobile robot that maintains a stable attitude without falling or slipping on a steep slope. This is realized by stabilizing the attitude through the thrust of a propeller using a quadcopter. In this section, the normal force, frictional force, moment acting on the mobile robot on the slope, and the torque required for the movement are discussed. The Quadroller combines the functionalities of a quadcopter with a ground mobile robot [17]. The Quadroller has two functions: flying and rolling. The rolling function is moving on ground with passive wheels and inclined propellers' thrust to extend operation time by rolling instead of flying where flight is not necessary. On the other hand, our robot moves with motorized wheels. Furthermore, the propellers are installed upside-down so that the thrust is able to push the robot against the ground to realize robust locomotion. In the proposed method, the thrust of the propeller pushes the robot's body against the slope thereby increasing the normal force and obtaining a large frictional force. The thrust of the propeller acts as an external force to support the mobile robot that falls from steep slopes. Therefore, the proposed robot can maintain a stable attitude without slip or fall even on steep slopes. When a mobile robot moves on a slope, the transmission efficiency of the driving force to the wheels can be improved. In addition, controlling the magnitude and direction of the thrust from the propellers enable the robot to improve the movability.

A. Slips and Falls

The relationship between the frictional force and the downward force acting on the mobile robot and the slope was analyzed. In Fig. 2(a), the case where only gravity acts on a mobile robot on a slope is presented. Assuming that the gravitational acceleration is g , the maximum coefficient of static friction between the ground and the wheels is μ, and the slope angle is θ, the gravity acting on the mobile robot of mass m on the slope can be considered as the downward and the normal forces. The frictional force acting on the robot is proportional to normal force. When the frictional force acting on the mobile robot on the slope is greater than that of the downward force, the mobile robot does not slip. Therefore, the stable conditions in which the mobile robot does not slip on a slope with an angle of θ is as follows:

$$\mu\, mg\cos\theta \geq mg\sin\theta \tag{1}$$

The downward force increases as the slope angle increases, but the normal force decreases. Since the frictional force is proportional to the normal force, the frictional force decreases as the slope becomes larger. Therefore, the mobile robot on the slope does not satisfy Eq. (1) and slipping of the robot occurs.

Moment causes falls of the mobile robot. Let h be the distance from the robot's center of gravity to the ground, l be the horizontal distance from the robot's downslope wheel to the robot's center of gravity, and L be the width of the robot, when the robot on the slope falls it turns around the downslope side wheel. By considering the downslope side wheel as the center of rotation of the moment and that in the clockwise direction is positive, the moment acting on a mobile robot must satisfy the following condition

$$lmg\cos\theta - hmg\sin\theta - LN_{up} \geq 0 \tag{2}$$

where N_{up} is the normal force of the upper wheels, which is the reaction force to the force that presses the robot against the ground. In the case where Eq. (2) is not satisfied, the N_{up} is negative, and then the upper wheels leave the ground and falling occurs. When the mass of the robot is large, the robot can get a large normal force from its mass, but the downward force will increase and hence, maintaining stable attitude is difficult. Further, improvement in the friction coefficient is limited to prevent falls on a steep slope.

In the case of the proposed robot as shown in Fig. 2(b), consider the case where the thrust F_p of the propeller presses the robot's body against a slope with an inclination angle ϕ with respect to the ground. We define that the thrust inclination angle of ϕ is positive when the propeller is tilted toward the valley side. The parameters, h, l and m, are same in both robots in Fig. 2(a) and Fig. 2(b) to compare the two conditions of stability even though these parameters are actually influenced by a robot structure and ϕ in a real situation. Here, the downward force will be reduced with the sine component of F_p and the frictional force will increase because of the cosine component of F_p. Therefore, a stable condition of the proposed robot is written as

$$\mu\,(mg\cos\theta + F_p\cos\phi) \geq mg\sin\theta - F_p\sin\phi \tag{3}$$

From the above equation it can be inferred that the slope angle at which the proposed mobile robot can maintain a stable attitude without slipping is larger than that without using the proposed method. When the thrust force pushes the robot body against the slope with the inclination angle ϕ, the thrust force works for not only increasing the frictional force but also decreasing the downward force that causes the slip of the robot. When ϕ is negative, the thrust force pushes the robot body downward. Therefore, the negative ϕ cannot prevent the slip. Hence, the moment acts on the robot must satisfy

$$\begin{gathered} lmg\cos\theta - hmg\sin\theta \\ -LN'_{up} + lF_p\cos\phi - hF_p\sin\phi \geq 0 \end{gathered} \tag{4}$$

