Paper Number 55

A Hopping Robot for Planetary Exploration

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Abstract

This paper presents the design and some preliminary analysis of a hopping robot for planetary exploration. The goal of this project is to explore a different mobility paradigm which may present advantages over conventional wheel and leg locomotion. The approach is to achieve mobility by hopping and perform science and imaging via rolling. The device is currently equipped with a single video camera representing the science sensor suite. The hopper is equipped with a simple microprocessor and wireless modem so that it can receive sequences of commands and autonomously execute them, making it suitable for exploration of distant planets, comets and asteroids. One important feature of this hopper is that it uses a single motor for hopping in a specified direction as well as pointing the camera via rolling.

rover

1 Introduction

The best method to achieve mobility on Planetary Bodies is still the subject of discussion. So far, wheels have been used with excellent results for manned and unmanned mobility, and legged prototypes have been successfully demonstrated during Earth-based experiments. However, these are neither the only possible methods nor perhaps the most efficient ones to achieve mobility for exploration in low gravity (planets) and in a micro gravity (small bodies) environments. Laboratory experiments have demonstrated the feasibility of slithering, rolling and hopping as alternate propulsion methods, thus paving the way to a more comprehensive approach to mobility than is currently considered. This paper describes the initial design and analysis of a small hopping robot whose mobility is achieved by a combination of hopping and rolling actions, to jump forward towards the selected target, and to orient the rover body in the desired direction. This approach extends previous designs by combining hopping and rolling mobility and by adding on-board computing, control, and sensing capabilities in a very compact and light weight device. The hopping robot proposed here is also intended as an experimental set-up for under-actuated mechanisms, with the objective of studying the mobility characteristics achievable with the lowest possible number of actuators.

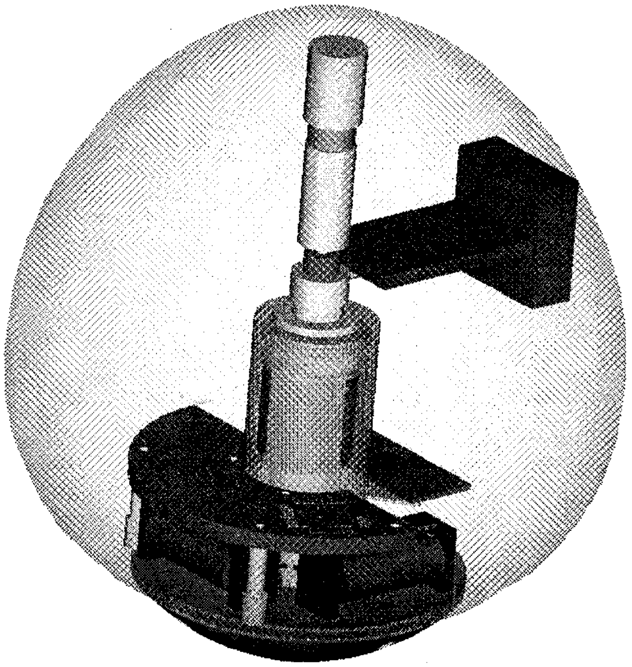

Figure 1: CAD rendering of the hopping rover.

Hopping systems for planetary mobility were first proposed in [13] as a promising transportation concept for astronauts in a Lunar environment. A first order analysis of the performance of Lunar hopper is presented in [5]. The authors propose a reference configuration consisting of a single-seater device, propelled by a gas actuated leg hinged under the astronaut seat and stabilized by with four elastic legs. The acceleration intensity and duration is limited by the tolerance of the human body. This design concept does not support the automatic reorientation of the hopper body,, since the thrust leg can only rotate with respect to the main body about an axis normal to the pilot's plane of sym-

Mobility	**Distance**(Km)	**Weight**(Kg)	**Payload**(Kg)	**Consumes**
Hopper	30	450	7	3 hours
Rocket	7	204	7	131 Kg of propellant
Rover	17	1749	larger	several hours

Table 1: Comparison of Lunar Mobility System.

metry. A two-seater hopping laboratory is also briefly discussed, which support reorientation during the acceleration and deceleration phases, when the leg is in contact with the Lunar surface. The paper includes also an interesting comparison among different approaches to Lunar transportation, as summarized in Table 1. The comparison is based on data from the Apollo missions and the subsequent studies, and from the calculations presented in the paper, and shows that hopping is an efficient form of transportation in a low-gravity environment. More recently, a hopping rover was described in [9], whose mechanical structure is the precursor of the device described in this paper. Common characteristics of these two hopping systems is motion discontinuity, since a pause for reorientation and recharge of the thrust mechanism is inserted between jumps.

