Hopper on Wheels: Evolving the Hopping Robot Concept

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Abstract: *This paper describes the evolution of our concept of hopping robot for planetary exploration, that combines coarse long range mobility achieved by hopping, with short range wheeled mobility for precision target acquisition. We show that a small number of actuators can control the vehicle's mobility, which now includes hopping distance and angle control, and independent wheel control. The electronic control of this prototype consists of a simple multiprocessor architecture, which is coupled to a mechanical timing logic for additional reliability and reduction in actuator number. This vehicle carries a color camera, a pair of dual-axis accelerometers, and an RF modem for remote communication. The paper summarizes the evolutionary development of our hopping robots, issues relevant to the design of jumping-wheeled systems, and experimental results obtained with the different prototypes.*

1 Introduction and Motivation

The recent trend towards small and frequent space mission to Mars and other celestial bodies such as moons, asteroids, and comets has sparked new interest towards multi-functional vehicles, capable of providing excellent mobility to dedicated scientific packages. Currently, the only deployed, and actively engineered, mobility paradigm is a 6-wheeled rover, as seen in the Pathfinder mission's Sojourner vehicle [12] and in the planned Mars 2003 exploration missions. Most 6-wheeled rover designs can traverse obstacles that are about 1.5 times their wheel diameter, but they also have significant drawbacks preventing their use as truly general exploration platform. For example, they can only drive over obstacles that are a fraction of the vehicle's body length, and use a significant number of actuators and complex suspension linkages.

To address the two goals of reducing the rover complexity and of developing more efficient mobility methods, in the past few years we have been developing 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 such designs are likely to be smaller and lighter, with lower risk of failure. Furthermore, since planetary bodies of current interest are characterized by low to medium gravitational environments, wheeled mobility can be replaced, for certain operations, by hopping, which is a more efficient mobility method.

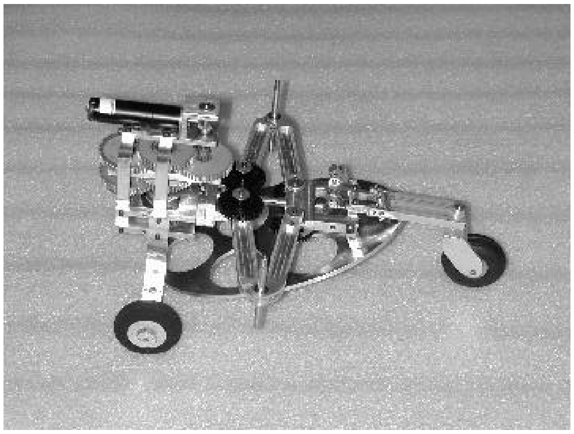
Figure 1: The 3^{rd} generation Hopping Robot.

Key to the good performance of these systems is the trade-offs between functionality and complexity in the context of the design and development of a small robot, capable of moving a camera and a science package by jumping. 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 a single actuator to propel, steer, self-right a simple hopper, and pan an on-board camera. Hence, this single actuation design offers surprising capability, compactness, and efficiency. There are, however, two main limitations with our second generation prototype, which may prevent its use in real exploration missions, namely the problems of fine motion control and navigation planning. The first issue refers to the robot capability of accurately controlling its trajectory, before taking off, and after landing. The second limitation refers to the robot ability of precisely locate itself, and of restoring this information after each landing. This paper presents our solution to the first of these problems, i.e. accurate hopping control and fine motion maneuvers, as implemented in the 3^{rd} generation hopping robot shown in Figure 1.

After summarizing relevant prior work by other authors in Section 2, Section 3 summarizes the first ("generation one") and the second ("generation two") prototypes, and describes their performance and shortcomings. The lessons learned from this system led to the third generation system, whose design and performance are described in Section 4. Finally, Section 5 summarizes the main characteristics of our current prototype and presents our plans for future research in this area.

