Feasibility Study for a Small Mars Exploration Rotorcraft

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Abstract

An aerial vehicle operating under the command of a rover has a potential to extend the coverage for Mars exploration. Especially, a rotorcraft equipped with an imaging camera can gather geographic information around the rover and enables us to make a smart strategy for the exploration. The development of such a rotorcraft, however, must solve some difficulty due to the thin Mars atmosphere. This is because the aerodynamic characteristics of the rotor depend mainly on the Reynolds number (Re) that decreases due to the thin atmosphere. In this paper, the aerodynamic characteristics of rotors were experimentally investigated to access a capability of the hover performance of the rotor in a very low Reynolds number regime (Re=10^2~10^4, Ultra-low Reynolds number) that is expected in the thin Mars atmosphere. Based on the experimental investigation, the feasibility of such a rotorcraft was demonstrated.

火星探査のためのロータクラフト機の検討
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火星地表探査においてローバと組になって探査を行うロータクラフトの可能性についての検討を行う。このようなロータクラフト機の併用により、ローバの活動性を向上させることが可能である。

Nomenclature

\begin{align*}
AR &= \text{Rotor blade aspect ratio } [2R/c_{0.75R}] \\
c &= \text{Rotor blade chord length (m)} \\
c_{0.75R} &= \text{Rotor blade chord length} \\
&\text{at } 0.75R (m) \\
C_T &= \text{Thrust coefficient } [T/\rho A(\Omega R)^2] \\
C_Q &= \text{Torque coefficient } [Q/\rho A(\Omega R)^2 R] \\
e &= \text{Hinge offset (m)} \\
E_b &= \text{Specific energy of battery (Wh/g)} \\
E_f &= \text{Flight endurance (min.)} \\
f/c &= \text{Maximum camber ratio, in percentage of the chord} \\
FS &= \text{Factor of safety} \\
g &= \text{Gravity acceleration (m/s^2)} \\
M_{\text{battery}} &= \text{Gross battery mass (g)} \\
M_{\text{motor}} &= \text{Gross motor mass (g)} \\
M_{\text{vehicle}} &= \text{Gross vehicle mass (g)} \\
M_{\text{tip}} &= \text{Mach number at the tip of a rotor} \\
N_b &= \text{Number of blades} \\
P &= \text{Power consumption of a single rotor (W)} \\
Q &= \text{Torque (Nm)} \\
Re &= \text{Reynolds number based on } c_{0.75R} \\
&= \rho c_{0.75R} U_{0.75R} [\pi R / \mu] \\
R &= \text{Rotor radius (m)} \\
S &= \text{Rotor disk area } [\pi R^2] (m^2) \\
t/c &= \text{Maximum Thickness ratio, in percentage of the chord} \\
T &= \text{Thrust of a single rotor (N)} \\
U_{0.75R} &= \text{Flow velocity at 0.75R,} \\
&\text{tangent to the disk plane (m/s)} \\
&\text{of a flat plate (m)} \\
\eta_g &= \text{Gearbox efficiency} \\
\eta_m &= \text{Motor efficiency} \\
\mu &= \text{Atmospheric viscosity (kg/ms)} \\
\rho &= \text{Atmospheric density (kg/m^3)} \\
\theta_0 &= \text{Collective pitch angle (deg.)} \\
\sigma &= \text{(Thrust weighted) Solidity} \\
[N_b c_{0.75R}/\pi R] &= \text{Rotation speed (rad/s)} \\
k_{\text{int}} &= \text{Induced power factor from interference} \\
&\text{between upper and lower rotor} \\
0.75R &= \text{75% position of a rotor radius} \\
\end{align*}

1. Introduction

For the exploration of the planet such as Mars, the rovers such as Sojourner in the Mars Pathfinder Mission or the Spirit and Opportunity in the Mars Exploration Rover Mission have played an active role for the in-situ surface exploration. The surface exploration in the present configuration by means of rovers, however, has various drawbacks and is expected to be improved in many ways for the future exploration. For instance, in the present configuration of the exploration by means of rovers, many time-consuming procedures are required for controlling the rovers; first, the geographical image around the rover is taken and is sent back to the commanding center on the earth, second, based on the geographical image, the target site where the rover is to move and the rough plan for rooting are decided and the commands giving those are sent back to the rover, third, the rover moves to the target site and takes the image around it. These procedures
are repeated until the mission end. For transmitting the data, however, the transmission delay more than 10 minutes must be counted, and the distance to the target site is restricted since the information obtained from the geographical image taken by the rover is restricted and the longer the distance to the target site is, the larger the risk which the rover will face becomes. In such a way, the planetary exploration by means of the rover system cannot be as efficient as we expect but remains much room to be improved.

To remove this drawback, we will propose to utilize a small aerial vehicle that will function as a scout for the sake of the rover. That is, the aerial vehicle will collect the geographical data around the rover, which is utilized to make a decision on the site to where the rover heads, thus, the rover and the vehicle can make an autonomous exploration that does not need a redundant communication with the commanding center on the earth as discussed previously. The geographical data collected will give not only abundant information for the rover to make a smart strategy for the exploration, but also the fruitful scientific information that may be difficult for the rover to acquire by itself. The aerial vehicle for such a purpose should be a rotorcraft rather than a fixed-wing airplane since only the rotorcraft can land and take off from the arbitrary place with a restricted area. The development of such a rotorcraft, however, must solve some difficulty due to the thin Mars atmosphere. This is because the thin atmosphere causes a decrease of thrust that must be overcome by developing an efficient rotor. The aerodynamic characteristics of the rotor depend mainly on the Reynolds number (Re) that decreases due to the thin atmosphere. Therefore it is inevitable to develop a rotor as efficient as possible in a Reynolds number regime lower than that experienced by the conventional rotorcraft in the Earth atmosphere.

In the present paper, the aerodynamic characteristics of rotors will be experimentally investigated to access a capability of the hover performance of the rotor in a very low Reynolds number regime (Re=10^2~10^4, Ultra-low Reynolds number) that is expected in the thin Mars atmosphere. Based on the experimental investigation, the feasibility of such a rotorcraft for Mars exploration will be demonstrated.

2. Overview of the Small Mars Exploration Rotorcraft

2.1 Mission scenario

Even though several tasks are possible for the vehicle, we will consider, in this work, the mission scenario in which only the geographical picture is to be taken and sent to the rover. Considering the features of the vehicle such as small size and lightweight, however, it is entirely feasible that groups of the small rotorcrafts that are assigned a single task respectively carry out several tasks. Thus, it is reasonable to assume such a single task for the vehicle as mission scenario.

![Small Mars Exploration Rotorcrafts flying around a rover](image1)

2.2 Vehicle Configuration

In the present paper, the vehicle configuration is assumed as so-called co-axial rotor configuration (Fig.2). The reasons why we selected this configuration are, firstly, its capability of compactness, that is, this configuration reduces net rotor size for a given total weight and does not need a tail rotor and tail boom because of its anti-torque capability, and therefore, secondly, its ease of packaging in the rover. In general, however, because of the complicated construction of a co-axial rotor system it is difficult to miniaturize a co-axial rotorcraft. But recently, the off-the-shelf radio controlled small helicopter, XRB (HIROBO, Japan[2]) of which total weight is 185 gram and rotor radius is 17.5 cm has demonstrated the feasibility of a small co-axial rotorcraft. Therefore we believe that the co-axial rotor configuration is not only appropriate but also feasible for the small Mars exploration rotorcraft.

