Obstacle climbing of tracked robot for unfixed cylindrical obstacle using subtracks

Ryosuke Yajima and Keiji Nagatani

September 4, 2019

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Abstract When a tracked robot moves in a volcanic environment, the robot often has to climb over unfixed obstacles such as rocks on the loose ground. On the other hand, tracked robots with sub-tracks have been proposed, and the climbing performance of these robots on fixed obstacles can be improved by optimally controlling the sub-tracks. However, the effect of sub-tracks on climbing over unfixed obstacles has not been clear. In this study, the effect of sub-tracks on the improvement of the climbing performance of tracked robots over unfixed obstacles was investigated. Specifically, the conditions that a tracked robot should meet in climbing over an unfixed cylindrical obstacle were derived. An experiment with a real robot revealed that the derived climbing-over conditions are valid, and that the climbing-over capability of the tracked robot can be increased by setting the sub-track angle optimally. Furthermore, the motion strategies of sub-tracks are discussed based on the experimental results.

1 Introduction

When an active volcano erupts, investigations are necessary for disaster prevention and mitigation because of the occurrence of various phenomena that lead to disasters. However, as active volcanoes are dangerous, volcano investigation robots for unmanned investigations are required [3]. Keeping in mind that volcanic environments are rough terrains, although there are various types of robots, tracked robots that have high traversability on rough terrains are suitable for volcanic investigations.

Ryosuke Yajima
Tohoku University, 468-1 Aramaki-Aoba, Aoba-ku, Sendai, Miyagi, Japan, e-mail: yajima@frl.mech.tohoku.ac.jp

Keiji Nagatani
The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan, e-mail: keiji@ieee.org

Fig. 1: Tracked robot ”Quince” sliding down due to the rolling of unfixed rocks between the robot and the ground. The field is Mt. Aso.

When a tracked robot moves in a volcanic environment, the robot often has to climb over obstacles. Here, obstacles in a volcanic environment are roughly divided into the following two types.

- Obstacles that are fixed on the ground and cannot be moved by the robot (roughness of the ground, buried rocks)
- Obstacles that are not fixed on the ground and can be moved by the robot (loose rocks)

In this paper, the former are called ”fixed obstacles” and the latter ”unfixed obstacles.”

In the field test that our research group conducted at Mt. Aso in 2013, the tracked robot ”Quince” had to climb over obstacles. The climbing scene is shown in Fig. 1. The Quince slid down due to the movement of obstacles underneath its body. It is necessary to solve such problems for smooth volcano investigations.

There has been considerable research on the obstacle climbing of a tracked robot for fixed obstacles such as steps and stairs [1, 7, 9]. However, although unfixed obstacles can cause problems leading to a failure, there has been little research on unfixed obstacles in the path of tracked robots. Therefore, our research group has been advancing research on unfixed obstacles to understand phenomena that occur when a tracked robot climbs over an unfixed obstacle and to improve climbing performance over unfixed obstacles [10, 11].

Various multiple-degrees-of-freedom-tracked robots with sub-tracks have been proposed to improve climbing performance [2, 4, 8]. The climbing performance of a robot is improved by suitably controlling sub-tracks [5, 6, 13]. However, it has not been clear whether controlling sub-tracks is a valid solution for unfixed obstacles. In our previous study about the single-tracked robot and unfixed obstacles, although it was suggested that there is a possibility that the robot can easily climb over by changing its attitude, the effect when the attitude of the robot is changed by sub-tracks was not investigated.

In this study, to improve the climbing performance of tracked robots for unfixed obstacles, the effect of sub-tracks on unfixed obstacles is investigated, and motion strategies are considered. In this paper, an unfixed cylindrical obstacle was dealt with as the target obstacle, and conditions that a tracked robot should meet in climbing over the obstacle were derived. Moreover, these conditions and the effect of sub-tracks were verified by an experiment using an actual robot, and motion strategies were considered based on the experimental results.

2 Research scope

In the first step, a simplified environment is considered because an actual volcanic environment is too complex. In this study, it is assumed that a tracked robot climbs directly from the lower side to the higher side of the slope, and the phenomena of the robot are considered in the two-dimensional plane of the robot ' s side view, as shown in Fig.2. The target obstacle is an unfixed cylindrical obstacle with a circular cross-section. The slope is flat and solid. Moreover, phenomena are considered from the state that the frontend of the main track is on the obstacle, and the approach to the obstacle is not dealt with.

