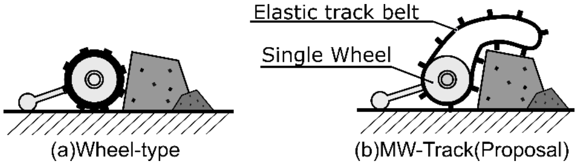
Mono-Wheeled Flexible Track Capable of Climbing High Steps and Adapting to Rough Terrains

Yu Ozawa*, Masahiro Watanabe*, Kenjiro Tadakuma*, Eri Takane*, Giancarlo Marafioti**, Satoshi Tadokoro*

Abstract— **In regions prone to disasters, the instability of the ground and risk of collapse are the primary factors limiting rescue operations. For ensuring the safety and effectiveness of these operations, a remotely controlled search robot is desired. Accordingly, projects are being conducted for exploring rapid and comprehensive rescue response by deploying a mass of small searching robots from aerial drones. As the payload of drones is limited, the robots must be small and lightweight; however, mobile robots with high mobility on rough terrain typically possess complex structures and tend to be heavy. In this study, we propose a novel mobile mechanism with a simple structure and high mobility that is composed of an elastic track belt, which deforms to adapt to irregular obstacles and is driven by a single sprocket. The system was evaluated and compared with a general wheel robot on the basis of its performance in step-climbing tests. The ratio of the maximum height climbed by the proposed mechanism to its wheel diameter is 145%, and its maximum height is 2.9 times than that achieved by the conventional robot. Furthermore, the results are superior when compared to those of the conventional continuous-track-type mechanisms. Overall, our method can be applied to any miniaturized robot that is required to possess high mobility on rough terrains.**

I. INTRODUCTION

Although the damage of natural disasters, such as earthquakes, storms, and floods, or human-related disasters, such as mining accidents, urban disasters, and explosions, have significantly reduced, it is difficult to completely prevent them. To prevent the occurrence of accidents in dangerous environments, a wide area should be explored while ensuring the safety of workers. To achieve an efficient exploration of wide areas, robots that remotely access and search dangerous and narrow places, such as collapsed rubble, could be used instead of humans at the site.



(a)Wheel-type

(b)MW-Track(Proposal)

Fig. 1. Concept of MW-Track. The elastic belt driven by a single wheel largely deforms adapting to the obstacle

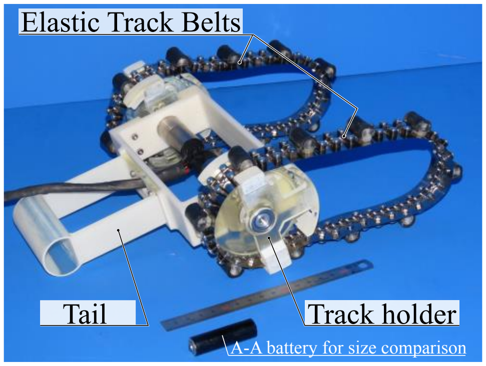


Fig. 2. Flexible continuous track without passive rollers

For these backgrounds, the CURSOR project [1] focuses on conducting a rapid and comprehensive exploration of wide areas by using a large number of search robots. In this project, these robots will be carried and dropped by an aerial drone to, thereafter, search for victims in debris. For the payload of the transport drones, we required lightweight robots.

The biggest limitation when developing a small mobile robot is its size and mass. Generally, it is difficult to realize a robot that shows high mobility and high performance on rough terrain but is also composed of a simple structure. For instance, a wheeled robot cannot climb a step that is higher than the radius of its wheels; therefore, to improve the mobility on rough terrains, large-diameter wheels are often adopted. As a result, the entire structure of the robot is enlarged. The other common methods to climb high obstacles are increasing the number of drive wheels, adding flippers of a continuous track, and introducing a wheel composed of a variable-diameter mechanism. In these methods, however, more actuators and axles are necessary, increasing the complexity of the configuration of the robot.

To overcome these problems, we proposed a novel mobile mechanism, called mono-wheel track (MW-Track), as indicated in Fig. 1. The structure of the MW-Track is unique as it was composed of an elastic track belt driven by a single active wheel, instead of passive rollers, which are usually employed in the general continuous track (Fig. 2). As the track is flexible and not strained, it can be easily deformed by external forces; therefore, it can adapt to the shape of the terrain. This new configuration has the following characteristics: (i) simple structure, as additional actuators or axles, such as flippers, are not required for climbing high obstacles; (ii) high mobility on rough terrain; (iii) efficient transmission of the driving force to the ground, as the adherence to the ground is high owing to several contact points to the ground that prevent it from spinning idly.

