Development of leg-track hybrid locomotion to traverse loose slopes and irregular terrain

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Abstract — The track mechanism has high mobility on irregular terrain, and is typically used as a locomotion mechanism for all-terrain robots. However, the track mechanism sometimes slips while traversing slopes comprising loose soil. Therefore, we developed a new locomotion mechanism, referred to as surface-contact-type locomotion, which has high mobility on weak soil. It uses a simple legged mechanism that has a wide contact area with the ground so as not to corrupt the contact surface. However, it has the disadvantage of low mobility on irregular terrain. To solve the problem of the above trade-off, we developed the leg-track hybrid locomotion mechanism by fusing the two locomotion mechanisms. In this paper, we detail the developed locomotion mechanism and report some initial experiments.

Keywords: *All-terrain robot, Loose slope, Track mechanism*

I. Introduction

The demands for locomotion mechanisms with high traversability on irregular terrain has increased recently, particularly for use in disaster and/or natural environments. One popular mechanism employs a track [1][2][3]. It has the capability to traverse steps, stairs, and rocky surfaces, and thus, it is used by many rescue robots and all-terrain robots. However, the track mechanism sometimes slips while it traverses slopes comprising loose soil. One reason for this is the track's rotation collapses the surface of the slope.

To increase the traversability of locomotion mechanisms on loose soil, we proposed the surface-contact-type locomotion mechanism Blade Walker, which is shown in Fig.1. Blade Walker is a very simple legged mechanism that uses a three-parallel cranks. One feature of the mechanism is that it can traverse loose soil without collapsing the surface. A similar mechanism was adopted for a locomotion of a jack-up robot[4]. However, these mechanisms do not have a high capability with regard to traversing steps and bumpy surfaces. This is because the maximum height of surmountable steps depends on the length of the cranks.

To solve the above problem, we propose a leg-track hybrid locomotion mechanism, called; Track walker, which is shown in Fig.2. The crank mechanism is the same as the mechanism used in Blade Walker, but the contact surfaces are replaced with tracks. Furthermore, two actuators that drive subtracks are added to the rotational joints of the legs. Past research has demonstrated that subtrack mechanisms drastically increase traversability on rough terrains. Therefore, the proposed mechanism has the potential of high traversability on both weak soils and rough terrains.

In this paper, we first introduce the Blade Walker mechanism and discuss its stability. We then introduce the Track Walker mechanism and report initial experiments.

