Fine Mobility for Hopping Robots

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Abstract: *This paper describes the evolution of our concept of hopping robot for planetary exploration, combining coarse long range mobility achieved by hopping with short range wheeled mobility for precision target acquisition. This new prototype responds to the needs of the scientific community of a versatile and yet precise mobile platform capable of carrying single instrument experiments rapidly and economically on a planetary surface. This paper describes the new mechanism developed to achieve precise mobility, and its multiprocessor control system. The scientific payload is simulated by a color TV camera and a pair of dual-axis accelerometers. The hopper communicates to a remote host via an RF link. The paper summarizes the evolutionary development of the robots and describes the preliminary tests of the latest prototype.*

1 Introduction and Motivation

The need of smaller space exploration missions carrying multiple scientific experiments has generated new interest towards miniaturized vehicles, capable of a single scientific function, but well suited to operate within large multifunctional groups. Currently, however, the only deployed, and actively engineered, mobility paradigm is a single-body, multifunctional, 6-wheeled rover, as seen in the Pathfinder mission's Sojourner vehicle [12] and in the planned Mars 2003 exploration missions. Inspite of its great achivements, this design has a limited mobility, since 6-wheeled rovers can only traverse obstacles that are about 1.5 times their wheel diameter. Furthermore, they can only drive over obstacles that are a fraction of the vehicle's body length, and therefore this design cannot be used as a truly universal mobile platform.

To address the two goals of reducing rover complexity and of developing more efficient mobility methods, in the past few years we have been developing prototypes of planetary robots equipped with a very small number of actuators and capable of moving by hopping. Reducing the number of actuators is an attractive goal for planetary robot design, since designs with few actuators are likely to be smaller, lighter, and with lower risk of failure. Furthermore, since planetary bodies of current scientific interest are characterized by low to medium gravitational environments, wheeled mobility can be replaced by hopping, which is more efficient in these environments.

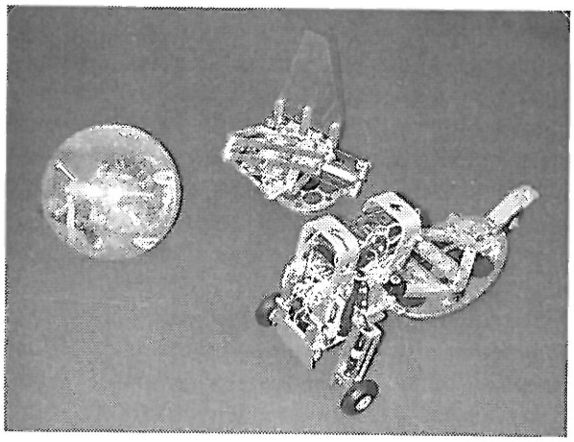

Figure 1: The Hopping Robot Family.

Our hopper's operation is more akin to the movement of a frog, rather than the oscillatory behavior of typical hopping robots [14]. In particular, with our second prototype we have shown that a system weighting less than 1.5 kg can efficiently convert the energy stored in a single actuator to propel, steer, and self-right a simple hopper, and pan an on-board camera. Hence, this single actuation design offers surprising capability, compactness, and efficiency. However, this design is limited to coarse mobility since no mechanism is provided to make fine position adjustments after landing and to accuratly adjust the hopping trajectory. The work described in this paper adds some fine mobility to the basic hopping mechanism. The family portrait of the hopping robots is shown in Figure 1.

The paper is organized as follows. A summary of relevant prior work is given in Section 2. In Section 3 the first ("generation one") and the second ("generation two") prototypes are briefly presented. Section 4 describes the third generation system. Finally, Section 5 summarizes the main features of our current prototype and presents our plans for future research in this area.

2 Relation to Prior Work

Hopping system were first proposed for military applications, as cited in [18], and for early concepts of lunar exploration systems [13]. However, realistic planetary hoppers were first described and analyzed in [16, 8] as replacements to Lunar Rovers during Apollo missions. These papers show that hopping is an efficient form of transportation in low-gravity environments.

Laboratory demonstrations of hopping robots have generally focused on continuous motion and dynamic stability, without pauses between jumps, as do the devices mentioned above. Raibert's seminal work in this area is summarized in [14], and analyzed mathematically in several works, such as [9, 10, 15]. These hoppers require several actuators for propulsion and stabilization. Research on non-holonomic systems has also produced a hopping device called the "Acrobot", a reverse double-pendulum with a single actuated joint and free to move its base [1, 2, 5, 17].