In general however, laboratory demonstrations of hopping robots have focused on continuous motion and dynamic stability, without pauses between jumps. The seminal work in this area is summarized in [10], and analyzed mathematically in [7, 11, 6, 8], among others, all discussing Marc Raibert's one-leg hopping robot. In its simpler configuration, this device consists of a thrust leg hinged at an actuated hip, and moves at controlled speeds on a linear trajectory. A later model is equipped with an articulated hip enabling three-dimensional motion, and programmed to perform gymnastic jumps [4].

Current research on non-holonomic systems is motivating a renewed interest in the control of hopping robots. The device more often analyzed is the acrobatic robot, or Acrobot, a reversed double-pendulum with a single actuator located in the joint and free to move its base [1, 3, 2, 14, 12]. Among these references, [1] describes how to make the Acrobot jump by accelerating its center of mass, located in the upper link, until the base loses contact with the ground. The Acrobot configuration is similar to Raibert's early one-leg robot, with the single actuated joint acting as thruster and hip. The Acrobot attitude at landing is controlled by compensating the non-zero angular momentum imparted to the robot at lift-off with a suitable number of rotations of the lower link.

By necessity, the hopping rover described in this paper is different from the Acrobot, since any realistic planetary mission requires three dimensional motion, whereas the Acrobot's motion is limited to the plane of the links. Other considerations guiding the design of this first prototype of a hopping rover are: (i) we assume hard flat ground, (ii) we aim at static stability, (iii) we allow reorientation only when at rest, and (iv) we desire large and fine motion capabilities. We achieve these features by designing the hopping rover with a self-righting egg-shaped body, equipped with a single motor providing hopping and orientation, as shown in Figure 1. The hopping action is generated by a spring which is loaded after each jump by the motor. The orientation of the body is performed directly by the motor, by rotating an off-axix mass towards the direction of the next jump. Large motion is produced by hopping, whereas fine motion is achieved by a combination of jumps away from the target and of rotations of the rover body. In the rest of the paper we describe these functions in detail and summarize our initial analysis and simulations.

The paper is organized as follows. Next Section presents the system description. Section 3 summarizes a simplified model of the hopping rover and some initial simulations. Section 4 proposes a hybrid method for fine motion. Finally, Section 5 draws some conclusions from this work and discuss the directions of our future research and development.

2 System Description

This section briefly describes the main components of the hopping mechanism and of its control and sensing electronics. The design is driven by the desire of minimizing the number of actuators and the overall size and weight, while achieving useful scientific capabilities.

2.1 The Hopping Mechanism

The mechanical design for the hopper is an evolution of the *Hoppet* described in [9]. The hopping rover described here is designed as an exploratory device, with a payload consisting of a few simple sensors and hopping as its main mode of locomotion.

Several configurations were considered for the hopping mechanism, such as three-joint multiple legs and single leg devices. However, the first design would have required several actuators, and the second would have needed dynamical balancing. None of the approaches met our desire of a simple, small and light weight design. The chosen mechanism is a very robust structure with self righting capability. However, this design may

