STUDY ON A REASONABLE Locomotion OF A Multi-Legged Rover Using Its Dynamic Motion

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ABSTRACT
This study deals with dynamic locomotion of an 8-legged planetary exploration rover with a spherically isotropic leg-arrangement to explore rough terrains. Because of its particular leg-arrangement, the 8-legged rover can be mobile with "dynamic rotational motion" in addition to a standard walking motion. By adopting the rotational motion, the rover is expected to climb over small bumps by utilizing the rotational energy like a rolling ball. Moreover, the locomotion works on a slippery terrain, because the vertical component of the leg’s force reacted to the terrain surface can induce the rotational motion. The effects of the kick velocity and timing on the locomotive performance are investigated on terrain’s different frictions and slope angles.

1. INTRODUCTION
Many lunar and planetary exploration rovers have been researched [1-7] since a great success of Mars Exploration Rovers [8]. Most of these rovers have wheel locomotion mechanisms. However, such wheeled mechanisms encounter difficulty in moving on rough terrains. Thus for exploration in rough terrains, multi-legged rovers have been studied [9-12]. Although the shape and locomotion mechanism of the legged rovers are modelled after those of animals or insects, those rovers have essentially a risk of overturning. To solve this overturn problem, most of researchers in this field have tried to improve their control algorithms more sophisticated. However, this approach results in very complicated algorithms, and even with such algorithms, the legged rover is still unreliable in practical planetary terrains with unexpected environments.

To traverse in such unexpected rough terrains, we have proposed a multi-legged rover with spherically isotropic leg-arrangement shown in Fig.1. This rover has legs radially attached on the center body. Since each leg consists of three links connected with three rotational joints, the foot can move in three-dimensional space. Therefore, even after the rover overturns, it can keep mobility with legs touching on the terrain. This indicates that our approach to solve the overturn problem is to improve the rover’s shape rather than control algorithms. In [13], an efficient leg-arrangement and design procedure for the leg’s link-lengths are discussed, and [14] discusses an efficient attitude for

![Figure 1. Schematic of the 8-legged rover with an isotropic leg arrangement](image-url)
Walking of the rover.

Planetary exploration rovers are sometimes required to climb a slope steeper than the maximum angle the rovers can climb up in a walking motion. Furthermore, the rovers may be stuck on a loose soil such as lunar regolith, because their legs slip easily. Therefore, it may be hard for the rover to traverse in rough terrains by a standard walk. In these terrains, our rover can exhibit a "dynamic rotational motion" introduced in [15]. This new locomotion is operated by kicking motion of the rover's legs. Reference [15] investigates an attitude for the locomotion to reduce the shock for kicking.

In this paper, the effects of the kick velocity and timing on the locomotive performance are investigated on terrain's different frictions and slope angles.

2. DYNAMIC ROTATIONAL MOTION

Fig.2 shows an illustration of a legged rover in the dynamic rotational motion: Leg 1 kicks the terrain surface (Fig.2(a)), the rover starts to rotate around the foot of Leg 2 (Fig.2(b)), and the rover rotates until Leg 3 touches on the terrain (Fig.2(c)) if the initial rotational velocity is enough. By repeating this rotational motion, the rover's body can be transferred forward. This motion resembles the rotation of a rimless wheel [16].

In the traditional walking motion, legged rovers are required to swing up and down their legs carefully to keep an equilibrium state with calculating a position of the mass center of the whole system. However, the dynamic rotational motion does not calculate the mass balance. Furthermore, the traditional walking motion thrusts the rover's main body forward by utilizing the friction force between its legs and terrain surface. Thus on a slippery surface, a necessary thrust force may not be obtained. On the other hand, the dynamic rotational motion can be induced by kicking motion on a terrain surface, and the vertical component of the kicking force to the surface can generate the rotational motion.

Reference [15] deals with the dynamic rotational motion operated intermittently; kicking motion is generated after Leg 3 in Fig.2(c) touches on the surface. The discussion, however, indicates that at the touchdown timing, the impact force between the legs and surface generates an inverse directional torque and the rover's rotational energy is lost. Thus, for a continuous and efficient dynamic rotational motion, kick velocity and timing are discussed in the following section.

3. ANALYTICAL MODEL

For simplicity, this paper deals with the rover's motion in the two-dimensional space as shown in Fig.3. Furthermore, we control only the rover's lower-side legs,
although a movement of the upper-side legs can affect the rover’s rotational motion. To distinguish the touching legs on the surface during the locomotion, we call the kicking leg as a backward leg and the touching leg after the rotation as a forward leg, respectively (for example, in Fig.2(a), Leg 1 is the backward leg and Leg 3 is the forward leg).