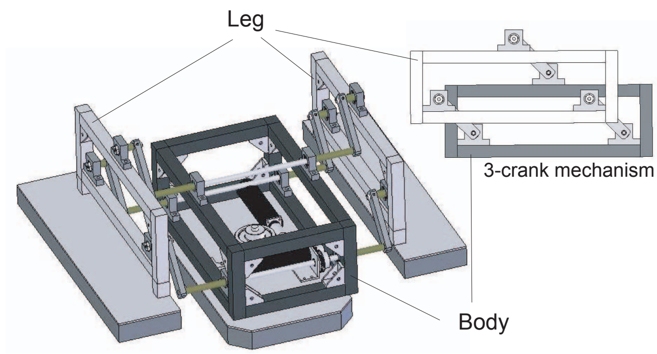

Fig. 1. Surface-contact-type locomotion mechanism Blade Walker

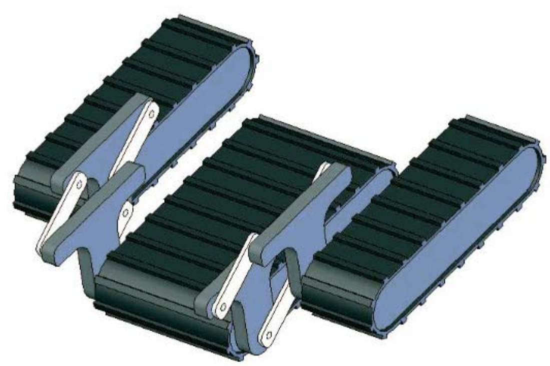

Fig. 2. Leg-track hybrid locomotion mechanism Track Walker

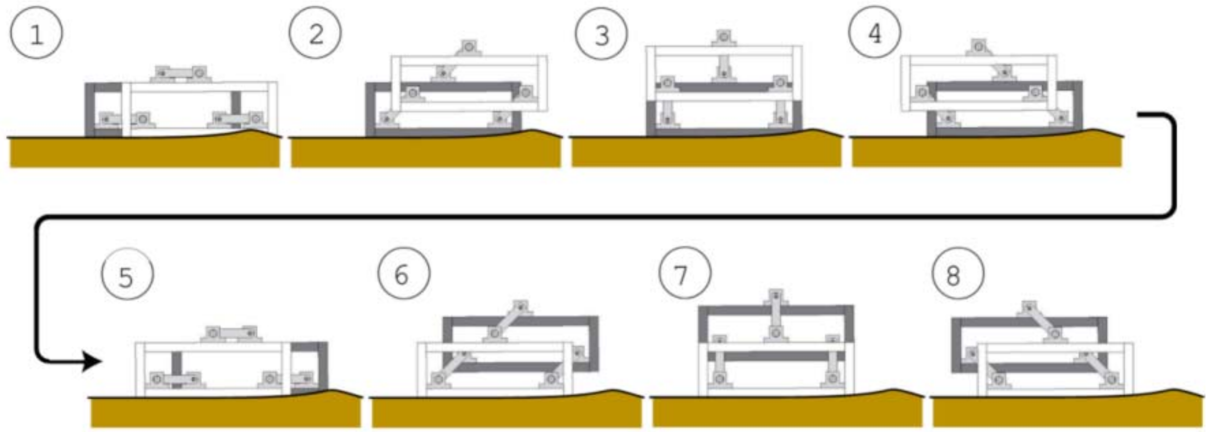

Fig. 3. Translation sequence of Blade Walker based on three-parallel-crank mechanism

II. Related works

For mobile robots to traverse rough terrain such as a volcanic field or planetary surface, a walking mechanism with multiple legs is one solution [5][6][7]. The traversability of such legged robots on rough terrain has been demonstrated in several field experiments. However, it was also found that such robots are slower than wheeled and tracked robots. To improve locomotion velocity, leg-wheel locomotion mechanisms have been proposed [8][9]. Such hybrid systems improve locomotion by changing locomotion mode according to the environments. However, hybrid systems typically require complex mechanisms. In this paper, we present a simple mechanism for legged motion not on rough terrain but on loose soil.

Another approach to traverse rough terrain is the track mechanism. To improve traversability, subtrack mechanisms have been proposed [10][11][12]. Our approach in this paper employs the same concept to overcome natural steps and bumps using subtracks. However, our tracks have large feet to realize legged motion in the case of traversing loose soil.

III. Development of surface-contact-type locomotion mechanism Blade Walker

Our experience in field-robotics research suggests that, in the case of weak soil, locomotion mechanisms require a large contact surface to distribute the vertical load and must not collapse the weak surface. Moreover, a simple mechanism is required from the point of view of reliability and durability. Therefore, we proposed the surface-contact-type locomotion mechanism Blade Walker (Fig.1). Blade Walker has large contact surfaces, and the collapse of weak surfaces is prevented by the distinctive motion of the legs. Details are explained in the following sections.

A. Simple legged mechanism

Blade Walker employs a three-parallel-crank mechanism. Each leg revolves while remaining parallel to the ground via rotation of one actuated crank and two passive cranks. It is one of the simplest mechanisms for realizing legged motion.