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*The authors are with the Graduate School of Information Sciences, Tohoku University, Sendai 980-8579, 6-6-01 Aramaki Aza Aoba, Aoba-ku, Sendai-shi, Miyagi-ken, Japan, (e-mail: ozawa.yu@rm.is.tohoku.ac.jp; watanabe.masahiro@rm.is.tohoku.ac.jp; tadakuma@rm.is.tohoku.ac.jp; takane@rm.is.tohoku.ac.jp; tadokoro@rm.is.tohoku.ac.jp).

**Department of Mathematics and Cybernetics, SINTEF Digital, Trondheim, Norway (email: giancarlo.marafioti@sintef.no)

TABLE I. COMPARISON OF WHEEL AND CONTINUOUS TRACK MECHANISMS

Type	Mechanism	Step climb ability (step height/mechanism height)	Adaptability on uneven terrain	Number of actuators per unit	Dependency of body inclination	Contact point	Mechanical complexity
Wheel	Elastic wheel [2]	58%	Large contact area than that of a general wheel	1	No	Edge	Simple
	Legged wheel [3 - 4]	89-117%*1	Single contact point	1	No	Edge or Top plane	Simple
	Rimless wheel [6 - 7]	38-91%	Single contact point	1	No	Top plane	Simple
	Slide grouser [2]	72%	Large contact area than that of a general wheel	1	Yes	Top plane	Rather complicated
	Swing grouser [8]	68%	Single contact point	1	No	Top plane	Require multiple special grousers
	Transformable [9 - 11]	133-187% of dia. before transformation (66-88% of dia. after transformation)	Single contact point	1–2	No	Top plane	Depends
Continuous track	Active flipper [12]	133%	Can adapt by controlling rigid flippers	3	No	Top plane	Rather complicated (additional belts and motors)
	Passive flipper [15][16]	125-230%	Can adapt passively	1-2	No	Top plane	Rather complicated (additional belts and motors)
	Powder-filled belt [18]	45%*2	Rather large deformation than general track	1	No	Edge	Simple
	Transformable [19]	100%	Can transform into several shapes	3 (two tracks)	No	Top plane	Rather complicated (additional motor)
	Mono-Wheel Track (Proposed)	145%	Can adapt passively with a large belt deformation	1	No	Top plane	Simple

*1 Estimated robot height is 223.5 mm [3]
(12.7(Body height)/2+160(Leg length) =223.5).
Estimated robot height is 152.4 mm [4]
(17.78(Step height) / 1.75(Step height / Leg length) * 1.5) =152.4).
*2 Estimated that the robot height is 350mm from the image [18].

In this research, we show the basic concept and principle of the MW-track and measure its mobility performance through a step-climbing test with a prototype mobile robot composed of two units of the MW-Track. In Section II, the conventional wheels and continuous track robot were further discussed and classified, and the concept and principles regarding obstacle climbing of our proposed mechanism are shown. In Section III, the mechanical designs of the prototype track belt and robots were, respectively, explained. In Section IV, the tests employed to evaluate the effectiveness of the proposed mechanism are discussed. In section V, we discussed the conditions in which the MW-Track succeeded and summarized the findings obtained from the tests. In section VI, we conclude the study.

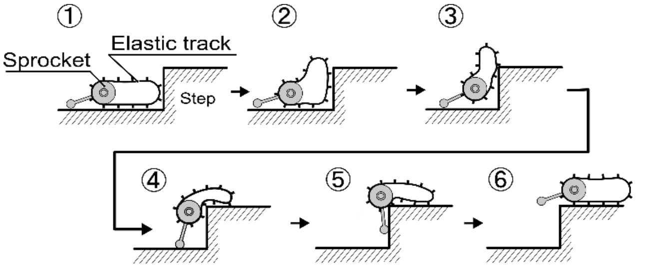

Fig. 3. Procedure to climb a step by hooking a grouser on the edge. The flexible track belt passively deforms to the environment.

II. CONCEPT OF THE MONO-WHEEL TRACK

A. Basic Configuration and Principle

The MW-Track was composed of an elastic track belt, wheel, which drove the belt, and belt holders. It was highly mobile, as it could climb obstacles, whose heights surpassed its diameter, owing to its flexible track. Thus, it could adapt to the shape of the obstacle. In addition, it contributes to improving mobility on rough terrain and soft ground owing to a large number of ground points.

