ATTITUDE CONTROL OF SMALL HOPPING ROBOTS FOR PLANETARY EXPLORATION: THEORY AND SIMULATIONS

ESA/ESTEC, NOORDWIJK, THE NETHERLANDS / 12 – 14 APRIL 2011

Ronald Tammepõld [1], Paolo Fiorini [2], Maarja Kruusmaa [1]

[1] Center for Biorobotics, Tallinn University of Technology, Tallinn (Estonia), Email: ronald.tammepold@gmail.com
[2] Department of Computer Science, University of Verona, Verona (Italy) Email: paolo.fiorini@univr.it

ABSTRACT

In the past years, several studies have been carried out to identify the main features necessary for a planetary hopping robot, including degrees of mobility, protection at landing, sensing algorithms and propulsion mechanisms. This paper elaborates that applying methods for attitude control of spacecrafts would efficiently achieve the dual objective of ensuring landing with a specified body orientation and of acquiring scientific information during the jump. The paper proposes to apply methods for spacecraft control based on reaction wheels to hopper attitude control, and we show that they compatible with the mass and volume budgets of a small hopping robot. After having identified a promising method, the paper presents the specific control equations of the hopping robot selected, and it demonstrates with extensive simulations that the two main objectives can be achieved.

1. INTRODUCTION

With the Soviet Lunokhod 1 & 2 rovers that landed on the Moon in the early 70s, the Pathfinder Sojourner rover that landed on Mars in 1997 and the Mars Exploration Rover Mission that began in 2003, the method of choice for robotic exploration of celestial bodies has been with wheeled rovers. So far, this concept has been successful and has sent back valuable data. Despite wheeled rovers being a successful concept, it is not the only one available, and depending on the mission, may be not the best concept. An alternative method for traversing the terrain of a celestial body, or any terrain, is by the means of discontinuous hops, like a frog or locust jumping.

The advances in technologies have led to a decrease in size and mass of measurement and communication equipment. Miniaturization could then lead to smaller robots that could be more cheaply sent to explore celestial bodies or for the price of launching one big rover, many smaller robots could be sent. Sending more robots to carry out the exploration could allow a bigger area of the celestial body to be explored and could give redundancy to the mission – the mission could still be accomplished even if some of the robots failed.

While the robots for exploring the celestial bodies become smaller, the terrain features the robots have to traverse stay the same. Wheeled rovers cannot overcome obstacles whose size approaches the size of the rovers' wheel. Therefore, there is a limit to the miniaturization of a wheeled rover. Furthermore, having small wheels in a low-gravity environment may not give enough grip for effective locomotion. Additional limitation would be the size of the terrain features, that would obstruct the robot field of view.

All of the previously mentioned problems could be overcome by a hopping robot that could traverse the terrain by hopping in single hops, like a frog or locust, thus being able to jump over obstacles many times its size and being able to observe the terrain from a higher point while being in the middle of the hop trajectory.
However, the current designs of small hopping robots also have shortcomings. So far, one of the main criticisms of the concept of hopping robots has been related to crash-landings and localization. In fact, it is believed that crash-landings would have such a degrading effect on the robot structure and instrumentation, that the survivability and mission length of these robots' would be very limited. There are numerous ways to make a structure more capable of enduring such crash-landings, e.g. surrounding it with a shock-absorbing material or re-inflatable airbags. However, surrounding the whole robot with a material to handle the crash-landings could limit the accessibility of science instrumentation to the environment or have too great an effect to the mass of the robot. Instead, by having control over the attitude of the robot, the robot structure could be optimally designed to handle the crash-landings; the air-bags or shock-absorbing material could be deployed only on one side of the robot and the robot attitude control system would ensure landing on that side.

The concept of hopping robot solves the problem of passing obstacles that are about its size or bigger. However, the same obstacles also obstruct the view of the robot while it is on the ground. For localization, and for choosing the area of interest for exploration and navigating to this area, the robot needs to have a visual overview of the environment. During the flight phase, the robot could have a good visual overview of the environment, but not without control over the camera line of sight. In the designs proposed so far, the camera has been fixed to the robot body and it has been directed together with steering the robots jump direction on the ground. It would require quite complex actuation mechanisms and control strategies to achieve the sole goal of directing the robots' camera during flight. By having the camera fixed to the robot structure and controlling the whole attitude of the robot would be an effective way to achieve good orientation control.

