

Investigation of Tip-Over Condition for Tracked Vehicles Climbing Over an Obstacle on a Slope*

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Abstract—Unmanned investigation of disaster sites using robots has become indispensable in avoiding the risk of secondary disasters or those associated with restricted areas. In fact, in cases of extended periods of investigation or detailed exploration of critical sites, tracked vehicles have proved to be quite useful. However, as a tracked vehicle traverses the terrain, it may be necessary for it to climb and negotiate unfixed obstacles such as loose rocks and rubble. Such cases could result in serious problems. The vehicle could tip-over or slide down as it rolls along with loose obstacles. The primary purpose of this research is to understand how these problems develop and to propose suitable solutions. In this paper, the geometric tip-over conditions relative to a basic obstacle were derived, and whether those conditions apply to fixed obstacles and unfixed obstacles was investigated through an experiment.

I. INTRODUCTION

Investigation of disaster sites, such as those affected by volcanic eruptions, or earthquake-damaged buildings, is necessary for a complete assessment of the situation and to search for victims. However, humans might not be able to directly investigate such sites because of the risk of encountering secondary disasters or the restrictions pertaining to the area. Under these conditions, unmanned investigations utilizing robots are indispensable and in this regard, researchers have been exploring and developing related technologies[1][2][3]. For instance, in situations involving large areas of investigation, flying robots, such as UAVs, are useful. However, in circumstances that require extended periods of investigation or detailed investigations on the ground, the use of ground-roving robots is appropriate. Especially, tracked vehicles are one of the most useful types of ground-roving robots under these conditions because they have high traversability on uneven terrain[4][5].

As tracked vehicles navigate through disaster sites, climbing over or negotiating obstacles along their paths is unavoidable (Fig. 1). These obstacles can be classified into two types: (I) Obstacles that are fixed on the ground and cannot be moved by the robot (e.g., ground contours, steps and rocks with most of their bulk buried under the ground). (II) Obstacles that are not fixed on the ground and can be moved by the robot (e.g., unstable rocks and rubble). In this research, obstacles in categories (I) and (II) are defined as “fixed obstacles” and “unfixed obstacles”, respectively. In



Fig. 1. A tracked vehicle navigating through a volcanic environment with unstable rocks

previous studies, climbing conditions and control methods, when tracked vehicles climb fixed obstacles such as steps and stairs have been examined[6][7]. However, although fatal problems such as tipping over and sliding down occur owing to the motion of the obstacles, climbing of unfixed obstacles has not been sufficiently studied.

The main objective of this research is to understand these phenomena and propose appropriate solutions to the problems resulting from them. In this paper, the geometric tip-over conditions were derived with respect to obstacles with circular cross-section, and an investigation of whether these conditions apply to fixed and unfixed obstacles was conducted through experiments.

II. DERIVATION OF TIP-OVER CONDITION FOR TRACKED VEHICLES CLIMBING AN OBSTACLE ON A SLOPE

A. Research scope and conditions

In order to climb over an obstacle, tracked vehicles must avoid two problems: tipping over and sliding down. This paper focuses on the tip-over phenomenon among these as well as the conditions leading to it, and on how these conditions differ between climbing fixed and unfixed obstacles. However, the sliding phenomenon is also observed because it can occur during the experiment.

The experimental robot, a tracked vehicle with two main tracks (left and right) but no sub-tracks, is made to navigate through flat and sloping terrains taking into account its potential use in volcanic environments. Although the shapes of real obstacles are complex, this research focused on basic objects

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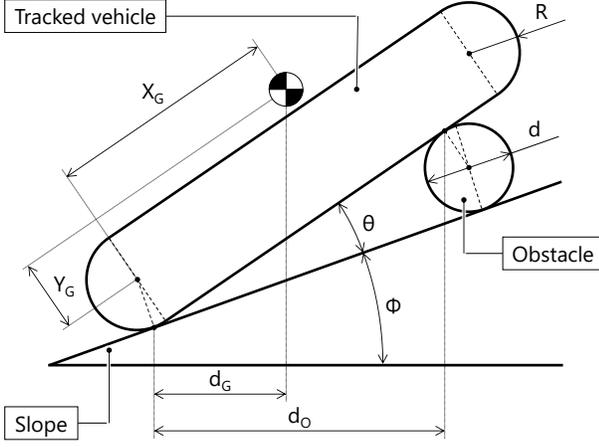