![The small Mars exploration rotorcraft](image2)

2.3 Design Requirements for the Rotor

Since efficient forward flight is not a merit of a rotorcraft configuration inherently and the mission scenario requires the vehicle not to carry out a high-speed forward flight but to perform an efficient
hover flight, only the design requirements for the hover performance will be considered. In addition, to simplify the problem, the design requirements for one of the pair of rotors are considered here.

The requirement for the power consumption is given by Eq.(1). This inequality means that the power consumption ($k_{int}P$) must be less than the available power from the half of the gross battery mass. On the other hand, the requirement for the thrust is given by Eq.(2). This inequality means that the thrust ($T$) must be more than the half of the gross vehicle mass.

$$\frac{1}{2} M_{battery}(60/E_f) E_k n_g n_m \geq k_{int}P$$  \hspace{1cm} (1)$$

$$T \geq \frac{1}{2} M_{vehicle} \times 10^{-3} \cdot g \cdot FS$$  \hspace{1cm} (2)$$

These two design requirements are summarized in Eq.(3). In Eq.(3), $(C_T/C_Q)^2(C_T/\sigma)$ is the critical aerodynamic term. That is, Eq.(3) means that when a gross vehicle mass ($M_{vehicle}$), size of the rotor blades ($S$ and $\sigma$), each efficiencies ($n_g$, $\eta_m$, $k_{int}$ and $FS$), flight conditions ($\rho$, $g$ and $E_f$) and battery specifications ($E_k$ and $M_{battery}$) are determined, the rotor must achieve the hover performance so that the $(C_T/C_Q)^2(C_T/\sigma)$ satisfies the requirement given by Eq.(3).

$$7.2 \times 10^{12} \cdot \frac{\rho S \sigma}{g^2 (FS)^3} \left( \frac{E_k n_g n_m}{E_f k_{int}} \right)^2 \times$$

$$\left( \frac{C_T}{C_Q} \right)^2 \left( \frac{C_T}{\sigma} \right) M_{battery}^2 \geq M_{vehicle}^3$$  \hspace{1cm} (3)$$

Therefore, in this work, our interests will be focused on assessing the $(C_T/C_Q)^2(C_T/\sigma)$ of hover performance.

Note that, in general, when comparing the performance of rotors with different blade areas, it is desirable to examine the ratio of thrust coefficient to solidity ($C_T/\sigma$) and the ratio of torque coefficient to solidity ($C_Q/\sigma$) in order to cancel the influence of the blade area on the thrust and the torque. Hence, $C_T/\sigma$ is adopted in Eq.(3).

3. Experimental Investigation on Rotor Performance in Hover

3.1 Experimental Setup

In order to assess the hover performance of the rotor, it is desirable to directly measure the aerodynamic characteristics of the rotor in its rotating state rather than to predict theoretically based on the characteristics of the two-dimensional (2D) airfoil. Hence, the aerodynamic thrust generated by the rotor directly driven by an electric motor was measured. For this purpose, the drive motor, on which the rotor is directly attached, is directly mounted on the measurement stand. The measurement stand is composed of a pendulum, the inclination of which is proportional to the aerodynamic thrust. The experimental setup for the measurement is depicted in Fig.3. The inclination of the pendulum was measured by the inclinometer (Midori-Precision, PMP-SI0LX). Prior to the measurements, the calibration curve for the thrust vs. the inclination angle was determined, which enable us to convert the measured inclination angle to the thrust generated by the rotating rotor. The electric motor to drive the rotor was a DC electric motor (Maxon Motor, RE25), of which rotation speed was measured by the installed tachometer. The output of the tachometer was 500 pulses per rotation. The torque required to rotate the rotor was measured based on the measurement of the electric current consumption to drive the electric motor, referring to a specific data of the motor on the relation between the torque and the electric current consumption ($K_M$). The measurements were carried out 3 times for each configuration and were averaged over. The extents of measurement error, therefore, are determined based on the standard deviation. In addition, to simulate the thin atmosphere in Mars, the measurement system is mounted inside a large evacuation chamber of which diameter and height are 2.40 m and 2.73 m, respectively.

![Figure 3: Hover test pendulum. Output sensitivity of the inclinometer is less than 0.01 deg., which is equal to the thrust of 0.025 gf. Torque constant of the drive motor ($K_M$) is 23.18 mNm/A [3].](image)

3.2 Rotor Models and Experimental Conditions

The rotor models are single rotors and are composed of the hub attached with two symmetric blades. The specifications for the airfoil of the rotor and the planform are depicted in Fig.4. Several combinations of the airfoil and the planform were investigated. When the airfoil is (no. 1) and the planform is (no. a) in Fig.4, for instance, the rotor configuration is represented by (1-a). The test conditions are summarized in Table 1. The Mach number at
the tip of the rotor \(M_{tip}\) is 0.013 and, hence, the compressibility effect can be neglected.

![Diagram of Airfoil and Planform](image)

**Figure 4:** Test airfoils and planforms.

**Table 1: Test conditions.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>4000</td>
</tr>
<tr>
<td>(M_{tip})</td>
<td>0.013</td>
</tr>
<tr>
<td>Test gas</td>
<td>Air</td>
</tr>
<tr>
<td>Collective pitch angle (\theta_0)</td>
<td>0°–50 deg.</td>
</tr>
</tbody>
</table>

### 3.3 Experimental Results

In the following subsection, the results for the measurements on the rotor performance in hover are described focusing on the effects of several features of the rotor configuration to the \((C_T/C_Q)^2(C_T/\sigma)\) in Eq.(3) of hover performance.

#### 3.3.1 Effects of Camber of Airfoil

The hover performances for various cambers are presented in Fig.5. When the camber ratio \((f/c)\) increases, the hover performance increases while this improvement is deteriorated for a blade with further camber. Therefore we can conclude that an appropriate camber of which ratio is around 10 % is most effective.

![Graph: Effects of Camber of Airfoil](image)

**Figure 5:** Effects of camber of airfoil

#### 3.3.2 Effects of Aspect Ratio of Blade

The influence of aspect ratio \((AR)\) on the hover performance is depicted in Fig.6. When the \(AR\) increases, the hover performance increases as expected.