where N'_{up} is the normal force of the upslope-side wheels. Here, when ϕ is 0° to 45° and l is greater than h, it can be said that the proposed robot is more resistant to falling than that designed without the proposed method because the left side of Eq. (4) is larger than that of the left side of Eq. (2). This is because the generated moment that is directed opposite to the falling direction increases owing to the pressing by the thrust force from the propeller. The moment applied to a robot can be increased by moving the center of gravity closer to the ground and toward the mountain side of the slope. Therefore, a robot satisfies the required stability condition against falling. However, the position of the center of gravity depends on the mechanism of the robot. Even if the condition against falling is improved, the stability condition against slip cannot be improved. By using the proposed method, it is possible to prevent slipping and falling at the same time.

B. *Locomotion Ability on Steep Slope*

The normal force applied on the wheels of upslope and downslope sides are different. In a normal robot, the normal forces of the wheels on upslope side and downslope side, N_{up} and N_{down}, are written as

$$N_{up} = \frac{mg}{L}(l\cos\theta - h\sin\theta) \tag{5}$$

$$N_{down} = \frac{mg}{L}(l\cos\theta + h\sin\theta) \tag{6}$$

N_{up} is larger than N_{down}, and the difference is proportional to the slope angle. Consider the driving force and torque of the wheels required for the wheels when the mobile robot moves on a slope: the driving force of the wheels pushes the mobile robot's body forward as a reaction force of the frictional force when the wheels rotate. Since wheels generate the driving force as a reaction force of the frictional force, the upper limit of the driving force is the generated frictional force. When the driving force reaches the limit, a slip occurs between the wheel and the ground, and the wheel spins. This means that even if the wheels of the mobile robot have a torque that outputs a driving force larger than that of the maximum driving force, the driving force cannot be larger than that of the frictional force of wheels of the mobile robot. The normal force on the mountain side is small and hence, the driving force is also small. The wheel of the upslope side tends to slip because of a lack of frictional force. While the driving force of the wheels on the downslope side is larger than that on the upslope side. This unbalance of normal forces causes unstable locomotion on a steep slope. Consider a case where a mobile robot with a propeller presses the robot body on a slope with thrust F_p and an inclination angle ϕ. The normal force on upslope and downslope sides, N'_{up} and N'_{down}, are

$$N'_{up} = N_{up} + \frac{l}{L}F_p\cos\phi + \frac{h}{L}F_p\sin\phi \tag{7}$$

$$N'_{down} = N_{down} + \frac{l}{L}F_p\cos\phi - \frac{h}{L}F_p\sin\phi \tag{8}$$

Therefore, the range of the driving force F'_{up} and F'_{down} that apply to the up and down side of the wheels, respectively; wherein the rolling friction coefficient of the wheels is μ_r, are:

$$\mu_r N'_{up} \leq F'_{up} \leq \mu N'_{up} \tag{9}$$

$$\mu_r N'_{down} \leq F'_{down} \leq \mu N'_{down} \tag{10}$$

The upper limit of the driving force is the generated frictional force and the lower limit is for the mobile robot to start moving on a slope. The normal force of the upslope side, which cause the small driving force, is enlarged by the thrust force. On the other hand, the normal force of the downslope side is also enlarged as it is needed to avoid slips. By appropriately selecting F_p and ϕ, the normal force difference between the upslope and downslope sides can be balanced.

C. *Climbing Up Ability on Steep Slope*

In the case of a normal robot, the range of the driving force F_w that realizes climbing up on a steep slope is as follows:

$$\mu_r mg\cos\theta + mg\sin\theta \leq F_w \leq \mu mg\cos\theta \tag{11}$$

The lower limit is for the mobile robot to climb on a slope with θ. Therefore, in order to improve the moving ability of a mobile robot on a steep slope, it is necessary to improve the performance of the motor and have an approach by considering the friction coefficient and the normal force. Consider a case where a mobile robot with a propeller presses the robot body on a slope with thrust F_p and inclination angle ϕ. The range of the driving force F_w' that can achieve proper locomotion is as follows

$$\mu_r mg\cos\theta + mg\sin\theta - F_p\sin\phi \le F_w' \le \mu mg\cos\theta + \mu F_p\cos\phi \qquad (12)$$

The lower limit of the driving force required to climb the slope is reduced by the thrust F_p with the inclination angle ϕ and the upper limit of the driving force that can be generated by the wheels become larger. Therefore, the proposed robot can move on a steep slope that the ordinary mobile robots cannot move on because of the lack of the driving force.