2. PRIOR WORK ON HOPPING ROBOTS

The concept of hopping mobility is not new. The idea of traversing the terrain of a celestial body by hopping was first proposed in [1] with a hopping vehicle for taking humans around the surface of the Moon. In a feasibility study described in [2], it was concluded that a vehicle for transporting humans on Moon is feasible. Since the 1990s, technological advances have made the idea of a miniature hopping robot for exploration of celestial bodies attractive and feasible. One of the first designs was proposed by researchers at NASA JPL and is described in [3]. It was followed by two series of improvements that would allow the hopping robot to move short disances on the ground by wheels, as shown in Fig. 1. The first generation of JPL hopper, shown on the right side of the picture, had an egg-shaped body that together with the low center of mass, made it passively self-righting. The foot was actuated by a linear spring, which was compressed by a motor via a ball screw. The prototype was equipped with a camera for capturing images through the transparent shell.

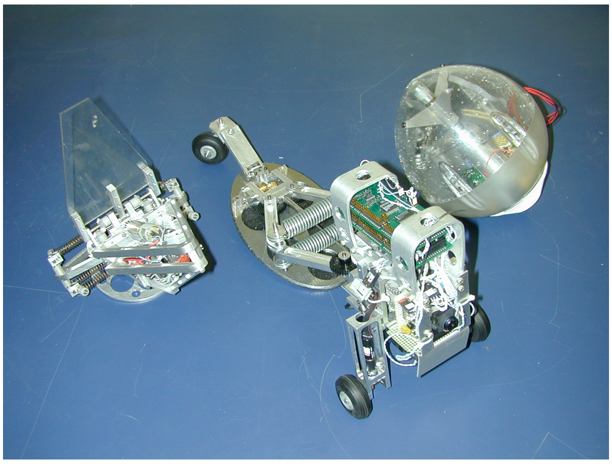

Figure 1. The three generations of JPL hoppers.

The 2nd generation hopper, shown on the left side of the picture, was designed to address the shortcomings of the previous design. An efficient non-linear spring was achieved by a 6-bar spring/linkage system. This mechanism gave peak acceleration during the last part of the spring decompression, solving the problem of premature liftoff. Robust steering of the hop direction was achieved by rotating the robots' structure on its foot. The 3rd generation design, shown at the center of the figure, was proposed to address the lack of fine mobility. It added three wheels to the robot to be able to reach the science targets precisely, while retaining one motor for spring compression, hop direction and take-off angle steering.

In an investigation to lower the cost of planetary exploration the Canadian Space Agency (CSA) targeted the exploration of Mars with the design of a tetrahedron-shaped jumping robot that is described in [4] and shown in Fig. 2. Like most hopping robots, this design uses a compressed spring to achieve the actuation required for hopping.

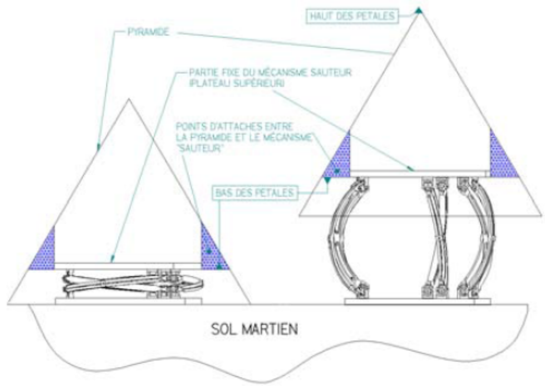

Figure 2. Hopping robot concept developed by the Canadian Space Agency with the hopping mechanism in compressed (left) and uncompressed state (right)

The hopping robot MINERVA (Yoshimitsu, et al.) was released from the Hayabusa (also known as MUSES-C) [5] space-probe to land on the 25143 Itokawa asteroid, traverse its terrain and take measurements. Unfortunately the rover missed the asteroid on landing, but this is so far the only attempt to use any kind of hopping mechanism in real space exploration.

Search and rescue in hazardous and inaccessible environments such as rubble is another task that is suitable for jumping robots. A cheap design with limited mobility for this task using a mechanism similar to that of MINERVA is described in [6].

Recently a few designs with two wheels and a hopping mechanism have been proposed, such as the robot described in [7] named as “Scout”, [8] and [9].

