MULTI-LIMBED ROVER FOR ASTEROID SURFACE EXPLORATION USING STATIC LOCOMOTION

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ABSTRACT

This paper presents the design and preliminary analysis of a mobile robot for asteroid exploration. The basic requirement for the robot is to achieve scientific investigation of the asteroid surface at arbitrary locations with fine positioning capability after a large stride movement. A preliminary discussion and simulation on the dynamic behavior of a multi-legged robot in microgravity is addressed. This paper considers the principle of the motion using 3D computer simulation, prototype design, feasible mission scenarios, grasping and control which is focused on the generation of statically stable gaits so the robot advances with a desired speed and direction.

1. INTRODUCTION

With the recent success of the MER Missions [1], there is an increasing interest in robotic exploration to small celestial bodies characterized by a medium to low gravitational environment such as moons, asteroids and comets. Such interest, especially in asteroids and comets, is due to their status as the remnant debris from the inner solar system formation process. The space exploration community has spent considerable effort and has significant interest in the development of mechanical mobility systems that could be capable of supporting long-range scientific exploration of such bodies, and so revealing their interesting nature, but the best method to achieve mobility on these planetary bodies is still the subject of discussion.

As an alternative, 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 [3]. It 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.

For the coming mission of a minor body exploration, a smart design of a robotic system that will allow scientists more accurate positioning on the microgravity surface condition is expected. One of mission scenarios may include scientific on site observation of a tiny crater hole that could be created when the main spacecraft would attempt impact sampling [4]. The rover will be deployed over the surface just before the sampling and then it would crawl to the pinpoint location of the fresh crash-hole after the sampling.

To comply with the previous requirements, in this paper, a limbed ambulatory locomotion system is developed inspired by clever solutions exhibited by biological systems and modeled as a free-falling manipulator which does not have a fixed-point but interacts with the ground. The main goal is to enable the rover to move using the natural features of the environment and the friction of the surface for forward progress in any direction having contact only in the limb end-points. This type of locomotion has the capacity to provoke minimum reactions on the asteroid surface that could push the robot into space, or even to grab the surface when some legs are controlled co-coordinately.

There are several issues to be addressed before real robots can really interact in such a hostile environment; this paper considers the principle of the motion using 3D computer simulation, prototype design, feasible mission scenarios, grasping and control which is focused on the generation of statically stable gaits.

2. BACKGROUND RESEARCH

2.1 Asteroids

Asteroids are metallic, rocky bodies without atmospheres that orbit the sun but are too small to be classified as planets. Known as “minor planets,” tens of thousands of asteroids congregate in the main asteroid belt: a vast, ring located between the orbits of Mars and Jupiter 2.1 AU[1] to 3.2 AU from the sun. Gaspra and Ida are main belt asteroids, and are most probably the remains of the process that

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[1] *AU stands for astronomical unit and is based on the mean distance from Earth to the Sun, 9.3×10^7 miles (1.5×10^8 km).*

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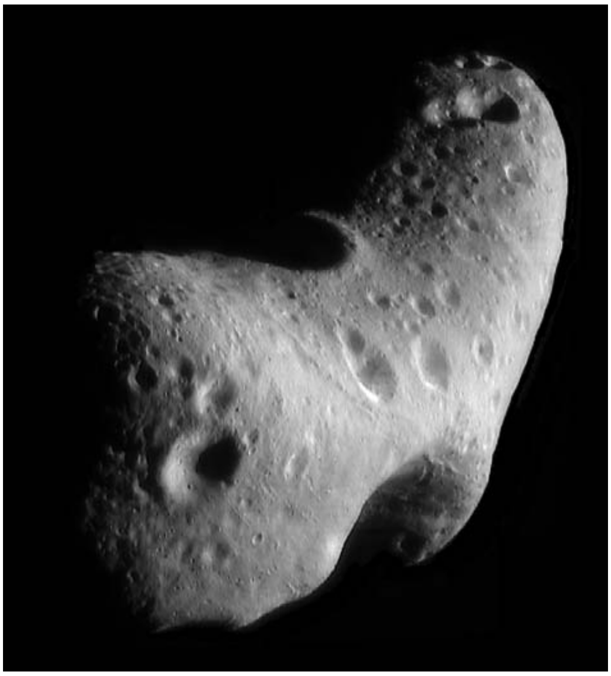

Figure 1 . Mosaic of Eros' northern hemisphere. ©Applied Physics Lab. Johns Hopkins University

formed the inner planets, including the Earth.

