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

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Abstract

A track mechanism has high mobility on irregular terrain, and is typically used as a locomotion mechanism for all-terrain robots. To increase its traversability, subtracks (additional actuated tracks that change its mounting angles) are effective, and many small-sized tracked vehicle uses such mechanisms. Recently, the performance of track mechanism is also much better than wheeled mechanism on loose soil, typically. However, it sometimes slips while traversing slopes composed of loose soil. To realize high mobility on weak soil, we developed a new locomotion mechanism, referred to as surface-contact-type locomotion. 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. It consists of three track modules. It mounts six actuators: three motors for standard tracked locomotion, two motors for subtracks' motion to change mounting angles, and one motor for simple legged motion. To validate the mechanism, we conducted indoor and outdoor experiments. In this paper, we introduce the simple legged mechanism and discussion of its stability, detail the developed leg-track hybrid mechanism, and finally, report some experimental results.

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1 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 (Miyakawa et al., 2007) (Guarnieri et al., 2007) (Y. Okada et al., 2009). It has the capability to traverse steps, stairs, and rocky surfaces, and thus, it is used by many construction machines 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 (left). Blade Walker is a very simple legged mechanism that uses three parallel cranks. One feature of the mechanism is that it can traverse loose soil without collapsing the surface. 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.1 (Right). 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 soil and rough terrains.

In this paper, we first introduce the Blade Walker mechanism, a fundamental mechanism of the Track Walker, and discuss its stability. We then detail the Track Walker mechanism and report some indoor and outdoor experiments.

2 Related work

For mobile robots to traverse rough terrain such as a volcanic field or planetary surface, a walking mechanism with multiple legs is one solution (J.E. Bares and D.S. Wettergreen, 1999) (Balibert et al., 2008) (K. Kato and S. Hirose, 2001). 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 (Halme et al., 2000) (M. Takahashi et al., 2006). Such hybrid systems improve locomotion by changing locomotion mode according to the environment. 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. A similar mechanism was adopted for the locomotion of a jack-up robot (Tsukagoshi et al., 2008).

Another approach to traversing rough terrain is the track mechanism. To improve traversability, subtrack mechanisms have been proposed (Yamauchi, 2004)(Michaud et al., 2005)(T. Yoshida et al., 2007). 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.

3 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 not to be sunk into the weak soil and should not collapse the surface of the ground to keep shear strength of the soil. However, rotation mechanisms, including the front part of track mechanisms, usually dig the weak ground by its lugs, and it decreases the shear strength of the soil. 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.

3.1 Simple legged mechanism

The Blade Walker employs a three parallel crank mechanisms. 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.

Figure 2 shows the motion sequence of Blade Walker based on the three parallel crank mechanisms. 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.
3.2 Stability analysis

It is very important to analyze the stability of surface locomotion mechanisms on steep slopes, particularly in terms of backward roll-over. We imagine that there may be many situations where the robot can roll over. Practically, the most unstable case is that the robot stays parallel to the inclined line when the robot climbs a steep slope. In this research, we adopt the normalized energy stability margin in the above case. (Hirose et al., 1998) (Hirose et al., 2001).

Originally, the energy stability margin (ESM), proposed by Klein (MESSURI and KLEIN, 1985), was defined in terms of the potential energy of the robot. However, professor Hirose considered that incrementing the robot’s weight did not always contribute to its stability because it also increased a dynamic disturbance around its center of gravity. Therefore, they proposed the normalized ESM (NESM), in which the robot’s weight was normalized. In this criterion, the NESM is 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.3. 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.

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 $\alpha$, which is defined as the angle between the actuated crank and the body. In the case that the angle $\alpha$ 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.4. In the figure, the slope angle $\theta$ increases toward the viewer. It is seen that a larger slope angle $\theta$ results in a smaller value of $S_{NE}$. Therefore, it is understandable that the NESM surface in the figure is a forward-leaning 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 $\theta$ and $S_{NE}$ is shown in Fig.4. The thick red curve is a plot of the minimum $S_{NE}$ at each slope angle $\theta$. The figure shows that the maximum slope angle that can be traversed is about $45^\circ$ when $S_{NE} = 0$ mm. Note that the thick red curve in the figure is equivalent to the thick red curve in Fig.4. 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 the left of Fig.5 and the 2D graph ($\theta$–$S_{NE}$) in the right of Fig.5. According to the 2D graph, the maximum slope angle that can be traversed is about $55^\circ$ 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.