Fig. 2. Tracked vehicle climbing an obstacle with a circular cross-section on a slope

with circular cross-sections to understand the phenomena described above. In the case of an unfixed obstacle on a slope, the obstacle is considered to be rolling down the slope. However, it is treated as not moving until the robot starts climbing. This investigation deals with conditions and motions after the robot has approached the obstacle and then begun to climb from the underside to upside of the slope. Moreover, the robot and the obstacles are treated as though they move without any slip.

B. Geometric tip-over condition for climbing an obstacle with a circular cross-section

The limiting diameter of obstacles with circular cross-sections, which determines whether the robots will tip over or not, is derived from the geometric relationship between the center of gravity of the robot and the contact point between the robot and the obstacle. Relative to this, the geometric climbing condition for a tracked vehicle climbing a step fixed on flat ground was described in a previous study [7]. This method predicts the step height that a robot can climb with relatively high accuracy and is adopted in investigating a tracked vehicle climbing obstacles with circular cross-sections.

Fig. 2 shows a tracked vehicle climbing an obstacle with a circular cross-section on a slope. In reference [7], the climbing condition is that the distance d_G (horizontal distance between the contact point between the robot and slope and the center of gravity of the robot) and the distance d_O (horizontal distance between two contact points—contact point between the robot and slope, and contact point between the robot and obstacle; d_S in the reference) are equal, and the differential values of both distances with respect the robot's pitch angle θ are the same. These conditions are represented

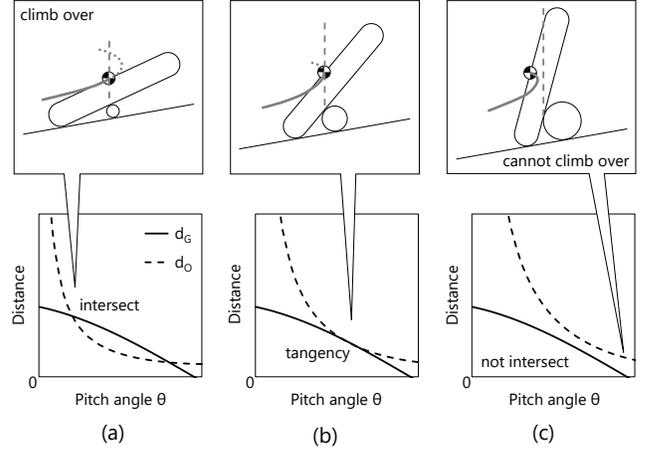


Fig. 3. Relationship between robot motion and graphs of distances d_G and d_O

as the following two equations.

$$d_G = d_O \quad (1)$$

$$\frac{dd_G}{d\theta} = \frac{dd_O}{d\theta} \quad (2)$$

These equations are based on the condition that the robot can climb over the obstacle if the center of gravity of the robot reaches just above the contact point between the robot and the obstacle (the edge of a step in the reference). Considering a graph in which the vertical axis is the distance and the horizontal axis is the robot's pitch angle, lines d_G and d_O intersect if the robot can climb over the obstacle (Fig. 3 (a)). If the robot cannot climb over the obstacle, the lines do not intersect (Fig. 3 (c)). At their points of tangency, d_G and d_O , as well as their inclinations, are equal (Fig. 3 (b)). Therefore, equations (1) and (2) are established. If d_G and d_O do not become equal, the robot's pitch angle will increase and tipping over will occur the moment d_G becomes zero.

