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Blade-Type Crawler Vehicle Bio-inspired by a Wharf Roach

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***Abstract*—Unmanned rescue, observation and/or research vehicles with high terrain adaptability, fast velocity and high reliability to reach difficult rough terrain locations are still demanded, but most vehicles increase rough terrain adapt ability at the expense of low velocity and/or complex mechanisms. We propose a novel vehicle consisting of a very simple blade-type crawler and active antennas with rollers, resembling a wharf roach. This configuration assures stable travelling over uneven terrain at high-speeds, with a very simple and reliable mechanism. This article presents the basic concept, mechanical design of the crawler and the antennas, and the basic motion control strategies. Moreover, we built and tested the first small mechanical prototype named KEIOS-I, and got successful results from experiments on uneven terrain at a high-speed traveling, and also lateral travelling and jumping motions. Future work will also implement roller skating mode using the active antennas equipped with rollers.**

I. INTRODUCTION

Many robots have been developed for rough terrain, such as rescue robots and observation robots. These robots are used instead of people to carry out data collection and other operations in locations that are dangerous or difficult for people to enter [1]. These robots must perform over rough terrain, have the ability to move in multiple directions, have speed, a simple mechanism, and should be easy to control.

Many studies have focused on improving the performance of mobile robots for rough terrain by compromising on other features. Furthermore, there is a concern that if the robots are expensive, situations in which they may be deployed will be limited. Therefore, we aimed to design a mechanism that improves robot performance over rough terrain using a simple and inexpensive system configuration, which to some extent does not require lowering of speed or use of complex controls and mechanisms. In this manner, Blade-type crawler mechanism was developed. This mechanism has blades mounted around the crawler belt. Furthermore, because the only modification is the addition of blades, the crawler belts move at a speed similar to ordinary crawler.

In this paper, we propose a small type unmanned ground vehicle with blade-type crawler mechanism adapted to narrow and uneven rough terrains intricate in high-speed traveling. Recently, by using the characteristics of the insects as a reference, small type robots achieved high mobility on rough terrain [2]~[4]. In order to improve the rough terrain drivability with small size, it is necessary not only to simply miniature analogously but also to inspire from the wharf roach, which has high mobility despite of small size.

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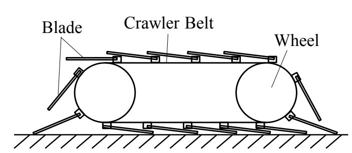
II. BLADE-TYPE CRAWLER VEHICLE

A. Blade-Type Crawler mechanism

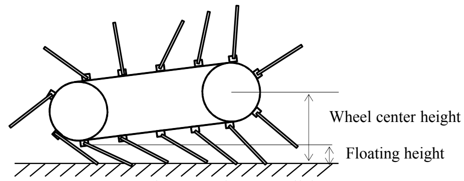
Typical mechanisms for moving robots over rough terrain include a leg-type, a wheel-type [5], and a crawler-type. The aim of the mobile mechanism developed in this study is to improve both performances of traveling speed and over rough terrain. In general, the over rough terrain performance of the leg-type mechanism is high, but the speed is low. In the case of the wheel-type mechanism, the speed is fast, but the performance over rough terrain is low. The crawler-type mechanism provides a balance between the above mentioned features. For the reasons outlined above, crawler-type mechanisms are often used for rescue robots, and thus, this study is based on that mechanism. However, in case of using ordinary crawler belts, the traveling performance over rough terrain of significant unevenness is inadequate.

Therefore, special devices, such as variable crawler belt mechanisms, have been introduced to address this problem [6][7]. However, with this kind of active variable mechanism there is often a trade-off with performance due to increase of the number of actuator and complexity of the mechanism.

In this study, we aim at performance improvement through other passive methods. Increasing the size of the crawler belt wheel diameter is one method for improving performance while still maintaining a simple crawler mechanism. However, if the wheel diameter is simply increased, the overall height of the vehicle increases proportionally, and its operability in narrow rough terrain is decreased. Failure to extend the wheelbase with the increased diameter will cause the device to tumble while traveling on steps.