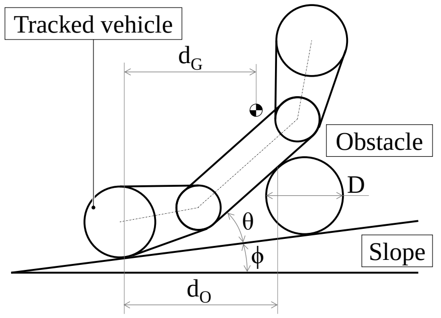
There are roughly three cases for the use of sub-tracks - only front sub-tracks, only rear sub-tracks, and both front and rear sub-tracks. As will be described later, the case that is mainly dealt with is the one with only rear sub-tracks because rear sub-tracks largely affect climbing. In addition, to consider the additional effect of front sub-tracks, the case having both front and rear sub-tracks is also considered.

Each symbol is defined as follows.

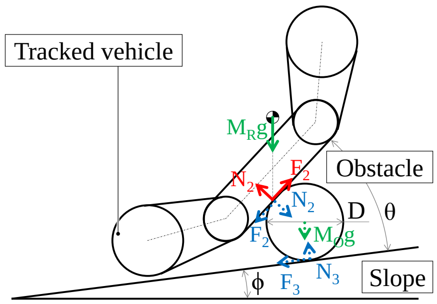
m, f, r	index that indicates the main track, the front sub-tracks, and the rear sub-tracks
l_m, l_f, l_r	length between the axes of each track
r_m, r_f, r_r	radius of each track
x_m, y_m, x_f, y_f, x_r, y_r	centroid position of each track
X, Y	centroid position of the whole robot
M_m, M_f, M_r	mass of each track
M_R	mass of the whole robot
θ	angle between the main track and the slope
θ_f, θ_r	angle between the main track and the sub-tracks
Δ_f, Δ_r	angle between the center line and the track belt of the sub-tracks
D	diameter of the obstacle
M_O	mass of the obstacle
ϕ	slope angle

3 Climbing over an unfixed cylindrical obstacle using sub-tracks

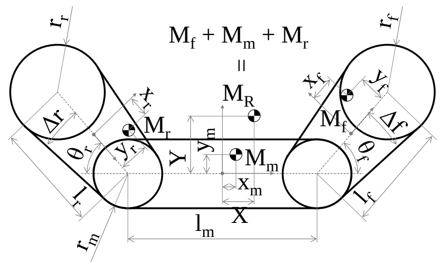
Although this study deals with the case in which only rear sub-tracks are used and the case in which both front and rear sub-tracks are used as described above, the former can be regarded as a special case of the latter, for which each parameter of the front sub-tracks is set to zero. Thus, conditions for the case in which both the front and the rear sub-tracks are used are derived.



(a) Model for climbing-over condition 1



(b) Model for climbing-over condition 2



(c) Parameters of the tracked robot with sub-tracks

Fig. 2: Assumed model

3.1 Conditions that a tracked robot should meet in climbing over an unfixed cylindrical obstacle

In the beginning, a sequence of climbing-over by the tracked robot on an unfixed cylindrical obstacle is considered. The sequence is as follows.

1. The frontend of the robot climbs the obstacle.
2. The robot moves forward, and the angle θ between the robot and the ground increases gradually.
3. The rear end of the robot leaves the ground when the center of gravity of the robot is just above the contact point between the robot and the obstacle.
4. The robot starts falling forward, and the obstacle is rolled to the higher side of the slope.
5. The frontend of the robot contacts the ground.

In this sequence, the important points to climb over are No.3 and No.4. If the center of gravity of the robot does not reach the point just above the contact point between the robot and the obstacle, the robot cannot climb over the obstacle. Furthermore, in No.4, if the obstacle is rolled to a lower side of the slope, the robot slides down and cannot climb over the obstacle.

Based on the above, the conditions that a tracked robot should meet to climb over an unfixed cylindrical obstacle are the following.

Climbing-over condition 1
The center of gravity of the robot reaches the point just the above of the contact point between the robot and the obstacle
Climbing-over condition 2
The obstacle is rolled to the higher side of the slope

When both conditions are satisfied, the robot can climb over the obstacle. In the following sections, each detailed condition is derived, and the effect of sub-tracks on them is considered.