Along the slope, the contact point between the robot and the obstacle is not just under the axis of the robot's rear sprocket wheel. In addition, as the robot moves forward, the contact point between the obstacle and robot moves over the surface of the obstacle because of its circular cross-section. Taking the above into account, d_G and d_O are represented by the following equations.

$$d_G = X_G \cos(\theta + \phi) - Y_G \sin(\theta + \phi) - R \sin \phi \quad (3)$$

$$d_O = \left\{ R \tan \frac{\theta}{2} + \frac{d(1 + \cos \theta)}{\tan \theta} - \frac{d}{2}(1 + \cos \theta) \tan \phi \right\} \cos \phi \quad (4)$$

Moreover, their corresponding derivatives are represented as

the following.

$$\frac{dd_G}{d\theta} = -X_G \sin(\theta + \phi) - Y_G \cos(\theta + \phi) \quad (5)$$

$$\begin{aligned} \frac{dd_O}{d\theta} = & R \cos \phi \frac{1 - \cos \theta}{\sin^2 \theta} \\ & - \frac{d}{2} \cos \phi \frac{1 + \cos \theta}{\sin^2 \theta} - \frac{d}{2} \cos(\theta + \phi) \end{aligned} \quad (6)$$

The limiting diameter d of the obstacle and the pitch angle of the robot, θ , when the center of gravity of the robot reaches just above the contact point between the robot and the obstacle, is derived by substituting the above equations for (1) and (2) and solving the simultaneous equations.

In this paper, the limiting diameter of an obstacle with a circular cross-section is called the “tip-over condition” and not the “climbing condition.” The reason is that the robot might not be able to climb over the obstacle if the unfixed obstacle rolls and both bodies slip down the slope.

C. Difference between fixed and unfixed obstacles

If the robot and the obstacle do not slip down the slope, the time it takes for the center of gravity of the robot to be just above the contact point between the robot and the obstacle must differ between fixed and unfixed obstacles. In an unfixed obstacle, the distance d_O and the robot’s pitch angle θ must change faster than that of a fixed obstacle because in the former, the obstacle rolls and approaches the robot. Therefore, the time referred to above is shorter in unfixed obstacles than in fixed obstacles although their diameters may be the same at tip-over condition.

Moreover, the motion after the center of gravity of the robot is just above the contact point between the robot and the obstacle must differ between fixed and unfixed obstacles. In a fixed obstacle, the robot falls upside of the slope following the pull of gravity, the rear of the robot lifts up from the slope, and the front of the robot touches the slope. In other words, the robot climbs over the obstacle. In the case of an unfixed obstacle, as the robot attempts to climb over and its rear leaves the slope, it then becomes supported only at the contact point between the robot and obstacle. As the result, the obstacle rolls, the robot slides down, and the robot is unable to climb over.

However, the tip-over condition and the process until tipping over or climbing over might differ from the one mentioned above owing to slip resulting from the inadequacy of friction and rolling of the obstacle.

III. EXPERIMENT

A. Experiment description

To verify the validity of the limiting diameter of an obstacle with a circular cross-section and to observe the difference between fixed and unfixed obstacles, experiments using an actual robot were conducted. In these experiments, the tracked vehicle was made to climb some circular cross-section obstacles and it was observed whether the vehicle tips over. The motion of the robot and the obstacles were also

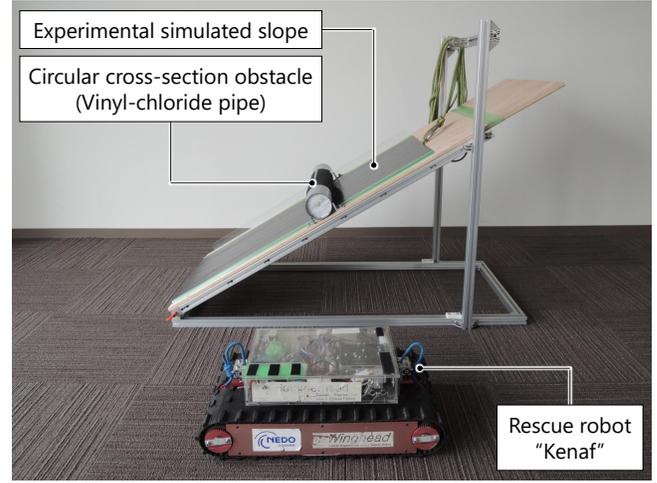


Fig. 4. Experimental equipments

examined. The slope angle ϕ and diameter d of both the fixed and unfixed obstacles were varied. For each condition, the experiment was conducted thrice.