### 3.3 Performance tests

After several indoor tests, we performed field tests, including tests on a sand slope and snow slope. In these experiments, we attached paddles on the contact surfaces of the body and legs, but we did not extend the leg length because the maximum slope angles in the target fields were small enough for stable motion of the robot.

Figure 6 (a) is a snapshot of the performance test on a snow slope. The slope angle was between 35° and
Figure 6: Field tests of Blade Walker: (a) traversing a snow-covered slope, (b) footprint on the snow-covered slope, (c) traversing a sand slope, (d) footprint on the sand slope.

Figure 7: Sequence of arm motion

40°. Figure 6 (b) shows tracks of the motion. The tracks show that the locomotion mechanism was suitable for climbing the slope without slippage.

Figure 6 (c) is a snapshot of the performance test on a sand slope. The slope angle was about 40°. Figure 6 (d) 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.

3.4 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 ~ 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.
4 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 (Figure 1-(right)).

Track Walker has not only a simple legged mechanism like that of Blade walker, but also a track locomotion function. Furthermore, two actuators are added to the rotational joints of the legs so that the robot has actuated subtracks (Figure 7.) 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 (Y. Okada et al., 2009).

4.1 Leg Mechanism

To enable legged locomotion, we adopted three parallel crank mechanisms 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 Figure 8.

According to the discussion in section 3.2, the leg length should be larger than the body length because usual weight of the body is larger than total weight of the legs. However, (1) long tracks decrease its cornering ability, (2) a typical maximum angle of weak slope is about 30 deg because of the internal friction angle, and (3) the body length can be extended by the subtrack mechanism shown in the next subsection. Based on the reasons above, we did not adopt longer legs for the Track Walker.

4.2 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 Figure 9.

4.3 Control system

One of the features of the locomotion is that it uses three parallel crank mechanisms 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 (R8/3048F-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 Figure 10.
Figure 8: Driving force transmission in the body

Figure 9: Driving force transmission in leg

Figure 10: System diagram
4.4 Performance tests

Performance tests were conducted to validate the advantages of the track mechanism, the subtracks mechanism, and the simple legged mechanism.

Before the tests, we mounted 30 mm lugs on the tracks to increase traction. Each lug was covered by rubber of 1 mm thickness to increase friction. Furthermore, sponge materials of 10 mm thickness were inserted between all lugs to increase the height of the track to prevent sand from getting inside. The track with lugs and an overview of the Track Walker are shown in Figure 11.

4.4.1 Performance test of traversability on weak soil

The first performance test was of traversability on weak soil.

Usually, the “slip ratio” is used for evaluation of traversability on weak ground, particularly, in the study field of Terramechanics (Wong, 1978). The slip ratio $s$ is defined in the following equation:

$$s = \frac{v_d - v}{v_d} = 1 - \frac{v}{v_d}$$

where $v_d$ denotes the reference velocity of the robot, and $v$ denotes the actual velocity.

In this performance test, we set a static velocity to the robot’s controller, and measured how long it took to traverse a fixed distance to calculate the slip ratio. The target environment was a sandy slope (about 35 deg) on a beach. The specifications of the environment are, a diameter of 0.1-1.0 mm for each sand particle, 40 deg internal frictional angle, and 1.29 gram/cm$^3$ sand density.

We conducted slope traversal tests using (1) simple legs’ motion, (2) side tracks only, and (3) all tracks. We conducted three trials in each condition. In the results, the track slipped constantly and the robot did not

Table 1: Specifications of Track Walker

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>520 mm~750 mm</td>
</tr>
<tr>
<td>Total width</td>
<td>480 mm</td>
</tr>
<tr>
<td>Total height</td>
<td>155 mm~245 mm</td>
</tr>
<tr>
<td>Leg unit size L×W×H</td>
<td>365 mm×100 mm×70 mm</td>
</tr>
<tr>
<td>Body unit size L×W×H</td>
<td>365 mm×200 mm×70 mm</td>
</tr>
<tr>
<td>Distance between crank axis</td>
<td>90 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>9.4 kg</td>
</tr>
</tbody>
</table>
move in case (2). However, the robot traversed the slope with the slip ratio $s = 0.3$ on average in case (3). Figure 12 shows the above results.

In comparison with other tracked robots on weak ground, JAXA reported a traversability of single-track mechanism on a weak slope (Wakabayashi et al., 2009). In this performance test, the slip ratio was about $0.3 - 0.6$ in condition that the slope angle was $25$ deg. Of course, it is difficult to compare directly because the sand conditions were different. However, our results confirm that our robot has a great capability for climbing steep and weak slopes. On the other hand, using simple legs’ motion, the traversal performance was not as good as expected. Frequent changes, in the center of gravity of the robot due to the legs’ motion, are believed to have caused slippage.

