The Bow Leg Hopping Robot

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Abstract

The bow leg hopper is a novel locomotor design with a highly resilient leg that resembles an archer's bow. During flight, a "thrust" actuator adds elastic energy to the leg, which is automatically released during stance to control hopping height. Lateral motion is controlled by directing the leg angle at touchdown, which determines the angle of takeoff or reflection. *The leg pivots freely on a hip bearing, and is automatically decoupled from the leg-angle positioner during stance to preclude hip torques that would disturb body attitude. Upright attitude is maintained without active control by allowing the body to "hang" from the hip joint. Preliminary experiments with a planar prototype have demonstrated impressive performance (hopping heights of 50 cm or more), high efficiency (recovers 70% of the energy from one hop to the next) and low power requirements (45 minutes of operation on a small battery pack). Current experiments are focused on developing control and planning schemes to enable locomotion over discrete "stepping stones" and obstacles.*

1 Introduction

Human beings and animals have remarkable abilities to walk and run over a wide variety of terrains. In running, as distinct from walking, a machine (or animal) exhibits periods of flight in which contact with the ground is completely lost. Running in general is a dynamic phenomenon in which inertial forces are significant, and balance is achieved by active means, not by static equilibrium. Elastic effects are typically significant and may be exploited for cyclic energy storage; this is known to occur and enhance performance in biological systems [1] [9]. Running allows higher speeds than walking, and exploits dynamics to negotiate widely spaced (horizontally or vertically) footholds. This paper focuses on the design of a novel running machine of the simplest form—a planar, one-legged hopper—that is energy efficient and simple. Planning and control of this machine are described in a companion paper [10].

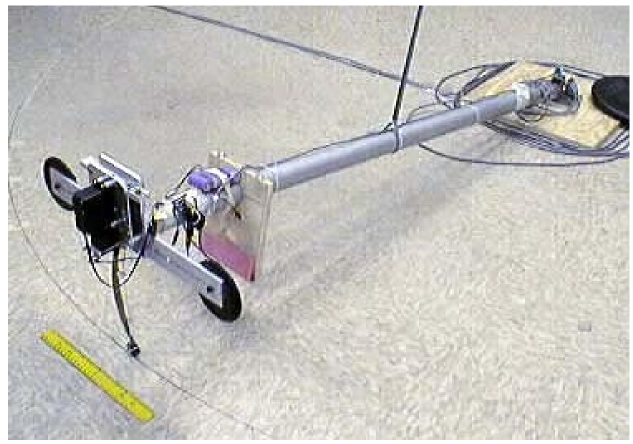

Figure 1: Photograph of the hopper prototype and boom. The leg is 25 cm long and the boom radius is 1.5 m.

While research on dynamically-stabilized legged locomotion dates back to at least 1979 [5], previous hopping/running machines have been characterized by numerous shortcomings:

- Inefficiency due to losses in the mechanical system and negative work
- Need for large, high-powered actuators for excitation and control of motion
- Requirement for excessive power via off-board power supply
- Large body-attitude disturbances and control effort
- Inability to perform precise motion control needed for reliable movement over complex terrains
- Control complexity
- Vulnerability to damage

In short, previous concepts of running machines have been confined to laboratory environments, and have not been suitable for practical legged locomotion.

The present research addresses these issues by first incorporating, as much as possible, the desired behaviors into the mechanical structure of the machine. To be practical, a running machine must efficiently handle the large amount of kinetic energy associated with its motion. We view a locomotor as a resilient system, like a highly elastic bouncing ball, whose energy must be directed in a way to produce useful, efficient motion. In the simplest form, a one-legged hopper comprises a mass (body) and spring (leg) wherein the mobility task is simply a matter of pointing the leg at touchdown to produce the desired subsequent take-off vector. In an ideal system, impact is a perfectly elastic collision with the ground, where the angle of reflection is determined by the leg angle. Attitude disturbances disappear because torques on the body are not permitted.

2 The Bow Leg

Figure 3 shows the configuration of a planar hopping machine that we have developed based on the above reasoning. The leg structure is a tapered curved leaf spring of unidirectional fiberglass, 25 cm long, with a fixed foot at the bottom, and a bearing at the top that allows the leg to swing freely at the hip. During stance the leg curvature increases, storing energy in elastic bending of the spring. Static equilibrium–neglecting leg inertia and bearing friction–dictates that the contact force with the ground must act through the hip. The free hip pivot allows not only free leg sweep motion but also unhindered hip rotation associated with the leg compression. A string, attached to the foot and running up through the hip centerline, provides a point of connection for the leg angle positioner; limits leg extension; and allows control of leg length by a leg "thrust" actuator attached to the body above the hip. An additional spring-loaded mechanism is built into the leg positioner to limit the torque coupling to the minimum needed for reliable positioning. Because of the striking similarity to an archer's bow, we call this design the "bow leg."