2 Relation to Prior Work

Hopping systems for planetary mobility were first proposed in [13, 16] as an interesting transportation concept in alternative to the Lunar Rover for astronauts of the Apollo missions. A first order analysis of Lunar hopper performance is presented in [8]. Based on data from the Apollo missions, this paper compares different approaches to Lunar transportation, showing that hopping is an efficient form of transportation in a low-gravity environment.

More recently, hopping robots have been the subject of renewed research interest. A precursor for some aspects of our first generation device, is described in [11]. However, for this device no experimental data have been reported. More recently, the fabrication and testing of the prototype of a gas propeller for a Mars hopper has been described in [19], potentially capable of hops of several thousand meters. A second hopping system is described in [7], and is powered by an internal combustion chamber with steering achieved by rotating an off-center mass. This prototype is said to be able to clear obstacles about 10 m of hight, however concerns about environment protection may limit its applicability. 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. However, they are currently limited to exploring small flat areas due to their small wheel size and quite limited hopping capability.

In the past, however, 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]. In contrast to our design, these hoppers required several actuators for propulsion and stabilization. Research on non-holonomic systems has also motivated a renewed interest in the control of hopping robots. An often analyzed device is the "Acrobot", a reversed double-pendulum with a single actuator located in the joint and free to move its base [1, 2, 5, 17].

In the last few years, smaller wheeled rovers for planetary exploration have been designed and fabricated in several research laboratories. The interest in these systems is motivated by the fact that 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* [18], 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 with helical cleats for skid steering. The robot is controlled by downlinked 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 those devices are the same also in the latest prototype, and thus need only be discussed once. Furthermore, lessons learned from and evaluation of this system motivate the improved version described in Section 4.

Our earlier designs were driven by a few main goals, such as the desire to minimize the actuator number and the 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 must be of some 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]. Fig. 2 depicts the essential internal components of the first generation design. A clear polycarbonate shell sur-

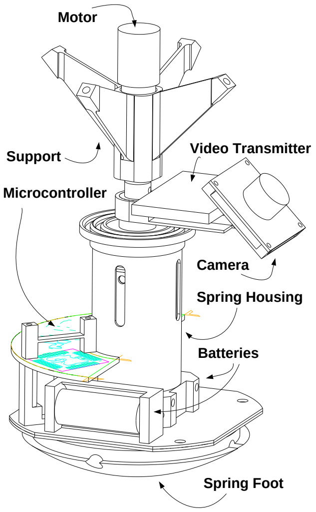

Figure 2: Schematic drawing of the 1^{st} generation mechanism. The surrounding polycarbonate shell is omitted for clarity.

rounds the mechanism, and is attached to the body at the upper support and lower plate, as is shown in Fig. 3. 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 the leg compression and leg release subsystem, while rotation in the other direction drives the camera rotation. Fig. 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 seven steps of the operational sequence are shown in the timing diagram of Figure 4.

The tests performed to assess this 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 prototype presented three major shortcomings of the first generation system: (1) inefficient hopping; (2) unrobust steering; (3) unrobust self-righting capability. In fact, we determined that the "theoretical conversion efficiency" of the hopper was only $\eta = 20\%$, i.e. 80% of the energy stored in the spring was not converted to

Figure 3: Photograph of the 1^{st} generation system.

motion during the launching process, with

$$\eta = \frac{\text{hopper kinetic energy at takeoff}}{\text{energy stored in compressed member}} \times 100\%$$

assessing how well a given hopping system converts elastic energy stored in the compressed member into actual hopper motion. Three main factors dominated the losses. First, at the end of decompression phase, the foot abruptly stops in an elastic impact with a mechanical stop, thereby dissipating its kinetic energy. Second, because the hopper tilts in order to steer, the ground reaction force is often not normal to the surface, and may falls outside the Coulomb friction cone, thus the more the leg thrust force exceeds the Coulomb limit, the greater is the percentage energy loss. Finally, the hopper linear spring has the tendency to generate *premature lift-off*, thus preventing the complete conversion of stored energy to kinetic energy.

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 of these objectives while still using only a single actuator. As seen in Figures 5 and 6, the , the design and construction of this device is considerably more complicated than that of the first generation.

