Analysis on Motion Control Based on Reaction Null Space for Ground Grip Robot on an Asteroid

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The surface of an asteroid features an irregular terrain and microgravity. Therefore, robotic exploration in an asteroid requires the adoption of an appropriate locomotion strategy. Moreover, an exploration robot is expected to be capable of moving to an area of scientific interest. In response to this, we have proposed a ground grip robot that moves by gripping the surface like a rock climber. By gripping the surface, the robot can prevent unintended flotation and rotation while propelling itself across the surface. When the idling arm is moved while the supporting arm’s gripper is attached to the surface, all of the reaction forces act on the gripper. If the gripping force is to be exceeded, however, the robot could come adrift from the surface. In this paper, therefore, we propose a motion control method that does not act the reaction force on the gripper by utilizing the reaction null-space. Additionally, the tip position trajectory is generated as an ellipse to enable smooth movement and eliminate any frictional force. This control law was validated by a planar dynamic simulation. The simulation model assumes a dual-armed robot with three degrees of freedom (DOF) in each arm, while the uneven surface is simulated under certain conditions. As a result, the robot was able to move continuously with reactionless motion and the propriety of the control law was confirmed.

Key Words: Asteroid Exploration, Ground Grip Robot, Reaction Null-Space, Locomotive Simulation

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>total number of links</td>
</tr>
<tr>
<td>$F$</td>
<td>force</td>
</tr>
<tr>
<td>$\tau$</td>
<td>torque</td>
</tr>
<tr>
<td>$H$</td>
<td>inertia matrix</td>
</tr>
<tr>
<td>$x$</td>
<td>position</td>
</tr>
<tr>
<td>$\phi$</td>
<td>joint angle</td>
</tr>
<tr>
<td>$c$</td>
<td>nonlinear velocity-dependent term</td>
</tr>
<tr>
<td>$J$</td>
<td>Jacobian matrix</td>
</tr>
<tr>
<td>$K$</td>
<td>control gain matrix</td>
</tr>
<tr>
<td>$R$</td>
<td>projector onto null-space</td>
</tr>
<tr>
<td>$\xi$</td>
<td>arbitrary vector</td>
</tr>
<tr>
<td>$r$</td>
<td>central coordinate of ellipse</td>
</tr>
<tr>
<td>$a$</td>
<td>length of long axis</td>
</tr>
<tr>
<td>$b$</td>
<td>length of short axis</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle between long axis and tip position</td>
</tr>
<tr>
<td>$\psi$</td>
<td>inclination of ellipse</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>tangent angle of ellipse at initial tip position</td>
</tr>
<tr>
<td>$\beta$</td>
<td>tangent angle of ellipse at desired tip position</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>acceptable error range</td>
</tr>
<tr>
<td>$P$</td>
<td>linear momentum</td>
</tr>
<tr>
<td>$L$</td>
<td>angular momentum</td>
</tr>
<tr>
<td>$\xi$</td>
<td>arbitrary vector</td>
</tr>
<tr>
<td>$k$</td>
<td>control gain of scalar value</td>
</tr>
</tbody>
</table>

Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>supporting arm</td>
</tr>
<tr>
<td>$m$</td>
<td>manipulator</td>
</tr>
<tr>
<td>$sm$</td>
<td>coupling of supporting arm and manipulator</td>
</tr>
<tr>
<td>$e$</td>
<td>tip of idling arm</td>
</tr>
<tr>
<td>$d$</td>
<td>desired value</td>
</tr>
<tr>
<td>$+$</td>
<td>pseudo inverse</td>
</tr>
<tr>
<td>$0$</td>
<td>initial value</td>
</tr>
<tr>
<td>$\wedge$</td>
<td>revision of constraint condition</td>
</tr>
</tbody>
</table>