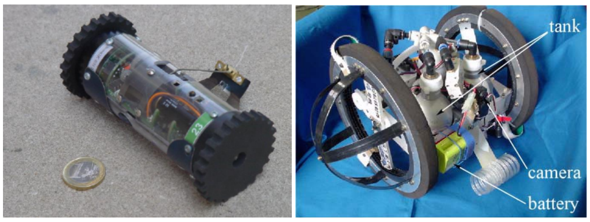

Figure 3. The miniature robot “Scout” and a similar design from Tokyo Institute of Technology, Japan

Recent interest in biomimetics has also led to biologically inspired design of hopping robots for traversing rough terrain. [10] describes a small frog-inspired jumping robot. One of the most recent and smallest hopping robot prototype that has the mass of just 7g is described in [11].

It must be noted that both the hopping robots developed in NASA JPL [12] and the one developed in CSA [4] have roughly the same dimensions and mass of up to 2kg. Both are specifically designed for planetary exploration and the latter specifically for Mars exploration. This may give an indication of the mass and dimension for hopping robots for Mars exploration.

Most of the research done on the field of hopping robots is on mechanical design to allow greater mobility and survivability. For a useful science mission, the hopping robot must also be capable of effective localization and navigation. In [13], localization of a hopping robot is achieved by fusing the data from a camera, accelerometers and gyroscopic sensors. Furthermore, landing protection is described in [14] by surrounding the instrumentation package with an elastic cage that could serve both as spring for the jumping mechanism and as protection of the instrumentation. Another study on the robustness concepts of hopping robots is presented in [15].

This brief summary of past work has introduced the concept of hopping robots and its advantages and disadvantages for space exploration. In this paper we argue that including the capability of in-flight attitude control in the design of a hopping robot for space exploration would address the two of the main limitations of this approach. First it would allow the control of the robot attitude on landing, thus allowing it to be designed for better survivability; for example, by cushioning the side of the expected impact. Secondly, it would allow directing the on-board camera during flight to gain a better view of the surrounding terrain.

To achieve attitude and landing control, this paper proposes that jumping robots could have two reaction-wheel actuators that would allow full control of the attitude of the hopping robot and a possible harvesting of kinetic energy at impact.

3. MODEL OF A RIGID BODY WITH TWO REACTION-WHEELS

The dynamics of a free-falling system with reaction-wheel actuators is governed by the law of conservation of angular momentum. A general equation for this kind of system is given as Eq. 1.

$$I \cdot \dot{\vec{\omega}} + \dot{\vec{h}} + \vec{\omega} \times \left(I \cdot \vec{\omega} + \vec{h}\right) = 0 \qquad (1)$$

Where I is the inertia matrix of the whole system, including the rotating wheels; $\vec{\omega}$ is the angular velocity of the system; $\vec{h}$ is the angular momentum of the reaction-wheels relative to the rest of the body.
For the special case, where the body’s principle axes of inertia coincide with the axes of the body’s co-ordinate frame, the inertia matrix is

$$I = \begin{pmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & I_3 \end{pmatrix}$$

If the system has two reaction-wheels whose axes coincide with the x- and y-axis of the body’s coordinate frame, the equation of motion can be written as Eq. 2.

$$\begin{gathered} I_1 \dot{\vec{\omega}}_1 - (I_2 - I_3)\omega_2\omega_3 - h_2\omega_3 = T_{w1} \\ I_2 \dot{\vec{\omega}} - (I_3 - I_1)\omega_3\omega_1 + h_1\omega_3 = T_{w2} \\ I_3 \dot{\vec{\omega}} - (I_1 - I_2)\omega_1\omega_2 + h_2\omega_1 - h_1\omega_2 = 0 \\ \dot{h}_1 = \dot{\omega}_{w1} J_{w1} = T_{w1} \quad \dot{h}_2 = \dot{\omega}_{w2} J_{w2} = T_{w2} \end{gathered} \qquad (2)$$

Where ω_{w1}, ω_{w2} are the angular velocities of the wheels relative to the body; J_{w1}, J_{w2} are the inertias of the wheels; T_{w1}, T_{w2} are the torques applied to the wheels by their motors.

A more detailed discussion on and derivation of these equations is presented in [16].

4. SPIN-AXIS CONTROL LAW FOR ATTITUDE CONTROL

In the special case where the system’s initial angular momentum is zero, two reaction-wheels can provide the system full attitude control. [17] [18] [19] There can be disturbance torques during the hopping robot’s lift-off phase and therefore it cannot be assumed that the system would always have zero initial angular velocity. In this case, it is possible only to achieve control over the direction of the axis that is perpendicular to the axes of the two reaction-wheels.