A key departure from previous approaches is the elimination of hip torque. Allowing the leg to pivot freely at the hip during stance and locating the body center of mass (COM) at the hip preclude generation of torques on the body by the leg[1]. This approach leads to the following benefits:

- Effort and energy loss in attitude control are minimized

[1] In fairness it must be noted that some researchers have sought to understand and mimic the behavior of humans and other animals in which the COM is well above the hip. We have no such constraints, and choose to distribute the mass however it is most advantageous to the machine's behavior.

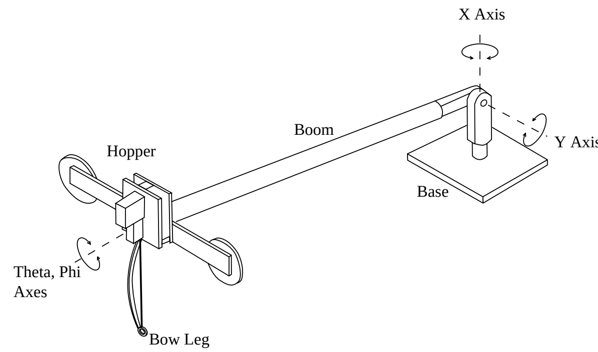

Figure 2: Schematic of the hopper and its constraint boom. The boom allows three degrees of freedom on the surface of a sphere: (x, y) position and θ body rotation. The leg rotates around the hip (ϕ axis) parallel to the body rotation. The boom is instrumented to measure $x, y,$ and θ.

- Leg/hip need not accept/produce large torques
- Hip actuators can be small
- The leg can be very light
- The model and control are simplified (body treated as point mass)
- Vulnerability to damage is minimized because of the leg's lateral compliance

In practice, placing the COM *slightly below* the hip produces a mild restoring effect that keeps the body upright passively, even when subjected to significant disturbances. The body then acts as a pendulum, with frequency essentially the same as a comparable statically suspended pendulum. Keeping this pendulum frequency well below the hopping frequency (by a factor of five or more) minimizes pitch oscillations excited by the hopping motion. This is similar to the phenomenon reported by Ringrose who used a large, curved foot to stabilize the pitch of a monopod hopper [8]. Friction in the boom pitch joint enhances the pitch stability. In the future, another DOF may be added allowing lateral adjustment of the COM relative to the hip. This would permit explicit control of body attitude, and provide a means for transfer of energy between rotation and translation. This could be useful to induce body rotations—e.g. for gymnastic motions—or as an additional control freedom for forward speed.

The mechanism for controlling the hopping energy of the system is shown in Figure 4. During flight, the "thrust" mechanism retracts the leg via the "bow string," adding elastic energy to the leg. It then automatically releases the string during stance, transferring the elastic energy to

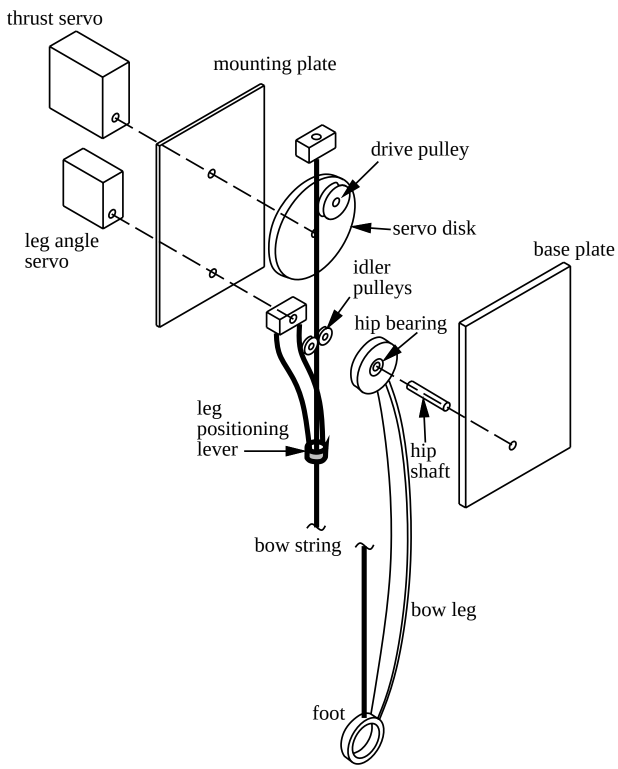

Figure 3: Exploded schematic of the hopper. The top servo rotates a disk carrying the drive pulley that can engage the bowstring in order to compress the leg. The bottom servo controls the leg angle during flight. The hip is an unactuated joint with a ball bearing, effectively decoupled from the leg-angle servo during stance. Several shafts and supports are omitted for clarity.