3.1.1 Climbing-over condition 1: the center of gravity of the robot reaches the point just above the contact point between the robot and the obstacle

This condition is a geometric condition that is determined from the relative position of the robot and the obstacle. Therefore, it is the same in the case of fixed obstacles and unfixed obstacles, and the condition described in reference [11] can be used. This condition is shown in the following equation by using the distances d_G and d_O, which are shown in Fig.2a. The distance d_G is from the contact point between the robot and the ground to the center of gravity of the robot. The distance d_O is from the contact point between the robot and the ground to the contact point between the robot and the obstacle.

$$d_g = d_o. \tag{1}$$

The distances d_G, d_O and the centroid position of the robot X, Y are represented as the following equations:

$$d_G = l_r \cos(\theta - \theta_r + \phi) - r_r \sin\phi + \frac{l_m}{2}\cos(\theta + \phi) + \sqrt{X^2 + Y^2}\cos\left(\theta + \phi + \tan^{-1}\frac{Y}{X}\right),$$

$$d_O = \left\{ l_r \cos(\theta - \theta_r) + r_m \sin\theta - \frac{D}{2}(1 + \cos\theta)\tan\phi + \frac{\frac{D}{2}(1+\cos\theta) - r_r - l_r \sin(\theta - \theta_r) + r_m \cos\theta}{\tan\theta} \right\} \cos\phi,$$

$$X = \left[M_m x_m + M_f \left\{ \frac{l_m}{2} + \left(\frac{l_f}{2} + x_f\right)\cos\theta_f - y_f \sin\theta_f \right\} + M_r \left\{ -\frac{l_m}{2} - \left(\frac{l_r}{2} - x_r\right)\cos\theta_r + y_r \sin\theta_r \right\} \right] / M,$$

$$Y = \left[M_m y_m + M_f \left\{ \left(\frac{l_f}{2} + x_f\right)\sin\theta_f + y_f \cos\theta_f \right\} + M_r \left\{ \left(\frac{l_r}{2} - x_r\right)\sin\theta_r + y_r \cos\theta_r \right\} \right] / M.$$

When the equation 1 is satisfied, the rear end of the robot leaves the ground and moves to the next step. From the reference [11], it is enough just to satisfy this condition to climb over a fixed obstacle.

3.1.2 Climbing-over condition 2: the obstacle is rolled to the higher side of the slope

The forces that work at each contact point must be considered for deriving this condition. Here, it is assumed that the velocity of the robot is sufficiently low, the motion is quasi-static, and the condition is considered based on statics. When the equation 1 is satisfied, the total weight of the robot is supported at the contact point between the robot and the obstacle. The forces that work at each contact point are defined as Fig.2b. Then, to roll the obstacle to the higher side of the slope, the following equation must be satisfied.

$$F_2 < F_3.$$

The forces that work at each contact point can be derived as the following equations from the equilibrium of the forces:

$$N_2 = M_R \cdot g \cdot \cos(\theta + \phi), \qquad F_2 = M_R \cdot g \cdot \sin(\theta + \phi),$$
$$N_3 = (M_R + M_O) \cdot g \cdot \cos\phi, \qquad F_3 = -(M_R + M_O) \cdot g \cdot \sin\phi.$$

By solving these equations, the condition can be represented as the following:

$$\theta < \sin^{-1}\left(-\frac{M_R + M_O}{M_R}\sin\phi\right) - \phi. \tag{2}$$

When the equation 2 is satisfied, the obstacle is rolled to the higher side of the slope, and the robot climbs over it. In reference [10], which is a study about a single-tracked robot and unfixed obstacles, the sliding-down was dominant. That is because the single-tracked robot could not satisfy this condition.

3.1.3 The effect of sub-tracks on the two climbing-over conditions

As the angle θ between the robot and the slope, the contact points of the robot and the centroid position of the robot are related to the two climbing-over conditions. Here, the effect of sub-tracks on them is considered.

First, in the case with only front sub-tracks, even if the front sub-track angle θ_f is changed, the angle θ is not changed and the contact points are not moved unless the front sub-tracks come in contact with the ground. Although the center of gravity of the whole robot can be moved, it is not by much because the weight of sub-tracks is generally much smaller than the main track. Therefore, it is concluded that the effect of front sub-tracks on the conditions is small.