(a) Static condition



(b) Running condition

(c) Running condition in the uneven rough terrain

Fig. 1 Blade-type crawler belt mechanism

To address this, we studied passive mechanisms with small diameter wheels that increases the diameter when the vehicle is moving. To keep the cost of the system low, not only does the mechanism need to be simple but also it must be easy to control. Therefore, the number of actuators used should be kept to a minimum. To use wheel speed to enlarge the wheel diameter, we focused on the centrifugal force generated around the wheel when the crawler is actuated, and we then applied this force during operation. For this purpose, we devised a "blade-type crawler mechanism" with blades that are mounted passively and are flexible on the crawler belt. Figure 1 shows an outline drawing of the mechanism. When the vehicle is static or moving slowly as in the Fig. 1 (a), the overall height barely changes from the ordinary-crawler, but during high-speed operation as in the Fig. 1(b), the blades open outward because of the centrifugal force and the wheel diameter is effectively increased. When the blades open, each of them make contact with the ground and act like legs. This creates a gap between the body of the vehicle and the ground, allowing the vehicle to move on an uneven ground efficiently as in the Fig.1 (c). Therefore, it is possible to adjust to the unevenness of ground surfaces. Furthermore, the performance over rough terrain is better than that for vehicles where the actual wheel diameter itself is increased. Furthermore, in the case of significant terrain unevenness, because the blades on the front crawler belts of the vehicle come in contact with the uneven ground ahead of the vehicle, the ability of the vehicle to overcome obstacles is improved. Moreover, the rear side of the vehicle is thought to be lifted by the blades. The advantages of the blade–type crawler over rigid grosser crawler are as follows:

・**Better step mobility**

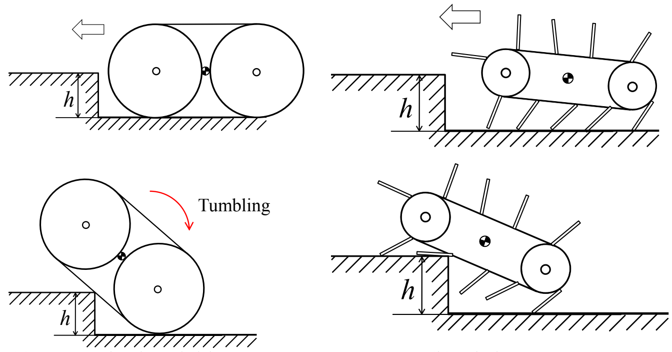
In rigid fixed grouser, increasing wheel diameter will cause the vehicle to tumble during step movements as shown in Fig. 2(a). In order to avoid tumbling, extending wheel base is required. In other words, this is just size up. On the other hand, in case of the blade–type crawler, even increase the wheel diameter temporarily, it is possible to travel high step without tumbling as shown in Fig. 2 (b) by adapting the flexible blade on the step. Therefore, blade–type crawlers provide high performance of over the step without vehicle size up.

・**Better terrain stability**

Since the elasticity of the blades themselves and attachment point of the blades plays a function of suspension, a suspension effect for stabilizing the vehicle body posture is provided. The fixed grouser does not provide this effect.

・**Better terrain adaptability**

The crawler vehicle can travel at fragile rough terrain because the crawler belts are distributed along the contact pressure and the grousers generate the advanced force. However, if rigid fixed grousers are extended for improving the performance when passing over steps, then the vehicle cannot pass on the fragile rough terrain because the crawler belts do not contact the ground and the grousers break the ground. Even with long blades, the vehicle with blade–type crawler can travel on fragile rough terrain



(a) Large wheel or rigid grouser (b) Blade-type

Fig. 2 Comparison of the traveling on the step

because the flexible blades distribute the contact pressure during slow speed movements [8].

Thus, adding the blade-type crawler provide advantages that cannot be obtained by extending the rigid fixed grouser.

B. Step mobility by the blade-type crawler

The blade-type crawler climbs over steps by lifting the vehicle with the blades on the rear ends, as shown in Fig. 2 (b). The lifting effect when the vehicle with the blade-type crawler climb over steps was studied. In general, for a crawler to be able to climb over steps, the center of gravity of the vehicle must be above the extended line of the vertical wall of the step. The model shown in Fig. 3 was used. It is assumed that the blades can flex in a direction tangential to the wheel. Here, h is the height of the step, L_G is the distance from the center of gravity to the center of the rear wheel, r is the radius of the rear wheel, H_G is the height of the center of gravity, a is the angle of inclination of the vehicle, and l is the length of the blade. The blade can lift the vehicle to a maximum height of h_b, which can be determined using Eq. (1).