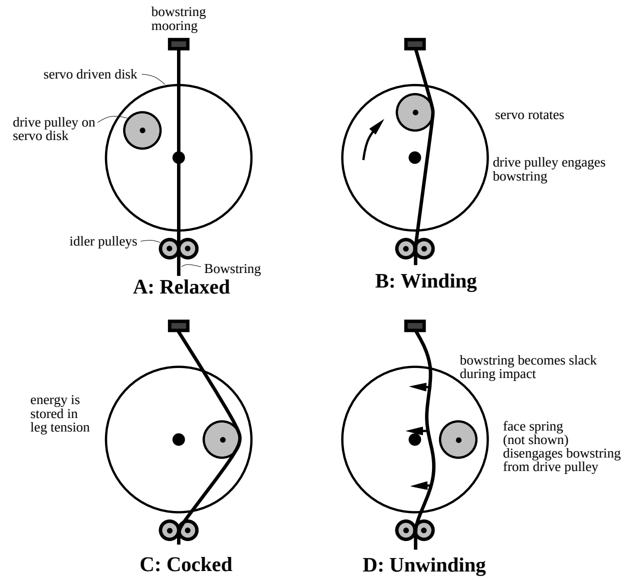

Figure 4: Schematic of the prototype thrust mechanism which stores energy in the leg during flight. The cycle begins in the relaxed state (A). During winding (B), the servo disk rotates, the drive pulley engages the bowstring, and the displacement of the bowstring compresses the leg (not shown). The energy stored in the cocked position (C) is a function of rotation angle. During the impact (D), the string goes slack, the face spring (not shown) nudges the bowstring off the pulley, and the leg extends to full length. Not shown are the servo body or the leg. The winding direction and string displacement alternate left-right.

system kinetic energy. This injection of energy can compensate for losses in the mechanical system, or produce an increase of system energy. Because energy is stored during relatively long flight periods, a small, efficient, low-power thrust actuator can be used. With some enhancements, this mechanism could also be used to store the machine's kinetic energy in elastic energy in the leg by limiting leg extension at takeoff to less than its touchdown value. This function would be useful to rapidly reduce hopping height or to absorb energy on descending terrains.

The current prototype of our planar hopper is shown in Figures 1 and 2. The machine runs in a circle, constrained to operate in a "planar" (actually spherical) surface by a tubular boom that pivots at the center. Angle sensors at the base measure the X (lateral) and Y (vertical) positions of the machine. A third angle sensor at the outboard end of the boom measures body pitch angle (θ). Two hobby servos on the body actuate leg angle and thrust. An off-board control computer (PC with I/O board) is connected via an umbilical that runs along the boom. Electrical power for the actuators is provided by batteries on board. A weight bar and two weights provide inertia to stabilize the body and allow tuning the location of the body COM relative to the hip. An elastic cord between the boom and the ceiling reduces the effective gravity, lowering the hopping frequency; this provides more time for control execution, facilitates visual observation of behavior, and reduces the power needed to sustain hopping. The lowered gravity is not a fundamental limitation, only an experimental convenience.

Below are the present machine specifications, which reflect little effort in design optimization or minimizing mass. Leg length is 25 cm and the running circle is 1.5 m in radius. Effective gravity, a result of the supporting elastic cord and boom geometry, is 0.35 G (3.5 m/s^2). Effective machine mass is 4.0 kg, including 0.8 kg in the hopper mechanism itself, 0.2 kg of batteries, and 3.0 kg of ballast and boom weight. The leg itself weighs only 30 g excluding the hip bearing. It is noteworthy that the hopper mechanism comprises only 20% of the total mass; the batteries 5%; and the leg 0.8%. A full 75% of the mass is in the "dead weight" of the weights and boom. Thus, there is great room for improved performance.

3 Control of the Hopper

The hopper is controlled by configuring the leg angle and stored leg energy during flight, which determine two initial conditions for the passive bounce. The new trajectory is a function of the impact state, the two control outputs, and the spring-mass physics of the hopper and leg. Unlike previous work, the mechanical design permits only one control cycle per bounce and the controller takes a discrete form that computes the desired leg angle and stored energy at touchdown $(\phi, \Delta E)$ from the apex position and horizontal velocity $(x_n, y_n, \dot{x}_n)$.