Although the relationship between asteroids and meteorites remains a puzzle, it is believed that asteroids are the sources of most meteorites that have struck the Earth's surface. The most common meteorites are composed of small grains of rock and appear to be relatively unchanged since the solar system formed. Since many of these meteorites have already been subjected to detailed chemical and physical analyses, the very next step is to identify if certain asteroids are the sources of those well-studied meteorites, thus its detailed composition and structure will provide important information on the chemical mixture, and conditions from which the Earth formed several billion years ago when the building blocks of life may have been brought to the Earth via asteroid and comet impacts. Therefore the study of asteroids is not only important for studying the primordial chemical mixture from which the Earth formed, but also they may hold the key as to how the building blocks of life were delivered to the early Earth.

Many questions remain about asteroids, because we have never been able to study them closely.

2.2 Past and Current Asteroid Missions

In the past, several missions to asteroids and comets have been done, some of the most important ones are the Galileo Mission to Jupiter via asteroids Gaspra and Ida, and the Near Earth Asteroid Rendezvous (NEAR) mission to 433 Eros (Fig.1), these missions were very successful in terms of fulfilling scientific and technological goals, having achieved important scientific firsts like making a close flyby of an asteroid (Gaspra), discovering a satellite of an asteroid (Ida's satellite Dactyl) and surviving a low-velocity, low-gravity impact landing on an asteroid. Yet recently, the exploration of an asteroid by a robot has just begun to be considered, ergo rover designs are being proposed for such task.

The NANO Rover [5] was studied as a candidate for the rover to be deployed in the MUSES-C asteroid mission. However, its cancellation was announced by NASA in November 2000. The NANO Rover had four wheels; each one is attached at the end of a swing able strut. The wheel itself will not work on micro-gravity surface because no traction force is generated without any normal force to push the wheel on the surface. However, the wheel may work with dynamic forces when it is swung down by the strut, and the rover will hop to a certain direction.

The hopping action could be generated by a simpler mechanism. MINERVA [3] uses a single reaction wheel inside the robot to produce the inertial reaction. In both designs, however, the location of the robot when the bounds are finally damped out is very opportunistic and difficult to predict or control.

Finally, while a snake-like articulated body that can tie around a rocky edge or push both lateral sides in a narrow ditch, is an interesting idea [6]; if the robot has limbs with a gripper, it can walk on the surface like a rock climber [7], or a spider. This is a very promising idea, but the development of a reliable gripper becomes an issue [8].

2.3 Our Next Mission Scenario

A rover will be located during the space trip in the main spacecraft that will be deployed on the asteroid surface 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 of about 10-100 meters. The specific values depend on the gravity of the target asteroid; although, if the size of target is equivalent to the target of MUSES-C (several hundred 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 could 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 communication between the Earth and the spacecraft.

Also for scientific purposes pictures of the asteroid's surface, boulders and cracks could be taken as the rover moves. Mineral composition analysis could also be conducted using on site mass (alpha/gamma-ray) spectrometry. Moreover, 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 [9], the target of the present Hayabusa mission.

3. DESIGN GOALS

There are several issues to be addressed in a possible mission scenario as noted in the previous sections. In order to achieve the desired level of success in such a case, a substantial amount of research and work must be done in some areas in order to develop a feasible limbed rover for asteroid exploration. This section describes some of the goals and challenges involved.