$$h_b = \sqrt{r^2 + \ell^2} - r \tag{1}$$

The x-coordinate of the center of gravity, x_G, is expressed using Eq. (2).

$$x_G = \frac{h - \sqrt{r^2 + \ell^2} + r}{\tan \alpha} - L_G \cos \alpha - r \tan \frac{\alpha}{2} \cos \alpha + H_G \sin \alpha \tag{2}$$

To enable movement over the step, the center of gravity of the x-coordinate should be negative, and therefore, Eq. (2) can be rearranged to formulate Eq. 3, with $x_G = 0$.

$$h = L_G \sin \alpha + r \tan \frac{\alpha}{2} \sin \alpha - H_G \sin \alpha \tan \alpha + \sqrt{r^2 + \ell^2} - r \tag{3}$$

The height of a step that can be overcome is obtained using this equation. The lifting height, h_b, of the rear wheels can be calculated using Eq. (1).

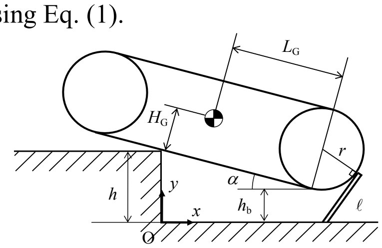


Fig. 3 Blade-type crawler moving over a step

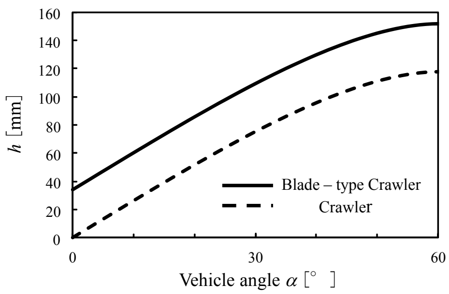


Fig. 4: Height of the climbed steps

Table 1: Parameter settings

L_G	150 mm
r	65 mm
H_G	30 mm
l	75 mm

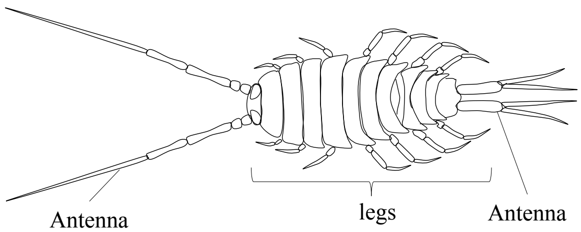


Fig. 5 Wharf roach

The potential overcoming height in case of an ordinary crawler and the one of a blade-type crawler, as well as the relationship between the angles of inclination of the vehicle with the respective overcoming heights are shown in Fig. 4. Table 1 lists the values for the vehicle parameters. The height of steps that can be climbed over increased in case of the blade-type crawler and it was confirmed that to enable climbing steps of the same height, the angle of inclination of the vehicle can be reduced. The height limit of the steps, in case of a blade-type crawler with blade length 75 m is about 150 mm, and in case of no blades, the height limit of the steps is 110 mm, which is an increase of about 36 % from the former case. Furthermore, it was confirmed that without employing any dynamic variable functions, such as sub-crawlers, blade-type crawlers with a total length of about 430 mm can climb over steps with height of about 150 mm, wherein the height is about 35 % of the overall length of the blade and 115 % of the diameter of the wheel.

III. Small type Blade-Type Crawler Vehicle

A. Bio Inspired from Wharf roach

Unexpectedly, the author encountered and watched a valuable race at the rocky coast of Yakushima island of Japan. It was a state where a race of a wharf roach (Fig. 5) and a roach aimed the same goal. The author was amazed of how the wharf roach won a sweeping victory from the roach. Observing the detail of the wharf roach movement, two features were found.

The first feature is that the wharf roach intensively traveled straightly instead of turning with large radius as follows: Quickly straight traveling, sudden stop after running a certain distance or if there was an obstacle, pivot turn (turn in short distance), and straight traveling towards the goal. This is close to the phenomena that occur when race cars of different sizes run in the same circuit.