More recently, a precursor, for some aspects, of our first generation device, is described in [11]. However, no mention of functional tests is reported. Another hopping system is described in [7], which is powered by an internal combustion chamber with steering achieved by rotating an off-center mass. Small two-wheeled cylindrical explorers (a few cm in diameter) that are launched from a cannon are described in [6]. These 2-wheeled robots contain a small appendage that allows them to hop a few centimeters over small obstacles and more readily climb slopes. Very recently, the prototype of a gas propeller for a Mars hopper has been fabricated and tested [20]. A hopper powered by this device is potentially capable of hops of several thousand meters.

Smaller wheeled rovers for planetary exploration have also been developed in several research laboratories. These systems are interesting because they can be effectively used in tandem with larger rovers to increase exploration range. The miniature rover for planetary exploration developed at NASA Jet Propulsion Laboratory, is the *Nanorover* [19], which consists of a body of approximately (15 cm x 15 cm x 5 cm) equipped with four movable struts each carrying a 6 cm wheel equipped with an internal motor and helical cleats for skid steering. The robot is controlled by down-linked commands combined with built-in behaviors for point-to-point navigation, body articulation, and instrument pointing.

3 The Earlier Hopping Prototypes

Before describing in some detail the 3^{rd} generation Hopping Robot developed at JPL-Caltech, we briefly summarize our previous prototypes. In fact, some of the computing, electrical, and sensing elements of these devices are the same also in the latest prototype, and thus need only be discussed once. Furthermore, lessons learned from the evaluation of this system motivate the improved version described in Section 4.

Figure 2: Photograph of the 1^{st} generation system.

Our earlier designs were driven by a few main goals, such as the desire to minimize the number of actuators and the robot overall size and weight, and to achieve sufficient mobility to realize some useful scientific capabilities. Furthermore, since the robot would mostly operate autonomously, energy efficiency is a concern. The mechanism must achieve a statically stable, steady-state posture between jumps for the purposes of scientific measurements. To reduce the number of on-board actuators, we forced as many operations as possible to happen sequentially, instead of simultaneously. The hopper's operational cycle was broken down into the following actions: (1) self-right the hopping mechanism after landing; (2) pan the camera to acquire images; (3) deploy scientific instruments as necessary; (4) recharge the thrusting mechanism (in preparation for a jump); (5) point the hopper in the desired direction; (6) jump (release stored energy); (7) go to step (1). The two earlier prototypes implemented the same basic sequence in two different ways, as discussed next.

The First Generation Design. The operation of the first generation design is described in detail in [3, 4]. Figure 2 shows the complete system with a clear polycarbonate shell surrounding the mechanism, attached to the body at the upper support and lower plate. Figure 3 depicts the essential internal components of the first generation design. Control of the vehicle by a single actuator is implemented with the aide of an over-running clutch. With the decoupling action of the clutch, rotation of the motor in one direction drives

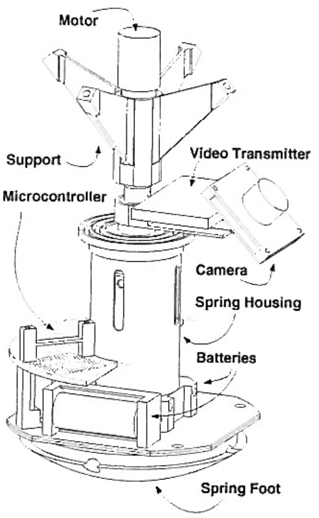

Figure 3: Schematic drawing of the 1^{st} generation mechanism. The surrounding polycarbonate shell is omitted for clarity.

the leg compression and leg release subsystem, while rotation in the other direction drives the camera rotation. Figure 4 schematically depicts the relative phasing and motor rotations for each operation described below. Vertical hopping motions are generated by the release of a simple linear spring, which is compressed after each jump via a ball screw that is driven by the motor. By reversing the motor rotation, a camera can be rotated so as to take images through the clear shell. The orientation of the body can also be modified by rotating the camera, whose off-axis center of mass causes the vehicle to tilt. Steering is achieved via this concept by tilting the vehicle in the desired direction prior to launch. The self-righting capability is implemented passively in this design by creating a low center of mass.

The tests performed to assess the design showed that this prototype could only realize vertical jumping heights of about 80 cm and horizontal leaping distances of 30-60 cm. Furthermore, we found that the first generation prototype presented three major shortcomings: (1) inefficient hopping; (2) unrobust steering; (3) unrobust self-righting capability. The first problem is due to the hopping mechanism design, whereas the remaing two are related to achieving the functions passively, i.e. by rotating the camera arm for steering, and by relying on the low center of mass for self-righting.