When a force generated by kicking at a proper timing can accelerate rotational motion, the efficiency of the dynamic rotational motion is improved. The kicking force generates a reaction force from the terrain surface, and the reaction force can be separated into the normal and tangential components to the surface as shown in Fig.4. This paper assumes that the normal component $F_n$ is proportional to the normal component of the kicking velocity to the terrain surface, and that the duration of kicking is instantaneous. Furthermore, by Coulomb’s law, we express the tangential component $F_t$ as

$$ F_t = -\mu F_n \text{sgn}(G_{\text{toe}}) $$  \hspace{1cm} (1)

where $\mu$ is the friction coefficient and $G_{\text{toe}}$ is a toe velocity along the terrain surface. By using Eq. 1, the angle of the kicking force $\xi$ in Fig.4 can be expressed as

$$ \xi = \tan^{-1}\left( \frac{F_n}{F_t} \right) = \tan^{-1}\left( \frac{\text{sgn}(G_{\text{toe}})}{\mu} \right) $$ \hspace{1cm} (2)

This expression indicates that the direction of the kicking force is dependent only on the friction coefficient of the terrain surface.

When a kicking force is denoted by $\mathbf{F}_{\text{kick}}$, a torque around the center of the rover’s body is expressed as

$$ T = |\mathbf{F}_{\text{kick}}| \sin(\xi - \lambda) $$ \hspace{1cm} (3)

where $\ell$ is the distance between the impact toe and the center of the rover’s body, and $\lambda$ is the angle indicating the direction of the center of the rover’s body relative to the impact toe (see Fig.4). By using Eq. 3 and the following relation

$$ |\mathbf{F}_{\text{kick}}| = \frac{F_n}{\cos(\frac{\pi}{2} - \xi)} = \frac{F_n}{\sin \xi}, $$ \hspace{1cm} (4)

the torque can be expressed as

$$ T = \frac{F_{n\ell}}{\sin \xi}. $$ \hspace{1cm} (5)

In Eq. 5, $\lambda$ changes according to the kick timing in the rotating motion. When the normal component of the kicking velocity is constant, $F_n$ is constant, and thus Eq. 5 indicates the normalized torque. By using this equation, we investigate an influence of $\lambda$ and $\mu$ on the torque generated by a kicking force.

The results are shown in Fig.5. Note that $\xi = \tan^{-1}(1/\mu)$ in Eq. 2, since $G_{\text{toe}} < 0$ to thrust the rover’s body forward. Fig.5(a) shows the normalized torque according to the angle $\lambda$ for several friction coefficients $\mu$. This figure indicates that for every case of $\mu$, the normalized torque becomes larger as $\lambda$ is lower. On the other hand, Fig.5(b) shows the normalized torque according to the friction coefficient $\mu$ for several $\lambda$.

Figure 5. Normalized torque obtained around the rover’s body by kicking.
This figure indicates that for every case of $\lambda$, the normalized torque becomes lower as $\mu$ is larger. However, it also should be noted that as $\mu$ is larger, a translational energy along the terrain surface becomes larger, since $F_z$ becomes larger. Thus, Fig.5 implies that to obtain the larger rotation torque, the rover should kick the terrain surface at the timing when $\lambda$ is as small as possible. However, the lowest value of $\lambda$ is restricted by the geometric condition when the forward legs touch on the surface. Therefore, the conclusion of this discussion is that the rover should kick the terrain surface just before the touchdown of the forward legs to obtain the larger rotation torque.

4. SIMULATION

With the dynamics simulator Open Dynamics Engine, we have produced the dynamics model of the rover considering the size and weight of our test bed as shown in Tab.1. By utilizing this simulator, we investigate the influence of the kick timing on the dynamic rotational motion, and a history of the body velocity during the motion.

Results of the simulations are shown in Figs.6-8. In these figures, the friction coefficient $\mu$ and slope angle $\delta$ of the terrain surface are varied, and the kicking interval is changed with 0.1 seconds increments in the graphs. The gravity is set to 1/6 G and the reflection coefficient of the terrain surface is assumed to be zero for the exploration on a lunar loose soil. In Fig.3, the representative posture before kicking motion is specified from [15] as follows.

- $h=0.18$[m]
- Toe position of the forward leg: $(B_x, B_z)=(h, \pm R)$
- Toe position of the backward leg: $(B_x, B_z)=(-h, \pm R)$

For the rotational motion, the rover stretches the backward leg, and the stretch length denoted by $h_{kick}$ in Fig.3 is 0.088 m. The rover controls the joints’ angular velocities as follows.

$$\dot{\theta}_i = k_p (\hat{\theta}_i - \theta_i) \quad (6)$$

where $k_p$, $\theta_i$ and $\hat{\theta}_i$ represent the proportional gain, a current angle and a desirable angle of the $i$-th joint respectively. $k_p$ is set to 16.5. However, according to the motor’s specification of the test bed, the maximum speed of the joint is limited to 6.98 rad/s. The kicking velocity is obtained as the result of this proportional control of the joints’ angular velocities.