Secondly, in the case with only rear sub-tracks, when the rear sub-track angle θ_r is changed, the angle θ can be changed because the main track moves accordingly. If it is assumed that the contact point between the robot and the ground is not moved, the contact point between the robot and the obstacle can be moved according to the rear sub-track angle. Moreover, the center of gravity of the whole robot can also be

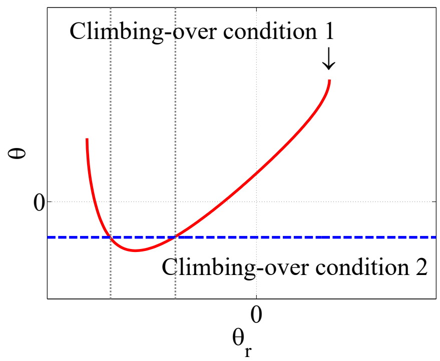


Fig. 3: Example of calculation of the climbing conditions in the case having only rear sub-tracks

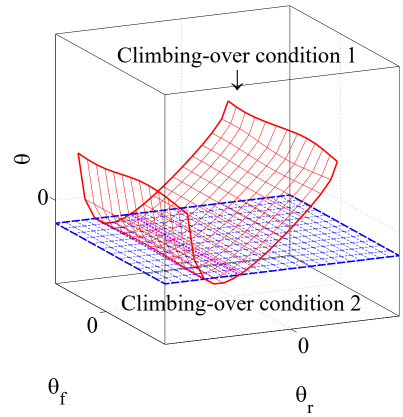


Fig. 4: Example of calculation of the climbing conditions in the case having both front and rear sub-tracks

moved. Therefore, the rear sub-tracks affect the conditions and have the possibility of increasing the climbing performance for unfixed obstacles.

Finally, although the case having both front and rear sub-tracks is almost the same as the case having only rear sub-tracks, the moving amount of the center of gravity slightly increases by the motion of the front sub-tracks.

Based on the above, the rear sub-tracks particularly affect the two climbing-over conditions, and it is considered that the climbing performance of tracked robots for unfixed obstacles can be increased by optimally controlling the rear sub-tracks.

3.1.4 Calculation of the climbing-over conditions

Substituting an obstacle diameter D and a slope angle ϕ and solving the climbing conditions in the case with only rear sub-tracks, a graph like Fig.3 can be obtained. The vertical axis represents the angle θ between the robot and the slope and the horizontal axis represents the rear sub-track angle θ_r. The solid red curve indicates the climbing-over condition 1. On the other hand, the broken blue line indicates the boundary of the climbing-over condition 2 and the area under the broken line satisfies the condition. Therefore, both climbing-over conditions are satisfied in the range of θ_r where the solid red curve is under the broken blue line (between the gray dotted lines). When the robot with a rear sub-track angle in this range climbs the obstacle and the angle θ reaches the value of the solid red curve, the robot climbs over the obstacle. Also, in the range of θ_r where the solid red curve is above the broken blue line, when the angle θ reaches the value of the solid red curve, the robot might slide down.

Moreover, in the case with both front and rear sub-tracks, a three-dimensional graph with an added axis for the front sub-track angle θ_f like Fig.4 can be obtained.

The changes in the direction of the front sub-track angle θ_f is smaller than the changes in the direction of the rear sub-track angle θ_r like the curved surface of Fig.4, and the effect of the front sub-tracks is small as described above.

4 Experiments

4.1 Description of the experiment

The purpose of this experiment is to verify the validity of the above climbing-over conditions and to find out whether a robot can climb over an unfixed obstacle by rotating its sub-tracks. In this experiment, a tracked robot with only rear sub-tracks climbed an unfixed cylindrical obstacle. Then, the sub-track angle was changed, and changes in the robot's behavior by changing its attitude were examined.

4.2 Experimental equipment and environment

The tracked robot "Kenaf" was used [12]. Kenaf was equipped with only two rear sub-tracks. Kenaf's specification is shown in Table 1. The velocity of the robot was set at a sufficiently low speed: 0.05 m/s. The initial attitude was the state at which the frontend of the main track was on the obstacle and the rear sub-track contacted the ground like Fig.5.

The rear sub-tracks were rotated to a target sub-track angle at a sufficiently high speed in order to reach the target sub-track angle before the center of gravity of the robot reached the point just above the contact point between the robot and the obstacle.

The angle θ between the main track and the slope was measured by the IMU equipped on Kenaf. The sub-track angle θ_f and θ_r were measured by the rotary encoders equipped on the motors of the joints.

As unfixed cylindrical obstacles, polyvinyl chloride pipes with diameters of 115 mm and 166 mm were used. In addition, to prevent slipping, non-slip tape coated with mineral particles were fastened over the pipes.