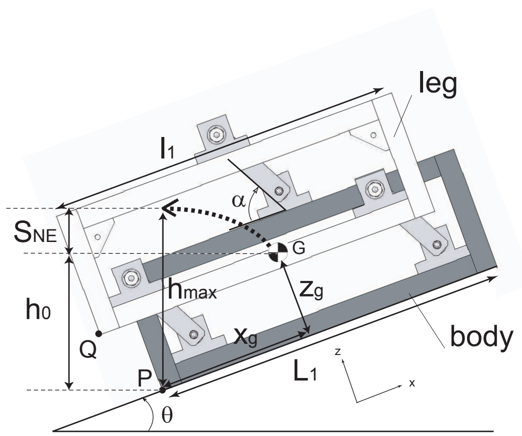

Fig. 4. Model of the target mechanism on a slope

Figure 3 shows the motion sequence of Blade Walker based on the three-parallel-crank mechanism. The mechanism generates translational motion by alternately bringing the bases of the body and legs into contact with the ground. Thus, Blade Walker traverses weak soil by padding and does not collapse the surface.

B. Stability analysis

It is very important to analyze the stability of surface locomotion mechanisms on steep slopes, particularly in terms of backward roll-over. In this research, we adopt the normalized energy stability margin (NESM) [13][14].

The NESM is a criterion used to evaluate the stability of a robot on the basis of the vertical distance (S_{NE}) between the initial height of the center of gravity (h_0) and the highest height h_{max} during roll-over, as shown in Fig.4. According to criterion, the smaller S_{NE} is, the less stable the mechanism. When S_{NE} is zero, the slope angle is the maximum that can be traversed.

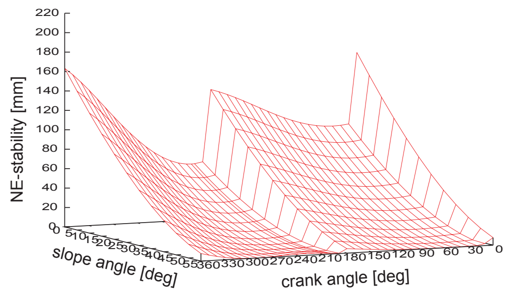

Fig. 5. 3D graph of the NESM when $L_1 = l_1 = 340$ mm

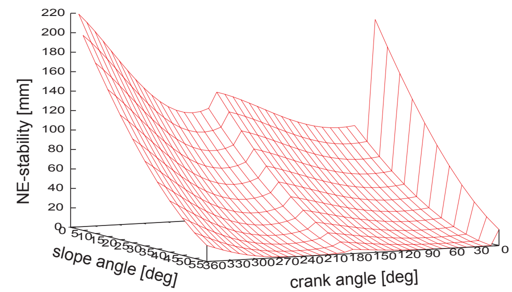

Fig. 7. 3D graph of the NESM when $L_1 = 340$ mm and $l_1 = 476$ mm

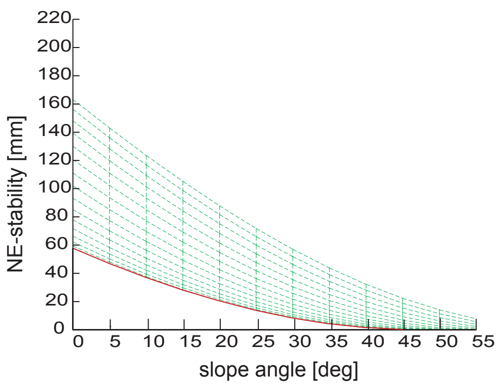

Fig. 6. 2D graph of θ and S_{NE} when $L_1 = l_1 = 340$ mm

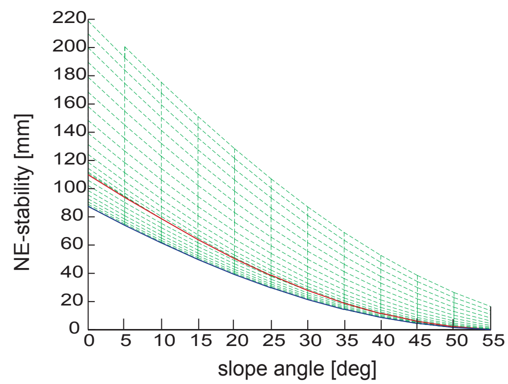

Fig. 8. 2D graph of θ and S_{NE} when $L_1 = 340$ mm and $l_1 = 476$ mm

In the case of our mechanism, the center of gravity changes according to the revolution of the legs. Therefore, S_{NE} is a function of α, which is defined as the angle between the actuated crank and the body. In the case that the α satisfies $0^\circ < \alpha \leq 180^\circ$, the base of the body supports the whole mechanism. In the other case, the mechanism is supported by its two legs. Therefore, there is a discontinuous point in the evolution of S_{NE}.