A spin-axis control law has been presented in [20] that gives control over the direction of the robot's axis that is perpendicular to the axes of the reaction-wheels. To describe the direction of the spin-axis, this control law makes use of the so-called "w-parameterization" that is presented in [21]. This parameterization can describe the direction of a three-dimensional vector with two parameters: $w_1$and w_2. The kinematic equation for this parameterization is given in Eq. 3.

$$\begin{aligned}\dot{w}_1 &= \omega_3 w_2 + \omega_2 w_1 w_2 + \frac{\omega_1}{2}(1 + w_1^2 - w_2^2) \\ \dot{w}_2 &= -\omega_3 w_1 + \omega_1 w_1 w_2 + \frac{\omega_2}{2}(1 + w_2^2 - w_1^2)\end{aligned} \tag{3}$$

Making use of the so-called "w-parameterization", the spin-axis control law proposed in [20] is given in Eq. 4.

$$\begin{aligned}T_{w1} &= I_2\omega_2\omega_3 + h_{w2}\omega_3 + k_1 w_1 + k_2\omega_1 \\ T_{w2} &= -I_1\omega_1\omega_3 - h_{w1}\omega_3 + k_1 w_2 + k_2\omega_2\end{aligned} \tag{4}$$

$k_1$and k_2 are constant control gains that satisfy $k_1 > 0$ and $k_2 > 0$. This law ensures that the system asymptotically converges to the point $\omega_1 = \omega_2 = w_1 = w_2 = 0$; i.e. the z-axis of the system coincides with the z-axis of the reference coordinate frame.

If the total angular momentum of the system is initially not zero, the angular momentum of the two reaction-wheels h_1, h_2, and ω_3 cannot converge to zero simultaneously according to the conservation of angular momentum. As $t \to \infty$, ω_3 will converge to constant value $\omega_{3\infty}$ and the dynamics of the angular momenta of the two reaction-wheels can be described by Eq. 5.

$$\begin{aligned}\dot{h}_1 &= h_2\omega_{3\infty} \\ \dot{h}_2 &= -h_1\omega_{3\infty}\end{aligned} \tag{5}$$

By differentiating these equations, it can be seen that h_1 and h_2 oscillate periodically. The practical effect of this is that in case the system has non-zero initial angular momentum, to keep the system in the desired attitude, the actuators have to constantly accelerate and decelarate the wheels and thus consume energy.

5. THE SIMULATED ROBOT

5.1. Mechanical design

For the simulations, a design concept based on the 2nd generation hopper designed in JPL is proposed. The need to control the camera direction and the landing configuration are both solved by having 2 reaction-wheel actuators that give control over the direction of one axis of the body. The moment of inertia of the RW actuators are $J_w = 10^{-4} kg\ m^2$which is the moment of inertia of a 2 mm thick steel disk with a diameter of about 9 cm that weights about 80 g. The inertia of the RW was chosen so that its RPM would not have to be higher than 10000 RPM to achieve the actuation in during the given time.

On Earth, the developed prototypes' spring energy gave it a hopping distance of 2.3 – 3 m and hop height about 1.2 m. The mass of the robot was 1.3 kg.

In our theoretical study of hopping robot with attitude control system, we consider that the spring energy of the prototype is the same as the prototypes' (although it could also be increased) and the additional mass of the attitude control system and perhaps some science instrumentation would be 0.4 kg. A very likely target for a future space exploration mission would be to the Earths' Moon. If the science mission were to Earths' Moon, its gravity of $1.62\frac{m}{s^2}$ would make the hop trajectory height 5.6 m, distance 22 m and flight time 5.2 s. During this flight time, the robot should be able to aim its camera to the desired object to be observed and before landing, achieve the desired landing attitude.

If due to disturbance torques during take-off phase, the robot has an initial angular momentum, the attitude of the robot cannot be stabilized absolutely and the robot will have angular momentum in the unactuated axis. In an ideal case, the unactuated axis would have mass-symmetry and the angular momentum of the system will cause the robot to rotate around that axis. However, having an ideal mass-symmetry around the camera axis that is to be directed is a difficult constraint to satisfy in the mechanical design of the robot. Additionally, the robots' structure may deform during its operation causing change in the inertia properties. Therefore it is important to consider the system with non-ideal inertia properties and an arbitrarily perturbed inertia matrix is proposed for evaluating the systems performance in simulations.

For an estimate of the robots' possible inertia properties, an approximate mechanical model of the robot was done in computer aided design software.