The rescue robot “Kenaf” was used as the experimental tracked vehicle (foreground of Fig. 4). The sub tracks of Kenaf were removed, leaving only two main tracks. Table I lists the parameters of Kenaf necessary to calculate the tip-over condition. The track has grousers 8 mm in height, 8 mm in width, and an interval of 40 mm between grousers.

The experimental simulated slope, shown in Fig. 4, is made of aluminum frames and a plywood board that can be adjusted to change the angle of inclination. In this experiment, the slope angle ϕ was changed from 0° to 30° at intervals of 5° . A urethane sheet, which has high frictional resistance, is fastened over the surface of the board to avoid slip between the surface of the track and the ground. The plywood board has fixing holes through which the fixed obstacles are secured.

Vinyl-chloride pipes with diameters of 18, 22, 26, 32, 38, 48, 60, 76, 89, 114, 140 mm were used as obstacles (upper part of Fig. 4). The pipes, 200 mm longer than the width of Kenaf, are set in such a way that the pipe axis coincides with the crossing direction of the slope to complete the setup in Fig. 2. A nonslip tape coated with mineral particles is fastened over the surface of the pipes also to avoid slip between the surface of the track and the obstacle. The pipes also have fixing holes for attaching them as fixed obstacles.

TABLE I
PARAMETERS OF KENAF FOR CALCULATING TIP-OVER CONDITION

Horizontal distance of the center of gravity X_G	222 [mm]
Vertical distance of the center of gravity Y_G	10 [mm]
Track radius R (excluding grouser height)	47.5 [mm]
Track radius R (including grouser height)	55.5 [mm]

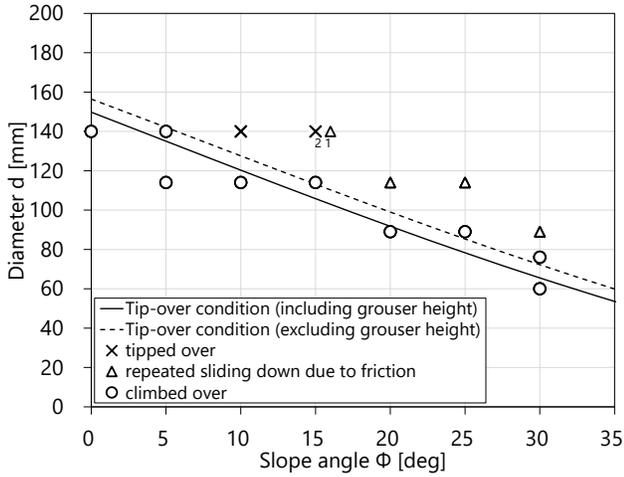


Fig. 5. Tip-over condition curves and experimental results of fixed obstacles

B. Experimental results on fixed obstacles

Fig. 5 shows the results of the experiments on fixed circular cross-section obstacles. The vertical axis of the graph represents the diameter d of the obstacle and the horizontal axis represents the slope angle ϕ . The solid line represents the calculated tip-over condition in which the grouser height is included in the track radius R , whereas the broken line represents the calculated tip-over condition without including the grouser height in the track radius. When the robot climbs an obstacle in which the diameter is below the curve, the robot would not tip over. However, when the robot climbs an obstacle in which the diameter is above the curve, the robot would tip over. Moreover, marks on the graph represent the motion of the robot and the obstacle when the robot climbs an obstacle of diameter d on an incline in which the slope angle is ϕ . The circular marks mean that the robot climbed over the obstacle without sliding down. The triangular marks mean that the robot slid down repeatedly from the same point owing to insufficient frictional resistance. The X marks mean that the robot tipped over. If different results are obtained from the three experiments, the marks and frequencies are arranged side by side.