![Graph: Effects of Aspect Ratio of Blade](image)

**Figure 6:** Effects of aspect ratio of blade

#### 3.3.3 Effects of Linear Twist of Blade

The effects of linear twist of the blade on the hover performance is depicted in Fig.7. We can observe that twisted blades have a little better maximum hover performance than untwisted blades. Although in general the use of twist in the rotor blades gives a more uniform inflow and reduces the induced part of \(C_Q\), since in the lower Reynolds number regime like in this work the profile part of \(C_Q\) is dominant, the marvelous benefits cannot be observed as seen in the higher Reynolds number regime.
3.3.4. Applicability of LMT

For the feasibility study of the rotorcraft as will be done later, it is necessary to know the aerodynamic performance for many specific rotors that are selected in the design process. For this purpose, it is useful if we can predict it by means of the existing theory such as Local Momentum Theory (LMT) [5]. In this section, we will examine the applicability of the LMT in the ultra-low Reynolds number regime. To this aim, we will compare the present experimental data with the prediction by the LMT.\(^1\)

Figure 8 shows a comparison of the LMT with the experimental result for the typical rotor at Re=4000. Note that for small collective pitch angles (\(\theta_0\)) until around 12 deg., the agreement is good enough for a preliminary design of the vehicle. For \(\theta_0 \geq 15\) deg., however, there is a serious underprediction of both \(C_T/\sigma\) and \(C_Q/\sigma\) because of the stall delay phenomena due to the three-dimensional effect.

Figure 8: Measured and predicted hover performance on the rotor(1-a). Source of the 2D airfoil data at Re=4000: reference [6].

4. Feasibility Analysis for the Rotorcraft

4.1 Design Criteria

Although Eq.(3) provides us with the design requirements for the rotor, we still need the mass constraint on a drive motor system and a power source system for the rotor. This is because even if a rotor satisfies the design requirements given by Eq.(3), the gross mass of drive motor system and power source system may be required to be more than the gross vehicle mass. Hence the mass constraint on a drive motor system and a power source system is given by

\[
M_{\text{battery}} + M_{\text{motor}} = M_{\text{vehicle}} - m
\]  \(\text{(4)}\)

Here, \(m\) means the gross mass expected for each components except a drive motor system and a power source system. That is, \(m\) includes a structure, rotors, a telecommunication system, and an imaging camera that are absolutely necessary for the vehicle.

Now, Eq.(3) and Eq.(4) provide us with the design criteria for the vehicle. These two inequalities are summarized in

\[
M_{\text{motor}} \leq M_{\text{vehicle}} - \sqrt{\frac{M_{\text{vehicle}}^3}{\alpha}} - m
\]  \(\text{(5)}\)

\[
\alpha = 7.2 \times 10^{12} \frac{\rho S\sigma}{g^3 (FS)^3} \times \left(\frac{E_k}{E_f k_{int}}\right)^2 \left(\frac{C_T}{C_Q}\right)^2 \left(\frac{C_T}{\sigma}\right)
\]

Note that the \(\alpha\) becomes constant when a rotor configuration (\(S, \sigma, \text{airfoil, planform and pitch angles}\), each efficiencies (\(\eta_k, \eta_m, k_{int}\) and \(FS\)), flight conditions (\(\rho, g\) and \(E_f\)) and battery specification (\(E_b\)) are determined. Then, when the \(\alpha\) is constant, we

\(^1\)Although, in the theory, the aerodynamic characteristics of the 2D airfoil that are estimated from those of the three-dimensional (3D) wing by the potential flow theory should be used, there is the possibility that the potential flow theory is not valid for the ultra-low Reynolds number regime [6][7]. Therefore, in the present paper, the aerodynamic characteristics of the 3D wing in the reference [6] were used as those of the 2D airfoil in the LMT.
can draw, retaining our attention on the assumption that the rotor configuration is determined, the chart of the design criteria as Fig.9, and the highlighted region in Fig.9 is allowed for designing the vehicle.

![Figure 9: The chart of the design criteria for the vehicle (1).](image)

4.2 Strategy for the Analysis

The assumption that the rotor configuration is determined as discussed previously makes the gross vehicle mass to have an appropriate range. That is, the requirement for the power-to-mass ratio of motors becomes more strict with decreasing gross vehicle mass, on the other hand, the requirement for the tip Mach number of the rotor blades becomes more high with increasing gross vehicle mass while the requirement for the power-to-mass ratio of motors becomes more relax.

Therefore, in the present feasibility analysis, we will carry out the analysis in the following procedure:

1) Estimate the $m$ in the design criteria given by Eq.(5) referring to the off-the-shelf products.

2) Assume flight conditions ($\rho$, $g$, and $E_f$), battery specification ($E_b$) and each efficiencies ($\eta_g$, $\eta_m$, $\kappa_{int}$ and $FS$).

3) Assume a rotor configuration.

4) Determine the $\alpha$ in Eq.(5) by the LMT and draw the chart of the design criteria.

5) Within an allowable design region such as in Fig.9, assuming a gross vehicle mass, predict the required power-to-mass ratio of motors for the available minimum gross vehicle mass and the required tip Mach number for the available maximum gross vehicle mass by the LMT.

6) As a result, if an available range for the gross vehicle mass is secured, we can conclude that the feasibility is demonstrated.

4.3 Feasibility of the Rotorcraft

A simple estimation for the $m$ in Eq.(5) that is mass expected for each components except the drive motor system and its power source system gives the gross mass of around 60 g all together as summarized in Table 2. And the assumption on flight conditions, battery specification and each efficiencies are summarized in Table 3. A rotor configuration is assumed as shown in Table 4 with the following reasons: Airfoil in a very low Reynolds number regime like in this work, it is well-known that a cambered plate has a good aerodynamic performance and our experimental results shows that an appropriate camber ratio around 10 % has the best hover performance of all airfoils of which experimental 2D aerodynamic characteristics at Re=4000 are provided in the reference [6]. Rotor size according to our experimental results, although the aspect ratio of the blade is desired to be as large as possible, considering the packaging space in a rover, the blade mass estimation as in Table 4 and rigidity of the blades, the rotor size as in Table 4 is almost allowable maximum size. Collective pitch) according to our experimental results, although any tested rotor has the maximum hover performance with around $15 < \theta_0 < 20$ deg., the applicability of the LMT is secured under around $\theta_0 = 12$ deg.. Twist of blade) according to our experimental results, although linear twisted blades have a little better maximum hover performance than untwisted blades, under around $\theta_0 = 12$ deg., the benefits cannot be observed. Planform) since there is a no sufficient experimental results on the effects of various planform, most simple configuration is adopted here.

Under these assumptions, we can determine the $\alpha$ by the LMT and draw the chart of the design criteria as Fig.10. Within the allowable design region, when the gross vehicle mass is around 120 gram, the required power-to-mass ratio of motors is more than around 1.0 W/g, which may be the most efficient power-to-mass ratio of motors available from today's micro motor technology. On the other hand, when the gross vehicle mass is around 275 gram, the required tip Mach number of the blade is around 0.6, which may be the allowable limit from the view point of the drag divergence.

As a result, the gross vehicle mass is secured in the range around 120 $\sim$ 275 gram, hence, we can conclude that the feasibility is demonstrated. Note that, however, since in this analysis the Reynolds number is in the range $3000 \leq Re \leq 4700$ and the tip Mach number is in the range $0.3 \leq M_{tip} \leq 0.6$, in order to further enhance the feasibility, we must take the effects of Reynolds number into consideration and will need more understanding on the effects of high-subsonic Mach number in the ultra-low Reynolds number regime.
Table 2: Estimation for mass of components of the rotorcraft except a driving motor system and its power source system (Estimation for the m in Eq.(3)).