III. Evaluation with a Simulation

The effectiveness of the proposed method, that uses a propulsion adhesion to stabilize the attitude and movement of a mobile robot is evaluated through a numerical analysis in this section. The mobile robot was designed based on the results of its behavior using simulation. The Bullet Real-Time Physics Simulation [18] and Open Dynamics Engine [19] (open source physics simulation composed of calculation of dynamics and collision detection) and V-REP [20] (a comprehensive development environment) were utilized for robot simulation. The mobile robot consists of five rigid bodies: robot body, drive wheels, propeller base, propellers, and connection part. At the center of the four propellers shown in Fig. 3, a force is evenly applied to vertically to the propeller. The weight of the mobile robot was 1.5 kg, and the center of gravity was at the center of the robot.

A. Maximum Stable Angle

The proposed method can improve the maximum slope angle at which the mobile robot can maintain stability of the attitude. The maximum stable angle is the maximum value of the angle of the slope where the mobile robot does not slip nor fall. The wheels are assumed to be locked in the rotation direction, and hence, the wheel direction was not considered.

When the friction coefficient was increased as in the conventional method, the change in the maximum slope angle at which the robot that could maintain its attitude was observed. The results are shown in Fig. 4. When the friction coefficient was small, the mobile robot slipped. When the friction coefficient exceeded a certain value, the mobile robot fell before the slip occurred, and the maximum slope angle that could maintain the attitude leveled off. Simulations have shown that increasing the friction coefficient is not enough to maintain the attitude of a mobile robot on a steep slope.

Then, the relationship between the magnitude of thrust generated by the proposed mobile robot with a propeller and the maximum slope angle that can maintain the attitude was determined. Fig. 5 shows the maximum slope angles achieved when the thrust of the propeller was changed from 0 N to 20 N in increments of 5.0 N. For this, the inclination angle of the thrust ϕ was 0°, and the mass of the robot was changed from 1.0 kg to 3.0 kg in increments of 0.5 kg. In the simulation, only m was changed not h and l. When the thrust pushes the robot body, the maximum slope angle increases. When the mass of robot increases, the frictional force also should have increased. However, the increasing mass brings no benefit toward maximizing the stable angle when thrust force is 0 N. This is because the downward dragging force also increases at the same time. As Eq. (1), the mass of the robot has no influence on the angle at which slip occurs. In addition, even when the mass of the robot is increased, the maximum slope angle that can maintain the attitude is 90° by appropriately selecting the thrust force. On the other hand, the method to increase mass is not effective in term of maximizing the stable angle. The proposed method exerts a greater beneficial effect not only by increasing the coefficient through the design of the shape of the wheels but also by utilizing the thrust of the propeller to improve stability of the mobile robot on a steep slope.

Finally, the change in the direction of the thrust that affects the attitude of the mobile robot was evaluated. The maximum slope angles were measured when the inclination angle of the thrust was changed from 0° to 45° in increments of 5°. The

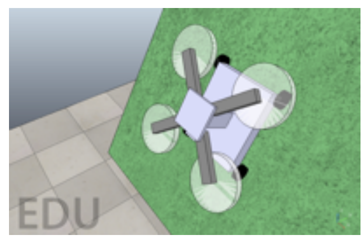


Figure 3 Simulation environment

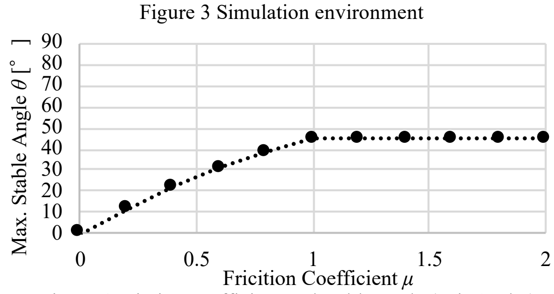


Figure 4 Friction coefficient and stable angle (*m* is 1.5 kg)

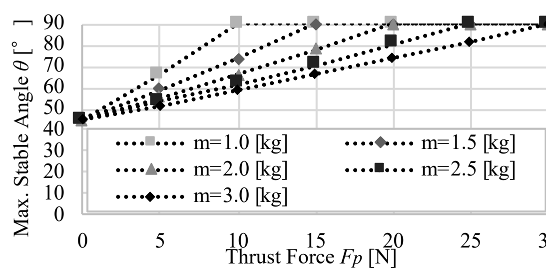


Figure 5 Thrust force and maximum stable angle with the different mass (μ is 1.0)