The graph shows that the robot climbed over obstacles with diameters below the curves and did not climb over obstacles with diameters above the curves. Therefore, for fixed circular cross-section obstacles, it appears that the tip-over condition is valid. However, on steep slopes, the robot repeatedly slid down from same point without climbing over and tipping over. The reason is because the friction to support the robot's body is insufficient because of increasing slope angle ϕ and the robot's pitch angle θ . However, only the geometrical relationship has been considered in this method and therefore, in order to predict the actual motion accurately, it is necessary to consider mechanics and insufficiency of friction.

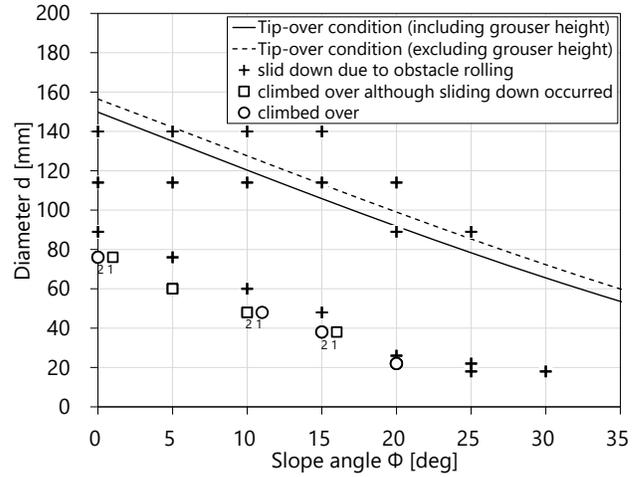


Fig. 6. Tip-over condition curves and experimental results of unfixed obstacles

C. Experimental results on unfixed obstacles

Fig. 6 shows the experimental results of unfixed circular cross-section obstacles. The definitions of the axes and lines are the same as those in Fig. 5. The meaning of marks on the graph is as follows. The circular marks mean that the robot climbed over the obstacle without sliding down. The square marks mean that the robot climbed over but slid down because the obstacle rolled. The plus marks mean that the robot slid down because the obstacle rolled. If different results are obtained in the three experiments, the marks and the frequencies are arranged side by side. It was observed that whenever the slope angle is over 20° , the robot could not maintain the initial posture and slid down occasionally. When this happened, the robot was temporarily supported until the track rotated.

It can be observed that the predicted curves and actual motion are not the same. The robot did not climb over but did not tip over regardless of whether or not the obstacle diameter is below or above the predicted curves. However, sliding down occurred because of obstacle rolling. The reason for this could be that the friction between the robot and the slope was not sufficient and the obstacle acted like a roller under the track.

The obstacle did not move until the robot reached a certain point and slid down (Fig. 7). This was possibly because of the grousers on the vehicle tracks. The obstacle was held in place between the grousers and these may have stopped the roll of the obstacle (Fig. 8). In the model of this method, the grousers on the track were not considered. It may therefore be a possible reason why the actual motion did not match the explanation deduced in section 2.3. This indicates that it is necessary to include the effect of the grousers or conduct additional experiments using a vehicle without grousers.

Moreover, in order to determine the diameter of obstacles that the robot climb over, further experimentation was conducted. It was found that the robot climbed obstacles with diameters of about 80 mm below the curves.

Clearly, in order to accurately predict the actual motion as well as all these phenomena, it is necessary to consider grousers and mechanics, and sliding condition due to obstacle rolling in the investigation.

IV. CONCLUSIONS

To understand the phenomena that occur when tracked vehicles climb unfixed obstacles, the geometrical tip-over condition as a tracked vehicle climbs over obstacles with circular cross-sections on a slope was derived. Moreover, experiments using an actual robot were conducted to investigate whether the conditions apply to both fixed and the unfixed obstacles. In the derivation of the tip-over condition, a previous method used for a fixed step on level ground was applied to circular cross-section obstacles on a slope. From the experimental results, it was confirmed that as the robot attempted to climb fixed obstacles, it tipped over according to the tip-over condition so long as sliding down did not occur. On the other hand, in unfixed obstacles, it was observed that the robot slid due to obstacle rolling and could not climb over the obstacles. However, it did not tip over regardless of whether the diameter was below or above the curves and the robot could climb unfixed obstacles having diameters of about 80 mm below the calculated curves.