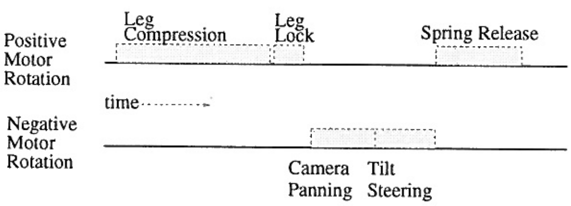

Figure 4: Relative timing of the operations driven by the primary motor.

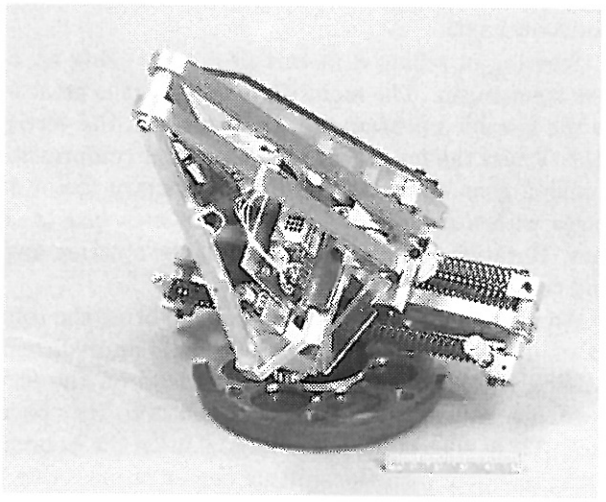

Figure 5: Photo of 2^{nd} Generation hopper in compressed state.

The Second Generation Design. The goal of the second generation design was to solve the main drawbacks of the previous design. We were able to realize all the desired objectives while still using only a single actuator. However, the design and construction of this device is considerably more complicated than that of the first generation, as shown in Figures 5.

To solve the inefficiency problem of the jumping mechanism, we designed the combined spring/linkage mechanism shown in Figure 6. The leg extension is along the y-direction in Figure 6. Displacements in the y-direction induce, through the linkage, displacements in the linear spring. In effect, the linkage creates a nonlinear spring from a linear spring. This linkage realizes the maximum leg thrust in the middle of the thrusting phase, while the thrust force at the onset of lift-off is quite low, thus substantially reducing the likelihood of premature lift-off. Experiments with this system verified that this leg realized a 70% conversion efficiency. The linkage and associated motor driver is mounted at a roughly 50 degree angle with respect to the foot's

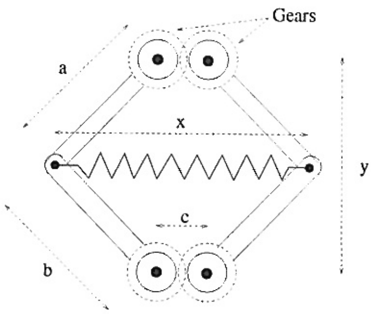

Figure 6: (a) The 2^{nd} generation energy storage linkage, a 6-bar geared mechanism.

horizontal axis.

Steering is achieved in this prototype using an active mechanism. The main robot structure is attached to the foot by a bearing that rotates about the vertical axis. When the leg reaches its maximum compression, a pinion gear that is driven by the primary motor engages with a ring gear that is rigidly attached to the foot. Rotation of the pinion controls the steering angle and camera panning.

An active mechanism was devised to bring the robot to an upright and stable posture from its unpredictable landing condition. Initially, flaps stored on the faces open up, causing the hopper to roll onto its "back" face. Then, the rotation of a large flap on the hopper's back, together with the shifting center of mass due to leg compression, forces the hopper toward an upright configuration, in preparation for the next operational cycle. The hopper's broad foot combined with its low center of mass in the compressed state ensures that the upright posture is statically stable. Figure 7 shows a moment of the self-righting sequence.

Finally, the operation sequence repeats the same actions of the first prototype, but with a few additional functions. Novel timing mechanisms, mechanical logic, and couplers were introduced to coordinate the various steps, as shown in Figure 8.

The experiments performed with the second prototype typically showed jumps of $\sim 2.5\ m$ of horizontal distance, with $\sim 1\ m$ of vertical height during free-flight.

4 The Hopper on Wheels

The development of the 3^{rd} generation Hopping Robot addresses specifically the usability of the robot as a science gathering device. In particular, this prototype gives a solution to the problem of positioning an instrument precisely where desired. Clearly, hopping with a fixed take-off angle is not flexible enough to reach a science target. We added to this prototype the capability of changing the take-off angle and of performing precise moves after landing.