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 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 on site analysis and for sub-surface exploration.

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

  Large Stride Mode:
  used to cover large distances by 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.

The Large Stride Mode is already implemented in the MINERVA rover, so its performance is to be improved 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 a matter of millimeters or centimeters.

4. THE ROVER DESIGN

4.1 Biomimetic Approach

Biomimetics is a scientific and technical discipline that finds inspiration in biological systems to define new engineering solutions. It's a multi-disciplinary field that involves a wide diversity of other areas like electronics, informatics, medicine, biology, chemistry, physics, mathematics, and many others. Currently this type of mechanisms' research is aimed at developing robots that might exhibit a much greater level of robustness in performance in un-structured environments, through the replication of some form of walking, with 2 legs or more. The possible advantages of ambulatory locomotion are a robust response to obstacles, the ability to position the body with 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 naturally uneven terrains with many obstacles. Legged animals can traverse such environments rapidly; therefore the study of legged vehicles is interesting.

The most challenging parts of a walking robot are the legs. The leg design presented on this research provides 3 DOF (Degrees of Freedom). We feel confident that 3 DOF is the minimum needed in a flexible outdoor capable walking robot, for example it provides the possibility to walk in any direction in narrow environments. The leg consists of a thoracic joint for protraction and retraction, a basilar joint for elevation and depression and a distal joint for extension and flexion of the leg.

There are two main types of legged locomotion: dynamic and static. 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.

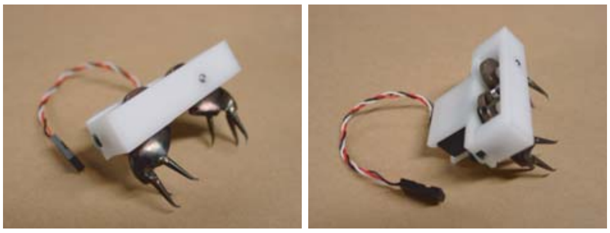

Figure 2. Prototype Gripper

4.2 Gripper Prototype

In order to get the sticking force required to grasp the asteroid a gripper prototype (shown in Fig.2) is currently being developed. A miniature servo motor commonly used for RC cars or planes was used as actuator. The developed gripper works to hold on the surface of a natural stone, even in $1G$ environment.

4.3 Control

Given that with an appropriate control of movements, a legged robot could climb boulders, cross ditches, and walk on extremely rough terrain to a desired position, this type of rover has previously been proposed for space exploration in order to overcome the limited movement of wheeled vehicles on rugged terrain and the lack of friction force for the wheels to work appropriately; but as a counterpart, there is a much higher complexity involved in the control of several actuators. This complexity is due in no small part by the two legged locomotion interconnected subsystems: the stance control and the swing control. Stance Control positions the centre of mass of the robot and reacts to external disturbances and Swing Control cycles the legs periodically.

Many approaches to control already exist, most of them being biologically inspired. When designing the control of the locomotion of a legged robot there are many aspects that have to be dealt with simultaneously and whose actions interfere with each other. For example, movements of legs must be carefully coordinated in order to advance the body without causing feet slippage; at each step, an appropriate foothold has to be found, avoiding invalid ground patches for placing a foot and keeping a sufficient range of leg mobility for future motion; body attitude must be set according to the terrain profile to avoid collisions with obstacles, keep stability, etc. To deal with such a complexity we basically have followed the behavior-based approach [10] in which the control process is broken down into hierarchically organized modules running simultaneously, each one providing a specific competence that solves some aspect of the control task. In this approach, processes of a given level perform their actions unconcerned with the operation of higher level ones. At the same time they take advantage of the competences provided by lower level processes, sometimes governing their workings by providing specific inputs to them.