In future studies, it is essential to consider grousers and mechanics, and to predict the sliding condition. The tip-over condition and the sliding condition should then be integrated in order to predict the motion of the robot and the obstacle accurately. Not only obstacles with circular cross-section but also obstacles with square cross-section, obstacles with more complex cross-sectional shapes, and those that have no definite cross-sectional shape should be examined. In addition, future research on design and control methods of tracked vehicles should be advanced for climbing over larger and more unstable obstacles.

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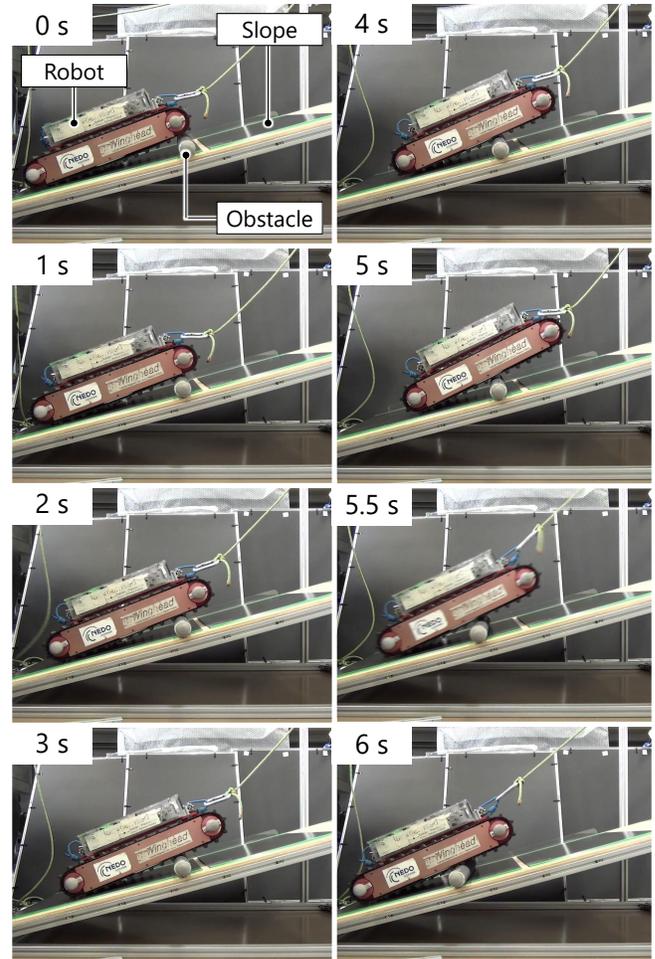


Fig. 7. Motion of Kenaf over an unfixed obstacle

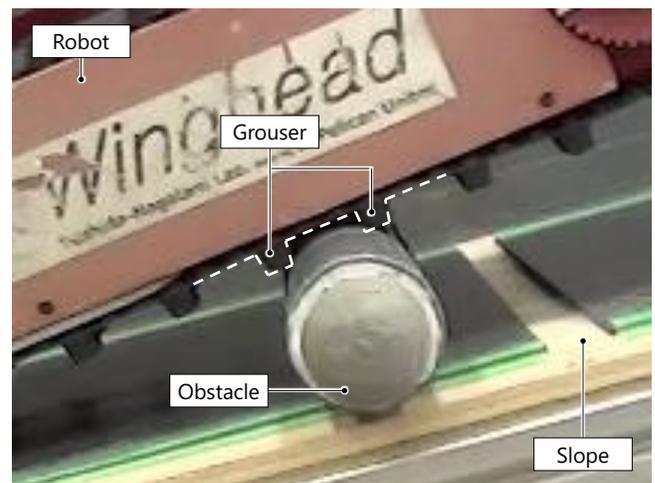


Fig. 8. An unfixed obstacle between grousers