4.4.2 Comparison test between the tracks’ motion and the simple legs’ motion

The second performance test was a comparison between the tracks’ motion and the simple legs’ motion. In the case of homogeneous weak ground, the tracked mechanism performed with better traversability than the simple legs’ motion. However, in a real world environment, such as in volcanic areas, the weak soil would include large rocks. Therefore, we conducted a qualitative comparison test between the tracks’ motion and the simple legs’ motion on a weak gravel slope with a large block buried on the robot’s path.

Figure 13 shows a traversal result using the simple legs’ motion. The robot succeeded in surmounting the block, finally. On the other hand, in case of tracks’ motion, the left track dug deeply into the gravel when the right track collided with the block, and it failed traversing. According to the results above, the simple legged mechanism avoids collapsing the surface of a weak slope, and it increases traversability of the robot.
4.4.3 Performance test of a traversability on a step field

A step field, made by many wooden square poles, was used for our traversability evaluation for urban search and rescue robots on rough terrain (V. Molino et al., 2007). It is typically used in the annual RoboCupRescue field. In our laboratory, we had constructed 1m × 1m step field, with 100 square poles (10cm × 10cm) of different heights) to evaluate the traversability of small-sized tracked vehicles.

In this research, the third performance test was of traversability on the step field. We configured a simple slope, and the maximum step gap was 10cm, shown in Figure 14. In this performance test, the Track Walker failed to traverse with both simple legs' motion and standard tracks' motion. However, it successfully traversed the field with combination motions between the main track and the subtracks, shown in Figure 14. It took about 30 sec for surmounting the step-field-hill.

In RoboCupRescue, the above configuration of the step field is typically categorized in the red arena, which means the most difficult area in RoboCupRescue fields. Only some middle-sized tracked vehicles, such as Negotiator (iRobot), can traverse in such an area stably. In small-sized tracked vehicles, we can say that it has high traversability even if it was slow.

5 Field experiments of Track Walker in Asama mountain

To evaluate a traversability of the Track Walker, we conducted field experiments in one of the active volcanic areas, Mt. Asama, from 5th to 7th in October, 2010. Recently, in Japan, robotic exploration in volcanic areas is one of very important and challenging applications for mobile robots. Basically, such an environment is covered by sands and small/large rocks. In this section, we introduce an improvement of Track Walker, and report the field experiments.
Figure 15: Traversing experiments in Mt. Koasama (left) and Mt. Asama (right)

5.1 Target environment

Our target environment is an active volcano area that includes Mt. Asama (2,568 m) and Mt. Koasama (1,655 m). The restricted area of Mt. Asama is currently 500 m from the crater because of its small volcanic activity. There is a requirement of robotic surveillance in case of a volcanic eruption.

We chose two areas for field experiments in this area. One was around the height of 1,600 m above sea level of Mt. Koasama. It is composed of small rocks and sands, and the inclination angle of it is about 25 deg. Figure 15 (left) shows the environment. The other was around the height of 2,300 m above sea level of Mt. Asama. The surface is free of ground vegetation. It is composed of small/large rocks, and the inclination angle of it is 25-30 degree. Figure 15 (right) shows the environment. We can see that particle diameters of rocks in the right figure is relatively larger than the left figure. In both the environments, people have difficulty climbing.

5.2 Track Walker (Mt. Asama version)

To apply the Track Walker to such challenging environments, we added two functions for traversal experiments.

The first improvement is to mount a conventional long-range wireless LAN. In Japan, the communication range of the ZigBee devices, which were used in the ex-system of the Track Walker shown in the Figure 10, are very small, less than 10 m. To extend the communication range, we mount a 2.4 GHz conventional long-range wireless LAN on the robot to communicate within 50 m. It is not a solution of the long distance communication problem in case of a volcanic eruption, but at least, it is a reasonable range for traversal experiments of robots.

The second improvement is to mount a wide-angle camera in front of the robot. It is for a teleoperation experiments. The visual information is transmitted via wireless communication.

Because of the above modifications, the total weight of the robot became about 12 kg.