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control unit and battery</td>
<td>11 g</td>
</tr>
<tr>
<td>Telemeter and battery</td>
<td>8 g</td>
</tr>
<tr>
<td>Imaging camera, transmitter and battery</td>
<td>15 g</td>
</tr>
<tr>
<td>Rotor (blades and hubs)</td>
<td>12 g</td>
</tr>
<tr>
<td>Fuselage</td>
<td>10 g</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>56 g</strong></td>
</tr>
<tr>
<td><strong>m</strong></td>
<td><strong>60 g</strong></td>
</tr>
</tbody>
</table>

Table 3: Assumption on flight conditions, battery specification and each efficiencies.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (in Mars)</td>
<td>0.0167 kg/m³ [4]</td>
</tr>
<tr>
<td>$g$ (in Mars)</td>
<td>9.81 m/sec² [4]</td>
</tr>
<tr>
<td>Sound velocity (in Mars)</td>
<td>229 m/sec [4]</td>
</tr>
<tr>
<td>$E_f$</td>
<td>15 min.</td>
</tr>
<tr>
<td>$E_b$</td>
<td>0.2 Wh/g</td>
</tr>
<tr>
<td>$\eta_s$</td>
<td>70 %</td>
</tr>
<tr>
<td>$\eta_m$</td>
<td>80 %</td>
</tr>
<tr>
<td>$k_{int}$</td>
<td>1.16 [1]</td>
</tr>
<tr>
<td>$FS$</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Figure 10: The chart of the design criteria for the vehicle (2).

5. Summary

In order to demonstrate the feasibility of a small rotorcraft in the Mars atmosphere the hover performance of rotors in a ultra-low Reynolds number regime (Re=10³ ~ 10⁴) have been experimentally investigated that is expected in the thin Mars atmosphere. Based on the experimental investigation, the feasibility of such a rotorcraft has been demonstrated.
Determination of the Positions of Stars with High Accuracy for JASMINE

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Abstract JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration) will measure trigonometric parallaxes, positions and proper motions of about a hundred million stars during the observational program with high accuracy. We present a method to estimate the positions of stars by observing along the great circle of the sky. In estimating positions of stars, we observe two fields of view. These two fields are perpendicular to the spin axis of the satellite. We can determine the positions of stars together with the attitude of the satellite by using the data from these two fields of view.

JASMINEにおける星の高精度位置決定について

摘要 JASMINE（近赤外線による位置天文観測衛星）は近赤外線を用いて銀河面やパルジにあるおよそ1億個の星の位置、距離、固有運動を高精度に測定する。天球の大円上をサーベイ観測する事により星々の位置を高精度に測定する手法を示した。JASMINEは観測する際に大円上にある大角度離れた2つの領域を同時に観測する事により衛星の姿勢と星の相対的位置を同時に高精度に解く方法がとられるが、ここではその詳細を示す。

1 Introduction

JASMINE (e.g., Gouda et al. 2003; Yano et al. 2003) is the acronym of the Japan Astrometry Satellite Mission for INfrared (z-band:0.9μm) Exploration, and is planned to be launched between 2013 and 2015. The main objective of JASMINE is to study the fundamental structure and evolution of the disk and the bulge components of the Milky Way Galaxy. Another important objective is to investigate stellar physics. In order to accomplish these objectives, JASMINE will measure trigonometric parallaxes, positions and proper motions of about a hundred million stars during the observational program, with the precision of 10 microarcsec at z =14.0mag. The satellite will be placed at the L2 Lagrange point of the Sun-Earth system because of the stability of the thermal environment.

In order to determine positions of stars, the central region of the Airy function on the CCD must be sampled by at least a few pixels. This is satisfied by the condition \( f_A/D_w = 2 \), where \( D, f, \lambda, \) and \( w \) are the diameter of the primary mirror (1.5m), its focal length (50m), wavelength, and pixel size, respectively. The size of the detector for z-band is 6cm×3cm with 4096×2048 pixels. Accordingly, the pixel size is 15 μm which corresponds to 62 milliarcsec (mas) on sky. The telescope has two fields of view as other astrometric satellites like Hipparcos and GAIA, in order to obtain the precise positions of stars and the posture of the satellite. The separation angle of these two fields, the basic angle, is about 99.5°. The size of each of the two fields of view is 0.49°×0.49° by using 98 detectors. These two fields are perpendicular to the spin axis of the satellite.
The satellite is designed to rotate with a 5 hour period. The rotational axis is 3.5° away from the Galactic pole. The spin axis is in slow precession around the Galactic pole direction every 37 days. Accordingly, JASMINE will scan the restricted regions around the Galactic plane and sweep repeatedly. The mission life is planned to be 5 years.

2 Determination of Positions of Stars and Attitude

We present a method for estimating the positions of stars with high accuracy. In estimating the positions of stars, we also need to determine the attitude of the satellite. In order to determine the attitude of the satellite in general, positions of stars are sometimes used as references. However, JASMINE mission must determine the positions of stars themselves with high accuracy. Therefore stars cannot be used as references of the posture of the satellite.

JASMINE scan along many great circles of the sky in order to estimate the positions of stars in our mission. Accordingly, a certain star is observed with different some great circles. From the data of the different great circle, we estimate the positions of stars in the sky. Therefore what we need to estimate the positions of stars along a certain great circle. In scanning along the great circle of the sky, two fields of view are observed. These two fields are perpendicular to the spin axis of the satellite. The separation angle of these two fields, the basic angle, is about 99.5°. We can solve the positions of stars and the attitude of the satellite simultaneously from the data of two fields of view.

In order to clarify that we need to observe two fields of view, we first consider the case that only one field is used for measuring the positions of stars.

2.1 Observation with one telescope

If the period of the observation is less than one revolution, the positions of stars cannot be determined. Here we assume the scanning law of the telescope on the satellite as follows,

\[ \phi = \omega t + \sum_{k}^{m} a_k \sin k\omega' t + \sum_{k}^{m} b_k \cos k\omega' t, \quad (1) \]

where \( \omega t \) is the nominal scan, and both \( \sum_{k}^{m} a_k \sin k\omega' t \) and \( \sum_{k}^{m} b_k \cos k\omega' t \) are the terms representing oscillation of a satellite. Then observation equations for star \( i \) is described as follows,

\[ \omega t_i + \sum_{k}^{m} a_k \sin k\omega' t_i + \sum_{k}^{m} b_k \cos k\omega' t_i = \lambda_i. \quad (2) \]

Here the number of equations is \( n \) parameters that we must determine are coordinates of \( n \) stars, \( \lambda_i \), parameters for a series of oscillation, \( a_k, b_k \), and \( \omega' \), angular velocity of the satellite, \( \omega \). Then total number of parameters is
\[ n + 2m + 2, \text{ which is more than that of equations. So, we cannot determine} \]
\[ \text{values of parameters from these equations.} \]