In case the axes of principle moments of inertia would coincide with the bodies' coordinate axes, an estimate of the inertia matrix would be

$$I_{ideal} = \begin{pmatrix} 0.012 & 0 & 0 \\ 0 & 0.017 & 0 \\ 0 & 0 & 0.002 \end{pmatrix} kg\ m^2$$

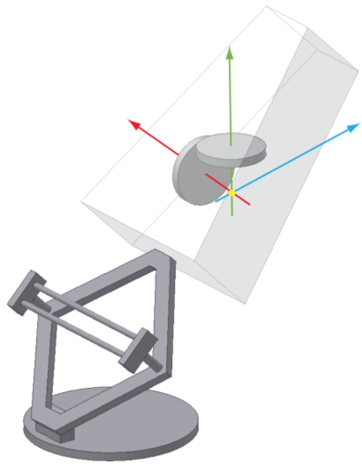

Figure 4. Approximate model of the 2nd generation model with reaction-wheel actuators added. Red, green, blue arrows are axes of the body's coordinate frame which in case of ideal inertia properties would coincide with the axes of principle moments of inertia.

An arbitrary inertia matrix of the non-ideal mass-symmetry around the camera line of sight is calculated by rotating the principle axes of inertia of the ideal inertia matrix by 20 degrees around the axis $[1\ 1\ 1]^T$. In this case, the inertia matrix would be

$$I_{not\_ideal} = \begin{pmatrix} 0.0125 & -0.0015 & 0.0016 \\ 0.0015 & 0.0169 & -0.0031 \\ 0.0016 & -0.0031 & 0.0031 \end{pmatrix} kg\ m^2$$

5.2. Feedback

For feedback, an attitude control system needs real-time information about the orientation, angular velocity and position in space. This must be provided by an on-board inertial measurements unit, composed of gyroscopes and accelerometers. In [13] an analysis is done on inertial measurement of the hopping robot. The paper reports that the readings of angular velocity captured by the gyroscopic sensor could be used with the help of Kalman filter for correcting the noisy initial accelerometer readings based on which the position of the robot in space is calculated.

5.3. Control gains and tracking

In search of optimal control gains, MATLABs' fminsearch optimization function was used on different control scenarios. It was found that the optimal gains were different for each scenario. A compromise between those different optimal gains was used for the control laws used in further simulations.
Spin-axis control law parameters: $k_1 = 18$, $k_2 = 1.5$
For the attitude tracking maneuver, it was empirically found that using a control reference lead of 0.5 s, i.e. a vector that describes the desired reference after 0.5 s gives a good tracking performance in every case.

6. SIMULATIONS

Simulations were done in the MATLAB/Simulink environment to validate the feasibility and measure the performance of attitude control with different system parameters and initial conditions. For an estimate of the power consumption, the energy consumed to accelerate the wheels was measured over the course of simulations.

To simulate the limited bandwidth of a practical control system, a low-pass filter with cut-off frequency of 100 Hz was inserted between the output of the simulated controller and input of the systems' model.

6.1. Single rotation

To be able to estimate the time and energy needed to make any rotation maneuver, the most pessimistic rotation will be simulated. The robot will have an initial attitude of being rotated from the origin by 179 degrees around the axis [1 1 0] and the attitude control system will have to restore the attitude back to origin.

To gain an overview of the attitude control systems' robustness towards initial angular velocity due to disturbance torques during take-off, the settling time was measured with respect to initial angular velocities in x and y axes in case of both ideal and non-ideal inertia properties. The angular velocity in z axis was zero and it was verified that angular velocity up to 3 rad/s did not change the convergence time significantly. The plots show the time it took for the system to reach an attitude error of less than 5 degrees. In areas the systems' convergence is not shown, it either did not converge, the convergence either took more time than 2.0 s or the final error angle was more than 5 degrees.

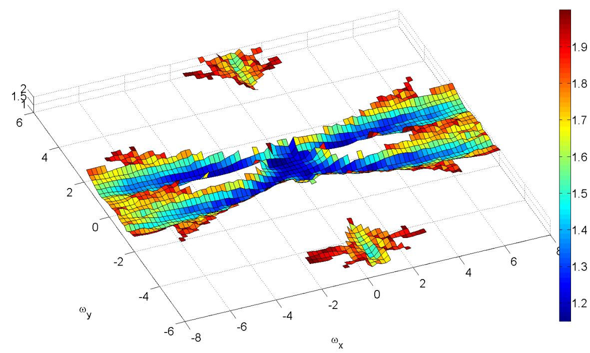

Figure 5. The systems' settling time with respect to all possible initial angular velocities in case of ideal inertia