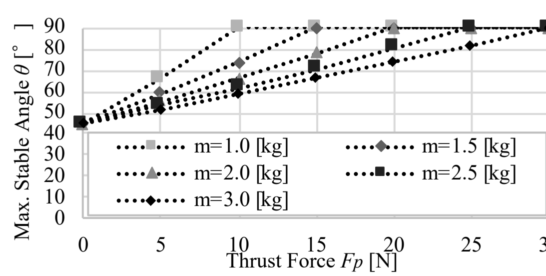


Figure 6 Thrust angle and maximum stable angle with the different thrust force (*m* is 1.5 kg, μ is 1.0)

simulation was performed with thrust magnitudes of 0 N, 10 N, 20 N, and 30 N. Fig. 6 shows the results. When the thrust force is large, the robot can maintain a stable attitude at a slope angle of 90° regardless of the inclination angle of the thrust. When the magnitude of thrust is 10 N and 20 N, the effect of the change in thrust direction on the maximum slope angle is smaller in the case of 10 N when compared to the case of 20 N. It was observed that the change of the angle had a large effect on the maximum slope angle to maintain the attitude.

From these results, it can be said that the direction of the thrust greatly affects the maximum inclination angle that can maintain the posture of the robot. In order to maximize the slope angle, it is necessary to select the appropriate value based on the relationship between the thrust and its direction

B. Climbing Ability

A simulation experiment to evaluate the climbing ability of a mobile robot on a steep slope was conducted. First, the influence of the wheel torque was investigated using torque magnitudes of 0.1 Nm, 0.25 Nm, 0.5 Nm, 0.75 Nm, and 1.0 Nm on the slope with angle from 0° to 90° in increments of 10°. Table I shows the results. When the proposed method was not used, the slope at which the climbing was achieved was up to a maximum of 40°. Increasing the torque is not enough to improve the climbing up ability because the torque transmitted to the ground depends on the frictional force. Therefore, it is necessary to increase the torque as well as the frictional force.

TABLE I. RELATIONSHIP OF WHEEL TORQUE AND CLIMBABLE SLOPE

Torque [Nm]	0.1	0.25	0.5	0.75	1.0
Max. Slope Angle [°]	30	40	40	40	40

TABLE II. RELATIONSHIP OF THRUST FORCE AND CLIMBABLE SLOPE

Thrust Force [N]		0	5	10	15	20
Thrust Angle [°]	0	30	50	60	70	80
Thrust Angle [°]	20	30	60	70	90	90

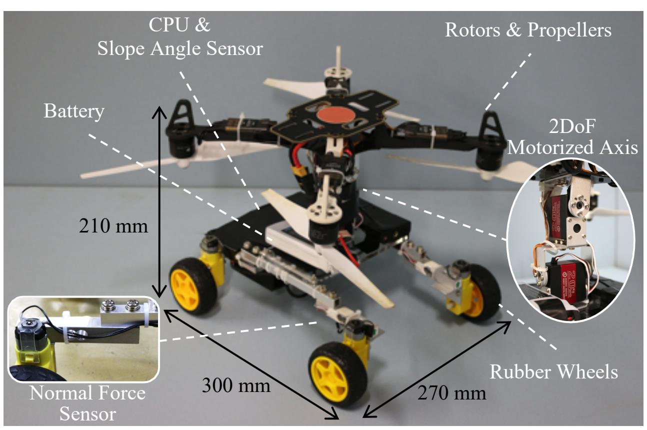


Figure 7 Developed robot

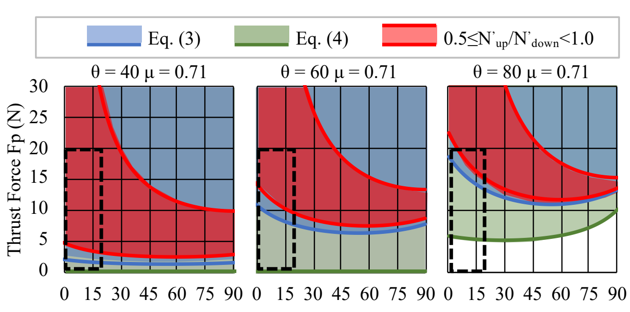


Figure 8 Strategy to derive thrust force and angle

An analysis was conducted to demonstrate whether the climbing ability was improved when the frictional force applied to the wheels of the mobile robot was increased by using the proposed method. The magnitude of thrust was set in 5 N increments from 0 N to 20 N to simulate the slope at which the robot could climb. In this simulation, the wheel torque was maintained at 0.25 Nm, the friction coefficient at 1.0, and the inclination angle of the thrust was fixed at 0° and 20°. Table II shows the results. The thrust force of the propeller caused an increase in the frictional force applied to the wheels causing a large driving force. Thus, the proposed method enable the robot to climb the slope of up to 90° by controlling the direction of the thrust force.