A variety of methods might be employed to compute this control function. So far, we have implemented two methods, a linear controller and a planning approach. The linear control is similar to the Raibert three part control: the touchdown leg angle is analogous to foot placement and controls forward speed, and the leg retraction at impact controls total energy, roughly equivalent to hopping height. Because body attitude is passively controlled as a result of the body mass distribution, the need to exert pitch torques during stance is eliminated. Currently, the controller seeks to maintain constant energy in the system by varying the energy stored with the leg retract mechanism before each stance period.

The planning approach uses graph search to explore possible sequences of steps that satisfy the constraints of the terrain. The leg angle is selected to produce the desired takeoff angle, based on a numerical solution of the impact physics. The thrust output is chosen to maintain approximately constant total energy. The plan is executed by a controller that evaluates the result of each bounce and adjusts the following two steps to return to the plan.

This approach requires accurately modeling the physics of the hopper. However, the simple mechanical design creates dynamics that may be well modeled. So far, we have used a closed form model of stance that combines an idealized, instantaneous, impact model with empirically determined adjustments for leg losses and the finite stance time. The flight model similarly combines a uniform acceleration model with adjustments for friction. The parameters in the model are determined from data by minimizing the least squares difference between the predicted and actual trajectory parameters over sets of approximately 400 bounces.

The hopper control still has a real time component to read sensors, issue servo commands, and cycle through states representing ascent, descent, and stance. At the lowest level, the hobby servos use position feedback to reach commanded positions encoded as PWM (pulse-width-modulated) signals from the control computer.

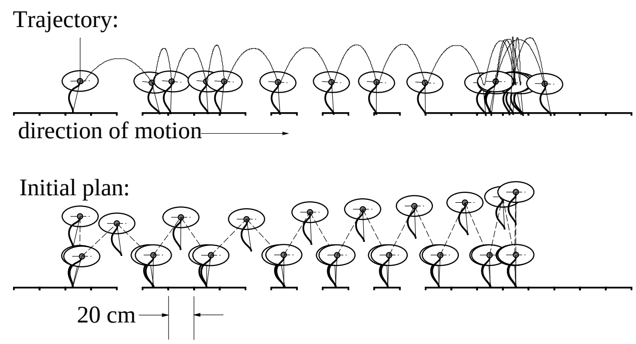

Figure 5: Experimental data showing the center of mass trajectory and touchdown positions. Below is the plan generated initially; error led to subsequent replanning.

4 Experimental Results

Performance of the hopper mechanism is impressive. Bouncing passively, the hopper loses only about 30% of its energy each hop. The machine has hopped as high as 50 cm; 80 cm is theoretically possible based on leg elastic energy capacity, with the present machine mass and reduced gravity. We have not pushed the horizontal running speed, but 1.0 m/s has been observed, and several meters/sec should be easily achievable. The inherent, passive pitch stabilization has effectively damped pitch errors of about 0.5 radians; larger angles could be tolerated with increased leg-sweep travel. Energy consumption is surprisingly low: the machine runs for 45 minutes on a single charge (approximately 5 w-hr) of the four sub-C cell nickel cadmium batteries, which comprise only 5% the total machine mass. The hopper has logged more than 5 hours of operation without major mechanical problems.

Experiments with the machine include hopping in place, running at low velocities across level ground, and crossing an obstacle composed of "stepping stones" separated by "holes" in which the hopper must not land. We are presently focusing on the stepping-stone problem, trying to minimize the foot-placement error, and maximize the permissible gaps between stones. An experimental run is presented in Figure 5 along with a typical, automatically generated plan. Typical foothold width is 20 cm, with 20 cm intervening holes.

The precision of the motion is limited by the inaccuracies and uncertainties in the flight and stance models, and the precision of actuator control. In particular, the motion is very sensitive to errors in the leg angle at touchdown: a 0.04 radian error in leg angle (1.0 cm lateral error in foot position) translates to a 17 cm error in lateral position at the next touchdown, based on typical hopping conditions (0.3 m hopping height and 0.2 m/s forward speed). We are currently considering mechanisms that will permit greater control and measurement precision of the leg angle.

5 Related Work

There have been a number of efforts at building running robots. Matsuoka [5] built a planar one-legged hopper that operated in low effective gravity on an inclined table. The machine had a short stance time, with thrust provided by a high-force electric solenoid. Following Matsuoka were a series of running machines produced by Marc Raibert's Leg Lab [7]. A succession of machines tested one-, two- and four-leg designs both in the plane and in 3D. Most used a telescoping leg with an internal air spring for compliance, and hydraulic actuators. All the Raibert machines were controlled by the same basic decomposition into three independent linear controllers: forward velocity controlled by foot placement, hopping height controlled by thrust, and pitch controlled by hip torque during stance. This control involved high force and power during stance.