As in the Fig. 6, in the same circuit, the section of straight running is increase, and the section of turning is decrease by

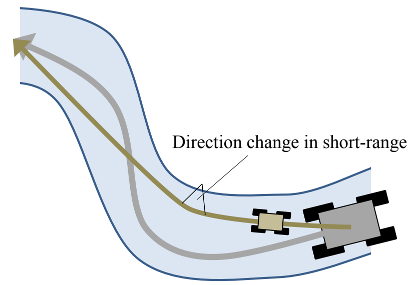


Fig. 6 The route different according to vehicle size

the smaller vehicle. Inevitably, the number of times of turning is reduced. The second feature is that the wharf roach has long strong two antennas in each front and rear. The antennas were seemed to play not only to searching the terrain, but also used for multi roles, such as outriggers to keep the posture and as a sub crawler introduced in previous sections when overcoming steps.

The authors were inspired from the two features of wharf roach: intensive straight traveling and multipurpose antennas.

Firstly, to enhance the performance of over rough terrain, the blade-type crawler, which operated continuously as multi-leg of wharf roach and roach, is installed. The blade-type crawler will be specialized in straight traveling in response to an increase of the straight traveling section due to vehicle size reduction. Secondly, in order to improve the performance degradation of over rough terrain due to size reduction, adding the multipurpose antenna mechanism. In addition, this antenna will achieve other multi roles by low degrees of freedom (actuator). Such a configuration was expected to achieve same effect of blade-type crawler in small blade-type crawler vehicle. In other words, it is expected to achieve both the performance of over rough terrain and high speed performance at the same time of having low degrees of freedoms.

B. Division of task in the direction change and straight

We designed a new blade-type crawler mechanism to specialize straight running by high speed. Normally, the crawler vehicle has two actuators (or transmission) to conduct turn or pivot turn by giving a different rotation for the left and right crawlers. In this case, if we want to provide the same performance by electric motors, two motors and two motor drivers, and more two gear box are required. It needs extra weight and space. In order to improve the efficiency and speed of straight traveling which was frequently used, we install synchronous drive of the left and right crawlers. In this method, one large motor provides high speed straight traveling. Turning is provided by utilizing multipurpose antenna that will be described in the next section.

C. Multipurpose Antennas

We developed the antenna mechanism which has multi roles as the antennas of the wharf roach. The roles of the antenna mechanism are as follows : 1):Supporting over step, 2) : Turning.

Once this function is achieved, we examined the antenna mechanism to enhance other roles to provide versatility in the small vehicle.

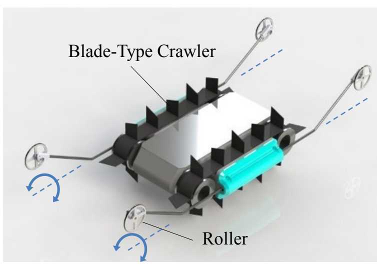
The developed multipurpose antenna is as shown in Fig. 5. The multipurpose antennas are mounted to be rotated parallel to the roll axis of the vehicle as in Fig. 5 (1). Both right and left antennas rotate infinitely clockwise and counter clockwise independently.

1) : Traveling on the steps
It is expected to support the movement during the step by setting the angle of the antenna mechanism as in Fig. 7 (1).

2) : Turning
Turning is conducted by tilting the vehicle body or floating a crawler from one of the sides by pushing the ground with the antennas as in Fig. 7 (2).

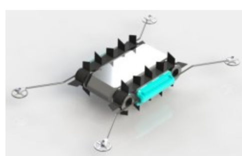
3) : Narrow terrain movement
In case of moving in narrow terrains, the overall height of the vehicle poised low by setting the antenna horizontally as in Fig. 7 (3).

4) : Lateral movement
The vehicle travels to lateral direction (across the direction

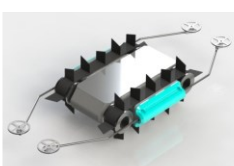


(1) Mode 1 (basic)