The climbing process of the MW-Track is shown in Fig. 3. First, the front of the track belt contacts the obstacle (Fig 3, 1). Afterward, the track belt deforms, adapting to the shape of the obstacle (Fig 3, 2). The grouser, thereafter, reaches the top of the obstacle and hook to its corner (Fig 3, 3). Then, the grouser pulls the body above the obstacle while the tail supports it (Fig.3, 4). Finally, the body get over the obstacle (Fig. 3, 5-6).

B. Comparison with Other Types of Mechanisms

Table I shows the comparison between several mechanisms, which can be distinguished by two types: wheels and continuous tracks.

1) Wheel type:

A single rigid wheel cannot climb a step whose height surpasses its radius even if the friction between the wheel and the step is large. To overcome this problem, the elastic wheel can be used to realize a strong grip and adaptable wheel. In this method, a low-air-pressure rubber tire is proposed [2] as an elastic wheel. Due to this, the system is capable of moving on rough terrain with smaller torque when compared to that of a high-pressure tire. In addition, its locus is smoothed, and the vibration and vertical movements of the wheel are restrained. Furthermore, the optimization of the design of the surface groove may increase the ratio, R, of the maximum height of the step that the robot can climb to the wheel diameter to 58%. As a result, although the structure is simple, the climbing ability is not dramatically enhanced.

Meanwhile, a legged wheel is composed of long legs that rotate [3 - 4]. The system can reach the top of the step and climb obstacles in situations where R is higher than 50%. However, in these situations, the climbing process is difficult to be executed as the top surface of the step cannot be reached. In addition, the wheel is not circular and rigid; therefore, a single rotating wheel can generate a high vertical vibration when moving, resulting in the low energy efficiency of the system even when it is moving on a flat plane. Furthermore, this mechanism is not effective when moving on soft ground.

Rimless wheels are also a common and simple method to increase R [5 - 7]. In this method, multiple fixed grousers are attached to the wheel surface. Although the system can climb obstacles in a situation in which R is higher than 50%, the same vibration problems as the previously mentioned mechanism occur. Furthermore, the system cannot contact the top surface of the step. Moreover, the hook capability of the robot is improved using a T-shaped or L-shaped grouser.

Slide grousers are mechanical wheels that can slide and lock the grouser [2]. In this method, linear slidable grousers are arranged on the wheel surface. The grouser can, therefore, slide when the posture of the robot is horizontal. However, the grouser is locked when it is near the ground, which allows it to reach higher steps, as opposed to the general wheel that cannot reach steps as high. However, as the slider is connected to the body, it is influenced by the inclination of the body, leading to low effectiveness of the mechanism for rough terrains. In addition, many mechanical parts are required, resulting in a relatively complex structure.

A wheel with a swing-grouser, which can be swing passively, can reach elevated steps by hooking the grouser on the corner of the step [8]. Thus, the system can contact the top surface of the step and it is not affected by body inclination. In addition, the use of a circular wheel can result in high energy efficiency when the wheel moves on a flat plan. However, the rigid wheel is only effective for step-shaped obstacles and the maximum R ratio that the system can achieve is can climb approximately 66%.

Transformable wheels also improve the mobility of the robot [9 - 11]. Generally, the anchors expand passively allowing the system to climb situations in which R is elevated. However, similar to rimless wheels, they do not improve mobility when moving on soft ground. In addition, only one contact point is present, and the system may not be able to climb fragile surfaces because the expanded anchor breaks the surface with its sharp shape.

2) *Continuous Track type:*

Generally, when a continuous track mechanism is employed, the mobility on rough terrain is improved owing to the presence of many ground points. As a result, the driving force is efficiently transmitted to the ground. In addition, the system involving this mechanism has a large contact area and is stable even when navigating rough terrains.

Single continuous tracks lead to limited R. Furthermore, the resulting system cannot adapt to rough terrains. The addition of active flippers [12-14] or passive flippers [15 - 17] are common solutions to these problems, as the flippers can reach high obstacles; therefore, the R ratio can be improved to higher than 50%. However, this method requires the addition of many actuators or passive wheels, leading to a complex structure. Furthermore, it cannot adopt flexibly because the flipper itself is rigid

The grip force of the robot can be increased by supplying power inside the track belt [18]. In this method, several powder-filled blocks are attached to the belt, which can deform and become rigid after the deformation, allowing the system to climb stairs. Although the gripping force on the stairs is significantly increased, the climbing ability of the step is the same as that of general continuous tracks. In addition, the track cannot adapt to rough terrain, and the additional power-filling block increases the weight of the robot.