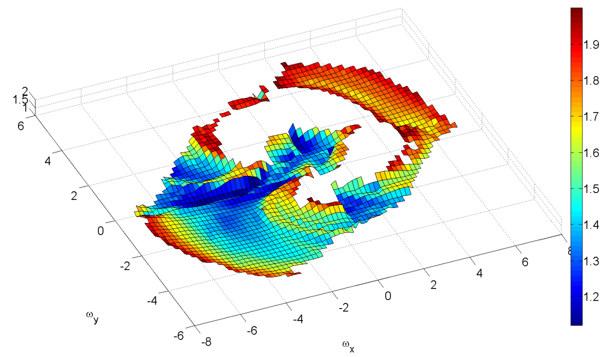

Figure 6. The systems' settling time with respect to all possible initial angular velocities in case of non-ideal inertia

The plot on Fig. 5 shows that the system with ideal inertia is capable of coping with more angular velocity in one axis than in others. This is due to both the limited bandwidth of the system and the ability for two RW-s to give combined torque in some axes. The plot on Fig. 6 shows that an error in inertia matrix can cause an irregular convergence performance with respect to initial angular velocities. These results are important for choosing the reaction-wheel axes for a practical system to be designed. The axes of the reaction-wheels should be chosen so that the system is most robust towards the likeliest axis of initial angular velocity caused by disturbance torques during the take-off.

To demonstrate the effect of initial angular velocity and non-ideal inertia matrix on the convergence and energy consumption. The initial angular velocity to be tested is [3; 0.1; 0.1] rad/s. This choice of initial angular velocity can be justified by the fact that in the current theoretical design, slippage of the foot would mostly cause angular velocity in the x axis.

The RW speed plots in Fig. 8 and Fig. 9 demonstrate that if the system has non-zero total angular momentum, the wheels must stay in rotation even after the desired attitude has been reached. This is also reflected in the energy consumptions given in Tab. 1 where it shown that the controller consumes more energy in the non-zero total angular momentum scenarios. In case of the non-zero angular momentum scenarios, the consumed energy would increase together with the time the system is simulated or the practical system has to control the attitude.

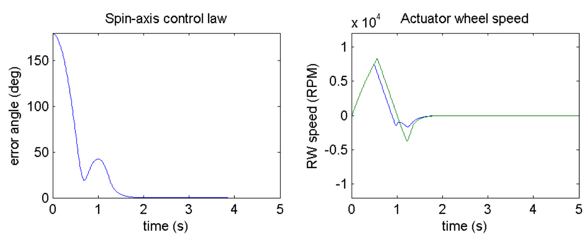

Figure 7. Convergence of the spin-axis controller in case of zero total angular momentum

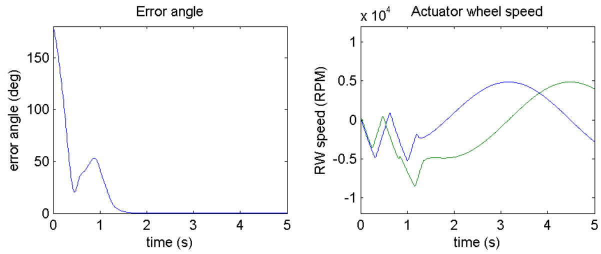

Figure 8. Settling of spin-axis control system in case initial angular velocity of [3; 0.1; 0.1] and ideal inertia

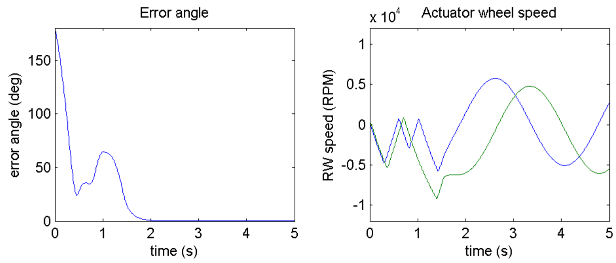

Figure 9. Settling of spin-axis control system in case of intial angular velocity [3; 0.1; 0.1] and non-ideal inertia

Table 1. Energy consumption in case of different parameters and initial conditions

Simulation scenario	**Energy consumption**
Zero angular momentum	77 J
Non-zero angular momentum	119 J
Non-zero angular momentum and non-ideal inertia matrix	137 J

6.2. Mission with camera tracking and landing maneuver

A conduct of a possible attitude control mission is simulated. Right after take-off, the attitude control system will start tracking the camera direction to a target 5 meters to the right of the projected hop trajectory. 2 seconds before the expected landing, the attitude reference is set to prepare for landing. This time was chosen based on the settling time of the pessimistic rotation scenarios described in previous sub-section.