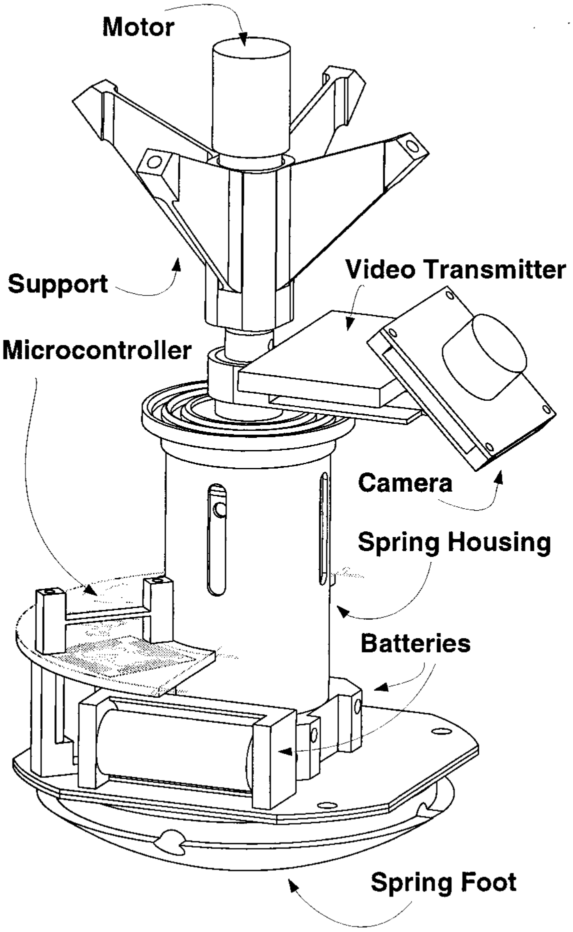

Figure 2: Schematic drawing of the hopper mechanism.

have limited mobility on soft sandy terrains, since the ground will conform to the shape of the rover and prevent it from self-righting. To overcome this possible problem, the center of gravity must be positioned extremely low. This design is also limited to a relatively flat terrain. Climbing hills may pose some difficulty from the point of view of stability. However, in spite of these limitation, the egg-shaped design chosen for this rover meets most of our design requirements and can be implemented with a simple, small package.

This hopper is intrinsicly very simple. It operates with a single actuator under on-off control for its simplest functions. The motor is powered by a 12 V DC supply at 100 to 300 mA. A 66:1 gear reduction produces 0.1 Nm of torque, which is transformed into force through a miniature ball screw. The screw has a 90% efficiency and generates 500 N. This force is used to charge a spring with 3.2 J of potential energy. By transferring this potential energy into kinetic energy, the hopper would make a maximum leap of 1.6 m on earth gravity. A ball detent/release mechanism is used to hold the loaded spring, since it ensures a simultaneous release of the spring rim. At the beginning of the spring loading phase, the bottom of the spring is blocked by the bearing. The spring release is activated by pushing against the bearing with a force higher than the bearing threshold, thus releasing the spring and accelerating the rover body. During rewinding, the spring is first retracted until it locks into the bearing, and then the loading phase is repeated.

The directional control of the hopping rover is achieved by rotating an eccentric mass attached to the motor shaft. As the motor turns during compression and retraction of the spring, the off-axis mass rotates around the hopper vertical axis, thus changing the location of the center of mass for the system and making the egg-shaped body lean in the direction of the mass. On a hard floor, this approach allows hopping in the plane identified by the vertical axis and the mass position. A one-way, over-running clutch is used to rotate the mass only in the counter-clockwise direction. In this way the mass can be positioned in the desired direction during the spring retraction, and then it remains in place during spring compression, since the clutch lets the motor shaft rotate freely in the clockwise direction.

The egg-shaped rover body consists of a shell made of transparent polycarbonate. The shell is divided transversally into two parts for ease of assembly. It provides protection for the internal components, and is also the main support structure. The top half of the shell is clear to allow the internal instruments to view the external environment.

Figure 2 shows schematically the internal components of the hopping rover. The components marked by the arrows are the hopper foot, the electronic control board, the spring housing, and the camera/transmitter assembly.

2.2 Computer and Sensor Electronics

The controller must be able to support autonomous navigation, science acquisition, and communication with other units. Furthermore, it must have very low power consumption to increase operational time, and minimal footprint and weight. To achieve these objectives, we are adapting the *Widget* board, a motor controller developed at JPL for other rovers, to the needs of this applications. The micro-controller powering the board is powerful enough to support the basic functions of the current prototype, and future computational requirements will be solved by increasing the number of boards.

The micro-computer is based on the PIC16C65A processor, a CMOS chip, and consists of a 2.5 cm X 9 cm circular board with motor controller circuits, a serial port, analog and digital I/O, and analog signal conditioning. The serial port can be programmed to satisfy the I^2C protocol, thus providing the hopper with a low power, multi-master, multi-drop serial bus. This protocol is well suited to implement a low speed (100 Kbit/second) serial bus supporting a multi-processor architecture, since it significantly reduces the mass of the cabling interconnection. The motor controller is the HP HCTL1100, which incorporates a digital PID controller to produce trapezoidal velocity and position profiles. Thus, it can relieve the micro-controller of most time consuming activities related to trajectory tracking. All the major functions of the board have power-down features which, coupled with the power-down of the micro-processor itself, are used for power management of the electronics. The power consumption of the board is approximately .35 W, excluding motor and science instruments. Communication with an operator and other units will be carried out with an RF modem currently under development.