1. Introduction

Asteroids are likely to hold clues that could reveal the origin of our solar system and its evolutionary process. Thus, asteroid exploration has become an important scientific objective in space development. In particular, unmanned exploration using robots is regarded as being an effective method for investigating harsh terrain such as the rock shadows and dips in the surface of an asteroid. Any such robot is required to have the ability to move to a scientifically significant area. However, it is not easy for the robot to implement locomotion on the surface. This is because, I) the asteroid surface is an unknown irregular terrain, and II) the gravity of the asteroid is extremely low. On uneven terrain, it is difficult for a robot to maintain its attitude. In a microgravity environment, moreover, the robot easily floats and rotates owing to the reaction force and the moment received from the surface. Therefore, wheels used for traditional planetary rovers are not suitable for asteroid exploration. Legged robots designed for planetary exploration have also been studied.1,2) However, it is thought that these robots would not be able to propel themselves over the surface of an asteroid for the above reasons. To overcome this problem, a different mobility approach was adopted by MINERVA, which was carried in the Japanese “Hayabusa” spacecraft. MINERVA uses a hopping method that relies on the reaction torque generated by a motor with a flywheel.3) In addition to MINERVA, other hopping robots have also been developed,5,5) but all incur the issue of not being able to maneuver to a particular destination due to the repetitive bouncing action. Recently, as an another option, Nagaoka et al. proposed ciliary microhopping locomotion actuated by an eccentric motor.6) This locomotion system was validated experimentally by using a testbed in a microgravity environment, but this system can only be applied to smooth surfaces.
As an unconventional approach to locomotion on the surface of an asteroid, Yoshida et al. proposed the Cliff Hanger, Rock Climber Rover, shown in Fig. 1.7,8 This robot moves by gripping the surface like a rock climber. Given the very low level of gravity on the asteroid surface, there will be very little gravel or sand. Therefore, the robot avoids flotation and rotation by gripping the asperities of the surface, and thus can move about and explore the surface.

When the idling arm is moved while the supporting arm’s gripper is attached to the surface, all of the reaction forces act on the gripper. If the force exceeds the gripping force, it becomes detached from the surface and the robot is not able to move forward. Thus, there is a need for a means of motion control for the idling arm which does not cause a reaction force to act on the supporting arm’s gripper. Regarding the reaction control of a manipulator, the control of the macro and micro manipulators mounted on large space structures such as the International Space Station has been studied.9 The macro and micro manipulators are required for approximate and precise positioning, respectively. However, the motion of the micro manipulator induces vibrations in the macro manipulator because the latter is long and lightweight. Hence, precise positioning becomes difficult. In this case, the macro manipulator can be regarded as being a flexible base for the micro manipulator. Nenchev et al. derived a constraint condition that does not affect the base velocity by exploiting the conservation law of the linear and angular momentum of the base, and generated a reactionless path for the base.10 Specifically, they utilized the projector onto the null-space of the inertia coupling matrix, which is called the “reaction null-space”.

In this paper, we present a means of motion control for enabling the locomotion of a ground grip robot on an asteroid. Especially, a means of reactionless motion control that does not cause a reaction force to act on the supporting arm’s gripper, in a direction perpendicular to the surface, is devised. Moreover, a tip position trajectory that is perpendicular to the surface is generated. This control method is validated by means of a planar dynamic simulation. In this simulation, a random terrain is simulated under certain conditions and it is confirmed that the robot can move across the surface. Furthermore, we analyze any changes in the motion due to differences in the initial base position.

2. Dynamic Model of Ground Grip Robot

In this section, a dynamic model of the ground grip robot is first presented, and then the control law is described. The dynamic model for a robot whose arms have \((n-1)/2\) links is shown in Fig. 2. For this study, we made some assumptions, as follows:

- the gravitational force is negligible.
- no external force acts, except on the supporting arm’s gripper.
- the supporting arm’s gripper is fixed and do not become detached from the surface of the asteroid.

