A Center-Actuated Walking Robot That Takes Advantage of Extraterrestrial Resources

Masafumi IAI1) and Ken FUJWARA2)

1)Axelspace Corporation, Tokyo, Japan.
2) The Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan

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This paper proposes a concept of a center-actuated walking robot whose design is suitable for use of the parts fabricated from in-situ resources on the Moon, Mars, and other planetary bodies. The core idea of this concept is concentrating any actuator or movable components at one section of the robot body so that the rest of the body can be manufactured and assembled with limited resources and capabilities that are expected in the early stage of manufacturing away from the Earth. Justification of this concept is made from the economical point of view as well as other aspects. As a walking mechanism, the proposed one consists of two rigid structures, which serve as legs, interconnected by one 6 degree-of-freedom actuator module (e.g. Gough-Stewart mechanism). It can be classified as a type of the walking mechanism with reduced degrees-of-freedom, which significantly reduces mechanical complexity, and thus makes a walking planetary rover a realistic option. Simulation results proved that a tetrapod based on the proposed concept can employ both static and dynamic gaits, such as static walk, trot, and pace. Potential of the concept, for example, reusability as man-made in-situ resources, is explored and future research topics are identified. Designers of space robots near future would be required to take advantage of in-situ resources. The work presented here is aimed at pioneering the robot design in the era of extraterrestrial resources.

Key Words: Walking Robot, Planetary Rover, Lunar Rover, Robotic Gait, In-Situ Resource Utilization

1. Introduction

As human is expanding the sphere of their activity outward to the low earth orbit, to the Earth-Moon system, and beyond, it must be essential exploiting locally available extraterrestrial resources to support their activity away from the Earth rather than relying on the Earth for supply of necessary resources and products.

The idea of using the extraterrestrial resources has long been discussed. It is a key technology to enable the shift of space activities from one time mission to the long term activity or settlement on the Moon or other planetary bodies.

Various studies have been and are being done on in-situ resource utilization mainly on the Moon. Mostly they are aimed at producing basic materials like oxygen, concrete, and brick. Also use of soil as it is has been proposed as physical shield against micrometeorite, galactic cosmic ray, and thermal extremes. In addition, assuming the availability of lunar-made concrete, a habitable concrete structure system on the Moon has been proposed.

Although those studies have proven the possibility of various materials manufactured in-situ from local extraterrestrial resources, it is not likely that every part of a sophisticated mechatronic system, e.g., a rover, can be made from in-situ resources in the beginning of in-situ resource utilization. It is rather reasonable to start with a product which is composed of a few parts made on the Moon and the rest made on the Earth. The proportion of Moon-made parts should then be increased on a step-by-step basis before achieving a product completely made from the locally available lunar resources. So the design of a mechatronics system needs to be compatible with such gradual transition from 100% Earth-made to 100% Moon-made. However, little attention has been paid to such needs in past robotics research.

This paper proposes a concept of center-actuated walking, which leads to the design of a walking robotic rover that is suitable for incorporating both Earth-made parts and Moon-made parts as an early realization of in-situ resource utilization. Other benefits of this design are explained below including economical consideration. Results of dynamics simulation are presented to show that the center-actuated walking can employ both static and dynamic gaits.

This paper focuses on an application of the concept to the quadrupedal walking mechanism although other configurations are possible. Moon is mentioned exclusively. Nevertheless this concept can be useful on any planetary bodies as well as on the Earth.

2. Review of Related Literature

2.1. Walking with reduced degrees of freedom

The idea of center-actuated walking may be considered as a type of walking with reduced degrees of freedom (DOF), which have studied by other researchers. Walking robots in general suffer various difficulties due to the fact that they tend to have higher DOF, which is a result of imitating the anatomy of animals. Ordinary walking robots have 3 or more DOF for each leg, which totals 12 or more DOF for a tetrapod. The higher DOF of a mechanical system means more actuators and
joints, which result in that a machine becomes heavier, more costly, less reliable, harder to design and optimize its control algorithm, and more difficult in maintenance. So researchers have made efforts to achieve walking mechanisms with reduced DOF.

Yoneda et al. suggested at least 4 DOF in total are necessary to allow a tetrapod to give 3 DOF to any one of its four feet at a time. Genta and Amatiproposed a walking mechanism with low DOF (8 DOF for a hexapod), and pointed out that reduction in DOF makes walking machines promising as planetary rovers.

A walking robot composed of two rigid frames interconnected by actuators has been design by others. Their designs, however, are only aimed at static walking, or unable to be a stable platform. The design proposed here, i.e. center-actuated walking, differs in that the design has good balance of stability and instability so both of static and dynamic gaits are possible, which gives a robot wider range of speed and maneuverability.