Following Raibert are several examples of electrically actuated hoppers. Papantoniou constructed a one-leg electrically actuated planar hopper with a leg constructed from a four bar linkage with a tension spring [6]. Martin Buehler's group at McGill built one-leg planar hopper similar to Raibert hoppers but with electric motors instead of hydraulics and a metal spring instead of an air spring [3]. Berkemeier and Desai designed an electrically actuated leg with three revolute joints that used an electric motor coupled with elastic tendons to drive the foot [2]. Lebaudy, Prosser and Kam at Drexel designed an electrically actuated telescoping leg constrained to the vertical [4]. It incorporated a DC motor driving a ball screw in series with a steel spring.

The bow leg hopper in many ways is descended from the work of Raibert, but there are significant differences. First is the freely pivoting hip which minimizes the torque coupling and attitude disturbances during stance. Second, locating the COM below the hip allows the body to be self righting, so little control effort or energy is needed for pitch control. Third, the leg is very lightweight, can be positioned with a low-power actuator, and its motion causes minimal disturbance on the body. Fourth, the leg has high passive restitution, minimizing the energy that needs to be added each cycle, and making the impacts relatively repeatable and predictable. These factors simplify the model of the machine dynamics and flight and stance phases, leading to simpler, potentially more precise control. A final difference is the thrust mechanism: by storing energy during flight the power demand is distributed across flight, so low-powered, electric actuators are suitable.

6 Discussion

The ultimate goal of this work is the development of 3D machines that can cross rugged, natural and man-made terrains. The bow leg concept has many characteristics amenable to this goal. First, the efficiency and low power requirements make self-contained, electrically-powered machines feasible. Second, the high energy storage capacity of the leg permits vertical and horizontal hopping distances on the order of meters, allowing mobility on very rugged terrain. Third, the natural control of body attitude greatly simplifies modeling and control of the machine. Fourth, because losses and control effort are small, we expect–although it remains to be verified–that dynamic behavior will be quite repeatable and predictable (compared to previous systems with lower efficiency). While the current research focuses on single-leg machines, the bow leg is equally applicable to multi-leg machines. We anticipate that bow leg hopping and running machines will be capable of practical operation on real terrains, including small footholds spaced irregularly and separated by large horizontal and vertical distances.

While walking machines are bounded by their kinematic limits, running machines are bounded only by dynamic limits. A high strength composite spring can have a specific energy of 100 meters or more; that is, it can store enough energy to lift its own weight more than 100 meters. Thus, a machine having 5% of its mass in the leg could theoretically hop 5 meters or more! Of course, this performance is dependent upon allowable accelerations and ground forces, and the ability to maintain body attitude during long flight periods. Lateral hopping distance is twice the height capability, assuming an ideal trajectory. In reality, the hopper may be able to store substantial additional energy due to its horizontal motion. This energy could be employed for hill climbing or long jumping, or converted to vertical motion in a "pole vaulting" mode.

7 Future Work

While the bow leg shows much promise, there are many problems yet to be solved. First, in order to achieve precise stepping motion, we need better state information, especially leg angle information. In addition to measuring and controlling the leg angle precisely relative to the body, we need to know the body attitude. This is straight-forward in a tethered, 2D system, but very challenging for an untethered system. This will require precise, low-drift sensing or clever inferences based on system behavior.

Second, the concept needs to be generalized to 3D. Building a 2-axis hip joint appears straight-forward. We expect that motion control will decompose readily into two, more or less independent, processes, as was demonstrated by Raibert [7]. Controlling yaw, however, is difficult with a single, small foot that cannot generate substantial torques. A number of mechanisms might be employed for yaw control: direct torquing with a yaw actuator and oversized foot; coordination of eccentric stepping and thrust control to generate yaw impulses; or momentum wheels or gyros for stabilization.

A third problem is the perception and modeling of terrain. This is a problem that many researchers are studying, and one that we do not plan to address. As a short term solution, we can rely on off-line terrain modeling and/or human supervision of motion.

In the immediate future, we plan to focus on improving the performance of 2D machines. We will refine the current machine for more precise leg-angle control and continue the control and planning experiments. Beyond that, we envision a second-generation machine without the dead weight of the current machine, that can operate for hours on a single battery charge in a 1-G environment. This machine will likely include the weight-shift mechanism that would enable explicit pitch control, and exploiting angular momentum as an additional degree of control freedom.

8 Acknowledgments

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