By dividing the links of the robot into the end link of the supporting arm that is gripping the surface and other links, the equation of motion of the robot can be presented as follows:

\[
\begin{bmatrix}
F_s \\
\tau
\end{bmatrix} =
\begin{bmatrix}
H_s \\
H_m
\end{bmatrix}^T
\begin{bmatrix}
H_s \\
H_m
\end{bmatrix}
\begin{bmatrix}
\dot{x}_s \\
\dot{\phi}
\end{bmatrix} +
\begin{bmatrix}
c_s \\
c_m
\end{bmatrix}
\]  

where the upper and lower parts of Eq. (1) denote the equation of motion about the end link of the supporting arm and that about the other links, respectively. In the following sections, those links other than the end link of the supporting arm are referred to as “the manipulator”. By eliminating the acceleration of the end link of the supporting arm \(\ddot{x}_s\) from Eq. (1), the control torque \(\tau\) can be expressed as follows:

\[
\tau = H'\dot{\phi} + c^* + H_{sm}^T H_s^{-1} F_s
\]  

where

\[
H' \equiv H_m - H_{sm}^T H_s^{-1} H_{sm},
\]

\[
c^* \equiv c_m - H_{sm}^T H_s^{-1} c_s.
\]

\(H'\) and \(c^*\) denote the generalized inertia matrix and the generalized nonlinear velocity-dependent term, respectively.

3. Control Method

In this section, the joint angular velocity needed to calculate the input torque is formulated. First, we present the control of the tip position of the manipulator and explain how to generate the desired tip trajectory. Subsequently, the constraint condition for realizing the reactionless control of the supporting arm’s gripper is described. Furthermore, a simultaneous control law that sets the task priority for these two control tasks is presented.

3.1. Tip Position Control

3.1.1. Control law

The relationship between the tip velocity of the manipulator \(\dot{x}_e\) and the joint angular velocity \(\dot{\phi}\) is generally expressed using the Jacobian \(J_e\) as follows:

\[
\dot{x}_e = J_e \dot{\phi}
\]  

From Eq. (5), the desired joint angular velocity \(\dot{\phi}_d\) can be written using the desired tip position \(x_d\) in the following form:

\[
\dot{\phi}_d = J_e^* K (x_d - x_e) + R_{NSJ} \dot{\xi},
\]

\[
R_{NSJ} \equiv I - J_e^* J_e
\]
where $R_{\text{NS},f}$ is a projector onto the null-space of $J_e$, which exists when the number of DOF of the manipulator is greater than that of the control task, allowing the manipulator to be utilized for an additional task.

### 3.1.2. Tip trajectory generation

When the reaction force acting on the tip of the idling arm exceeds the gripping force of the supporting arm’s gripper, the gripper becomes detached from the asteroid surface. For that reason, the robot cannot continue to move forward. Therefore, it is necessary for the force acting on the idling arm’s gripper to be as small as possible. In this study, the trajectory whereby the tip of the idling arm is detached and then reattached in a direction perpendicular to the surface was generated in two dimensions. In this way, an external force caused by the friction between the tip of the idling arm and the surface can be eliminated. As one solution which satisfies this condition, the trajectory is made elliptical so that the trajectory from the current position to the desired tip position is smooth. Fig. 3 shows a model of the elliptical trajectory. In Fig. 3, $x_0$ and $x_d$ denote the vector of the current tip position and that of the desired tip position, respectively. The coordinates of the current and desired tip position are expressed as follows:

$$x_{0x} = a \cos \theta_1 \cos \psi - b \sin \theta_1 \sin \psi + r_x,$$

$$x_{0y} = a \cos \theta_1 \sin \psi + b \sin \theta_1 \cos \psi + r_y,$$

$$x_{dx} = a \cos \theta_2 \cos \psi - b \sin \theta_2 \sin \psi + r_x,$$

$$x_{dy} = a \cos \theta_2 \sin \psi + b \sin \theta_2 \cos \psi + r_y.$$

Moreover, conditional equations whereby the tip of the idling arm detaches and reattaches in a direction perpendicular to the surface can be written as follows:

$$\left| a \tan \left( \frac{dy}{dx} \right)_{\text{detached}} - \alpha \right| \leq \epsilon_o, \quad (12)$$

$$\left| a \tan \left( \frac{dy}{dx} \right)_{\text{attached}} - \beta \right| \leq \epsilon_d, \quad (13)$$

where acceptable error ranges are set in order to deal with those cases in which a perfect elliptical trajectory cannot be generated in a direction perpendicular to the surface. By solving the constrained non-linear optimization problem by using from Eq. (8) to Eq. (13), the desired elliptical trajectory can be generated.