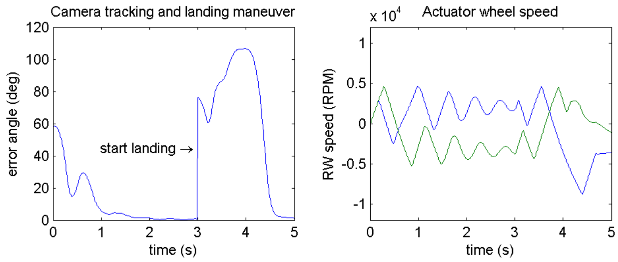

Figure 10. Attitude error and actuator RPM through camera tracking and landing attitude maneuver

The measured energy consumption during this maneuver was 180 J.

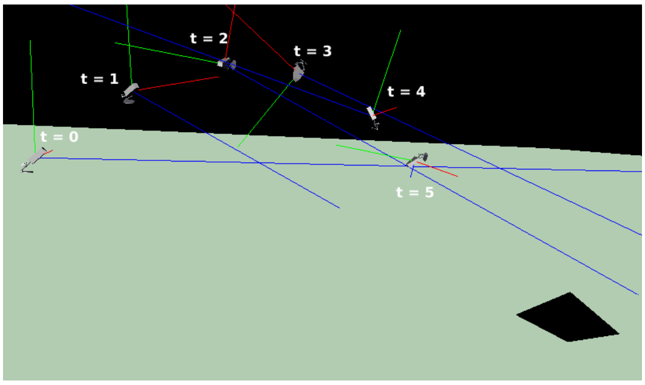

Figure 11. A rendering of attitude control mission in Simulink Virtual Reality Toolbox. The blue line denotes the unactuated camera line of sight axis and the black polygon the object observed during camera tracking

The simulations have shown the feasibility of attitude control with certain initial conditions and possible mission scenario of tracking a target with camera during flight and achieving preferable landing attitude has been demonstrated. However, the presented simulations are done for only a few samples of all possible initial conditions and mission requirements. The systems effectiveness to real mission scenarios cannot be guaranteed based on the results of these simulations and further study and simulations are required to validate the systems' effectiveness once more details are known about the practical system and the missions scenarios.

The energy consumed to accelerate the reaction-wheel actuators was measured to reach an estimate of the on-board energy requirements of the system. It assumes that braking does not consume nor regenerate energy. The 180J consumed in the whole mission of camera tracking and landing attitude control is equivalent to only 7mAh from a 7.2 V (2-cell Lithium-Polymer) battery-pack. Although this theoretical energy consumption is low, the power consumption of the actuators is quite high. The rated torque and RPM of the actuators defines the rated power of an actuator to be 104 W that makes the rated current 14.4A. This is still in the limits of conventional batteries that could be mounted on such a small robot. These measured values could be very different if the inertia properties of the robot, required response time of the control system or the properties of the actuator were different from the ones stated in this work.

7. CONCLUSION

This paper has argued that being able to control its attitude during the ballistic hop trajectory would improve the capabilities and survivability of hopping robots. An actuator configuration with two reaction-wheel actuators was chosen to be used for the attitude control of a hopping robot. Based on the performance and mechanical parameters of the 2nd generation hopper designed by JPL, actuator parameters are proposed that would satisfy mission requirements on Earth's Moon. The weight of the additional actuators would be a few hundred grams and the power requirements could be satisfied with a realistic battery. Significantly, these parameters are compatible with the small size and mass requirements of the hopping robot. Convergence, robustness towards initial angular velocity and perturbations of inertia properties were simulated and the results showed that the attitude control system is effective also in case of reasonable disturbances.

8. FUTURE WORK

The next obvious step in this field would be trying to conceive the considered system practically. Although similar systems have been built hundreds or even thousands of times for satellites, the constraints on size, weight and power consumption that is posed to the system by the concept of a miniature hopping robot would make this task non-trivial. Besides the actuators and power systems, the robot would need to include a precise sensor-package that would need to be immune to the high mechanical and electrical noise created by the actuators.

The spin-axis control law presented in section 4 is one of the first that has been proposed for this task. However, the algorithm can be modified to perform faster by considering that the control law does not consider the bodies' rotation around the unactuated axis. In some cases the attitude maneuver could be done trivially by using only one wheel.