Also the presented control approach combines two biological control principles, the Central Pattern Generator (CPG) and reflex. Whereas a Central Pattern Generator is able to produce rhythmic motion without the need of sensory feedback, reflexes are based on the sensor-motor-feedback. It is assumed that the CPGs produced motion patterns are not learned or adapted by the animal but represent a set of low-level locomotion mechanisms specific for the species. Applied to a robotic system this implies, that is possible to define a set of Motion Patterns a-priori, which can be produced without the need of sensory feedback.

This control strategy fulfills the requirements that will make the rover 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 in a microgravity environment. At this state of the project this is the main point that the simulation intends to prove.

Redundancy:
Although it is acknowledged that the configuration of the rover involves several actuators, as it is seen in Fig.3, many legs and the fact that each one has 3 DOF makes the robot very movable and versatile [11]. This will also minimize the possibility of mission failure due to the amount of contact and grasping points to the asteroid.

5. SIMULATION STUDY

5.1 Modeling the rover

The rover (see Fig.3) moves in a 3D environment. It consists of six identical limbs meeting at the body. Each limb has three links and three actuated revolute joints. Self-collision between limbs is ignored, meaning links are allowed to cross each other. For simulation purposes equal mass and length L is assumed for all eighteen links, and that the joints are limited by internal mechanical stops. A inertia coordinate system O_{xyz} is embedded in the World, with gravity pointing in the negative direction of the z-axis. Any configuration of the robot can be defined by a set of parameters, the coordinates and orientation (x_b, y_b, z_b, r_b, p_b, y_b) of the body and the joint angles (θ_1, θ_2, θ_3) of each limb.