In the future, the rover will be powered by a panel of solar cells located on the top part of the shell and by re-chargeable batteries located in the base. Currently, the power for the rover is provided by four Panasonic primary batteries. Each battery has an output voltage of 3 V and a maximum discharge current of 300 mA.

The instrument suite of this first prototype consists only of a a video micro-camera coupled with a transmitter to convey remote images to an operator. The camera operates at 12 V DC and 175 mA, and the transmitter at 12 V DC and 100 mA. The transmitter sends a full streaming video to any standard television on the amateur band occupied by channel 14. Clearly, this video system is large and power hungry (over 3 Watts), but in the future, smaller Active Pixel Sensor cameras could be used to reduce size, mass and power consumption.

The camera is installed on an arm and is rotated about the rover main axis in the counterclockwise direction during the retraction of the thrust spring. This set-up performs the dual function of re-orienting the rover body by rotating the camera arm, and of taking a panoramic view of the terrain surrounding the rover. In the laboratory demonstrations we intend to show that the operator can operate the rover by simply pointing the camera to the desired direction, and then instructing a jump command, leaving the rover orientation and execution of the jump to the internal controller.

3 Model and Control

The modeling and analysis carried out for this prototype have been primarily concerned with the static stability of the system, to ensure that the design requirements of self-righting and orientation can be met. To simplify the analysis, we consider the two-dimensional model shown in Figure 3. Here, the hopping rover is represented by three masses: M_f, M_m, and M_c, representing the mass of the spring and foot mechanism, of the motor, and of the camera arm, respectively.

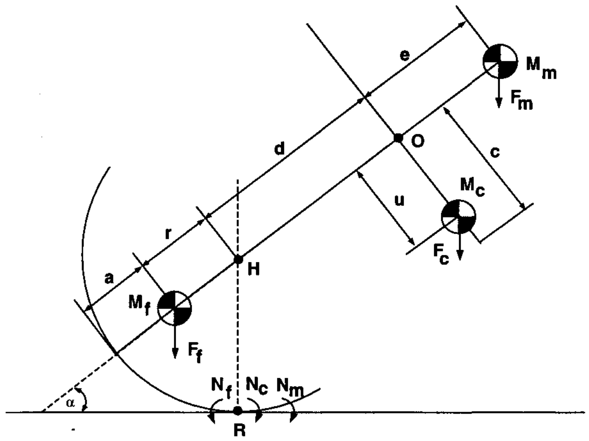

Figure 3: Two-dimensional model of the hopping rover.

The control input to the system is the position u of the camera mass, m_c, on the support arm, assuming that in this simplified model, m_c can be moved up and down the arm. Therefore the control input is $-c \leq u \leq c$, with c being the length of the camera arm.

The mass distribution required to have the hopping rover lean at an angle α on its side is given by:

$$F_f r \cos\alpha = F_m(d+e)\cos\alpha + F_c(d\cos\alpha + u\sin\alpha) \quad (1)$$

where F_c, F_f and F_m represent the gravitational force applied by the camera body, the foot and spring mechanism, and the motor, respectively. The other model parameters indicated in Figure 3 are:

a is the distance from the bottom of the foot to the cg of M_f,

$(r + a)$ is the radius of the emispherical foot,

$(d + r + a)$ is the distance form the camera arm attachment to the foot bottom, and

e is the distance from the camera arm attachment to the cg of M_m. The numerical value of these parameters is as follows: $M_f = 575g$ including lower shell, batteries, foot, spring assembly, and electronics; $M_m = 200g$ including upper shell, motor, bracket, and bearings; $M_c = 65g$ including camera, camera mount, arm, and transmitter; $a = 30mm$, $(r + a) = 80mm$, $(d + r + a) = 100mm$, $c = 45mm$, $e = 50mm$.

The critical design constraint required to achieve maximum hopping distance, i.e. $\alpha = 45^o$ and $u = c$, is satisfied when:

$$1.3F_c = F_f - 1.4F_m \quad (2)$$

which is used to compute the balancing weight on the camera arm.