Table 1: Specification of kenaf

	Main track		Front sub-track		Rear sub-track	
Mass [kg]	M_m	18.2	M_f	1.6	M_r	1.6
Length [mm]	l_m	470	l_f	155	l_r	155
Radius [mm]	r_m	47.5	r_f	84	r_r	84
Position of center of gravity [mm]	x_m	-13	x_f	16	x_r	-16
	y_m	10	y_f	0	y_r	0
Track angle [°]		-	Δ_f	13.62	Δ_r	13.62

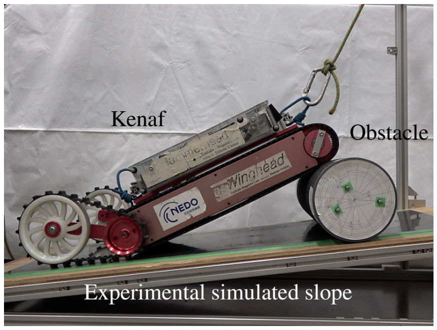


Fig. 5: Experimental equipment

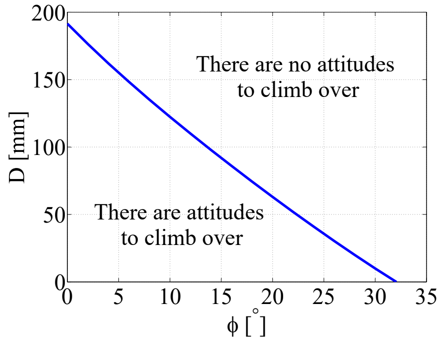


Fig. 6: The boundary whether the attitudes to satisfy both two climbing-over conditions exist

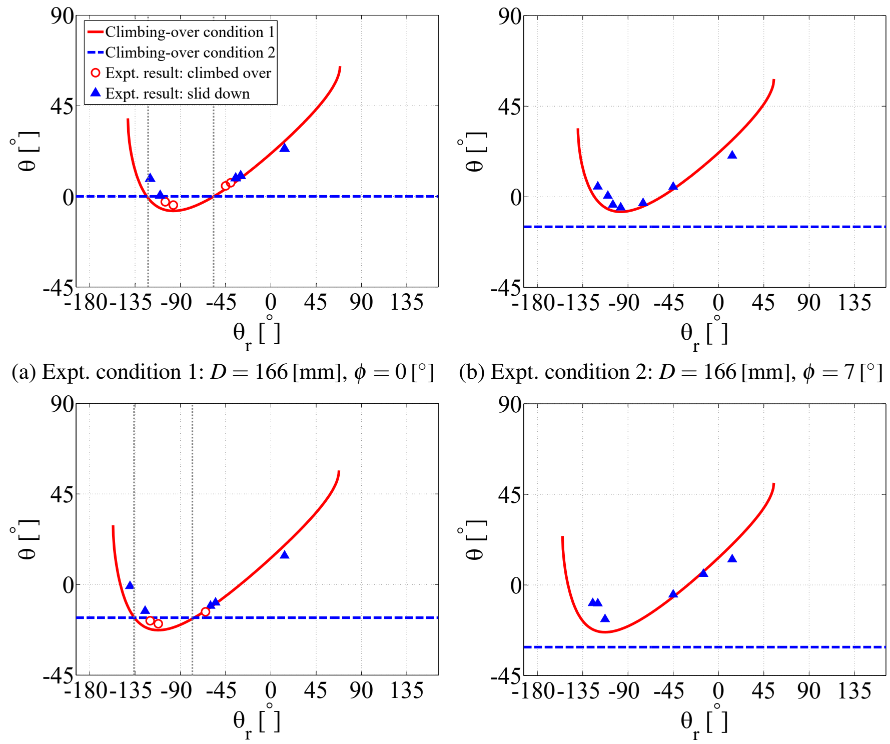
The experimental simulated slope consisted of aluminum frames, and plywood board was used as the slope. The incline angle of this slope can be changed to any angle. A urethane sheet with high friction was fastened to the surface of the slope to prevent slipping.