IV. DEVELOPMENT OF ROBOT

A. Developed Robot

This section describes the robot that was developed (Fig. 7) and its control method. A dji E305 2312E motor (960 kv) was used as the propeller mechanism to realize the proposed method. E305 420 Lite ESC manufactured by dji was used as the ESC to control the rotor speed. The frame of the robot was made lighter by using aluminum pipes. A LiPo battery (1800mAh, 11.1V, 150 g) and the control unit were installed in the lower body of the robot because the center of gravity influences the stability against falls. In addition, a DC motor was used for the drive unit. Control of each actuator was performed using Microchip Atmega328p, and an acceleration sensor was used for measuring the slope angle. Four load cells as the normal force sensors were attached to the wheels. In addition, the connection between the propeller and the body of the robot has two degrees of freedom consisting of two servo motors, so that the mobile robot can achieve an arbitrary inclination angle regardless of its attitude on the slope. The thrust of the propeller is controlled by PWM. The size of the mobile robot is 270 mm in width, 210 mm in height, and 300 mm in depth. The weight of robot is 1.55 kg. The robot can generate a maximum thrust force of 20 N. We employed a quadcopter instead of one huge propeller which generate 20 N to ensure that, although it is up to the condition, the robot can avoid a sudden fall when the one of propellers is accidentally damaged and stops as the robot has four propellers. The thrust force can be inclined from -20° to 20° in any directions.

B. Control Strategy

Here, we describe the control method of the propeller when the thrust of the proposed robot presses the slope. As described in Section II, there is a lack of frictional force that is required to maintain the attitude. The required pressure is small on gentle slopes and large on steep slopes. Pressing the robot body against the slope with a constant thrust to generate a constant large frictional force is not a problem while considering only the stability of the attitude on the slope. The target mobile robot is likely to be deployed in an environment where human intervention is difficult. Further, in the likelihood of the robot being driven by a battery minimizing energy consumption comes into focus. Therefore, instead of pressing the slope with a constant thrust, the thrust is controlled according to the lack of frictional force according to the slope angle. The slope angle is measured by the angle sensor mounted on the robot, calculation of the required thrust, change in the rotation speed of the propeller, and control of the thrust force were obtained.

In order to calculate the required thrust force magnitude and inclination, two environmental parameters are required to realize control. The slope angle is measured in real time by the angle sensor mounted on the robot. The friction coefficient is measured in advance. Fig. 8 explains how the values of the thrust force F_p and its inclination angle ϕ are selected in three different slope angles on rubber surface. The green region corresponds to the condition to avoid slips as described in Eq. (3). The blue region is the area that satisfies Eq. (4), which is the condition of no fall. The red region corresponds the thrust force F_p and its inclination angle ϕ realize the ratio of N'_{up} and N'_{down} from Eqs. (7) and (8) satisfies ≥ 0.5 and < 1.0 to balance the driving force of each wheel. The black lines represent the mechanical limitation of the developed robot. Finally, F_p and ϕ are selected from the overlap region of the three regions where the robot can realize stable locomotion.

V. Experiments and Results

The stability of the developed robot on a slope was evaluated. The stabilities of the attitude of the mobile robot when in a resting position and during movement, and its control are presented in this section. The developed robot was evaluated in three different uneven surfaces: on rubber sheets, on concrete surfaces, and on artificial grass. The range of the coefficient of friction is 0.52 to 1.03 to show the fundamental ability of the robot's potential for application. Table III shows the friction coefficient of each surfaces. The experiments were performed on an experimental slope that can produce any slope angle. The researcher wore safety glasses and protective gloves and the robot was equipped with a safety cord with emergency stop switch to prevent sudden dropping for safety.

A. Fundamental Experiment

An experiment to evaluate attitude maintenance of the developed robot against the slope induced by the thrust force of the propellers was conducted. First, the robot was set on the experimental surface. The angle of the surface where the robot was installed was gradually increased from 0° to 90°. When the slope became large, the robot may either slip or fall, making it difficult to maintain the attitude. The maximum slope angle at which the mobile robot does not slip or fall over the slope was measured. The output of the propeller was 0 N and 20 N were maintained during the experiment. In order to evaluate the effect of the thrust inclination angles on attitude maintenance, when the output of the propeller is 20 N, two inclination angles ϕ of 0° and 20° were performed.