4 Large and Fine Motion

We plan to achieve the mobility of the hopping rover prototype mostly by jumping in the direction of a target specified by the operator. However, because of the fixed load of the spring, there will be no adjustment possible on the length of the jump. Furthermore, the uncertainty of the terrain condition and of the lift-off angle will prevent the advanced calculation of the trajectory parameters.

To cover short distances and to approach the desired target, we are planning to develop and test two new methods for fine motion control of the hopping rover. The first will consist of two lateral jumps, such that the base of the resulting isosceles triangle is the desired distance. On a hard terrain, it will be possible to move the hopper with higher accuracy by rolling it on its base, as an eccentric spherical wheel. Unfortunately, both methods will only be carried out in open-loop control, since the camera will not be able to track the target during motion, and therefore will not provide any visual feedback.

5 Conclusions

The prototype of a hopping rover suitable for simple exploratory missions in low gravity environments is described in this paper. The robot consists of an egg-shaped shell enclosing a thrust mechanism, power storage devices and control and sensing electronics. The hopping robot is designed as an autonomous rover, capable of autonomous navigation and scientific data acquisition. Mobility is achieved by hopping in the direction of a suitable target, and data collection is currently represented by a video camera transmitting a video stream to a controlling computer. Hopping is powered by a spring released under computer control, whereas orientation is achieved by rotating an off-axis mass, consisting of the video camera and its transmitter, about the rover vertical axis. By using a uni-directional bearing, the rover achieves mobility and orientation with a single actuator. Control is carried out by an on-board micro-controller communicating with the control station using a wireless modem. In the future, we plan to carry out extensive simulations and experiments with the prototype to test its mobility capabilities and fully develop a new method of fine motion control based on hopping and rolling.

6 Acknowledgment

The research described in this paper has been carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] M.D. Berkemeier and R.S. Fearing. Sliding and hopping gaits for the underactuated acrobot. *IEEE Transaction on Robotics and Automation*, 14(4):629–634, August 1998.

[2] A. De Luca and G. Oriolo. Stabilization of the acrobot via iterative state steering. In *IEEE Conference on Robotics and Automation*, pages 3581–3587, Leuven, Belgium, May 1998.

[3] J. Hauser and R.M. Murray. Nonlinear contorllers for non-integrable systems: the acrobot example. In *American Control Conference*, pages 669–671, 1990.

[4] J. Hodgins and M.H. Raibert. Biped gymnastic. In *4th International Symposium on Robotics Research*, pages 5–14, Cambridge, MA, 1988. The MIT Press.

[5] M.H. Kaplan and H. Seifert. Hopping transporters for lunar exploration. *Journal of Spacecraft and Rockets*, 6(8):917–922, August 1969.

[6] D.E. Koditschek and M. Bühler. Analysis of a simplified hopping robot. *International Journal of Robotics Reseach*, 10(6):587–605, December 1991.

[7] V.V. Lapshin. Motion control of a legged machine in the supportless phase of hopping. *International Journal of Robotics Reseach*, 10(4):327–337, August 1991.

[8] Z. Li and R. Montgomery. Dynamics and optimal control of a legged roboti in flight phase. In *IEEE Conference on Robotics and Automation*, pages 1816–1821, Concinnati, OH, May 1990.

[9] L. Lorigo, C. Paul, R. Brooks, J. McLurkin, and M. Moy. Autonomy for Mars exploration. In *Workshop on Planetary Rovers at IROS'97*, Grenoble, FR, September 7-11 1997.

[10] Marc H. Raibert. *Legged Robots that Balance*. The MIT Press, Cambridge, MA, 1986.

[11] M'Closkey R.T. and J.W. Burdick. Periodic motion of a hopping robot with vertical and forward motion. *International Journal of Robotics Reseach*, 12(3):197–218, May 1993.

[12] F. Saito, T. Fukuda, and F. Arai. Swing and locomotion control for a two-link brachiation robot. *IEEE Control System Magazine*, pages 5–12, February 1994.

[13] H.S. Seifert. The lunar pogo stick. *Journal of Spacecraft and Rockets*, 4(7):941–943, July 1967.

[14] M.W. Spong. The swing up control problem for the acrobot. *IEEE Control System Magazine*, pages 49–55, February 1995.