First Hops of the 3D Bow Leg

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ABSTRACT

We have constructed several hopping machines using a new type of resilient, flexible leg that we call the "Bow Leg." The Bow Leg (patent pending) comprises a curved leaf spring, foot, freely pivoting hip, and the "Bow String" that holds the leg in compression. The leg spring is used for multiple purposes: as the leg structure, as the elastic element to store and release ground collision momentum, and as an energy accumulator to store thrust actuation energy during flight. This design features high energy efficiency and low-power actuation, and it has enabled the development of hopping robots that carry all power on-board. This paper focusses on the design of the one-legged 3D Bow Leg hopping machine currently under development. Specific issues include three-freedom control of the flexible leg using tension elements. The prototype is a work-in-progress that has demonstrated short hopping sequences on level ground under remote control.

1 INTRODUCTION

This paper presents work-in-progress on a hopping robot that uses a "Bow Leg," a flexible leg that is intended to make running robots more efficient by eliminating negative work, reducing leg sweep forces, and reducing peak motor power. Previous versions of this machine were constrained to three planar freedoms. They carried power on-board and required little actuator power or control bandwidth. The current prototype is a 3D machine (i.e., without any kinematic constraint) that carries power on-board, but which is remotely controlled. This paper is primarily concerned with the mechanical design of a 3D hip and leg drive mechanism that is compatible with the Bow Leg.

A more theoretical view of this work is as a rethinking of natural locomotion in light of the limits of mechanical systems. The fundamental difference from vertebrate locomotion is that our system is active during flight, but passive during ground contact. The control and power actuators operate during the flight phase to store energy in the leg spring and information in the leg position. This sets the initial state of the body-leg system that passively bounces off the ground during contact. Since the flight phase is longer than the stance phase, the average motor power is reduced, and since the leg is very lightweight, the peak control force is greatly reduced as compared to ground forces. This is possible because the leg operates as a conservative spring during ground contact and can passively accommodate high power mechanical energy transfer.

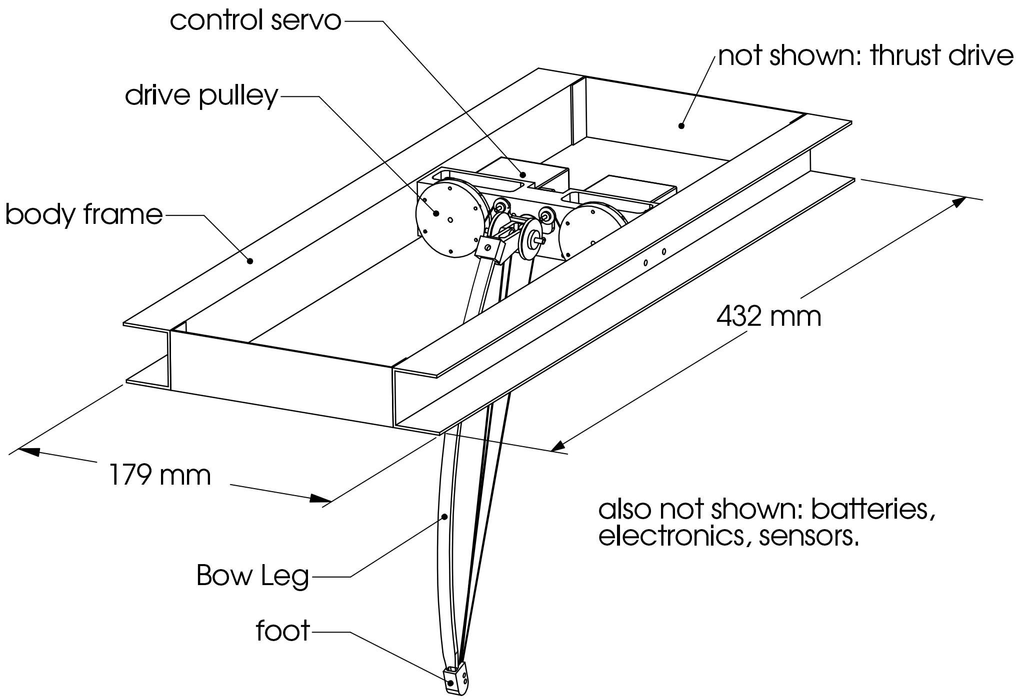

Figure 1: Partial assembly diagram of the 3D Bow Leg Hopper.