The results are shown in Table IV. It was confirmed that the proposed method achieves stable attitude on slope up to 90°. By adding the inclination to the thrust force, the maximum slope angle at which the attitude is maintained was further increased. The experimental results are in close agreement with the simulation results.

B. Control Experiment

In order to confirm whether the designed control method enables optimal control on the slope, the magnitude and direction of the thrust of the mobile robot were controlled from the angle data obtained from the angle sensor. Fig.8 shows how the inclination angle changed with slope angle. The results confirmed that the thrust of the propeller and its angle changed with the change in slope to adjust optimal control.

TABLE III. Friction Coefficients

Surface	Minimum	Maximum	Average	Std. deviation
Rubber	0.68	0.74	0.71	0.02040
Concrete	0.90	1.03	0.96	0.04279
Grass	0.52	0.71	0.62	0.06888

TABLE IV. Maximum Stable Angle in Resting Position

Force [N]	Thrust Angle[°]	Concrete [°]		Rubber [°]		Grass [°]	
		Exp.	Cal.	Exp.	Cal.	Exp.	Cal.
0	0	40.5	43.8	37.5	35.3	35.5	31.7
20	0	90	90	80	87.2	78.5	77.5
20	20	90	90	90	90	90	90

Further, even at an inclination of 90°, slipping and falling did not occur, and it was possible to maintain a stable attitude. Fig. 10 shows the result of the control experiment. Fig. 10(a) shows the values of the thrust force and the thrust angle maintained during the experiment. Fig. 10(b) shows the values of the angle and normal force sensors. The broken lines are the estimation values of the normal force when the proposed method is not used, which are calculated by using the obtained slope angle.

On a gentle slope, the output is small and the thrust is not produced because the robot can maintain its attitude by its weight. As the slope angle increases, the frictional force and the moment becomes insufficient causing slip or fall. To keep a stable attitude, the magnitude of the thrust and its angle must be large to compensate for the insufficient frictional force owing to the increase of the slope. The robot without the proposed method falls from the slope at which the estimated normal force N_{up} became negative when the slope angle increased. However, the thrust force prevented the robot from fall as the measured normal forces N'_{up} always satisfy Eq. (4).

From the point of view of the robot's weight, there is a remarkable difference between the normal forces on the upslope and the downslope wheels. This normal forces difference was significantly reduced by controlling the thrust force and the inclination angle according to the measured sensor values. When the inclination angle ϕ set to 0°, F_p is directly and equally added to N_{up} and N_{down}. Therefore, the gap between the two normal forces cannot be lessened. The gap between the two normal forces is reduced by the control strategy developed and the results are shown in Fig. 10(b). It can be inferred that each wheel of the robot can generate almost the same amount of driving force. Balancing normal force through the proposed method improves the locomotion of the robot on a steep slope by avoiding the slip of wheels.

C. Evaluation of Locomotion on Steep Slope

To evaluate the mobile performance of the developed mobile robot on a slope, its behavior during movement was studied. Using a rubber sheet as the material of the flat surface, the slope was set to 20°, 40°, 60°, 80°, and 90° and the respective movements were observed. Similarly, experiments were performed on concrete and artificial grass surfaces.

Fig. 11 shows the experiment performed at a slope angle of 60° with the proposed method. Fig. 12 shows the result of the robot's positions in a three-dimensional space during the experiments. It is observed that when the proposed method is not used, the robot is unable to maintain its attitude on slopes of more than 40°. While only the thrust force is applied without the inclination angle, the robot can move on the slope; however, side slip occurs at higher slope angles. When both thrust force and its inclination angle are controlled, the robot can move on a steep slope of 80° and 90° without the occurrence of side slip. As shown in Fig. 12(g), the proposed robot slipped slightly on the artificial grass surface even when the thrust force and its inclination angle were controlled. The grass surface has a large variation of friction coefficient as shown in Table III. The thrust force and its inclination angle were calculated based on an average friction coefficient. The robot's wheels were stuck into the grass surface when the friction coefficient is larger than the average, and the slip occurs when the friction coefficient is smaller than the average. Therefore, the frictional force required to control during movement is unpredictable, and unexpected movements occurred on the grass surface. The proposed method achieved stable attitude and movement even on a steeper slope where slippage could occur. The experiment result shows that stable movements without slips, falls, and side slips were realized on surfaces which have different coefficients of friction.