In order to obtain the rotational energy as much as possible, it is preferable that the kick direction is adjusted to the slope angle of the terrain surface. However, this strategy requires detecting the slope angle. Thus, in the simulation, the kick direction is fixed to the body as follow. In Fig.3, the kick direction is parallel to $-B_z$ direction when the backward leg is Leg 1, and the direction is parallel to $+B_x$ direction when the backward leg is Leg 2.

Fig.6 is the result for $\mu=0.6$ and $\delta=0[\text{deg}]$. In Fig.6(a)-(e), the second kicking motion is operated before the first touchdown of the forward legs. In these cases, it is found that the dynamic rotation is accomplished because the value of the body velocity along the terrain surface is consistently positive. Furthermore, as the kicking interval becomes longer, the velocity in the second rotation becomes higher. On the other hand in Fig.6(f), the kicking and the touchdown occur almost at the same time. As a result, the kick force is spent to jump the rover’s body from the surface. Thus, the body velocity along the terrain surface is lower than in Fig.6(e), although the dynamic rotational motion is accomplished. In Fig.6(g), the second kicking motion is operated shortly after the first touchdown of the forward legs. Since the most of rotational velocity is reduced due to the first touchdown of the forward legs, the second rotation is barely accomplished. However in Fig.6(h), the second rotation is failed, because the rotational velocity is completely lost by the first touchdown. Consequently, the reasonable kick interval to obtain the rover’s rotational energy as much as possible is 2.4 s.

Fig.7 is the result for $\mu=1.0$ and $\delta=0[\text{deg}]$. In Fig.7(a)-(d), the second kicking motion is operated before the first touchdown of the forward legs. In these cases, the dynamic rotational motion is accomplished and the velocity in the second rotation becomes higher as the kicking interval is longer. In Fig.7(e), the kicking and the touchdown occur almost at the same time. In this case, the body velocity along the terrain surface is lower than in Fig.7(d), although the dynamic rotational motion is accomplished. Contrary to the case of Fig.6,

<table>
<thead>
<tr>
<th>symbol</th>
<th>explanation</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>Radius of the circumscribed sphere of the center body</td>
<td>$0.088$ m</td>
</tr>
<tr>
<td>$l_1$</td>
<td>Length of 1st link</td>
<td>$0.057$ m</td>
</tr>
<tr>
<td>$l_2$</td>
<td>Length of 2nd link</td>
<td>$0.0945$ m</td>
</tr>
<tr>
<td>$l_3$</td>
<td>Length of 3rd link</td>
<td>$0.1165$ m</td>
</tr>
<tr>
<td>$M$</td>
<td>Overall weight</td>
<td>$3.22$ kg</td>
</tr>
<tr>
<td>$m$</td>
<td>Weight of each link</td>
<td>$0.065$ kg</td>
</tr>
</tbody>
</table>

**Table 1. Rover’s size and weight in the simulation**


as shown in Fig.7(f)-(h), the second rotation is accomplished even when the kick motion is operated a little later of the touchdown. This is because a larger friction force generates a larger translational energy along the terrain surface. As a consequence, to obtain the rover’s rotational energy as much as possible, the reasonable kick interval is 1.1 s.

Fig.8 is the result for \( \mu=1.0 \) and \( \delta=5.0[\text{deg}] \). The rover’s velocity at the second rotation becomes higher when the kick interval is 1.4 s. At this interval, the kicking motion is operated just before the touchdown of the forward legs, and this interval is longer than the case for the horizontal terrain (\( \delta=0.0[\text{deg}] \)).

From the above results, we can summarize as follows:

(i) Once the forward legs touches on the terrain surface after rotation, the second rotation becomes difficult, because the stored rotational energy is reduced or fully lost. Thus the kicking motion should be operated when the rotational energy is stored as much as possible not to brake the rotational motion.

(ii) Obtaining the kicking force enough to generate the rotation on the terrain with a lower friction coefficient becomes difficult.

It also should be noted on the kick timing that the kick direction is nearly vertical to the terrain surface, and the normal component of the kicking force to the surface becomes large. To wait for such timing, the kick interval should be longer on the terrain with a lower friction coefficient and steeper slope.
5. SUMMARY

This paper has treated the dynamic rotational motion of the multi-legged rover with spherically isotropic leg-arrangement as a new locomotion using its particular leg-distribution. In the locomotion, the rotational energy can be increased by adjusting the kick timing, and the rover can move on the terrain with a low friction and steep slope.

Nonetheless, it is very hard to start the rotation on a steep slope. Therefore, it may be reasonable that the rover tries to move on a steep terrain after storing the rotational energy enough to generate the rotation on a relatively horizontal terrain.

6. REFERENCES