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 pa-

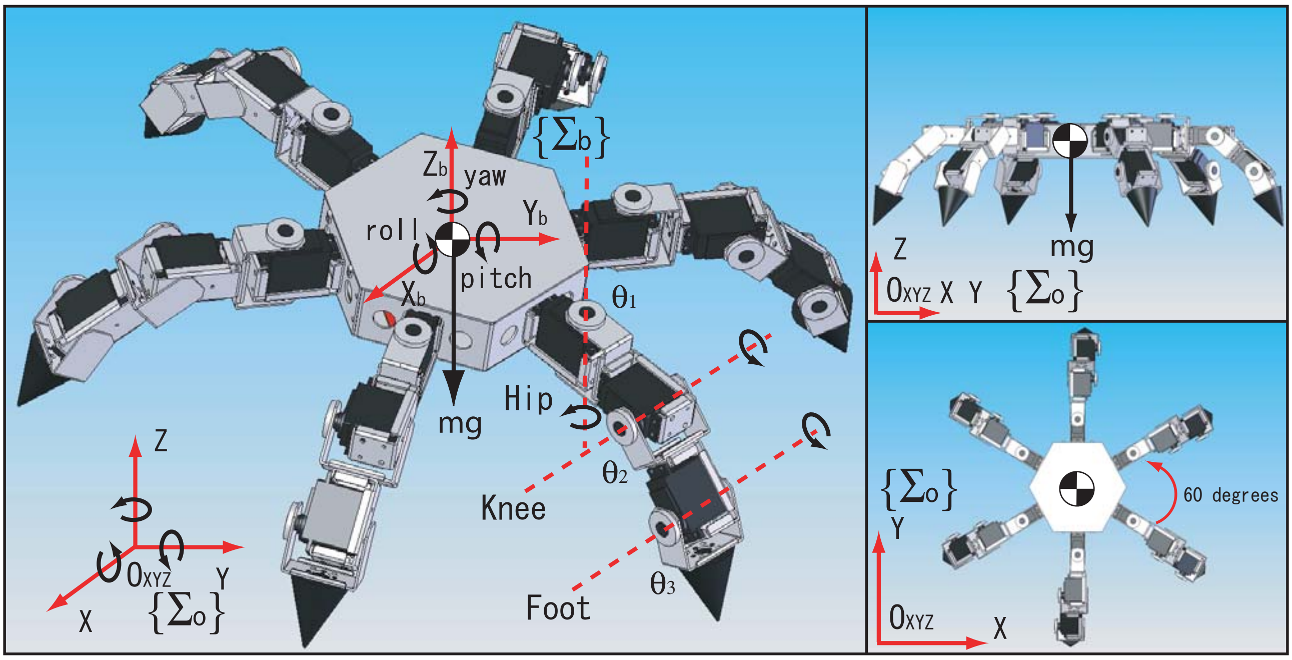

Figure 3. The design of the asteroid surface robot discussed in this paper

rameters as the mass and the inertia. The robot is considered as a free-falling manipulator which does not have a fixed point but has interaction with the ground. First the dynamics of a free-falling manipulator are formulated in the next section by introducing the variables representing position and posture of the base link (the body), and then the formulation of the reaction forces from the ground at end tip of the limbs.

5.2 Kinematics of the Robot

The considered 3D structure is formed by a central body, with a hexagonal shape and six legs [12]. The legs are similar and symmetrically distributed around the body. Each leg is composed by two links and three rotational joints. Two of these joints are located in the junction of the leg with the central body. The third joint is located at the knee, connecting the upper and lower link. Therefore each leg has 3 DOF. Considering six legs and the additional 6 DOF for central body translation and rotation, the system has a total of 24 DOFs.

The described robot legs are similar to simple manipulator with 3 DOF; therefore the The Denavit-Hartenberg method can be used to compute the transformation matrices between the referential frames. The derived transformation matrices are presented in [17].

The six legs and the central body must be integrated to solve the global kinematics problem.

5.3 Dynamics of the Robot

To produce an accurate representation of the simulated rover, a dynamics simulation model of a free falling manipulator was obtained from an expansion of the general manipulator simulator scheme. Then the global motion dynamics can be expressed as follows:

$$\begin{aligned} H(x)\ddot{x} + b(x,\dot{x}) &= u + K(x)f_{ext} \quad (1) \\ b(x,\dot{x}) &= C(x,\dot{x})\dot{x} + g(x) \quad (2) \end{aligned}$$

Here, $x^T = [p_b^T, q^T]$, $u^T = [f_b^T, \tau^T]$, and the other parameters are:

p_b : position of the base link
q : joint angles
$H(x)$: inertia matrix
f_b : base force
τ : actuators torque
$C(x,\dot{x})$: centrifugal and coriolis effects
$g(x)$: gravity
$K(x)$: states forces transformation matrix
f_{ext} : external forces

In order to simulate the above dynamics, we integrate equation (2) about $\ddot{x}$ numerically, and after solving equation (2) for the accelerations given x, $\dot{x}$, and the input $u^T = [0^T, \tau^T]$. $H(x)$ and $b(x,\dot{x})$ can be obtained by inverse dynamics calculation using the

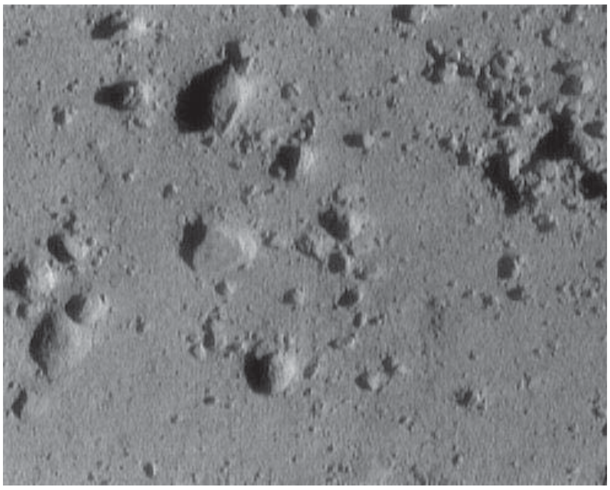

Figure 4 . NEAR Shoemaker's picture of asteroid Eros taken from a range of 250 meters used for the simulation surface. ©Applied Physics Lab. Johns Hopkins University

Newton-Euler formulation, that is, given x, $\dot{x}$ and $\ddot{x}$ solve for u.