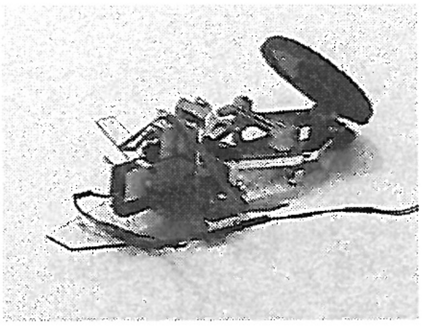

Figure 7: A phase of the self-righting sequence.

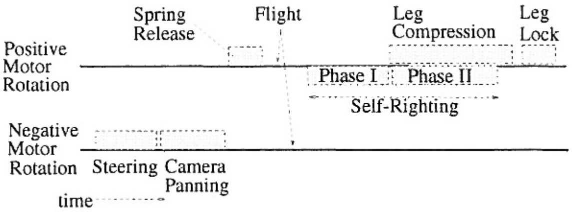

Figure 8: Depiction of Timing/Phase of motor operations driven by the single primary motor.

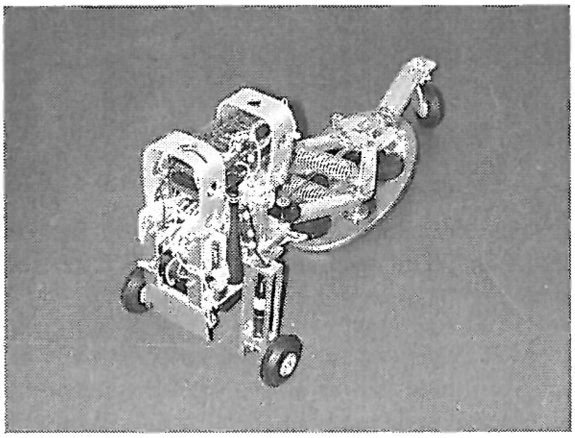

Figure 9: The 3^{rd} generation hopper in extended configuration.

Figures 9 shows the complete hopping robot with the foot extended, and 10 show the Hopper in the take off position (for clarity, springs, wheel motors, electronics, and crash cage have been removed from the prototype). The main body of the hopper is the gear-box required to load the spring mechanism. The loading mechanism uses a cable to pull the spring. The cable is pulled by a motor mounted on top of the gear-box. The twin wheels below the gear-box are powered by two independent motors. The third wheel at the rear of the hopper is a passive caster for stability. The hopper foot is elliptical to support different take-off positions

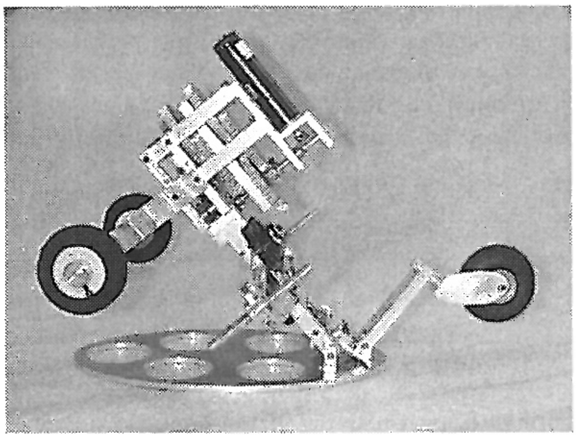

Figure 10: The Hopper 3^{rd} ready for take-off.

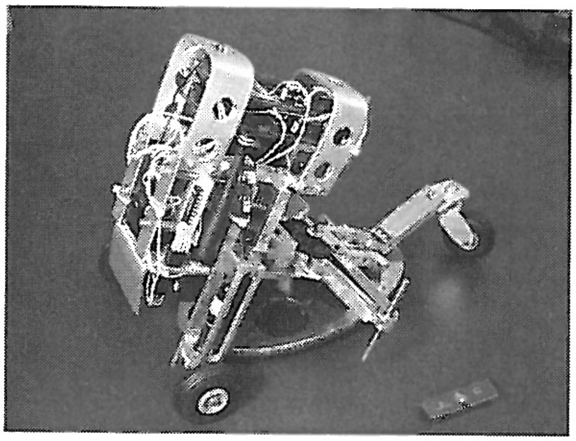

Figure 11: The 3^{rd} gen. hopper in crusing configuration.