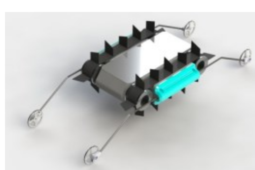
(2) Mode 2



(4) Mode 4

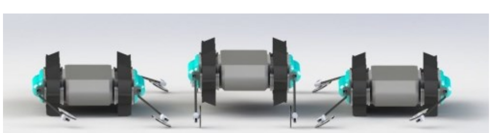


(3) Mode 3

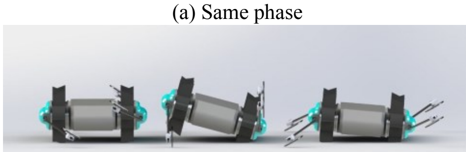


(5) Mode 5

Fig. 7 Move modes

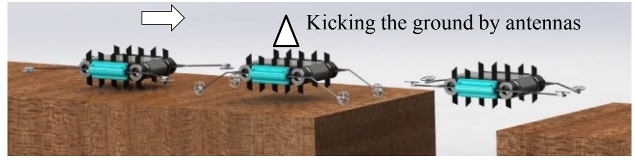


(a) Same phase

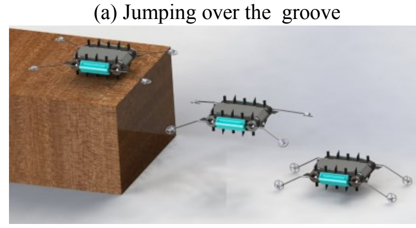


(b) Opposite phase

Fig. 8 Lateral traveling



(a) Jumping over the groove



(b) Landing

Fig. 9 Jump and Landing

Fig. 10 Direction change with roller

5) : Jumping over the groove
It is expected that the vehicle jumps the groove which length is longer than its length by rotating the antennas and kicking the ground during the running as in Fig. 9 (a).

6) : Landing
When the vehicle gets off from a high step, the posture change of the antennas is as in Fig. 9 (b). During landing, it is expected to reduce the fall distance and work as a shock absorber.

It should not merely mimic the biological, but it is also necessary to add new element based on the understanding of its features.

Hence, we tried an extension by installing the rollers which rotate passively in the antenna tips. It is expect the following enhancements.

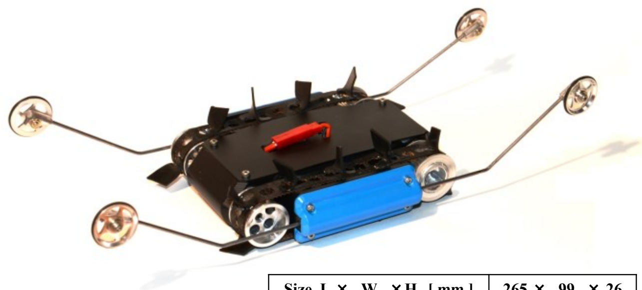
7) : Skating
The vehicle can skate in the hills or during the running by supporting its body with rollers as in Fig. 7 (5).

8) : Direction changing with roller
The vehicle can change direction smoothly by deploying antenna mechanisms with left and right rollers when it crashed into a wall or obstacle as in Fig. 10.

As described above, using the multipurpose antennas with 2 degrees of freedom inspired from the wharf roach, the vehicle is expected to perform 9 types (Normal traveling + 8 types of movement forms by multipurpose antennas) of movement forms.

IV. Development of KEIOS-I

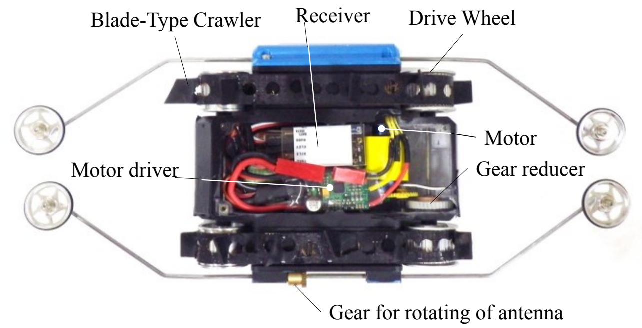
In this section, we develop the prototype model named "KEIOS-I" which has the blade-type crawler and the multipurpose antennas. The KEIOS-I is designed according to the section 3.