A three-dimensional (3D) graph of S_{NE} for our developed mechanism ($L_1 = l_1 = 304$ mm) is shown in Fig.5. In the figure, the slope angle θ increases toward the viewer. It is seen that a larger slope angle θ results in a smaller value of S_{NE}. Therefore, it is understandable that the NESM surface in the figure is a forward-declining slope. Furthermore, there are two discontinuities at crank angles of $\alpha = 0^\circ$ and at $alpha = 180^\circ$. A two-dimensional (2D) graph presenting the relationship between the slope angle θ and S_{NE} is shown in Fig.6. The thick red curve is a plot of the minimum S_{NE} at each slope angle θ. The figure shows that the maximum slope angle that can be traversed is about 45° when $S_{NE} = 0$ mm. Note that the thick red curve in the figure is equivalent to the thick red curve in Fig.5. Thus, in a rotational cycle of the crank, S_{NE} is a minimum when $\alpha = 204^\circ$. In this case, the legs support the body weight.

To improve stability, we virtually changed the lengths of the legs ($L_1 = 340$ mm, $l_1 = 476$ mm, $l_1/L_1 = 1.4$) and calculated S_{NE}. The 3D graph is shown in Fig.7 and the 2D graph (θ–S_{NE}) in Fig.8. According to the 2D graph, the maximum slope angle that can be traversed is about 55° when $S_{NE} = 0$ mm. Thus, increasing the length of the legs improves the maximum slope traversal angle. The minimum value of S_{NE} is shown by thick blue curves in both graphs. According to the 3D graph, S_{NE} is a minimum when $\alpha = 30^\circ$. In this case, the bottom of the body supports the body weight. Therefore, to improve stability further, increasing the body length is effective but increasing leg length is not. When the two minima curves are fitted for $-180^\circ < \alpha \leq 0^\circ$ and $0^\circ < \alpha \leq 180^\circ$, the ratio between the body length L_1 and leg length l_1 is optimized. It is typically difficult to increase the body length; thus the leg length should be designed employing the above stability analysis.

C. Performance tests

After several indoor tests, we performed field tests, including tests on a sand dune and snow slope. In these experiments, we attached paddles on the contact surfaces of the body and legs.

Figure 9 (left) is a snapshot of the performance test on a snow slope. The slope angle was between 35° and 40°. Figure 9 (right) shows tracks of the motion. The tracks show that the

Fig. 9. Traversing a snow-covered slope

Fig. 10. Traversing a sand dune

locomotion mechanism was suitable for climbing the slope without slippage.

Figure 10 (left) is a snapshot of the performance test on a sand dune. The slope angle was about 40°. Figure 10 (right) shows tracks of the motion. The tracks show that the locomotion mechanism was suitable for climbing the slope. However, the mechanism collapsed the surface of the sand and there was large slippage. Therefore, the mechanism requires a better method of controlling the legs and suitable patterns on the contact surfaces.

D. Problem of surmounting a step

The above tests demonstrate that Blade Walker has high potential to traverse weak slopes. However, the mechanism is not applicable to rough terrain because the maximum traversal height of steps depends on the length of the cranks. The current length of each crank is 80 mm in height. Therefore, Blade Walker can theoretically surmount up to 80 mm in height. In practice, we confirmed that Blade Walker traversed debris with dimensions of $40 \sim 60$ mm.