Transforming the shape of the track based on the surface of the obstacle is also effective for climbing high steps, as the robot is always in a stable position during the procedure [19 - 21]. However, shapes in which the track can be transformed are limited, and additional actuators are required, leading to an increase in weight.

III. MECHANICAL DESIGN

A. *Design of the chain-track belt*

In contrast to all alternatives mentioned in the previous section, the MW-track is highly flexible and can adapt to rough terrains. As a result, high mobility is realized via a simple

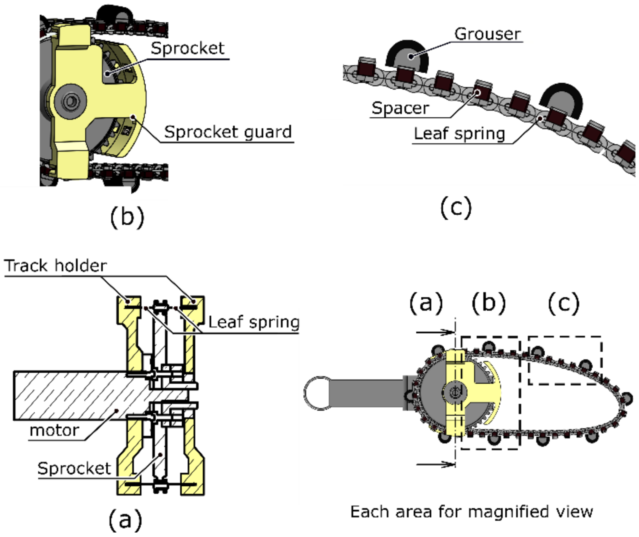

Fig. 4. Mechanical elements of the track

structure. The MW-Track is composed of a metal chain belt and leaf springs, as indicated in Fig. 4 and described as follows.

1) Track belts:

The track is composed of leaf springs that are attached to a metal chain, which is partially wrapped around a sprocket and supported by a holder. The leaf springs have uniformly spaced holes and are fixed to the attachment using screws. Furthermore, a spacer is located between these screws. The leaf spring passes through the center of rotation of the chain, enabling it to easily bend in both directions.

Similar to wheels, a large loop facilitates easy movement past obstacles. However, if the chain belt is not sufficiently elastic, the loop will collapse owing to gravity, and the belt will be locked when it comes in contact with the obstacle. As a result, the elasticity of the tracks in the proposed system is ensured to be sufficient so as to avoid chain locks and enable smooth adaptation to obstacles.

2) Belt holder and sprocket guard

The holder, which is covered by a guard, is attached to the side of the sprocket. The belt holders support the leaf spring in two places (above and below the sprocket) to ensure that the track belt is always attached to the sprocket. The holders have a taper at the entrance to enable the track to guide the sprocket. The sprocket guard covers the front of this element to prevent the track belt from touching the sprocket and become jammed.

3) Grouser:

The grousers are 3D printed and covered by rubber on the surface. The grousers are fixed to the chain attachment with screws at regular intervals to avoid contact when the track belt is bent at 90°. Because the angle of the grouser easily changes, owing to the deformation of the crawler, the shape of the grouser was rounded, resulting in a constant frictional force. Optimal grouser shapes that can be hooked to various surfaces will be examined in the future.

B. Basic Configuration of Experimental Robot

The experimental robot shown in Fig. 2 is composed of two units of the MW-Track, two motors, a tail, and a body frame. The tail and the body frame are parallel to the track holder; therefore, the robot is vertically symmetrical. The specifications of the robot are listed in Table II.

TABLE II. SPECIFICATION OF ROBOT WITH MW-TRACK

Length (mm)	350
Width (mm)	242
Height (mm)	110
Mass (g)	1050
Mass of a track belt (g)	200
Length of the track belt (mm)	240
Lap length of the track belt (mm)	508
Width of the track belt (mm)	22
sprocket outer diameter (mm)	84
Length of the shaft to tail end (mm)	160
Height of the grouser (mm)	10

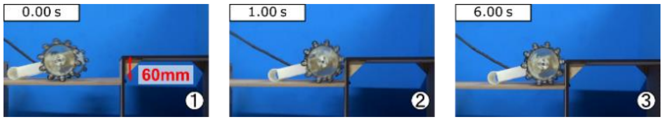

Fig. 5. Step-climbing experiment of wheel type robot.