D. Climbing Up Experiment

We evaluated whether the developed mobile robot has enough torque to climb up on the slope, and whether it can generate enough frictional force and transmit the driving force to the ground. Specifically, the maximum angle of a slope that a mobile robot can climb on three different material surfaces was measured. In the experiments, the thrust force of the propeller was 20 N, and the inclination angle was 20°. As a result, we observed that the developed mobile robot was able to climb all surfaces for up to 90° without any slips and falls.

E. Limitations

The coefficient of friction is an important parameter in controlling the thrust magnitude and direction; however, it is difficult to measure this coefficient in real time. To keep a stable attitude on a slope with an unknown coefficient of friction, the thrust force should be controlled assuming the lowest expected value of the friction coefficient. In the case of deviation of friction coefficient is large, the thrust force causes the stuck of wheel because the thrust force presses the robot against ground too strong. The thrust force should be reduced by monitoring the stuck. Sensing the motor current of wheels to detect the stuck is one of our future works.

Battery running time is determined by the thrust force that is generated during moving on steep slope. Quadroller [17] prefers low coefficient of friction to extend running time for smooth movement on the flat plane. The theoretical running time is longer when the robot is on a gentle slope with a large coefficient of friction. If the robot moves on a steep slope with a small coefficient of friction, the running time is short. For example, the theoretical running time is more than 20 minutes when moving on a 40° concrete surface. When moving on an 80° grass surface, the running time will be less than 5 minutes.

VI. Conclusion and Future Work

Mobile robots on steep slopes encounter slips, falls, side slips causing difficulty in stabilizing their attitude while moving. In this paper, the mobile robot that uses the thrust force of the propellers was proposed. The proposed robot can generate a large frictional force on a steep slope by pushing the robot's body against the slope caused by the thrust of the propeller, and thus prevent slipping. Through proper control of the magnitude and direction of the thrust force, the moment acting on the mobile robot can be improved to prevent falling. The behavior of the proposed robot was evaluated through simulation and experimentation. Both the processes yielded comparable results affirming the results of the research. Experimental results show that the propellers on the

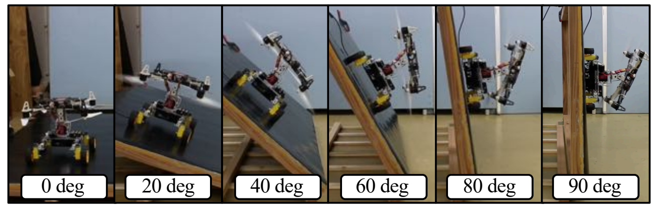
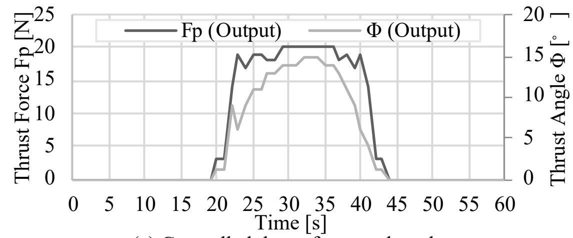
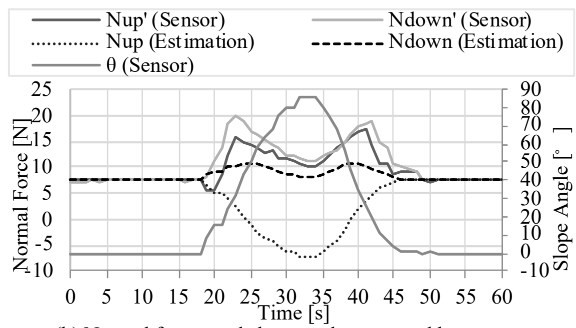


Figure 9 Thrust angle controlling

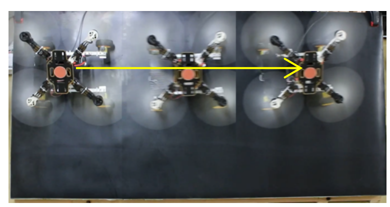


(a) Controlled thrust force and angle



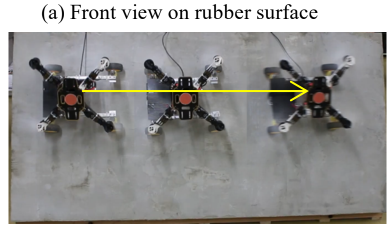
(b) Normal forces and slope angle measured by sensors