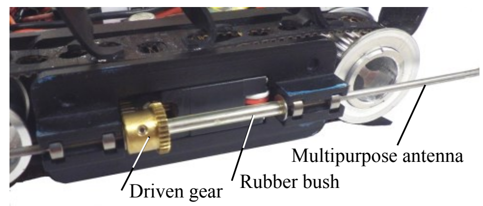
Size L × W × H [mm]	265 × 99 × 26
Mass [g]	255
Degree of Freedom	3

Fig. 11 Overview of the KEIOS-I and its specification

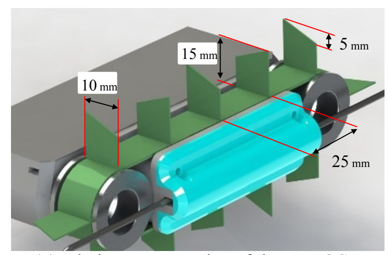
The KEIOS-I is shown in Fig. 11. The total length is 265 mm and crawler section length is 115 mm. The blade length of the crawler is 15 mm and width 10 mm. The length of the multipurpose antennas are 75 mm and they are bent about 30 degree to their rotation axis. As seen from the appearance, the vehicle has a symmetrical shape in front and rear, upper and down. In order to avoid to upright on the side, the side parts of the vehicle colored as sky blue are composed as semicircle cross-sectional shaped. Then, the driving methods of the blade-type crawler and multipurpose antennas are explained. As shown in Fig. 12 (a), the drive wheels which are synchronous right and left are driven by a brushless motor. 7.4 V × 300 mAh lithium polymer battery is mounted on the bottom of the vehicle body. The max output of the vehicle is 64 W. Reduction ratio is 16.25 : 1. The RC servos that rotate the multipurpose antennas are mounted right and left side between the front and rear crawler wheels as shown in Fig. 12 (b). The antennas are capable of infinite rotation by the RC servos. The antennas are made of 1.8 mm diameter piano wire and possible to be elastically deformed. In the future, the multipurpose antenna will be made by leaf spring to get the anisotropic elastic. Furthermore, the torque limiter mechanism which holds the appropriate friction between the antenna and gear prevents damages of the servo motor or gears when large torques are applied with respect to the rotation direction of the antennas. Finally, we explain about the blade-type crawler of the KEIOS-I. The crawler belts are arranged on the left and right sides of the vehicle and 12 sheets of the blades attach at 25 mm intervals to one crawler as in Fig. 12 (c). The blades that are rubber plate with 1 mm thickness are connected by adhesion to the crawlers, the postures of the blades are held by their elasticity. The tip of the blade is cut at an angle as shown in Fig.12 (c) and it is devised to capture the ground like spike shoes. The number of blades, material and shape of the KEIOS-I are determined in a qualitative judgment based on heuristics with the past blade-type crawler vehicles.



(a) Drive system of the KEIOS-I



(b) Multipurpose antenna



(c) Blade- type crawler of the KEIOS-I

Fig. 12 Mechanism of the KEIOS-I

V. Experiment

In section 3, it is introduced the performance expected by the combination of the blade-type crawler and the multipurpose antenna. In this section, we will confirm that multi movement forms are performed.

A. Running and Turning

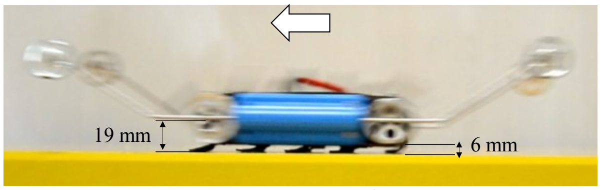
The basic driving performances of the KEIOS-I by the blade-type crawler are presented as follows:

・**Maximum speed**

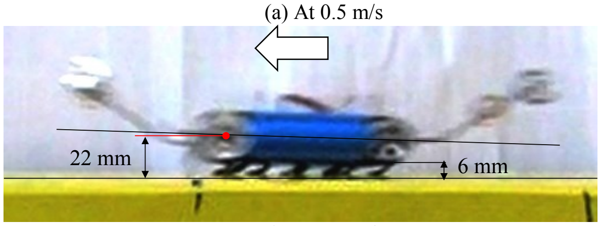
The maximum speed of the KEIOS-I was calculated by measuring the time when it ran 3 m straightly. The vehicle reached the top speed at about 0.4 m and ran 2.6 m with 1.24 sec with top speed. Therefore, maximum speed is about 2.1 m/s.

・**Floating height and Low steps movement**

The floating height at the slow speed (0.5 m/s) and top speed (2.1 m/s) were measured from video movies during running. The floating height at slow speed was about 6 mm as in Fig. 13 (a). The floating height at top speed was also about 6 mm as in Fig. 13 (b). However, the front wheel center height at top speed was about 22 mm and higher than at slow speed. This height increase is directly linked to performance improvement of rough terrain. We conducted the following experiments as an example of the stability during traveling low steps. In the Fig. 14, the vehicle was moving at 0.5 m/s on low steps with 3 mm height and located at 80 mm intervals. As shown in Fig. 14 (a), the height change and pitching movement of the vehicle were very small. In addition, as shown in Fig. 14 (b), the direction of the vehicle did not change even though moving on steps without suspension system and steering system.