2.2 Observation for more than one revolution

Here we consider that data for two revolutions can be used in the analysis. Then
the observation equations for first one revolution are as follows,

\[
\begin{align*}
\omega t_1 + \sum a_k \sin k\omega t_1 + \sum b_k \cos k\omega t_1 &= \lambda_1 \\
\omega t_2 + \sum a_k \sin k\omega t_2 + \sum b_k \cos k\omega t_2 &= \lambda_2 \\
\omega t_n + \sum a_k \sin k\omega t_n + \sum b_k \cos k\omega t_n &= \lambda_n.
\end{align*}
\]

(3)

The observation equations for the other revolution are as follows,

\[
\begin{align*}
\omega t_{n+1} + \sum a_k \sin k\omega t_{n+1} + \sum b_k \cos k\omega t_{n+1} &= \lambda_1 + 2\pi \\
\omega t_{n+2} + \sum a_k \sin k\omega t_{n+2} + \sum b_k \cos k\omega t_{n+2} &= \lambda_2 + 2\pi \\
\omega t_{2n} + \sum a_k \sin k\omega t_{2n} + \sum b_k \cos k\omega t_{2n} &= \lambda_n + 2\pi.
\end{align*}
\]

(4)

The above 2n equations (3) and (4) are equivalent to the following 2n equations, that is, the equations (3) and the following equations (4)-(3),

\[
\begin{align*}
\omega(t_{n+1} - t_1) + \sum a_k (\sin k\omega t_{n+1} - \sin k\omega t_1) + \sum b_k (\cos k\omega t_{n+1} - \cos k\omega t_1) &= 2\pi \\
\omega(t_{n+2} - t_2) + \sum a_k (\sin k\omega t_{n+2} - \sin k\omega t_2) + \sum b_k (\cos k\omega t_{n+2} - \cos k\omega t_2) &= 2\pi \\
\omega(t_{2n} - t_n) + \sum a_k (\sin k\omega t_{2n} - \sin k\omega t_n) + \sum b_k (\cos k\omega t_{2n} - \cos k\omega t_n) &= 2\pi
\end{align*}
\]

(5)

If the parameters are determined, we obtain the positions of stars, \( \lambda_i \), by the
former \( n \) equations (3). Accordingly we must determine parameters by using
the latter \( n \) equations (5).

If \( \omega' \) is not equal to \( \omega \), we obtain parameters for scanning law from the
equations (5). On the other hand, when \( \omega' \) is equal to \( \omega \), the phases of \( \sin k\omega t_{n+1} \)
and \( \sin k\omega t_1 \) are the same with each other, and those of \( \cos k\omega t_{n+1} \) and \( \cos k\omega t_1 \)
also the same. In this case, the latter \( n \) equations are described as \( \omega(t_{n+i} - t_i) = 2\pi \) \( (i = 1, \ldots, n) \). From the above equations, we only solve \( \omega \). We cannot obtain
parameters of a series, \( a_k, b_k \). Consequently we cannot estimate the positions
of stars.
We obtain the positions of stars by using the scanning law when \( \omega' \) is not equal to \( \omega \). On the other hand, we cannot determine the positions of stars when \( \omega' \) is equal to \( \omega \). There is a possibility to realize that the parameter \( \omega' \) is equal to \( \omega \). Therefore we need the other informations in order to solve the positions of stars and the attitude of the satellite simultaneously in this case.

2.3 Observation with two fields of view

We consider the scanning with two fields of view. The angle between these two fields of view, basic angle, has the constant value of \( \gamma \). In this case, the observation equations with telescope 1 are as follows,

\[
\begin{align*}
\omega t_{1,1} + \sum a_k \sin k\omega' t_{1,1} + \sum b_k \cos k\omega' t_{1,1} & = \lambda_1 \\
\omega t_{2,1} + \sum a_k \sin k\omega' t_{2,1} + \sum b_k \cos k\omega' t_{2,1} & = \lambda_2 \\
\omega t_{n,1} + \sum a_k \sin k\omega' t_{n,1} + \sum b_k \cos k\omega' t_{n,1} & = \lambda_n, \quad (6)
\end{align*}
\]

where \( t_{ij} \) is the time when we observe the position of the star \( i \), \( \lambda_i \), using the telescope \( j \). The observation equations with telescope 2 are as follows,

\[
\begin{align*}
\omega t_{1,2} + \sum a_k \sin k\omega' t_{1,2} + \sum b_k \cos k\omega' t_{1,2} + \gamma & = \lambda_1 \\
\omega t_{2,2} + \sum a_k \sin k\omega' t_{2,2} + \sum b_k \cos k\omega' t_{2,2} + \gamma & = \lambda_2 \\
\omega t_{j-1,2} + \sum a_k \sin k\omega' t_{j-1,2} + \sum b_k \cos k\omega' t_{j-1,2} + \gamma & = \lambda_{j-1} \\
\omega t_{j,2} + \sum a_k \sin k\omega' t_{j,2} + \sum b_k \cos k\omega' t_{j,2} + \gamma - 2\pi & = \lambda_j \\
\omega t_{n,2} + \sum a_k \sin k\omega' t_{n,2} + \sum b_k \cos k\omega' t_{n,2} + \gamma - 2\pi & = \lambda_n. \quad (7)
\end{align*}
\]

There are \( 2n \) equations. The above \( 2n \) equations (6) and (7) are equivalent to the following \( 2n \) equations, that is, the equations (6) and the following equations (7)-(6),

\[
\begin{align*}
\omega (t_{1,2} - t_{1,1}) + \sum a_k \Delta\sin k\omega' t_1 + \sum b_k \Delta\cos k\omega' t_1 & = \gamma \\
\omega (t_{2,2} - t_{2,1}) + \sum a_k \Delta\sin k\omega' t_2 + \sum b_k \Delta\cos k\omega' t_2 & = \gamma \\
\omega (t_{j-1,2} - t_{j-1,1}) + \sum a_k \Delta\sin k\omega' t_{j-1} + \sum b_k \Delta\cos k\omega' t_{j-1,2} & = \gamma
\end{align*}
\]
\[ \omega(t_{j,2} - t_{j,1}) + \sum a_k \Delta \sin k\omega' t_j + \sum b_k \Delta \cos k\omega' t_j = \gamma - 2\pi \]

\[ \omega(t_{n,2} - t_{n,1}) + \sum a_k \Delta \sin k\omega' t_n + \sum b_k \Delta \cos k\omega' t_n = \gamma - 2(8) \]

where

\[ \Delta \sin k\omega' t_i = \sin k\omega' t_{i,2} - \sin k\omega' t_{i,1} \]
\[ \Delta \cos k\omega' t_i = \cos k\omega' t_{i,2} - \cos k\omega' t_{i,1}. \]  \hfill (9)

As described above, the number of equations is \(2n\). On the other hand, the number of parameters for coordinates of stars, \(\lambda_i\), terms for a series of oscillation, \(a_k, b_k\), is \(n\) and \(2m\), respectively. Also, we have two parameters, \(\omega'\) and \(\omega\). Therefore the total number of parameters is \(n + 2m + 2\). If we observe much larger number of stars than that of the parameters, we can solve these equations. Here we note that if the ratio of basic angle, \(\gamma\), and \(2\pi\) are the fraction, \(m/n\), made by small natural number, \(m\) and \(n\), the degeneracy appears in equations (8), because the terms shown in (9) becomes 0 when \(k = n\). In this case again, we cannot determine the positions of stars.