The ability of Blade Walker to traverse rough terrain can be improved by extending the crank length. However, this is not a realistic approach because (1) the stability decreases as the highest position of the center of gravity rises, (2) the energetic efficiency decreases as the width of the pitch motion of the body increases, and (3) the torque requirement of the actuator increases. We therefore believe that there is no simple solution to the problem.

IV. Development of leg-track hybrid locomotion mechanism Track Walker

To solve the problem of surmounting a step as presented in the previous section, we propose the leg-track hybrid locomotion mechanism Track walker (Fig.2).

Track Walker has not only a simple legged mechanism like that of Blade walker, but also a track locomotion function.

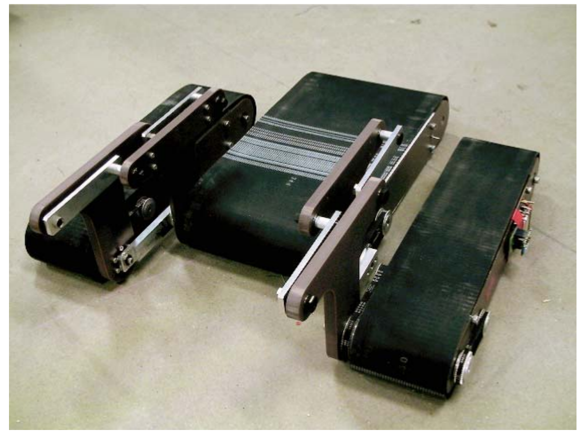

Fig. 11. Overview of leg-track hybrid locomotion mechanism Track walker

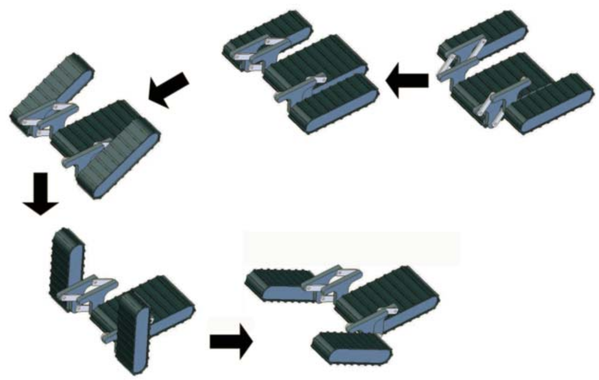

Fig. 12. Sequence of arm motion

Furthermore, two actuators are added to the rotational joints of the legs so that the robot has actuated subtracks. They allow Track Walker to surmount steps higher than those that the legged device can surmount. Our research group has demonstrated the effectiveness of the actuated subtrack system for traversing challenging rough terrain in research on rescue robots[3].

A prototype of a device employing the leg-track hybrid locomotion mechanism Track Walker is shown in Fig.11, and the proposed mechanisms are detailed in the following.

A. Leg Mechanism

To enable legged locomotion, we adopted three-parallel-crank mechanism on both sides of the body, the same as for Blade Walker. The device consists of one actuated crank and two passive cranks. The driving force transmission is from a DC motor, through a spur gear, a timing pulley, and a timing belt, to the actuated cranks attached to both sides of the body. Details of the mechanism are shown in Fig.13.

B. Track and subtrack mechanisms

The mechanism has three track modules, two for the legs and one for the body. Each track is actuated independently: each track module includes one DC motor for actuation of the track through a timing belt.

To enable actuated subtrack motion, each leg includes an extra DC motor that changes the mounting angle of the subtrack through a timing belt. Both DC motors in the leg are located close to the rotational joint of the leg to minimize the inertia moment of the arm. The driving force transmission in the leg is shown in Fig.14.

C. Control system

One of the features of the locomotion is that it uses three-parallel-crank mechanism that includes a limitless revolving part. Therefore, it is difficult to connect power and signal cables between the body and each leg. In this research, we established the mechanism as three independent modules. Each module includes batteries (Eneloop rechargeable NI-MH batteries, Sanyo), a micro-controller (H8/3048F-ONE, Renesas Electronics Corporation), a motor driver (1-Axis DC power module, HiBot Corp.), and a ZigBee wireless communication device (ZIG-100B, BestTechnology Co., Ltd.). In our current implementation, the three modules are controlled independently by a ground computer via three ZigBee communications. The system diagram is shown in Fig.15.