### 3.2. Reactionless motion control

When we assume that no external force acts on the robot and the initial linear and angular momentums with respect to the mass center of the tip of the supporting arm are zero, the following conservation law of the linear momentum $P$ and the angular momentum $L$ can be established:

$$\begin{bmatrix} P \\ L \end{bmatrix} = H_s x_s + H_{sm} \phi = 0 \quad (14)$$

The first term of Eq. (14) is the linear and angular momentums caused by the tip of the supporting arm, while the second term is that caused by the manipulator. From Eq. (14), the condition whereby the linear and angular momentums caused by the tip of the supporting arm are both zero is written as follows:

$$H_{sm} \phi = 0 \quad (15)$$

Provided the manipulator moves under this constraint condition, the reaction force does not act on the supporting arm’s gripper. Therefore, a reactionless path for the gripper can be generated. Eq. (15) is the constraint condition for six dimensions which are a combination of three dimensions for the position and three for the orientation with respect to the inertia frame. In these dimensions, the force acting on the supporting arm’s gripper in a direction perpendicular to the asteroid surface is most likely to cause a situation that the gripper detaches from the surface. Moreover, an increase of a reactionless axis poses a limitation on possible trajectories of the manipulator. Therefore, we applied a reactionless control in one direction vertical to the surface in order to guarantee its manipulability. The revised constraint condition is given as follows:

$$\dot{H}_{sm} \phi = 0 \quad (16)$$

In the simulation, the derivation of the constraint condition, in a direction perpendicular to the surface by using coordinate transformation, is required for calculation on the basis of the inertia frame. In an actual mission, however, the robot moves based on the coordinate system of the tip of the supporting arm. Therefore, the coordinate transformation procedure is not needed. The desired joint angular velocity which satisfies Eq. (16) can be expressed as follows:

$$\dot{\phi}_d = R_{\text{NS}} \xi,$$

$$R_{\text{NS}} \equiv I - \dot{H}_{sm}^* \dot{H}_{sm}$$

where $R_{\text{NS}}$ denotes the projector onto the null-space of the inertia coupling matrix $H_{sm}$ and is called the reaction null-space.
3.3. Simultaneous control

For this study, the motion of the robot was controlled by combining the tip position control law of Eq. (6) with the reactionless motion control law of Eq. (17). To arrive at an approach that combines these two control laws, we used task-priority redundancy resolution. This technique controls the robot based on the priority order of the given tasks. With this approach, the lower-priority task is implemented by utilizing the null-space of the higher-priority task. To enable the robot to continue moving, it is important that the reaction force does not act on the supporting arm’s gripper. Therefore, we set the reactionless motion control as the primary task and implement tip position control by utilizing the reaction null-space.

At first, the vector $\xi$ is calculated as follows by substituting Eq. (17) into Eq. (5):

$$\xi = J_e^+K(x_d - x_e)$$

(19)

where $J_e$ is expressed as follows:

$$J_e \equiv J_eR_{RNS}$$

(20)

Moreover, the desired joint angular velocity for simultaneous control is written as follows, by substituting Eq. (19) into Eq. (17):

$$\phi_d = R_{RNS} J_e^+K(x_d - x_e)$$

(21)

If precise tip position control is required, it is only necessary to substitute Eq. (6) into Eq. (16), after which a similar approach is applied.

4. Analysis

In this section, a planar locomotive simulation is carried out in order to validate the simultaneous control law proposed in the previous section. At first, as the simulation conditions, the simulation model for the robot is expressed, and then a means of generating the asteroid surface and other conditions are presented. Subsequently, we conduct two types of simulations related to the initial height of the base and consider the behavior of the robot.

4.1. Simulation conditions

The robot model was a dual-arm robot, with each arm having three links, as shown in Fig. 4. Table 1 lists the link parameters. For this study, the gripping of the asteroid surface was simulated by setting the inertia parameters of the supporting arm’s gripper to large virtual values. Moreover, locomotion was simulated by replacing the inertia parameters of the idling arm’s gripper with those of the supporting arm when the idling arm’s gripper reaches the desired position. Additionally, the force acting on the supporting arm’s gripper $F_s$ was calculated by applying the following equation:

$$F_s = -k_p \Delta x_s - k_e \dot{x}_s$$

(22)

where we set $k_p = k_e = 3000$.