From the point of view of locomotion functions, three locomotion modes still exist: (1) conventional track mode, (b) simple leg mode, and (c) subtrack mode.
5.3 1st field experiment in Mt.Koasana

The first field experiment was conducted at a steep (about 25 deg) slope in Mt. Koasana. The surface of it included small rocks (5 mm ~ 20 mm) and sands, and it was very weak. Figure 15 (left) shows an experimental scene.

In this environment, the Track Walker successfully traversed along a path in the maximum angle of inclination. Basically, it traversed in the conventional track mode because it is the fastest mode. The improvement of lugs was effective to increase friction between tracks and the ground. However, sometimes, it slipped because of a change of surface inclination or weakness of the sand. In such case, we changed the locomotion mode from the conventional track to the simple leg mode. It worked fine to escape from slippery areas.

5.4 2nd field experiment in Mt.Asama

We conducted long traversal field experiments of the Track Walker along the maximum slope angle around the height of 2,300 m above sea level of Mt. Asama. The surface of it included small and large rocks shown in Figure 15 (right), and it was also very weak. It is obvious that the size of gravel is larger than Mt.Koasana. The reason is because the field of the 2nd experiment is closer to the crater.

In this field, the Track Walker successfully traversed along a path in the maximum angle of inclination. Basically, it was operated by the conventional track mode. When the track slipped, we changed the locomotion mode to the simple leg mode.

In case large bumps or potholes appeared in front of the robot, it was impossible to traverse by the above two modes. (Actually, when the robot stepped upon a middle-sized rock in case of simple-leg mode, the robot tipped over. At that time, it continued rolling down toward the base of the mountain until a student caught it.) Therefore, we changed to subtrack mode to negotiate the bumps or potholes. Figure 16 shows an example of subtrack mode to traverse a rocky field. Please keep in mind that the figure seems to show a traversal on a horizontal plane, but actually, the inclination is about 30 deg. It was the most robust mode in such a challenging environment. However, there are 2 disadvantages of the mode. The first disadvantage is the difficulty of teleoperation because the operator needs to control many degrees of freedoms. In this experiment, the skilled operator controlled the robot from just behind the robot. The second disadvantage is steering, because the total size of the track becomes very long in comparison with its tread.

5.5 discussions

Overall, the Track Walker traversed about 50 m in the Mt.Koasana field, and about 100 m in the Mt.Asama field. The speed of the robot was about 8 cm/s in the conventional track mode, 4 cm/s in the simple leg mode, and it took more than 30 sec to overcome a large bump in the subtrack mode. Figure 17 shows where the robot traversed in Mt.Asama and Mt.Koasana in Google Earth. Based on the field experiment, we concluded that three locomotion modes were effective to traverse on such a challenging environment. However, the size of the mechanism was currently a problem. To improve the speed and traversability of the robot, we are now developing a larger version of the mechanisms.

From the point of view of teleoperation, it was difficult to control the robot without direct vision. Particularly, in subtrack mode, the key to traverse large bumps or potholes was to obtain the status of the robot, but it was impossible to estimate from only a front camera’s view. Sensor-based autonomy should be included for control of subtrack.
6 Conclusions

In this article, we proposed a simple legged locomotion mechanism, called the Blade Walker, and analyzed its stability during locomotion. Initial field tests of it proved a capability of simple legged motion to traverse on weak soil. However, a disadvantage of the mechanism is that it cannot surmount a large bump. Therefore, we proposed leg-track hybrid locomotion mechanism called the Track Walker that fuses both legged locomotion and a track mechanism. Initial tests have demonstrated the usefulness of its basic functions. Finally, we reported field tests using the Track Walker in Mt. Asama and proved its high-capability and found some problems.

We plan three future work elements. (1) We will develop a new version of Track Walker. Based on the results of our experiments, we have determined that the most important design elements for mobile robots, to improve mobility on such steep slopes, are: light weight, low center of gravity, and large contact area. Therefore, the new version will be 1.5 times larger than the current version. Furthermore, we will mount a tilt sensor and gyroscopes to enable a tip-resistant system. (2) We will perform a stability analysis for side roll-over of the robot on steep slopes. In this paper, we introduce a stability analysis in case that the robot climbs straight up a steep slope, however, the robot will likely also traverse steep slopes laterally in exploration missions. (3) We will research slip mechanisms of tracks on weak soil. According to our experiments, we understand that slippage on sand is also a serious issue in such a hazard environment. Our research group has research experience in slippage between wheels and weak soil (Ishigami et al., 2007) based on the Terramechanics (Wong, 1978). Therefore, we will apply the analysis method to the slippage problem of the Track Walker on weak soil.
Figure 17: Experimental locations

References