D. Initial tests

On a flat surface, we performed initial tests to check the operation of the leg-track hybrid locomotion mechanism Track walker, and to check an advantage of the simple legged mechanism on a weak ground, qualitatively.

The first test was a traverse using the three-parallel-crank mechanism. In this test, we observed that the mechanism traversed a flat surface by contacting both the track of the body and the tracks of the legs alternately. Therefore, the mechanism has promising traversability on weak ground.

The second test was of the translational and turning performance of the mechanism using tracks. We confirmed good translational motion having the same velocity controls for all track modules. In addition, steering was achieved by opposite rotational control of the tracks of the legs. In this case, the body was controlled so as not to be in contact with the ground.

The third test was of the surmounting performance of the mechanism using actuated subtracks. The target step was made of concrete blocks, and the step height was 220 mm. A skilled operator operated the track and subtrack mechanisms to surmount a large step that was impossible to overcome with only legged motion. The motion in surmounting the obstacle is shown in Fig.16.

The fourth test was of performance comparison of traversability on a weak soil between the track mechanism

TABLE I

SPECIFICATIONS OF TRACK WALKER

Total length	520 mm∼750 mm
Total width	480 mm
Total height	155 mm∼245 mm
Leg unit size L×W×H	365 mm×100 mm×70 mm
Body unit size L×W×H	365 mm×200 mm×70 mm
Distance between crank axis	90 mm
Weight	9.4 kg