To solve the inefficiency problem of the jumping mechanism, we designed the combined spring/linkage mechanism shown in Fig. 7. The leg extension is along the y-direction in Fig. 7. Displacements in the y-direction induce, through the linkage, displacements in

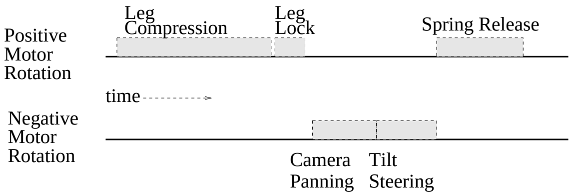

Figure 4: Relative timing of the operations driven by the primary motor.

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

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 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 (Fig. 8). 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 mechanism 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 6: (a) Photo of 2^{nd} generation thrust leg uncompressed.

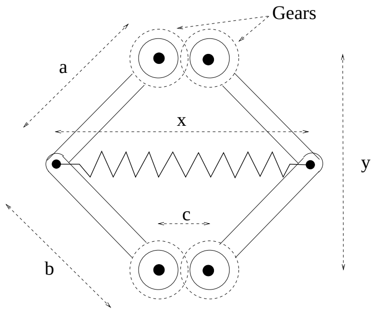

Figure 7: (a) The 2^{nd} generation energy storage linkage, a 6-bar geared mechanism.

Finally, the operation sequence repeats the same operations of the first prototype, but with many more operations, and novel timing mechanisms, mechanical logic, and couplers were introduced to coordinate the various actions, as shown in Fig. 9.

The experiments performed with the second prototype typically showed jumps of 70-80 inches of horizontal distance, and of ∼35 of vertical height inches during free-flight.

Comparison with Wheeled Rover. It is interesting to compare the performance of our second generation prototype with that of the Nanorover, since they address similar exploration missions. We do not intend to suggest with this comparison that the Nanorover is anything but an excellent vehicle. Instead, our comparison suggests that our proposed hopper is a viable alternative that could profitably be pursued for some applications. Based on the data collected from exper-

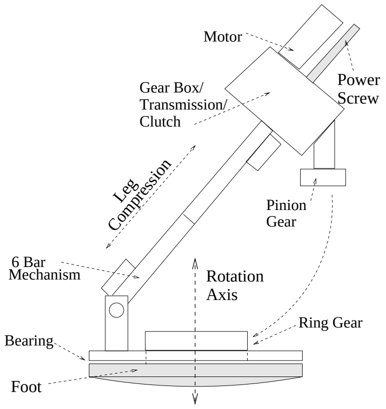

Figure 8: Schematic of steering mechanism. The self-righting mechanism and several components are omitted for clarity.

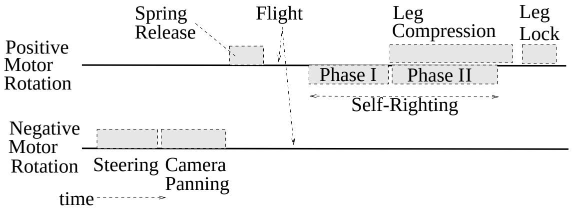

Figure 9: Depiction of Timing/Phase of motor operations driven by the single primary motor.

iments with our prototype, we can make the following quantitative comparisons for Martian applications. The latest Nanorover prototype has 1 Kg mass. Our second generation prototype has approximately 1.3 Kg mass. Based on its maximum speed of 3 cm/sec, the Nanorover would require at least 4.3 minutes to travel an 8 m path, making the unrealistic assumption that no time is spent on obstacle avoiding maneuvers. On Mars, our hopper can travel this 8 m distance in a single hopping cycle, whose duration (including thrust charge, steering, and self-righting) is approximately 1.5 minutes. Hence, our hopper is effectively 3 times as fast. Our system draws 4 W of power for 30 secs during leg compression, approximately 100 mW during 50 seconds of self-righting, and a negligible amount for steering. The total energy required for the 8 meter hop is approximately 125 Watt-sec. The Nanorover has a maximum power feed of 1 W, but requires less for nominal travel–on the order of 350 mW. With the assumption that no obstacles need be avoided, the Nanorover will consume 93 Watt-sec for the same traverse. Taking obstacle avoidance maneuvers into account, the energy consumption of the two will be essentially equal. Based on the Nanorover's 6 cm wheel diameter, it can only avoid approximately 9 cm tall abrupt obstacles. On Mars, our next generation hopper will be able to leap 4.5 m above the surface. Thus, our hopper can overcome abrupt obstacles that are nearly 50 times higher.