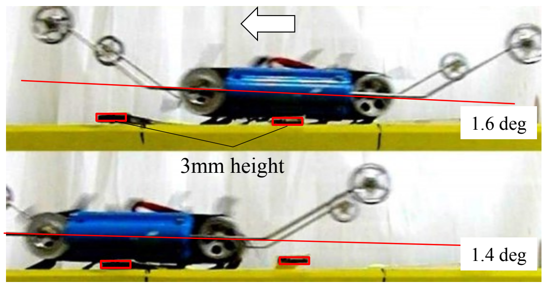


(a) At 0.5 m/s

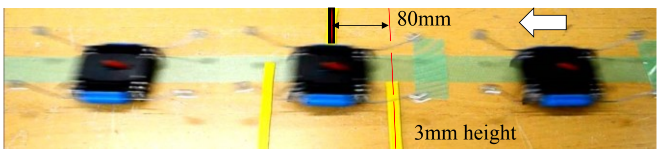


(b) At 2.1 m/s

Fig. 13 Floating height



(a) The side view



(b) The bird's-eye view

Fig. 14 Traveling on low steps at 0.5 m/s

・**The maximum climbing angle of slope**

It was measured the angle of the slope which the vehicle can climb up. The tests were conducted with 5° increments slope angle from 20° until the vehicle cannot climb up. The slop surface is enough to climb. In the result, the vehicle could climb up to 35 degrees.

・**Turning**

The way of turning changed by the antenna was experimented. As shown in Fig. 15, smooth turning was conducted.

B. Lateral traveling

The lateral movement by the multipurpose antennas were experimented.

・**The lateral movement at opposite phase**

The opposite phase movement was conducted as shown in Fig. 16. The moving speed was insufficient. We considered the cause was the insufficient grip of the rollers. It is planned to improve by adding rubbers of semi-circular cup shape on the rollers.

・**The lateral movement at same phase**

The same phase movement was conducted. The movement was succeed, however the moving speed was insufficient and the phase of antennas was changed during the movement. The reason is assumed to be a torque limiter of the antenna rotating.

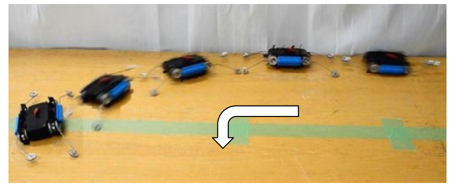


Fig. 15 Turning by the multipurpose antenna

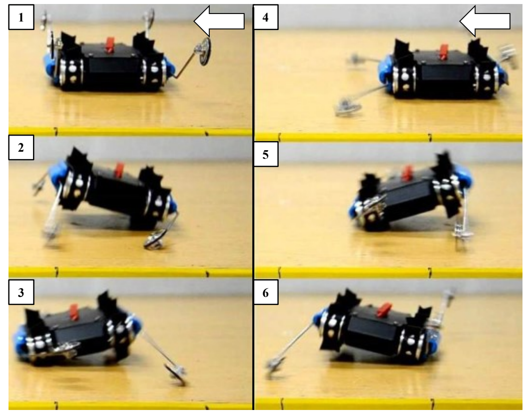


Fig. 16 The lateral traveling by the multipurpose antennas

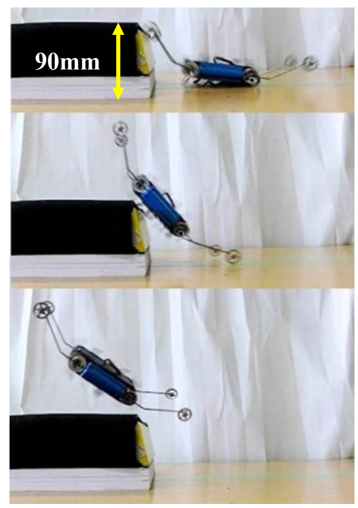


Fig. 17 Traveling on the 90 mm height step

While lateral movement in the same phase, the torque of the antenna rotating axes were over the torque limiter and phase was changed. Since this vehicle was a prototype, the torque limiters were achieved by friction retention. To achieve this with elastic elements, such as the torsion bar spring, it will be solved by the displacement of the antenna phase.