3 Basic Angle

![Degeneration Angle](image)

Figure 1: degeneration angle

In order to avoid the degeneracy as much as possible, it is preferable that the ratio of basic angle, \(\gamma\), and \(2\pi\) are not the fraction, \(m/n\), made by small natural numbers, \(m\) and \(n\). Then we must avoid angles in which we show lines in Figure 1. There are some preferable angles for our objectives. As one of these angles, we select the \(99.5^\circ\) for basic angle.
4 Estimation of Centroiding of Stars

In order to obtain the accurate positions of stars, we must estimate the centers of stars. The photon weighted means are easily calculated from the number of photons for each pixel. However, those photon weighted means are different from the real positions. In our algorithm, we assume that the difference between the photon weighted mean and the real position is proportional to the deviation of the photon weighted mean from the center of the pixel. Then we estimate the real positions of stars from the photon weighted mean by using least square method (Yano et al. 2004; Triebes et al. 1999, 2000).

We have experimented the measurement of centers of star images on a CCD for investigating the accuracy of finding the positions of stars, using our algorithm. Then we have obtained the results from the experiment that the accuracy of estimation of distance between two stars is about a variance of 1/300 pixel, that is, the error for one measurement is about 1/300 pixel, which is almost an ideal result given by Poisson noise of photons.

References

- Yano, Taihei; Gouda, Naoteru; Kobayashi, Yukiyasu; Tsujimoto, Takuji; Nakajima, Tadashi; Hanada, Hideo; Kan-ya, Yukitosh; Yamada, Yoshiyuki; Araki, Hiroshi; Tazawa, Seichi; Asari, Kazuyoshi; Tsuruta, Seisaku; Kawano, Nobuyuki 2004, The Publications of the Astronomical Society of the Pacific, Volume 116, Issue 821, pp. 667-673
Bio-mimetic Mechanism for Rovers  
Under Microgravity Surface Environment  

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Abstract: This paper presents the design and preliminary analysis of a mobile robot for asteroid exploration. The goal of this research is to investigate different mobility systems which may present advantages over conventional wheel or leg locomotion in microgravity environment. The requirement for the robot is to achieve scientific investigation of the asteroid surface at arbitrary locations with fine positioning capability after large stride movement. We show that a robot which has multiple simple legs in a symmetric arrangement can have both large stride and crawling mobility. The paper discusses dynamic behavior of a multi-legged robot in different gravity conditions and shows that the behavior in microgravity environment becomes similar to that in normal gravity by reducing the magnitude of the leg motion and control forces accordingly.

1 Introduction

With the recent success of the MER Missions [1], there is an increasing interest in robotic exploration to other celestial bodies such as moons, asteroids and comets. These bodies are characterized by a low to medium gravitational environment. The space exploration community has spent considerable effort and has significant ongoing interest in the development of mechanical mobility systems that are capable of supporting long-range scientific exploration of such bodies, therefore a number of probes have been launched to explore some of those bodies, revealing their interesting nature. Among these probes are: NEAR-Shoemaker to asteroid Eros, Stardust to a comet and recently MUSES-C Hayabusa mission, which is set to be the first mission to return a sample from an asteroid and thus allowing scientists to analyze the composition of the asteroid [2].

But the best method to achieve mobility on these planetary bodies is still the subject of discussion. So far, wheels have been used with excellent results in manned and unmanned mobility, and legged prototypes have been successfully demonstrated during Earth-based experiments. However, these are neither the only possible method nor perhaps the most efficient ones to achieve mobility for exploration in low gravity and microgravity.

Lately it is believed that the most successful parading for space exploration is a multi-wheeled rover. This concept is currently being extended to both larger and smaller sized rovers. Smaller rovers can be effectively used in tandem with rovers to increase exploration range, in spite of their limited size, by exploring difficult areas. Legged rovers have previously been proposed for space exploration [3] in order to overcome the limited movement of wheeled vehicles on rugged terrain. These approaches to surface mobility have significant drawbacks. First, even exotic type of wheels rovers can only drive obstacles that are at best a fraction of the vehicle's body length. Thus, some terrains are not accessible to wheel vehicles. While legged robots can potentially access rough areas, they are mechanically complex, requiring numerous joints, actuators and linkages. Even wheeled robot vehicles use a significant number of actuators and complex suspension linkages. There are a number of obvious drawbacks in using many motors and their associated linkages: an inherent risk of system failure; a need for larger power supplies and/or solar cells; a need for complex power electronics; and increased weight (which reduces the weight that can be allocated to science payloads).

As an alternative to all these mobility methods hopping systems for planetary exploration were first proposed and used in the MUSES-C mission, a robotic device named MINERVA will be deployed on
the target asteroid [4]. As appointed previously, unlike the surface of major bodies, such as Earth, Moon or Mars, the gravity level on the surface of minor bodies is remarkably small, then a conventional lander can not stay on the surface, or a robot can not move on the surface with conventional locomotion strategies. MINERVA will use an internal reaction wheel to obtain a thrusting force in order to move on the surface. Even with this idea, the motion of the rover will be hopping and bouncing on the asteroid, therefore the location of the robot when the bounds are finally damped out is very difficult to predict or control.

As an earlier prototype of the second generation rover, a robot named “Rock Climber Rover” was proposed [5][6], which used multiple limbs with a sticker at the end. After a careful consideration of possible sticker forces, centimeter-long claws were concluded as the most effective way to grab a boulder that might have millimeter-long roughness on its surface. This rover had three multi-DOF forceps limbs that were supposed to hold the rover to the asteroid while moving on the surface, picking up rock fragments, and conducting in-situ analysis.

2 Biomimetic Approach

Biomimetics is a scientific and technical discipline finding inspiration in biological systems to define new engineering solutions. It is a multi-disciplinary subject involving a wide diversity of other domains like electronics, informatics, medicine, biology, chemistry, physics, mathematics, and many others. This discipline has already shown the way to a number of innovations and improvements in space engineering.

The area of environment which an organism can directly access and influence is obviously vastly increased if the organism is able to move around in the environment. Movement is a vital component of the survival repertoire of animals, and many different modes of movement are employed depending on the environment in which the animal operates.

The majority of work on biomimetic robotic locomotion has centered on replicating some form of walking, with 2 legs or more. The possible advantages of amputalatory locomotion are a robust response to obstacles, the ability to position the body to a high degree of accuracy, and rapid movement over complex and unpredictable terrain. Wheeled vehicles are obviously superior when the terrain is relatively smooth, but have difficulties when encountering natural uneven terrains with many obstacles. Legged animals can traverse such environments rapidly, therefore the study of legged vehicles can be interesting.