IV. PERFORMANCE TESTS

We performed a climbing test with a step-shaped obstacle as the basic mobility test to analyze the MW-Track performance in a mobile robot. We compared the results of this experiment with those of a wheel-type robot (Fig.5). The components of wheel-type robot were the same as the robot for MW-Track except wheels. For the wheels, the wheel-type robot has the sprockets with the track, which were used for MW-Track as well, tightly wrapped around them. The robot has balancing weight to equal its weight to the robot for MW-Track. The test was performed using steps of variable heights composed of Medium Density Fiber boards; the height of this setup could be changed in 5 mm installments.

A. Experimental procedure

1) Run the robot straight and get over the step with an approach angle of 90 °

2) If the robot succeeded in climbing the step within three trials, the height was increased by 20 mm (Δh).

3) If the robot failed to climb the obstacle, the height of the step was changed to 5 mm higher than that in the previously succeeded attempt in climbing and Δh was set to 5 mm

4) Step 2 was repeated considering the new value of Δh (5 mm), until the maximum step height was reached again. This value was defined as the highest possible height that could be reached by the robot.

V. EXPERIMENTAL RESULT

Fig. 6 shows pictures of the MW-track type robot climbing the possible highest step while Table III shows the results of the experiment for the wheel type robot and MW-track type robot.

Table III shows that the robot with a 110 mm diameter wheel could climb only a 55 mm height step (*R* of 55%).

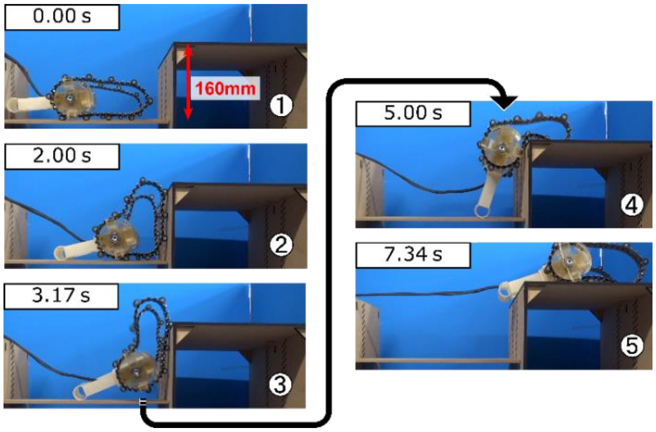

Fig. 6. Step-climbing experiment of MW-Track. The continuous track climbed a step of 160 mm, which is 1.45 times higher than itself.

TABLE III. RESULTS OF THE STEP CLIMBING TEST PERFORMED BY THE WHEEL TYPE ROBOT(LEFT) AND THE PROPOSED TRACK(RIGHT)

Result of wheel type robot	
Step height	Result
20 mm	Successful
40 mm	Successful
45 mm	Successful
50 mm	Successful
55 mm	Successful
60 mm	Failed

Result of proposed track	
Step height	Result
20 mm	Successful
40 mm	Successful
60 mm	Successful
80 mm	Successful
100 mm	Successful
120 mm	Successful
140 mm	Successful (in the second trial)
160 mm	Successful (in the second trial)
165 mm	Failed
180 mm	Failed

A. *Tests on Simulated Environments*

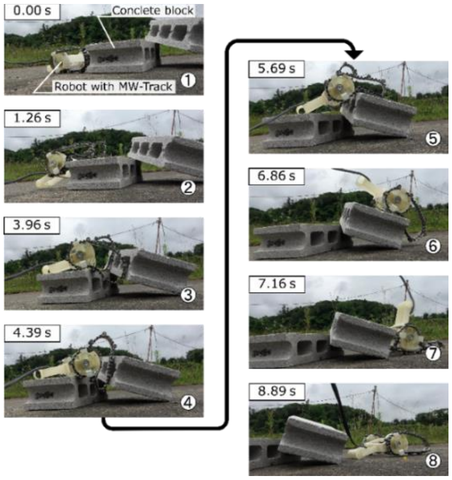

Fig. 7. Climbing experiment with concrete blocks. The robot with MW-Track largely deformed between the gap of two blocks and got over it.

In contrast, the robot with a 110 mm height continuous track could climb a 160 mm step (*R* of 145%) at the maximum. It was 2.9 times higher than that of the conventional wheeled robot.