In the mechanical design of a hopping robot with the reaction-wheels for attitude control, it may be possible to optimize the design so that the reaction-wheels couple as actuators also for other tasks, or vice versa. For example, before take-off, the reaction-wheels could be used to compress the spring for hopping. The reaction-wheels could also be motors for the driving wheels that would give the robot fine mobility on the ground or the wheels could be used as reaction-wheels during flight.

Also Nature has needed to solve the attitude control problem and has done it very effectively. When a cat is falling, it is able to orient its body to the preferred landing position moving parts of the body. Similarly to attitude control with rotating wheels, this way of attitude control is due to conservation of angular momentum. The difference is that the masses that are actuated for reaching the goal are not otherwise useless wheels but useful parts of the animals' body and the trajectories of these actuations are very complex. A practical hopping robot could have manipulators for interacting with the environment, the robots' camera could be actuated or there may be more parts of the robots' structure that are actuated. It may be possible to design the system in such as way that these useful and actuated parts of the structure could be actuated during the flight phase of the robot to achieve attitude control.

9. REFERENCES

[1] J Oberth, *The Moon Car*. New York: Harper and Brothers, 1959.

[2] M H Kaplan and H Seifert, "Hopping transporters for lunar exploration," 1969.

[3] Paolo Fiorini, Sayad Hayati, Matt Heverly, and Jeff Gensler, "A Hopping Robot for Planetary Exploration," 1999.

[4] Erick Dupuis, Steeve Montminy, Mohamad Farhat, and Henri Champliaud, "Mechanical design of a hopper robot for planetary exploration".

[5] Tetsuo Yoshimitsu, Takashi Kubota, Ichiro Nakatani, Tadashi Adachi, and Hiroaki Saito, "Hopping rover "MINERVA" for asteroid exploration".

[6] Ryutaro Misumi, Shigeki Kurata, and Hisayuki Aoyama, "Design and Development of Micro Hopping Robots for Rescue Operation".

[7] Sascha A Stoeter, Paul E Rybski, Maria Gini, and Nikolaos Papanikolopoulos, "Autonomous Stair-Hopping with Scout Robots," 2002.

[8] Hideyuki Tsukagoshi, Masashi Sasaki, Ato Kitagawa, and Takahiro Tanaka, "Design of a Higher Jumping Rescue Robot with the Optimized Pneumatic Drive," in *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, 2005.

[9] Kim Byeong-Sang, Kim Ki-Seok, Min Deog-In, and Song Jae-Bok, "Development of Jumping Mechanism for a Portable Guard Robot," in *International Symposium on Robotics*, 2008.

[10] Umberto Scarfoglierol, Cesare Stefanini, and Paolo Dario, "Design and Development of the Long-Jumping "Grillo" Mini Robot," in *IEEE International Conference on Robotics and Automation*, Rome, Italy, 2007.

[11] Mirko Kovac, Manuel Schlegel, Jean-Christophe Zufferey, and Dario Floreano, "A Miniature Jumping Robot with Self-Recovery Capabilities," 2008.

[12] Fiorini and Burdick, "The Development of Hopping Capabilities for Small Robots," , 2002.

[13] Paolo Fiorini, Claudio Cosma, and Mirko Confente, "Localization and Sensing for Hopping Robots," 2004.

[14] Paolo Fiorini, Francesco Bovo, and Lorenzo Bertelli, "Solving the landing problem of hopping robots: the elastic cage design,".

[15] Paolo Fiorini and Massimiliano Marchesi, "Robustness Concepts for Hopping Robots," in *ESA Workshop on Advanced Space Technologies for Robotics and Automation*, Noordwijk, Netherlands, 2004.

[16] Jens Wittenburg, *Dynamics of Multibody Systems*.: Springer, 2008.

[17] Peter E Crouch, "Spacecraft Attitude Control and Stabilization: Applications of Geometric Control Theory to Rigid Body Models," 1984.

[18] Frédéric Boyer and Mazen Alamir, "Further Results on the Controllability of a Two-Wheeled Satellite," 2007.

[19] Nadjim Mehdi Horri and Stephen Hodgart, "Attitude Stabilization of an Underactuated Satellite Using Two Wheels," 2003.

[20] Kim Sungil and Kim Youdan, "Spin-Axis Stabilization of a Rigid Spacecraft Using Two Reaction Wheels," 2001.

[21] Panagiotis Tsiotras and James M Longuski, "A New Parameterization of the Attitude Kinematics," 1995.