Legged locomotion can be broadly divided into two interconnected subsystems: stance control and swing control. Stance control positions the centre of mass of the robot and reacts to external disturbances and swing control cycles the legs periodically. In the case of insect ambulation control, the walking system is divided into six coupled relaxation oscillators, consisting of intraganglionic interneurons, motoneurons, muscles, tendons and mechanoreceptors situated on the leg itself at various points. For biomimetic imitation of insect legged movement, it is not possible or desirable to try and replicate this complexity. However, a good muscle analogue is thought to be the most important component that must be emulated well in order to achieve the goal of a controllable leg and hence locomotion. So, this is the main point, try to emulate, not to replicate exactly.

3 General Design Goals

The main design points that have driven this project are indicated below:

- To explore a different mobility paradigm which may present advantages over conventional wheel and leg locomotion in microgravity environment.

- Power, communication and science instruments functions must be all contained in the rover. The Surface Science Package (SSP) will consist of the Science Payload for in-situ analysis and for subsurface exploration.

- Improve the mission performance of MINERVA implementing two mobility modes:

  - **Large Stride Mode**: used to cover large distances hopping using an inner gimbals joint system as a reaction wheel for thrusting.

  - **Crawling Mode**: to be used to move toward a location within small distances from the actual position.

In the mobility modes, it is necessary to say that the first one, the Large Stride Mode, is already implemented in the MINERVA rover, so the improvement and the new idea of this project is to give the rover the second mobility mode, the crawling one, which will allow the robot to move small distances in order of millimeters or centimeters.

4 Mission Scenario

The Main Mission Scenario will consist of a rover located during the space trip in the main spacecraft that will be deployed on the asteroid surface.

The rover will be deployed from the spacecraft to touch down on a boulder. For soft touch-down, the deployment should be done not from a high altitude of orbit, but from the spacecraft hovering at the height about 10-100 meters. The specific values are depend on the gravity of the target asteroid; although, if the size of target is equivalent to the target of MUSES-C (several hundreds meters in a mean diameter,) the touch-down velocity will be 1-10 [cm/s] after the free fall from the height of 10-100 [m].

One issue for the control policy is how to know the exact position of the rover on the surface asteroid. One solution can be to map the asteroid surface in advance from the spacecraft and then using star
sensors the exact location of the rover could be estimated on the asteroid surface represented by the numerical grid.

In this scenario, power, communication, and other house-keeping functions must be all contained within the rover. If the spacecraft goes back to the orbit after the deployment of the rover, it will be helpful to relay the communication from/to Earth.

Pictures of the asteroid's surface, boulders and cracks are taken as the rover moves. Mineral composition analysis is conducted using in-situ mass (alpha/gamma-ray) spectrometry. Seismometers can be carried and set on designated points of the asteroid's surface.

The sub-surface studies have in this case a great importance. Space weathering shows a huge influence in asteroid surfaces. The elements located in the surface of the asteroid can experience some chemical alterations by exposure to solar wind, so the information about the original materials is simply lost. In the same way, small impacts by micrometeorites modify in a certain degree the composition, and not only the shape, of the asteroid surface. We assume that the environment faced by the rover proposed in this project will be similar to the asteroid Itokawa [7], the target of the present Hayabusa mission.

5 System Design

5.1 General Design

The inspiration of the design was found in sea urchins that are spherical-shaped echinoderm with movable spines covering the body. Long and sharp spines are used for protection and locomotion.

The rover we proposed here is basically a sphere of 20 [cm] of radius and a total mass, after allocating the Surface Science Package and the subsystems of the robot, of 2 [kg]. It has 6 legs distributed in an isometric way and each leg has only 1 DOF. The orientation of the legs is radial. See Figure 1.

Every leg is normal to the others except to the one that is located in the same direction; and the movement of every of them is content in the one plane.

There are two main types of legged locomotion: static and dynamic. Dynamic locomotion means that the walker changes from one unstable position to another. In such a situation, the center of gravity is not always right over the point (or area) where the foot has contact with the ground. In static locomotion, the walker remains constantly well balanced, at every instant of time.

In this robot the kind of legged locomotion chosen is dynamical, thus the rover performs the crawling mode of the movement with three legs, and therefore no intermediate equilibrium positions during the movement are expected.

In the beginning of the development, several configurations including the choice of static locomotion have been considered. After some discussions, the dynamic approach was chosen because it is less time consuming in the control issues rather a static one, with four legs coordinated to perform the crawling. The reason of this choice was because of the fact that the main aim of the project was to find out if the concept itself worked in microgravity.

This design pretends to fulfill the requirements that will make the rover be eligible for a mission in a microgravity surface environment:

Mobility:
As it will be shown in the results of the simulation, the rover is able to move itself over a surface under microgravity environment. At this state of the project this is the main point that the simulation intends to prove. The control issue is not faced up to date; but as a next step, to move to a desired location some control algorithms will be necessary applied. This leg distribution allows the rover to move even if it runs into a high slope and begins to roll down.

Simplicity:
The configuration of the rover is quite simple, as it is seen in the figure. Not many legs and the fact that each one has only one DOF makes the robot very reliable; this will minimize the possibility of failure.

Robustness:
The simple general design and the particular one
movement of the contact point are preferable in order to minimize the impacts with the surface. It is important to remember that a great impact with the ground can make the rover just be expelled from the surface, because of the low escape velocity in small bodies.

6 Movement of the rover on the surface

If we consider that while no contact points of the rover are in touch with the ground, the trajectory of the rover is ballistic one, it is possible to realize that should exist an analogy between the behavior in normal gravity (1G) and the behavior in microgravity ($\mu G$) conditions.

The ballistic trajectory is defined in the $xz$ plane as follows:

$$x = V_{ox}t$$  \hspace{1cm} (1)

$$z = z_0 + V_{oz}t + \frac{1}{2}(-g)t^2$$  \hspace{1cm} (2)

When the rover touches again the ground after performing the leap, $z = 0$:

$$V_{oz} = \frac{gT}{2}$$  \hspace{1cm} (3)

where $T$ is the flight time between two leaps.

On the other hand,

$$f\Delta t = mV_0 \Rightarrow f = \frac{mgT}{2\Delta t}$$  \hspace{1cm} (4)

considering,

$\Delta t$ : time in contact with the ground

$m$ : total mass of the robot

$$V_0 = \sqrt{V_{ox}^2 + V_{oy}^2}$$

and approximating $V_{oz} \approx 0$, the expression of the force in microgravity becomes

$$f = \frac{mgT}{2\Delta t}$$  \hspace{1cm} (5)

while in normal gravity:

$$F = \frac{mGT}{2\Delta T}$$  \hspace{1cm} (6)

Keeping the flight times almost constant, the relation between the forces applied in microgravity and in normal gravity becomes:

$$\frac{f}{F} = \frac{g\Delta T}{G\Delta t}$$  \hspace{1cm} (7)

$\Delta t$ : time in contact with the ground in $\mu G$

$\Delta T$ : time in contact with the ground in normal $G$

$m$ : total mass of the robot

$T$ : flight time between two leaps

5.2 Leg Design

The mechanism proposed for every leg is a closed chain planar one. It has only one DOF and consists of two links and three joints. A sketch of the mechanism with its main components is shown in Figure 2.