The asteroid surface was simulated by randomly setting an inclination and heights of lines that are 9 mm apart on the $x$-axis of the inertia frame, and then connecting those lines with lines that are 1 mm apart on the $x$-axis of the inertia frame. The range of the inclination was set to $\pm 30^\circ$, relative to the $x$-axis of the inertia frame. On the other hand, the range of heights was set based on the height of center position of the previous line. Before the tip of the left arm passes through the initial $x$-coordinate of the tip of the right arm, the range was set to $\pm 5$ mm and, after that, the range was set to $\pm 10$ mm. Moreover, a condition stating that the initial attitude of the robot must be horizontal was added to the generation of the surface.

For this study, two types of simulations that differ in the initial height of the base were performed, after which we analyzed the motion of the robot, the tip positions, the reaction forces, the base positions, and the base rotations. Table 2 lists the initial joint angles in each case. The initial height of the base in case 1 was higher than that in case 2. Furthermore, we set $K = 12$ for both conditions. In addition, the stride length and the number of motion cycles were set as 40 mm and 8 cycles, respectively.

4.2. Results and Discussions

Figures 5 and 10 show the motion sequences of the robot when the initial base position is either high or low. From these graphs, we can see that the robot was able to move across the surface in both cases. In the case of the high base position, however, the attitude of the robot changed considerably as time passed. Moreover, Figs. 6 and 11 show the tip trajectories of the idling arm in both conditions. From these graphs, we can see that the two tip trajectories are consistent and that the tips were able to vertically disconnect from and attach to the surface. Furthermore, Figs. 7 and 12 show the reaction forces acting on each tip of the arms under the two conditions in the base coordinate.
with almost no reaction force for the $x$-axis, which is vertical to the surface. Thus, manipulation that does not cause a reaction force with the surface for the ground grip robot was realized by utilizing the reaction null-space. In addition, Figs. 8 and 13 show the base positions for both conditions. The motions of the base can also be confirmed from Figs. 5 and 10. From these graphs, we found the tendency that the base position becomes higher with the locomotion of the robot in both cases. This implies there is a risk that the robot cannot move continuously when the initial base position is high. To eliminate the risk, therefore, it is important to make the initial base position low. Additionally, we can see that the initial base position is independent of the change rate of the base position. Moreover, Figs. 9 and 14 show the base rotation under both conditions. When the initial base position was high, the base rotation changed with the locomotion more than in the case when the initial base position was low and the posture changed greatly. Therefore, the results also suggest that it is desirable for the initial base position to be set low. The above results point to the necessity for the initial base position to be set low in order to enable ongoing stable locomotion.

On the other hand, for a few types of surfaces, there were cases when the calculation diverged while the robot was moving. These cases arose because the constraint condition for realizing reactionless motion was added to the tip position control, such that the desired joint angular velocity could not be solved. Thus, the divergence condition caused by adding the dynamic constraint condition is called the “dynamic singularity,” for which a solution has not yet been established.\cite{12} For the future, therefore, it will be necessary to construct a control law for avoiding or passing through the dynamic singularity.

5. Conclusions

This study derived a simultaneous control law which combines tip position control with reactionless motion control to realize the locomotion of a ground grip robot on the surface of an asteroid. The validity was confirmed by dynamic simulation. At first, a dynamic model of the robot was presented and the equation of motion was expressed. Then, the simultaneous control law was derived by utilizing the reaction null-space. Regarding the tip position control, especially, a means of generating an elliptical trajectory whereby the tip of the idling arm detaches from and attaches to the surface in the direction perpendicular to that surface was proposed. Moreover, two types of locomotive simulations related to the initial height of the base were performed and the results demonstrated the propriety of the control law. Additionally, it was revealed that a robot for which the initial height of the base is low exhibits a smaller
change in the orientation of the base than one for which the initial height is high, allowing it to move steadily across the surface. In future research, it is needed that an establishment of a method for avoiding or passing through the dynamic singularity. Furthermore, it will be necessary to experimentally validate a control law including the simultaneous control by developing an air-floating testbed with which the motion of the robot in a microgravity environment can be simulated.

References