2.2. Past lunar and mars rovers

In the past space missions, no legged rover has been used whereas wheeled rovers were successfully operated: 4 wheeled (Apollo Lunar Roving Vehicles), 6 wheeled (Sojourner, Spirit, and Opportunity), and 8 wheeled (Lunokhod-1 and 2).

Preventing from getting stuck in loose soil is one of the major concerns in designing and operating a rover. As a recent example, Spirit rover became immobile in loose soil, which resulted in the termination of its mission. Immobility is the last thing that mission planners want to face. To avoid such incident, various efforts are made in different areas such as control of wheel speed, visual odometry, and planning of exploration paths.

However, rather than being cautious about loose soil, more robust strategy is to design a rover capable of escaping from loose area when a rover is partially submerged in soil. Legged rovers in contrast to wheeled rovers can be such a solution. Therefore, ability of walking is essential aspect of the proposed design.

3. Concept

Center-actuated walking is a concept design of a legged robot that can incorporate the less-sophisticated parts produced by extraterrestrial in-situ manufacturing. It is aimed at pioneering realistic utilization of the mechanical parts made of in-situ resources. The core idea of this concept is concentrating any actuator or movable components at one section of the robot body so that the rest of the body can be manufactured and assembled with limited capabilities and resources that are expected in the early stage of manufacturing away from the Earth.

The design consists of two rigid structures that serve as legs and one 6 DOF actuator that interconnects those two rigid structures. As the most basic implementation of the center-actuated walking, a four legged robot is discussed although this concept is not limited to a tetrapod. Its uniqueness can be highlighted by comparing it with conventional designs of robots.

First, the design of center-actuated walking gives a priority to separation of a movable segment from solid segments by concentrating movable parts, such as actuators and joints, in one segment of the robot body (Fig. 1). This separation is advantageous when the lunar-made parts are used as discussed later.

Contrary, conventional designs of a robot have movable parts placed throughout its body because a designer of such a robot wants optimal layout of mechanical parts to achieve best mobility assuming little restriction in manufacturing and assembling.

Second, the center-actuated walking is characterized by use of only one 6 DOF actuator module rather than separate actuators located throughout the robot body. It is important to note that a 6 DOF mechanism is not a specific design for the proposed robot, but the proposed robot is made suitable to be actuated by a general design of a 6 DOF mechanism.

The reason for choosing 6 DOF is its generality, not trying to minimize DOF. As the basic kinematics principle states that 6 DOF is necessary and sufficient to determine any relative position of two rigid bodies, its use is not limited to a specific application. Thus it has a potential to be reused as man-made in-situ resources (Fig. 2).

An actual implementation of 6 DOF mechanisms may be the Gough-Stewart (GS) mechanism or any other parallel or serial mechanisms with actuated 6 DOF. The following subsections details the benefits of this concept from several points of view.
3.1. Economical reasoning behind use of lunar products

The purpose of using in-situ resources is to cut the cost of launching and transporting the materials from the Earth to the Moon. Jones has analyzed the economic viability of production on the Moon. In contrast to production in the low Earth orbit where high unit value products are more profitable, he concluded “feasible lunar product in early stage will be low unit value products that is a product for which transport costs are dominant if made on the earth and transported to the Moon.”

Based on Jones’ analysis, Fig. 3 illustrates the cost breakdown of a product used on the Moon in four scenarios generated by two variables: the location of fabrication (on the Earth or on the Moon) and the unit value of the product (low or high). The unit value here means the value per a unit mass.

The production location could affect the production cost, which is likely to be more expensive on the Moon than on the Earth. The unit value of the product determines the relative significance of the transportation cost. The transportation cost of the low unit value products takes up larger portion of the total cost than that of the high unit value products. Thus, if the low unit value product was made on the Moon, the reduction in the transportation cost would result in substantial decrease in the total cost.

Contrary, for high unit value products, the proportion of the transportation cost from the Earth is less. If the production location is switched from the Earth to the Moon for high unit value products, reduction in transportation cost may be cancelled by increase in production cost. Therefore, production on the Moon can be economical if the reduction of transportation cost outweighs the increase of production cost. By this analysis, Jones concluded that low unit value products would be good to be made on the Moon.

<table>
<thead>
<tr>
<th>Low unit value products</th>
<th>High unit value products</th>
</tr>
</thead>
<tbody>
<tr>
<td>If made on the Earth</td>
<td>Trans. Cost</td>
</tr>
<tr>
<td>Trans. Cost</td>
<td>Trans. Cost</td>
</tr>
<tr>
<td>Prod. Cost</td>
<td>Prod. Cost</td>
</tr>
</tbody>
</table>

Fig. 3. Cost breakdown of a product used on the Moon.