In fact $H(x)$ can be calculated by solving the inverse dynamics, setting x to the current state, $\ddot{x} = \epsilon_j$, and ignoring the centrifugal and coriolis forces, the gravity effect and the external forces. Here ϵ_j means a unit vector with its jth element equal to 1 and others are 0. The solution about u corresponds to the jth column of H. The biasing vector $b(x, \dot{x})$ can also be computed by setting $\ddot{x} = 0$.

5.4 Ground Contact Model

The relationship between fingered manipulators and legged locomotion has been established before [13]. Such relation states that any motion of a legged robot is similar to re-grasping an object by changing the position of the fingers, so while a robot hand grasps an object, a legged robot "grasps" the surface.

In the simulation, a "grasp" is achieved if the robot is able remain attached to the surface while resisting forces (and torques) applied to it from any direction [14]. Algorithms for computing grasps of given objects are described in [15]-[16].

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 (Fig.4). 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-damper in the z direction. Using a non-linear (hardening) spring in the z direction is a standard way to prevent ground chatter or bounce while still simulating a stiff ground.

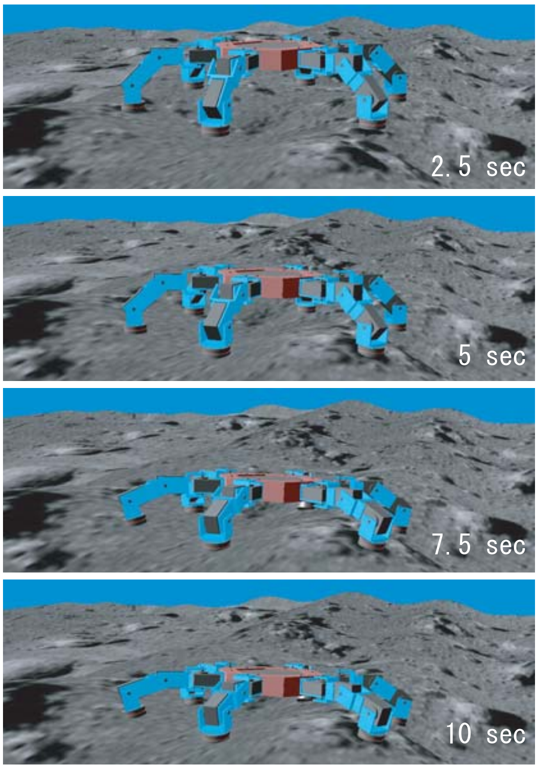

Figure 5 . The rover on the simulated Eros surface model

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

$$F_z = -k_z \frac{z - z_p}{L_{nom} + (z - z_p)} - B_z \dot{z} \tag{3}$$

where,

F_z : normal component of the end tip
k_z : spring elastic constant
z : position in z of the end tip
$\dot{z}$: velocity in z of the end tip
z_p : penetration in z of the end tip
L_{nom} : nominal length of the spring
B_z : viscous constant

It is observed that as the stiffness is lowered, greater penetration in the ground occurs. The lower the damping constants are, the longer the vibrations occur. 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.

5.5 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 a ballistic one, so it is possible to realize that an analogy should exist between the behavior in normal gravity ($1G$) and the behavior in microgravity (μG) conditions.

The ballistic trajectory is defined in the $x-z$ plane as follows:

$$\begin{aligned} x &= V_{ox}t \qquad (4) \\ z &= z_o + V_{oz}t + \frac{1}{2}(-g)t^2 \qquad (5) \end{aligned}$$

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

$$V_{oz} = \frac{gT}{2} \tag{6}$$

where T is the flight time between two leaps.