4.3 Climbing-over conditions for Kenaf

Using the method in the previous section, the climbing-over conditions for Kenaf were calculated. In the beginning, the boundary for whether the attitudes to satisfy both two climbing-over conditions exist, that is, the condition when the solid red curve of climbing-over condition 1 touches the broken blue line of climbing-over condition 2, was calculated. This is shown in Fig.6. The vertical axis represents the obstacle diameter D and the horizontal axis represents the slope angle ϕ. This graph indicates whether the sub-track angles to climb over exist when the tracked robot climbs an obstacle with diameter D on a slope with a slope angle of ϕ. There are sub-track angles to climb over in the area under the curve in the graph, and there are no sub-track angles to climb over in the area above the curve.

In this experiment, the following four experimental conditions were verified based on this calculation.

Expt. condition 1
$D = 166$ [mm], $\phi = 0$ [°]
Expt. condition 2
$D = 166$ [mm], $\phi = 7$ [°] (No sub-track angles to climb over)
Expt. condition 3
$D = 115$ [mm], $\phi = 8$ [°]
Expt. condition 4
$D = 115$ [mm], $\phi = 15$ [°] (No sub-track angles to climb over)



(a) Expt. condition 1: $D = 166$ [mm], $\phi = 0$ [°] (b) Expt. condition 2: $D = 166$ [mm], $\phi = 7$ [°]

(c) Expt. condition 3: $D = 115$ [mm], $\phi = 8$ [°] (d) Expt. condition 4: $D = 115$ [mm], $\phi = 15$ [°]

Fig. 7: Experimental results

The graphs of the climbing-over conditions in each experimental condition are shown in Fig.7. The target rear sub-track angles examined in this experiment depend on the experimental conditions.

4.4 Results

The experimental results are shown in Fig.7. The angle θ when Kenaf with a target rear sub-track angle θ_r climbed over or slid down in this experiment were plotted in the graph of the climbing-over conditions. The vertical axis represents the angle θ between the robot and the slope and the horizontal axis represents the rear sub-track angle θ_r. The solid red curve and the broken blue line represent the climbing-over conditions 1 and 2, respectively. The red circle denotes the attitude that the robot climbed over the obstacle and the blue triangle denotes the attitude that the robot slid down. If the derived climbing-over conditions are valid, the red circles are plotted on the solid red curve under the broken blue line, and the blue triangles are plotted

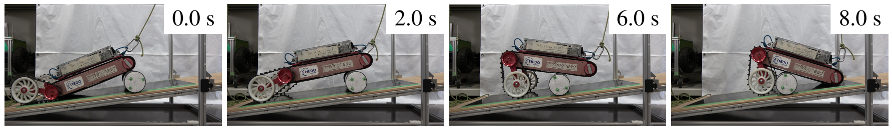


Fig. 8: Motion of Kenaf: $D = 115$ [mm], $\phi = 8$ [°], $\theta_r = -111.9$ [°], Kenaf climbed over

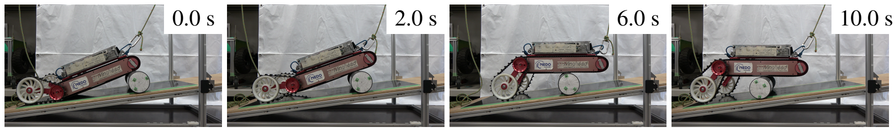


Fig. 9: Motion of Kenaf: $D = 115$ [mm], $\phi = 8$ [°], $\theta_r = -55.0$ [°], Kenaf slid down

on the solid red curve above the broken blue line. In addition, Fig.8 and Fig.9 show motion of Kenaf.

In experimental conditions 2 and 4, the robot should not be able to climb over the obstacle with any sub-track angle. The results show that the robot slid down almost according to the derived conditions and could not climb over.

On the other hand, in experimental conditions 1 and 3, sub-track angles to climb over the obstacle exist. The results show that the robot climbed over the obstacle at the sub-track angles to climb over and slid down at the other sub-track angles almost according to the derived conditions. The reasons for the error at the boundary between climbing-over and sliding-down are (1) measurement error of the centroid position of Kenaf and (2) the existence of grousers on track belts of the sub-tracks.

Moreover, in all experimental conditions, when the sub-track angle is high in minus (left side of the graphs), the results do not follow the climbing-over conditions because the rear sub-tracks touches the obstacle.

From the above experimental results, it is considered that the climbing-over conditions proposed in this paper are valid unless the sub-tracks touch an obstacle. Therefore, depending on the obstacle and the slope, the tracked robot can improve its capability of climbing over obstacles by rotating its sub-tracks to the optimal sub-track angle.