Figure 10 Control Experiment Results



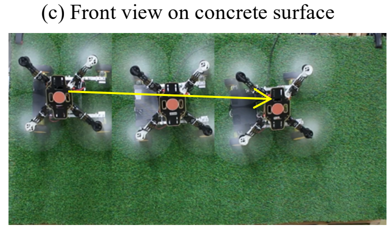
(a) Front view on rubber surface

(b) Side view



(c) Front view on concrete surface

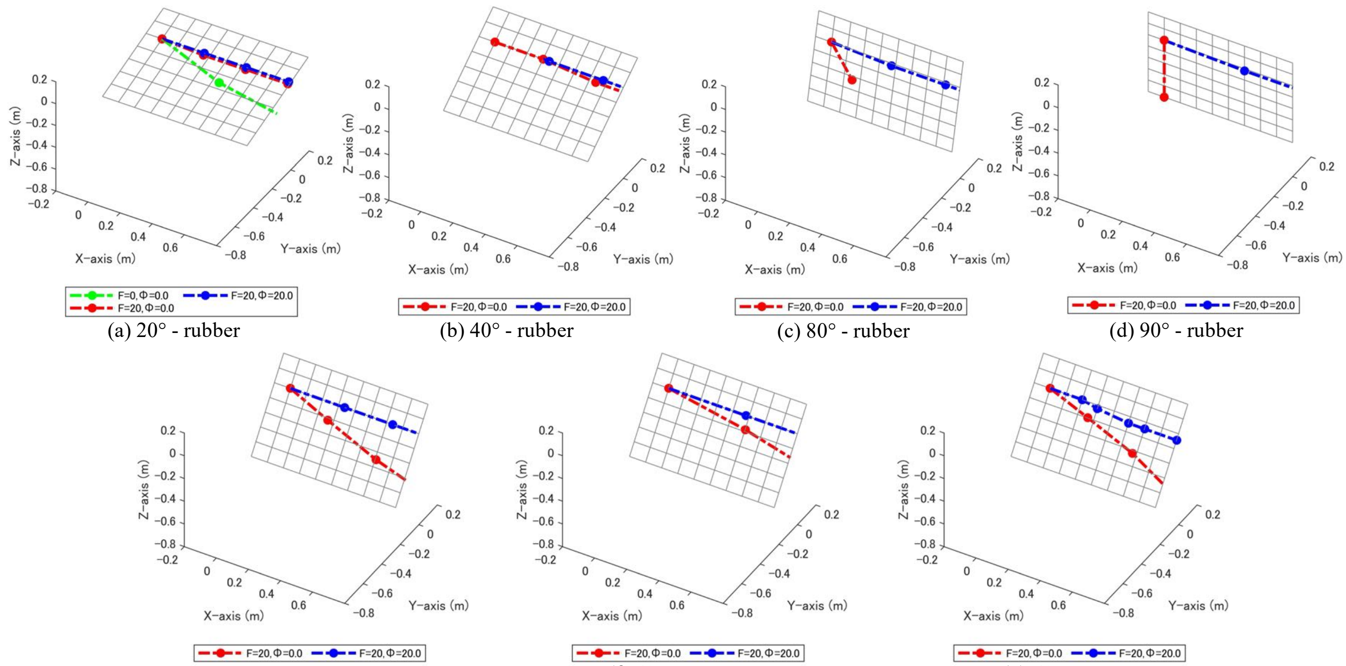
(d) Side view



(e) Front view on grass surface

(f) Side view

Figure 11 Horizontal movement on 60° slope



(a) 20° - rubber (b) 40° - rubber (c) 80° - rubber (d) 90° - rubber

(e) 60° - rubber (f) 60° - concrete (g) 60° - grass

Figure 12 Trajectory of developed robot on steep slope

developed robot were used to control the magnitude and direction of thrust on slopes made by different materials up to 90°. It was found that the proposed method is effective for slopes with different coefficients of friction.

The estimation of unknown coefficient of friction is one of our future work as the slope surface in a real environment is uneven and rough. We will evaluate the influence of unevenness or roughness on a steep slope such as when the robot faces a bump on a steep slope. The mobile robots are expected to automate and replace works in dangerous environments, and in this case, on a steep slope. In actual practice, the robots are required to carry additional weight because of sensors and actuators. The effect of weight was tested only in simulation, and further study on this method is needed. The complex trajectory will be evaluated in practical usage experiment in real environmental situation.

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