Before selecting this mechanism, some trade-offs were made with other closed chain planar mechanisms, as four bar linkages. The main reason of studying several topologies is to try to figure out the best one considering the trajectory of the end tip point of the leg. For this purpose, a Chebyshev trajectory of the end tip point can be considered as a promising option for further steps in the project. Also some studies about the contact geometry of the leg should be carried on.

O: Rotational joint fixed to the body of the robot.

A: Rotational joint between the crank and the slider.

S: Rotational and Translational joint fixed to the body of the robot.

5.3 Operation

A torque is applied in the crank to make the mechanism work. The point C, en end tip of the slider, is the contact point with the ground. When the end tip of the slider touches the ground, a reaction force is induced and, due to the normal component of this reaction, a friction force ($F_r = \mu N$) yields to thrust the robot forward.

The topology of the mechanism defines the trajectories of the end tip points; it is desirable to have trajectories in which the contact can be the smoother as possible, so smaller amplitudes in the periodical
\( f \) : reaction with the grounds in \( \mu G \)  
\( F \) : reaction with the grounds in normal \( G \)

From the last equation, it can be deduced that rover behavior in microgravity should be analogous to the one observed in 1G. This deduction will path the way to the policy that is followed during the simulation process.

### 6.1 Ground Contact Model

Surfaces of asteroids show the characteristics of fragmental debris (regolith) and not bare rock: boulders are everywhere, there are patches devoid of craters; it seems likely that they have been filed in by loose material. Other patches appear bright; it seems likely to be freshly uncovered regolith.

The ground is modeled as a linear spring damper in the \( x \) and \( y \) directions and a non-linear spring and a linear damper in the \( z \) direction. Using a non-linear (hardening) spring in the \( z \) direction is a standard way to prevent ground chattering or bounce while still simulating a stiff ground.

\[ k_{xy} = 1500, B_{xy} = 16, k_z = 125, B_z = 300, \mu = 1.5 \]

In \( z \) direction, the non-linear force in the normal to the contact plane is defined by the following equation:

\[ F_z = -k_z \frac{z - z_p}{L_{nom} + (z - z_p)} - B_z \dot{z} \]

where,

- \( F_z \) : normal reaction to the plane in the end tip point  
- \( k_z \) : spring elastic constant  
- \( z \) : position in \( z \) direction of the end tip point  
- \( \dot{z} \) : velocity in \( z \) direction of the end tip point  
- \( z_p \) : penetration in \( z \) direction of the end tip point  
- \( L_{nom} \) : nominal length of the spring  
- \( B_z \) : viscous constant

It is observed, naturally, as the stiffness is lowered, greater penetration in the ground occurs. The lower the damping constants are, the longer they occur the vibrations. However, a very high increment in stiffness or in damping constants can produce instabilities in the simulation due to numerical issues. Here the ground parameters have been tuned experimentally until an acceptable ground penetration and bounce was achieved.

### 7 Simulation Study

#### 7.1 Modeling the rover

In the implementation of the different parts of the robot in the computer code, all of them are considered like rigid bodies, with defining dynamical parameters as the mass and the inertia.

The body of the robot is a free point, that is to say 6 DOF, without any constraint to the referent frame. Its shape is spherical. The legs are located in a radial configuration. Their characteristics were explained in previous sections of this report.

![Figure 3: Normal component of the velocities at the end tip points in \( 10^{-1} G \)](image3)

![Figure 4: Normal force on the surface at the contact moment in every leg in \( 10^{-1} G \)](image4)

#### 7.2 Simulation Process

The rover was test in different gravity environments, from the normal one to microgravity (\( 10^{-2} G \)) as shown in Table 1. Every time the gravity is decreased in a factor of ten. Also the torque applied in the crank and their lengths are lowered in the same factor.

<table>
<thead>
<tr>
<th>Gravity ( G )</th>
<th>( 10^{-1} )</th>
<th>( 10^{-2} )</th>
<th>( 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length ( L [\text{m}] )</td>
<td>( 10^{-1} L )</td>
<td>( 10^{-2} L )</td>
<td>( 10^{-3} L )</td>
</tr>
<tr>
<td>Torque ( T [\text{N/m}] )</td>
<td>( 10^{-1} T )</td>
<td>( 10^{-2} T )</td>
<td>( 10^{-3} T )</td>
</tr>
</tbody>
</table>

Table 1: Simulation parameters for the leg motion

#### 7.3 Results

The microgravity simulations were performed to verify the achieved rover model. Preliminary simulations
showed that the robot was capable of performing very short jumps on a flat surface in normal gravity. In each simulation case, an initial constant torque is given to the cranks of the legs that are actually in contact with the ground. During the flight time the torques are no longer applied. Under these conditions the rover could achieve a ballistic flight with tangential movement on the surface.

After running the first simulations it could be observed that flexibility (in terms of low stiffness and high damping ratio) of the legs might help to improve the movement, but this improvement has to be done so that the locomotion should be maintained continuously without or with less tipping over.

To have similar performance in microgravity environment, the amplitude and speed of the cyclic motion decreased according to the gravity level. For this reason, under lower gravity conditions the lengths of the cranks will be decreased to make the trajectory of the end tip points have lower amplitudes.

Figures 3 and 4 show a typical profile of the leg motion and contact force obtained from the simulations. It can be inferred that the robot is hopping with almost 0.5-1.0 [s] interval between two successive leg contact on the ground.

Simulation results are summarized in Table 2. In the simulation, L is assumed in the order of centimeters and T is 1 [N]. Then in case of microgravity, L has to be in the order of micrometers or small. It seems difficult to develop such a tiny crank mechanism by conventional materials, but applying MEMS (Micro Electrical Mechanical Systems) technology it would be possible to fabricate those micromechanisms.

In Table 2, the flight time remains in almost constant level whereas the magnitude of other parameters reduced by the factor of 10 in each case. This result is a good evidence to support the similarity of the dynamics in the different gravity levels described the Equation (7). The result shows that the dynamic locomotion with very small stride, thus equivalent to crawling locomotion, can be possible on the microgravity surface with an appropriate scale of the mechanism and input torque (or force) for the motion control.

8 Conclusions
After obtaining the results shown in the previous section, some conclusions are deduced.

In this study, we develop a simple design for a mobile robot (rover) for future asteroid exploration with the capability of large stride and fine crawling locomotion. The proposed rover is meant to touch the ground in three points and to perform the crawling mode only moving the three that are making contact in the moment. The design of the rover meets the main requirement: simplicity, mobility and robustness.

A dynamic simulation model for the proposed rover was developed and used for the simulation of the rover over different gravity conditions. As the gravity level is reduced, the forces and the velocities in the end tips should be decreased in the same factor in order to have keep the same flight time and height for each single stride. This means that the relationship between the behavior of the rover in normal gravity and microgravity is linearly analogous as expected. The result shows that dynamic locomotion is possible on the microgravity surface with an appropriate scale of the leg motion and control forces.

9 Future Work
The main task for the future is to develop motion planning and control algorithms for the rover based in the design presented in this work. To accomplish this aim, it will be necessary to update the initial design to achieve a static way of movement in the crawling mode as well as the dynamic movement. For instance, the topology of the rover should be refined to facilitate arbitrary crawl gait on natural rough terrain.

References