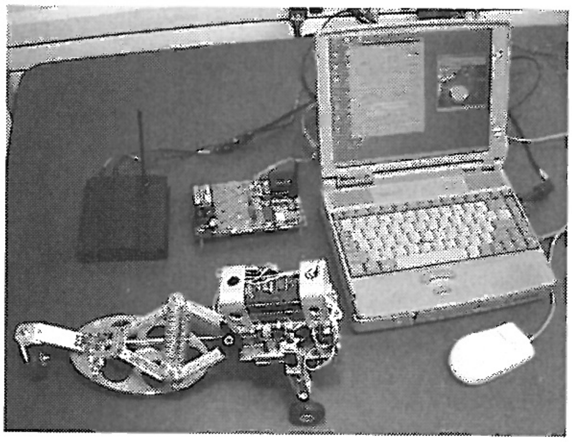

Figure 12: The 3^{rd} generation hopper and its control station.

of the hopper, and it is connected to the distal end of the spring linkage by a four-bar mechanism. This mechanism is powered by the motor via a shaft, and it is used to bring the hopper body to the desired take-off angle, while lifting up the rear caster.

Fine motion control is provided by the two front wheels, which can be used for steering the robot to the desired hopping direction, and to cover short distances to reach suitable scientific targets. Generally, the hopper moves while in compressed configuration, as shown in Figure 11. Wheel type and dimension have been chosen for ease of design and fabrication, and the are clearly suited only for tests on flat laboratory floor.

This prototype is equipped with an electronic package, mounted above the gear-box, providing motor control and communication with a remote operator. The electronic control is provided by two micro-controller boards each equipped with a PIC CMOS microprocessor, motor controller and power circuits, communication ports, and analog/digital signal acquisition. The boards are communicating with each other using the I^2C protocol and with the operator's PC via an RF connection. Each board consumes $\sim$ .35 Watts, excluding motor and science instruments. Additionally, the major board components have power-down features to conserve energy. Power is provided by four primary 12 V batteries located below the gear box. The instrument suite is currently simulated by a video micro-camera, mounted in front of the hopper, broadcasting images directly to operator's PC. A crash cage surrounding the electronic and motor package gives some protection during landing.

The complete system, including operator station, is shown in Figure 12. The operator station consistis of a laptop computer equipped with two radio links: a full duplex channel for command and data exchange with the hopper, and a TV link to download images taken by the on-board camera. The computer screen shown in Figure 12 displays a window with an image from the hopper camera showing the computer mouse, and the command window. Using icons in the command window, the operator can control hopper motion, initiate a hop, and acquire data about wheel position and take off angle.

During the month of December 2000, preliminary tests were performed to verify the operational capabilities of the hopper in an indoor test area. The hopper was able to drive on a flat carpeted area and hop above rocks approximately 30 cm high, all under remote operator control. Figures 13 show one of the tests performed.

5 Conclusion

This paper presents the main features of the hopping robot for planetary exploration currently under development at JPL and Caltech. After summarizing the main design characteristics of two earlier generations of hopping robots, we identify the main challenges of hopping robot technology, and propose a new design that partially addresses those issues. The 3^{rd} generation prototype is a Hopper on Wheels, capable of long, but coarse, jumps using the hopping mechanism, and short, precise motions using wheels. The prototype was tested in an indoor fecility, showing versatile mobility and good performance. Development is under way to adapt the self righting mechanisn to the new design and prepare for outdoor tests.

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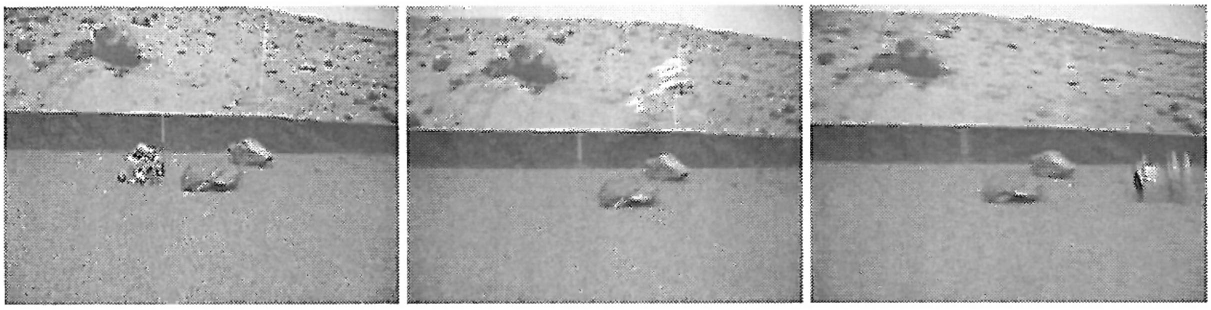

Figure 13: A test jump of the 3^{rd} generationhopper.

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