In addition to Jones’ analysis on unit value, it is expected that variety of available raw materials, precision of manufacturing and complexity of assembling would be limited on the Moon. Thus, these factors have to be considered. The parts worth producing on the Moon are the ones that have low unit value, are tolerant of low precision, and are made only of the materials available on the Moon. They are termed ‘low quality parts’ in this paper.

Any types of parts that do not meet the criteria of low quality part shall be made on the Earth and transported to the Moon, which are called ‘high quality parts’ here.

This above consideration leads to a robot composed of the Earth-made high-quality parts and the Moon-made low-quality parts. It is, then, required that the parts from the Earth and the parts made on the Moon have to be assembled on the Moon. Assembling is not an easy task when it is done away from the Earth. Thus the need of assembly has to be reduced as much as possible.

Here the concept of center-actuated walking proves itself beneficial in simplifying assembling. Since all of the high quality parts are concentrated into one segment of the robot body, only one segment per a robot is required to be transported from the Earth. Then that segment is attached to two solid parts made on the Moon. Other robots in Fig. 1 (Sojourner has operated on Mars; ATHLETE is an experimental lunar robot 16); RHex 17) and TITAN VIII 18) are mostly research oriented) would require a prohibitively complicated assembly procedure if low and high quality parts were to be integrated on the Moon.

3.2. Possible gaits

The center-actuated walking tetrapod uses 6 DOF to achieve static and dynamic gaits. The next section is going to prove by simulation that static walk, trot, and pace are achievable.

Nevertheless, the proposed design should allow more types of gaits such as bound gait and bipedal gait if appropriate control algorithm is used (Fig. 4). Generality and versatility of the 6 DOF mechanism make the robot very simple, which is always favorable, while use of rigid structures results in some limitations.

The center-actuated walking tetrapod can give only 2 DOF to the tip of a swing leg when three other legs are in contact with the ground. If more DOF is needed, the dynamic gait should be employed. Another limitation is that the robot has to switch the direction of traverse according to the type of gaits. The direction of static walk and trot is perpendicular to that of pace. This is the cost of achieving various gaits using the simple mechanical design of center-actuated walking—two rigid structures connected by one 6 DOF module.

3.3. Reusability as man-made in-situ resource

When talking about in-situ resources, man-made in-situ resources should not be forgotten, in addition to natural in-situ resources like regolith. As repeated visits to the Moon are expected in coming decades, it would be helpful if facilities, equipment or parts brought to the Moon in earlier missions are used as a part of another new system in the following missions.

The 6 DOF actuator module of the proposed robot can become a valuable man-made in-situ resource for later missions. The 6 DOF actuator assembly sent to the Moon as...
part of a proposed robot may be reused as an antenna pointing actuator, a part of more sophisticated robot, or various other applications requiring actuators (Fig. 2). Such reuse inevitably requires disassembling and reassembling, which could be done by astronauts, by another robot, or by self-reconfiguration capability. As a 6 DOF module can move by its own like an inch worm, self-reconfiguration should be a challenging future research topic.

4. Simulation

Numerical simulation was conducted to prove that both static and dynamic gaits were possible with the proposed design. The results presented below are based on tentative choice of parameters, thus not meant to present optimized or best performance of the design. The simulation code was written in C++ using a dynamics simulation library called Open Dynamics Engine (ODE).

Fig. 5 shows a sketch of the robot with dimensions and associated coordinate frames. A 6 DOF mechanism is implemented as a combination of a spherical joint (3DOF), a universal joint (2DOF), and a linear slider (1DOF), all of which are actuated.

Two rigid parts, called bodies 1 and 2, attached to the ends of the 6 DOF mechanism have the shape identical to each other, whose dimensions are defined by A, H, and W. Their positions and orientations are represented by coordinate frames, \{A1\} and \{A2\}, respectively.

![Fig. 5. Shape of tetrapod in simulation. Cylinder represents the 6 DOF actuator, and thick line represents the rigid structures. Coordinate frames \{A1\} and \{A2\} are fixed to the rigid structures to the right and left, respectively.](image)

The relative position of body 2 or \{A2\} with respect to body 1 or \{A1\} was described by the parameters, \(\Psi_1, \Psi_2, \Psi_3, \theta_1, \theta_2, \) and \(\delta L\) (Fig. 6).