Furthermore, in some cases, Kenaf slipped or slid down before the angle θ reached the value obtained from the climbing-over condition 1. This is because the frictional force became insufficient. The above climbing-over conditions are the condition when the center of gravity of the robot reaches just above the obstacle without sliding down and do not include the effect of friction and sliding down. To understand this phenomenon, the sliding-down condition considering the friction is necessary apart from the climbing-over conditions.

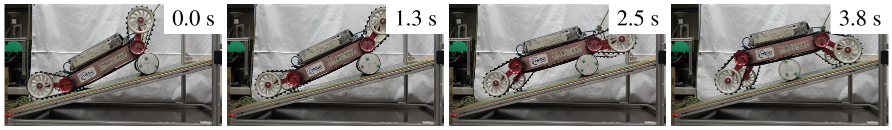


Fig. 10: Climbing over with front and rear sub-tracks by Kenaf

5 Discussion

5.1 Motion strategy of rear sub-tracks

For a tracked robot to climb over an unfixed obstacle, the rear sub-tracks must be rotated to a sub-track angle at which the robot can climb over the obstacle before the center of gravity of the robot reaches the point just above the contact point between the robot and the obstacle. Thus, the target sub-track angle and the way to rotate the sub-tracks should be considered.

The rear sub-track angle at which the robot climbs over the obstacle has a range. The difference between the angles in the range is the size of the angle θ between the robot and the slope when the robot climbs over the obstacle. The optimal rear sub-track angle depends on the case. If it is desired to reduce the shock to the robot when it climbs over, the rear sub-track angle that the angle θ makes minimum is better. If it is desired to keep the robot and the ground parallel to each other, the rear sub-track angle that the angle θ makes zero is better.

The way to rotate the rear sub-track angle has two policies. The first is to not move the obstacle as much as possible. In the experiment, as the forward speed of the robot and the rotational speed of the rear sub-tracks were constant, the main track was pulled backwards, and the obstacle rolled to the lower side of the slope. That is because the rear sub-tracks were rotated. However, the robot may be able to climb over the obstacle without obstacle rolling by cooperative control between the robot's forward movement and the rotation of the rear sub-tracks. The second is to roll the obstacle to the higher side of the slope. The obstacle is rolled to the higher side of the slope when climbing-over occurs, and it is rolled to the lower side of the slope when sliding-down occurs. Thus, when the robot moves the obstacle, rolling it to the higher side of the slope is safer. The reason why the obstacle was rolled to the lower side in the experiment is the rotational direction of the rear sub-tracks. By rotating the rear sub-tracks in reverse, the main track might get pushed forward and the obstacle may be rolled to the higher side.

5.2 The effect of the front sub-tracks and utilization

As described above, the front sub-tracks do not affect the climbing-over conditions largely because they are lightweight and only slightly move the centroid position of the whole robot. However, if the front sub-tracks come in contact with the ground in front of the obstacle by rotation, the robot can be in a stable state earlier. Particularly, if the main track can leave the obstacle like in Fig.10, the obstacle can be ignored. Therefore, it is desirable that the front sub-tracks contact the ground in front of the obstacle as soon as possible. The above conditions are the conditions when the front sub-tracks do not touch on the ground. To analyze the situation and phenomena when they touch on the ground, an additional climbing-over condition must be derived.

6 Conclusion

In this study, to improve the climbing capability of tracked robots over unfixed obstacles, the climbing-over conditions of a tracked robot with sub-tracks for an unfixed cylindrical obstacle were derived. They were determined from the geometric relationship between the contact points and the rotational direction of the obstacle. The validity of the proposed conditions was verified by the experiment. As a result, the climbing-over conditions are valid, and the tracked robot can climb over the obstacle by rotating its sub-tracks to the optimal sub-track angle depending on the obstacle and the slope. Furthermore, the motion strategies of sub-tracks are discussed based on the experimental results. Although this analysis has a limitation, it is thought that these climbing-over conditions can be used in the real world when a tracked robot climbs an obstacle the cross-section shape of which is close to a circle.

The following are considered for future work: (1) The control described in the motion strategies will be implemented, and the climbing-over motion using sub-tracks will be realized. Moreover, (2) it is necessary to expand to obstacles with more complex shapes and three dimensions. Finally, (3) the robot will recognize obstacles by external sensors mounted on the robot, determine the target sub-track angle based on the sensor data, and climb over the obstacle automatically.

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