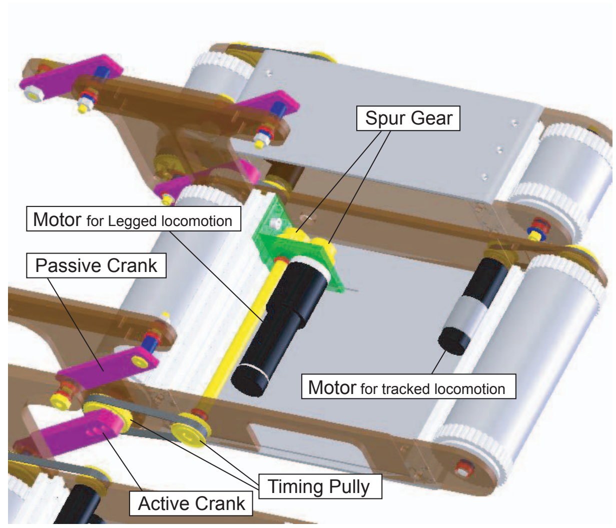

Fig. 13. Driving force transmission in the body

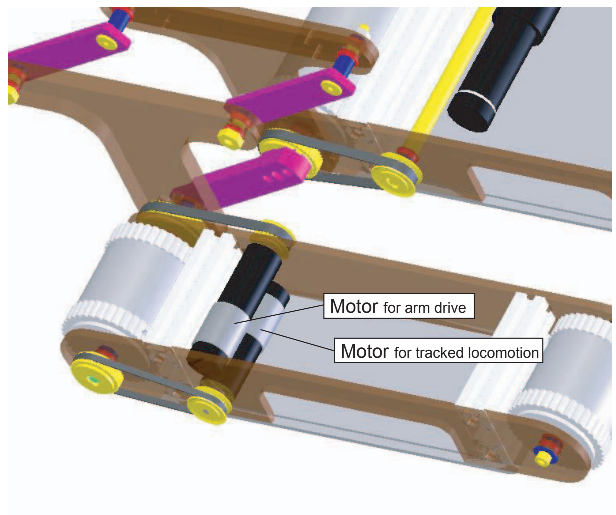

Fig. 14. Driving force transmission in leg

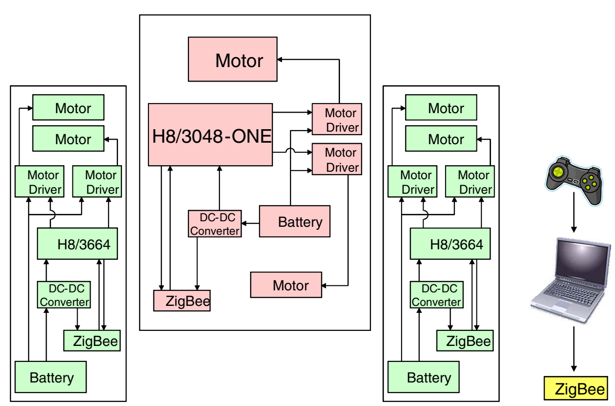

Fig. 15. System diagram

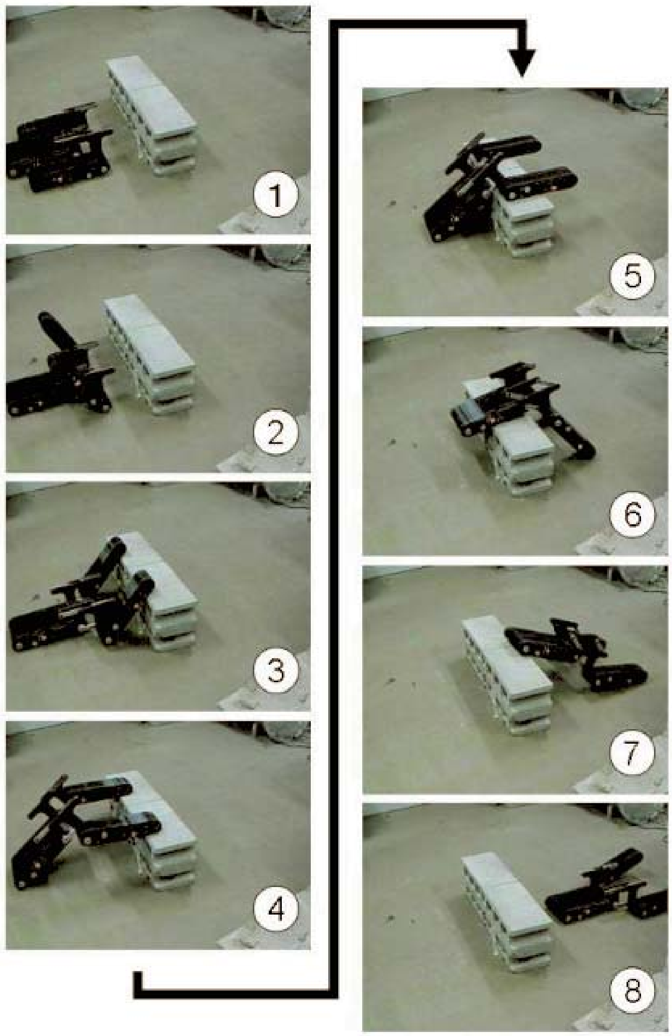

Fig. 16. Track Walker surmounting obstacle

and the simple legged mechanism. The target environment was a small hill in the sandbox in our laboratory that was made by the Toyoura sand that is very loose soil. The traversing results were that the simple legged mechanism traversed the hill very easily. However, the track mechanism got stuck at the base of the hill and was buried into the soil. The comparison experiments are shown in Fig.17. The left figure shows a traversal motion using the simple legged mechanism, and the right figure shows a stuck situation using the track mechanism.

V. CONCLUSIONS

We proposed a simple legged locomotion mechanism called Blade Walker and analyzed its stability during locomotion. We also reported the development of a prototype employing a leg-track hybrid locomotion mechanism called Track Walker that fuses both legged locomotion and track mechanism. Initial tests have demonstrated the usefulness of its basic functions.

In our future works, we will perform navigation experiments in several environments to evaluate the effectiveness of its

Fig. 17. Comparison: traversing sand-hill

design. Furthermore, we aim to design a second testbed based on the basis of the experiment results.

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