4 The Hopper on Wheels

Having solved some of problems of hopping mobility with the previous prototypes, 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 tries to solve the problem of positioning an instrument precisely where it is desired. Clearly, hopping with a fixed take-off angle is not flexible enough to reach a science target and we added to this prototype the capability of changing the take-off angle and of performing precise moves after landing.

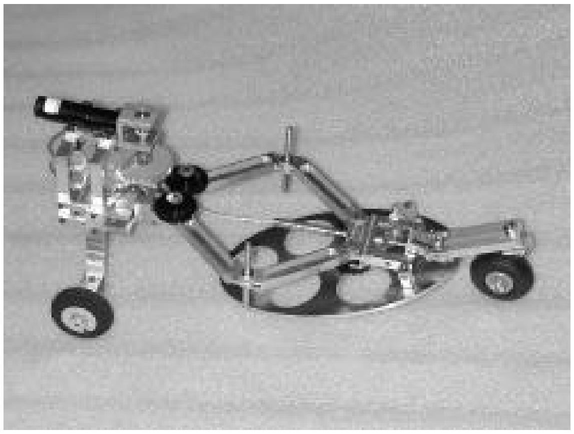

Figure 10: The Hopper 3^{rd} in extended configuration.

Figures 10 and 11 show the Hopper fully extended and in the take off position, and we use these figures to point out the main mechanical details of the new prototype (springs and the self-righting mechanism have been removed from the prototype). the main body of the hopper is a gear-box required to load the springs needed to perform long jumps. Figure 10 shows the extended six-bar linkage attached to the rear of the gear-box, and the cable used to load 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 (removed from the assembly). 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 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.

This prototype is equipped with an electronic pack-

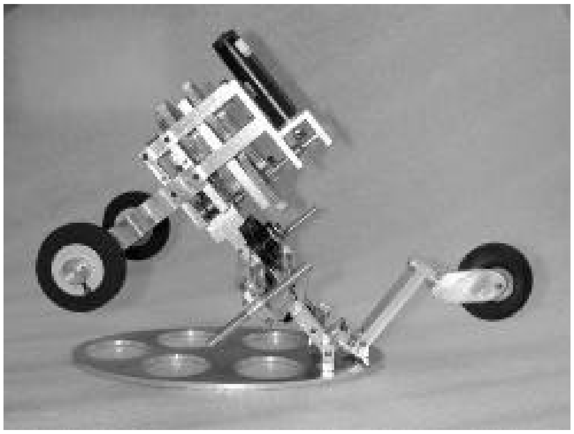

Figure 11: The Hopper 3^{rd} ready for take-off.

age (which will be mounted around 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. The 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. 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 will be added to the hopper to protect the electronics during crash landing.

During the month of December 2000, experiments will be performed to verify the operational capabilities of the hopper, in particular the variation of hopping distance by adjusting the take-off angle and the short range mobility using wheels.

5 Conclusion

This paper presents the main features of the hopping robot for planetary exploration currently under development at JPL. After summarizing the main design characteristics of two earlier generations of hopping robots, we compare the experimental results of the 2^{nd} generation prototype with the performance of the state of the art in miniature planetary rovers. Furthermore, 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, motion using the hopping mechanism, and short, precise mobility using a pair of wheels. The prototype is currently being assembled and we plan to run extensive field tests in the next months to verify the performance and the limits of the combined hopping/wheeled mobility.

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