C. Traveling on the high step with multipurpose antenna

We verified the effect of the multipurpose antennas to support movements on a high step. The tests were conducted with two conditions with and without antennas. In the results shown in Fig. 17, in case of without the antennas, the vehicle climbed up to a 25 mm height step. In case of with antennas, up to 90 mm height with 2.1 m/s of the vehicle speed at the front of the step. From this result, the vehicle with the multipurpose antennas could climb 3.6 times a higher step than without the antennas. In other words, the KEIOS-I can climb up to 3.5 times its own height.

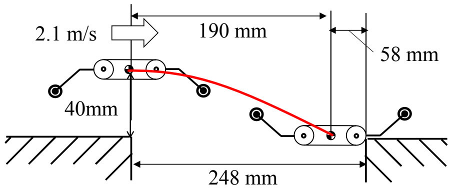
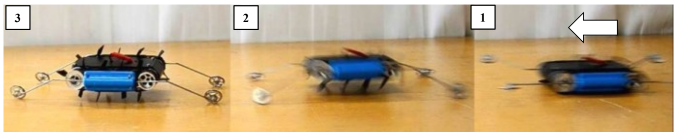
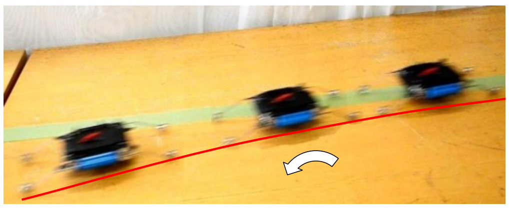


Fig. 18 Jumping over the groove



(a) The side view of switching to skating from traveling



(b) Turning during skating
Fig. 19 Skating

D. Jumping over the groove and Landing

・**Jumping over the groove**

It was verified the widest groove that the vehicle can jump over by moving the antennas as in Fig. 9 (a) at maximum speed. The vehicle can jump over without the antenna rotation up to 155 mm groove length.

The jumping length of the grove with the antenna rotation was expected up to 248 mm from the relationship shown in Fig. 18, however, it was not succeeded. The assumed reason was that the traveling speed was decreased by friction of the roller side, acting as a brake when kicking the ground. From this result, the vehicle was jumping over a 155 mm groove.

・**Landing**

The vehicle was tested landing from 730 mm height table. The KEIOS-I can get off up to 28 times its own height. However, the landing way was not as in Fig. 9 (b). The vehicle prototype did not land with the four rollers of the antennas because it has not a posture sensor. However, the vehicle did not break after 40 times landing from the table to the concrete floor because the antennas absorbed the shock.

E. Skating

We verified the skating by using rollers of the multipurpose antenas In Fig. 19 (a), it was the case of swtiching to the skating form while moving by the crawler. In Fig. 19 (b), it was turning by the rollers. Hence, the KEIOS-I achieved an efficiently move on slope and smooth surface by skating with rollers.

VI. Conclusion

This paper presented the KEIOS-I as a small unmanned vehicle to aim high performance over rough terrain and high speed movements inspired on a wharf roach. The following conclusions were achieved:

1. KEIOS-1 provides 9 movement forms by using 3 degrees of freedom of the blade-type crawlers and the multipurpose antennas.
2. The maximum speed is 2.1 m /s.
3. Lateral movement was performed by multipurpose antennas.
4. High speed and stable movement on low steps by floating 6 mm from the ground.
5. Climb up 35 degree slopes.
6. Moving on steps 3.5 times higher than the height of the vehicle body.
7. Jumping over 155 mm length grooves.
8. Getting off from high steps 28 times higher than the height of the vehicle body.

Thus, the KEIOS-I achieved compatibility with high performance over rough terrains and high speed movements in spite of being a small vehicle.

In the future, we plan to challenge the followings: To continue skating with roller by rowing in the antennas, the attaching methods of the rollers will be devised. Adding the floats to the tops of the antennas and thrusting by the crawler's blades, moving above the water surface. It is expected to enhance the stability by floating higher by attaching the wings to the antennas. In this way, we try to achieve high performance with low degrees of freedom.

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