![Fig. 6. Relative Position and Orientation of Two Rigid Structures.](image)

An arbitrary vector, \(p^1\), expressed in \{A2\} is related to a vector, \(p^0\), expressed in \{A1\} by

\[
p^0 = T_1^0 \cdot (p^1 - r_1^0)
\]

where \(T_1^0\) is a coordinate transformation matrix from \{A1\} to \{A2\}, and \(r_1^0\) is the position vector of the origin of \{A2\} expressed in \{A1\}. \(T_1^0\) and \(r_1^0\) are defined as

\[
T_1^0 = R_4(\Psi_3) R_3(\Psi_2) R_2(\Psi_1) \quad \text{for} \quad \delta L = L_0 + \delta L
\]

in which \(R_i(\cdot)\) is a 3×3 rotation matrix of a rotation angle, \(\cdot\), about axis \(i\); \(L_0\) is the initial distance between the origins of \{A1\} and \{A2\}; \(x = [1 \ 0 \ 0]^T\).

4.1. Gaits and parameter profiles

The simulated robot locomotes using three types of gaits: static walk, trot, and pace. The static walk keeps three legs in contact with the ground and the center of mass within the triangle formed by the contact points of those three legs. The trot moves the diagonal pairs of legs at the same time. It includes dynamic phase where only two legs in contact with the ground. The pace also has the dynamic phase and moves two legs on the same side of the body together.

In addition to choice of three gaits, the size of the robot body is set to three different levels. Thus, nine conditions were tested as listed in Table 1. The dimensions, A, H, and, W, are set equal to each other for static walk and trot. Yet, for the pace gait, the value of A has to be smaller than H or W.

![Table 1. Travel speed of each gait with various leg dimensions.](image)

<table>
<thead>
<tr>
<th>Gait</th>
<th>A (m)</th>
<th>H (m)</th>
<th>W (m)</th>
<th>V (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Walk</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>30.5</td>
</tr>
<tr>
<td>30s/cycle</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Trot</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>30.7</td>
</tr>
<tr>
<td>30s/cycle</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>3.2</td>
</tr>
<tr>
<td>Pace</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>184.8</td>
</tr>
<tr>
<td>2.5s/cycle</td>
<td>0.3</td>
<td>1</td>
<td>1</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

A gait is given as a predefined trajectory in the 6-dimensional parameter space, which is input to a PD controller so that the actuators follow that trajectory. The same trajectory was applied regardless of the size of the robot. The values of those parameters were logged. They were, then, converted to the link lengths of the GS mechanism using the Jacobian matrix. Also the robot position is calculated at every time step by averaging the position vectors of the four feet.

4.2. Simulation results and discussion

Table 1 summarizes the average traversing speed for nine conditions. For static walk and trot, the average speed is proportional to the size of the robot body. For pace, the large size robot makes progress six times faster than the medium size robot; the small size robot failed to move forward recording negative speed. The possible cause of this failure is the effect of bouncing and the choice of one of the parameters that defines the trajectory.

As the feet make contact with the ground, the robot inevitably bounces off, which could have interfered with locomotion to varied degrees depending on the simulation conditions. Another possible cause of the failure is\(\delta L\), being one of the six parameters defining the gaits. Improvement can be made by replacing \(\delta L\) with the ratio of the distance change to the initial distance.

Figures 7, 8, and 9 show the robot position for static walk, trot, and pace, respectively, over ten cycles or more of a gait. The position plots of all of the gait shows that the robot
drifts off a straight line. Such drift occurred because the movement of each actuator simply follows the predefined trajectory. To correct it, the resulting orientation of the robot should be fed back to the controller.

Figures 10, 11, and 12 show two cycles of link length history of the GS module for three gaits. The link lengths fluctuate several times in a cycle of gait.

The number of alternation between increase and decrease is larger in static walk than in trot, and larger in trot than in pace. Also the peak to peak difference in the link length is largest for static walk and smallest for pace. These observations coincide with an intuition that static walk can be slower than trot, which can be slower than pace if the allowed maximum speed of length change is bounded.

5. Conclusions and Future Work

This paper proposed a design concept called center-actuated walking, that is compatible with gradual and economical use of local extraterrestrial resources. The key point is separation of high quality parts brought from the Earth and low quality parts manufactured in-situ. Simulation results proved that the proposed design can employ static walk, trot, and pace. Also the paper identified its potential and future research topics.

Designers of space robots near future, including planetary rovers, would be required to take advantage of in-situ resources in order to reduce the mass to be launched, to allow robots to be updated in-situ, and to expand space activities. The work presented here is aimed at pioneering the robot design in the era of extraterrestrial resources.

References

3) Ishikawa, N., Karamori, H. and Okada, T.: The Possibility of Concrete Production on the Moon, Proceedings of The Second Conference on...