On the other hand,

$$f\Delta t = mV_o \Rightarrow f = \frac{mgT}{2\Delta t} \tag{7}$$

considering,

Δt : time in contact with the ground
m : total mass of the robot
$V_o = \sqrt{V_{ox}^2 + V_{oy}^2}$

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

$$f = \frac{mgT}{2\Delta t} \tag{8}$$

while in normal gravity:

$$F = \frac{mGT}{2\Delta T} \tag{9}$$

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

$$\frac{f}{F} = \frac{g\Delta T}{G\Delta t} \tag{10}$$

Δt : contact with the ground in μG
ΔT : contact with the ground in $1G$
m : total mass of the robot
T : flight time between two leaps
f : reaction with the grounds in μG
F : reaction with the grounds in $1G$

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 pave the way for the policy that is followed during the simulation process.

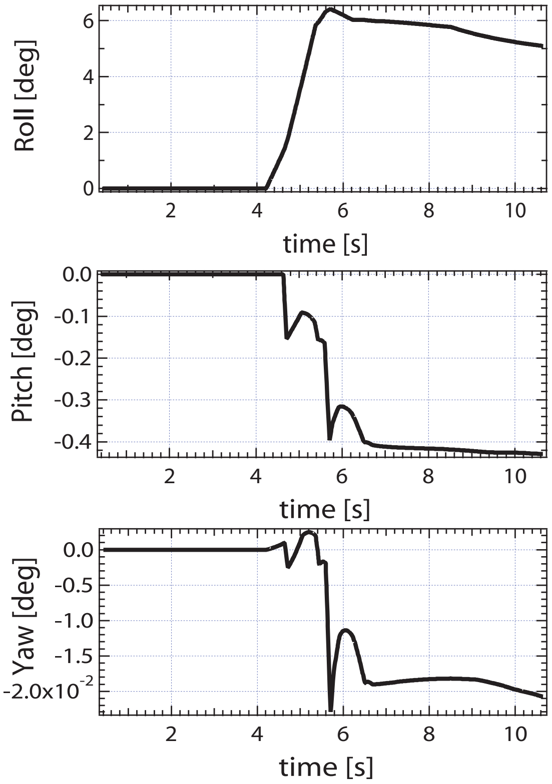

Figure 6 . Roll-Pitch-Yaw motion of the body during the landing sequence

5.6 Simulation Results

A six legged hexapod was created using simulation software that emulates physically based dynamics. The microgravity simulations were performed to verify the achieved rover model. Preliminary simulations showed that the robot was capable of performing the landing sequence on a uneven surface in 10^{-2} gravity. The simulator was able to measure the position and velocity of the hexapod's body, also the angle and angular velocity of all joints was outputted. The position of each foot and the information stating whether it was contacting the ground was also provided all these variables are mentioned because they were used in the control algorithm. Since the rover is actually in the developmental stage, appropriate sensor technology will be employed to obtain this information. Such sensors might include gyroscopes, accelerators, and foot switches.

In each simulation case (Fig.6), minimal motion in the roll and pitch direction is desired. Although during the landing sequence the rover stands on a boulder on the surface (which makes the roll angle to change undesirably) the position of the body in these directions should be stable at zero during walking (crawling mode).

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 tipping over.

6. CONCLUSIONS

This paper has described a new design for a mobile rover for future asteroid exploration with the capability of large stride and fine crawling locomotion. The proposed rover is to touch the ground in five points and to perform the crawling mode only moving the five that are making contact at the same time.

A dynamic simulation model for the proposed rover was developed and used for the simulation of the rover over different gravity conditions. So far the results show that static locomotion is possible on the microgravity surface with an appropriate scale of the leg motion and control forces, assuming that a grasping force to the surface has been achieved.

7. FUTURE WORK

There are clearly several issues to be addressed. Motion planning and better control algorithms for the rover based on the design presented in this work are the main tasks which need to be further developed.

A full scale engineering model of the rover is shortly forthcoming to demonstrate its capacities, the walking algorithm among them. A number of tests will be done to ensure that the rover is able to perform the movement on the asteroid, testing in different situations, obstacles and unexpected problems.