For all successful cases of the proposed robot, the grousers continuously scratched the corner of the step until one them hooked it. Afterward, the body was pulled with the support of the tail. In case of failure, the grousers were either not hooked at the corner or detached from the surface, following which the robot fell off.

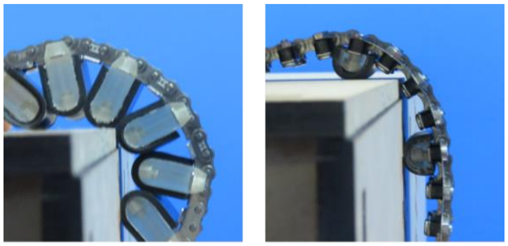
(a) Long grousers with short intervals
(b) Short grousers with long intervals

Fig. 8. Comparison of the grousers with different length and intervals

To confirm the motion of MW-Track on rough terrain, we tested it with the mobile robot shown in Fig. 2 on concrete blocks. The size of block was H 390 mm x W 190 mm x D 100 mm. The one of the blocks was lay flat and the other was piled on the first one with inclined. The procedure of the experiment was shown in Fig.7. The robot climbed the first block with same way as step-climbing (Fig.7, 1-2). Second, it got over the gap between the blocks without stacking by deforming the track belt and hook the grouser on the corner of the second block (Fig.7, 3-5). Then the robot got down the block from the front (Fig.7, 6-8)

VI. DISCUSSION

The proposed robot could only climb the step if the grousers remain attached to the corner of the obstacle during the climbing procedure. In this section, we consider the possible optimizations that may improve the MW-Track mobile performance on rough terrains.

A. *Grouser:*

1) *Shape:*

In this study, round grousers were used to generate constant friction regardless of the angle between grouser and ground. Owing to this, the grousers may have rolled over the obstacle and level at the corner, improving the hook capability. Alternatively, their shape may have resulted in the detachment. L-shaped or T-shaped grousers may be effective in preventing these consequences.

2) *Size and Intervals:*

The length of the grousers of the first fabricated robot, which is not mentioned in this paper, were larger and the distance between them was smaller than those fabricated afterward. This made the tips of the grousers contacted each other when the track was bent to adapt to the obstacle (Fig. 8); therefore, the corners could not be gripped in the gap between the grousers, hampering the climbing. To avoid this issue, the dimensions of the grouser should be reduced, and the distance between them should be increased. The reduction of dimensions may, however, negatively impact the hooking capability and mechanical resistance of the grousers.

In addition, if the intervals between the grousers are narrow, the robot will be mostly contacted by one grouser on the ground, as the MW-Track has only one sprocket, resulting in instability when moving on a flatland. Thus, the size and intervals of the grousers should be optimized considering these tradeoffs.

B. *Track belt:*

1) *Length:*

By means of increasing the belt length, the maximum height that the grousers can reach is improved. However, the distance between the hook point and the belt holder is also increased; therefore, the gripping force due to the elasticity of the belt is reduced. As a result, the probability of detachment is also increased. The length of the belt, therefore, should be sufficiently large until this effect is observed.

2) *Elasticity:*

By means of increasing the elasticity of the belt, the deformation of the belt is suppressed, and the hook capability of the grousers is improved. However, the flexibility of the belt is harmed; therefore, it may not adapt to complex terrain.

3) *Extending the belt behind the sprocket:*

In this study, only one step was considered in the experiment; however, for multiple steps or obstacles with complex shapes, such as rubble, extending the belt behind the sprocket may be an effective strategy. With the current configuration, the robot drops toward the ground when descending a step. Moreover, in a simulated experiment, in which multiple blocks were stacked randomly, sometimes the tail could not reach the horizontal ground owing to the multi-level structure of the blocks. With this technique, the grouser may hook the corner of the steps behind; therefore, the robot can descend slowly.

VII. CONCLUSION

In this paper, we proposed the concept regarding the development of the MW-Track. Furthermore, the principle for climbing an obstacle was shown, and the effectiveness for step-shaped obstacles was confirmed by the experiments.

In the future, we will construct a dynamic model and analyze the conditions for climbing a step. Moreover, the structure of the MW-track will be optimized to reduce its weight and increase its width to improve the adaptability of the system to obstacles of complex shapes. The shape of the grousers will also be optimized to improve their hook capability. In the end, further tests in environments with different characteristics, such as fragile, muddy, or narrow and confined spaces, will be conducted.

ACKNOWLEDGMENT

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