References

[1] http://marsrovers.jpl.nasa.gov/home/ (as of June 2005)

[2] http://www.hayabusa.isas.jaxa.jp/ (as of June 2005)

[3] T. Yoshimitsu, et al. "Autonomous Navigation and Observation on Asteroid Surface by Hopping Rover MINERVA," *In Proc. 6th Int. Symp. on Artificial Intelligence and Robotics & Automation in Space, i-SAIRAS 2001,* Canadian Space Agency, Quebec, Canada, June 2001 (CD-ROM).

[4] K. Yoshida, T. Kubota, S. Sawai, A. Fujiwara, M. Uo, "MUSES-C Touch-down Simulation on the Ground", *In AAS/AIAA Space Flight Mechanics Meeting, Paper AAS 01-135,* Santa Barbara, California, February 2001.

[5] http://robotics.jpl.nasa.gov/tasks/nrover/ (as of November 2002)

[6] http://www2.jsforum.or.jp/bosyu/contest/ (as of November 2002, in Japanese)

[7] K. Yoshida, T. Maruki and H. Yano; "A Novel Strategy for Asteroid Exploration with a Surface Robot," *In Proc. of the 3rd International Conference on Field and Service Robotics,* Finland, 281-286, June, 2002.

[8] K. Yoshida, Y. Nishimaki, T. Kubota, T. Maruki and H. Yano; "Sampling and Surface Exploration Strategies in MUSES-C and Future Asteroid Missions," *In Proc. 2002 IEEE Int. Conf. on Robotics and Automation,* pages 3155-3160, 2003.

[9] D. Scheeres, "Dynamical Environment About Asteroid 25143 Itokawa," University of Michigan, Department of Aerospace Engineering, USA.

[10] R. Brooks, "A Robust Layered Control System for a Mobile Robot," *In IEEE Journal of Robotics and Automation,* Vol. RA-2, No.1, 1986 pages 14-23.

[11] Mure, K. Inoue, Y. Mae, T. Arai, N. Koyachi, "Sensor-based Walking of Limb Mechanism on Rough Terrain", *In 5th International Conference on Climbing and Walking Robots(CLAWAR)*

[12] K. Inoue, T. Arai, Y. Mae, Y. Takahashi, H. Yoshida, N. Koyachi: "Mobile Manipulation of Limbed Robots -Proposal on Mechanism and Control-", *In Preprints of IFAC Workshop on Mobile Robot Technology,* pages 104-109, 2001.

[13] E. Rimon, S. Shoval, and A. Shapiro. "Design of a quadruped robot for motion with quasistatic force constraints." Autonomous Robots, 10:279-296, 2001.

[14] A. Bicchi and V. Kumar. "Robotic grasping and contact: A review." *In IEEE Int. Conf. on Robotics and Automation,* pages 348-353, San Francisco, CA, 2000.

[15] A. V. der Stappen, C. Wentink, and M. Overmars. "Computing form-closure configurations." *In IEEE Int. Conf. on Robotics and Automation,* pages 1837-1842, 1999.

[16] J. Ponce, J. Burdick, and E. Rimon. "Computing the immobilizing three-finger grasps of planar objects." *In Workshop on Computational Kinematics,* 1995.

[17] J. Craig. *Introduction to Robotics: Mechanics and Control,* Addison-Wesley, 1989.

[18] J. Bares, M. Hebert, T. Kanade, E. Krotkov, T. Mitchell, R. Simmons, and W. Whittaker. "Ambler: An Autonomous Rover for Planetary Exploration," *IEEE Computer,* 22(6): 18-26, Aug. 1999.

[19] M. Chacin, J. Merino, K. Yoshida and H. Yano; "Biomimetic Mechanism for Rovers Under Microgravity Surface Environment," *In Proc. of 14th Workshop on Astrodynamics and Flight Mechanics,* pages 227-232, 2004.