2 BOW LEG PRINCIPLES

The Bow Leg comprises a curved leaf spring, foot, freely pivoting hip, and a string that holds the leg in compression (see Figures 1 and 2). The name comes from the resemblance to an archery bow. The function of the Bow String is to control the potential energy in the leg. It may be retracted during flight to store thrust energy in leg compression and released to full length upon impact to release that energy into body motion. The leg pivots freely at the hip in order to minimize body disturbance torque.

The basic principle of the Bow Leg is that a single spring can provide the functions of leg structure, elasticity, and energy accumulation. The absence of other joints means that the high forces of ground impact are carried conservatively by the mechanical components—the spring and the hip bearing—and no forces or torques need to be supported by actuators during stance. The leg is controlled with strings that become slack as the leg compresses with the ground force. As a result, all energy input to the leg occurs during flight and the stance is passive.

These principles address the typical losses of legged systems: negative work and leg sweep. Negative work occurs in articulated legs when an actuator applies force in the direction opposite its motion and thus absorbs energy from the system[2]. This can waste a significant amount of energy, but negative work can be eliminated by design by avoiding articulation. Leg sweep losses result from the need to accelerate the foot to match the ground speed and are kept small by using a very low-inertia leg. The tradeoff of using a single spring is a lack of generality, but a significant advantage is high energy efficiency.

The leg spring element is made of unidirectional fiberglass as used in archery bows, which exhibits specific energies on the order of 1000 N-m/kg. A 30 g leg can thus store about 30 N-m of elastic energy, sufficient to lift the weight of the leg approximately 100 meters in earth gravity, or a 3 kg machine one meter. This leg material offers very high restitution; in the planar machine typically 80% of the kinetic energy stored during stance was returned to the body.

3 THE PLANAR BOW LEG HOPPER

The first prototype of a hopping robot using the Bow Leg[9][8] is constrained to three body DOF using a radial constraint boom. It operates in simulated 35% gravity provided by a counterspring attached between the boom and the ceiling. The machine uses two hobby servomotors for control, one to apply thrust by compressing the leg via the Bow String, and the other to position the leg using a pair of control strings. The leg attaches at the hip using a freely pivoting pin joint. The hip joint attaches to the body slightly above the center of mass so the body effectively hangs from the hip during ground contact and the natural pendulum forces passively stabilize body attitude.

Since the actuators are decoupled during ground contact, the trajectory during stance and the subsequent take-off is determined by the physical state at the moment of impact and the passive physics. For this reason, the control may be treated as a discrete function that specifies leg angle and thrust compression as a function of the desired flight trajectory. On level ground, a simple linear control function is sufficient to hop stably at constant speed.

The leg length is 25 cm, with a total machine mass of 2.5 kg, of which the leg spring itself masses only 30 g. In the reduced gravity it has hopped as high as 50 cm, and as fast as 1 m/sec. Motive power is supplied by an on-board battery pack of four NiCd sub-C cells, sufficient for about 30–45 minutes operating time.

4 3D BOW LEG HOPPER PROTOTYPE

The performance of the planar prototype motivated the goal of constructing a fully self-contained hopping robot based on the Bow Leg. The design goal of this prototype was to develop the leg and body design by building a machine intended for remote control. The first prototype has been constructed and has demonstrated some limited hopping abilities. It is serving as a testbed for further development of the mechanical and sensor design.

A fundamental question is whether a freely pivoting hip can passively stabilize body attitude in the 3D case. The planar machine has parasitic torques from the constraint boom that we believe increase the body damping; the 3D machine is only damped by air friction. The first strategy we have employed to increase body stability is the addition of a body stabilizing gyroscope. Other possible strategies include actively adjusting the center of mass location or using aerodynamic effects to produce small correction torques on the body.

Moving from planar to 3D geometry has required rethinking the body, hip, and leg positioner design. Since the hip uses a gimbal instead of a pin joint, the placement of the leg positioning and tensioning strings has been an especially challenging problem.

4.1 Detailed description

The discussion of the design that follows may be more clear if the kinematics and operation of the mechanism are described first. Please refer to Figures 1 and 2 for the following.

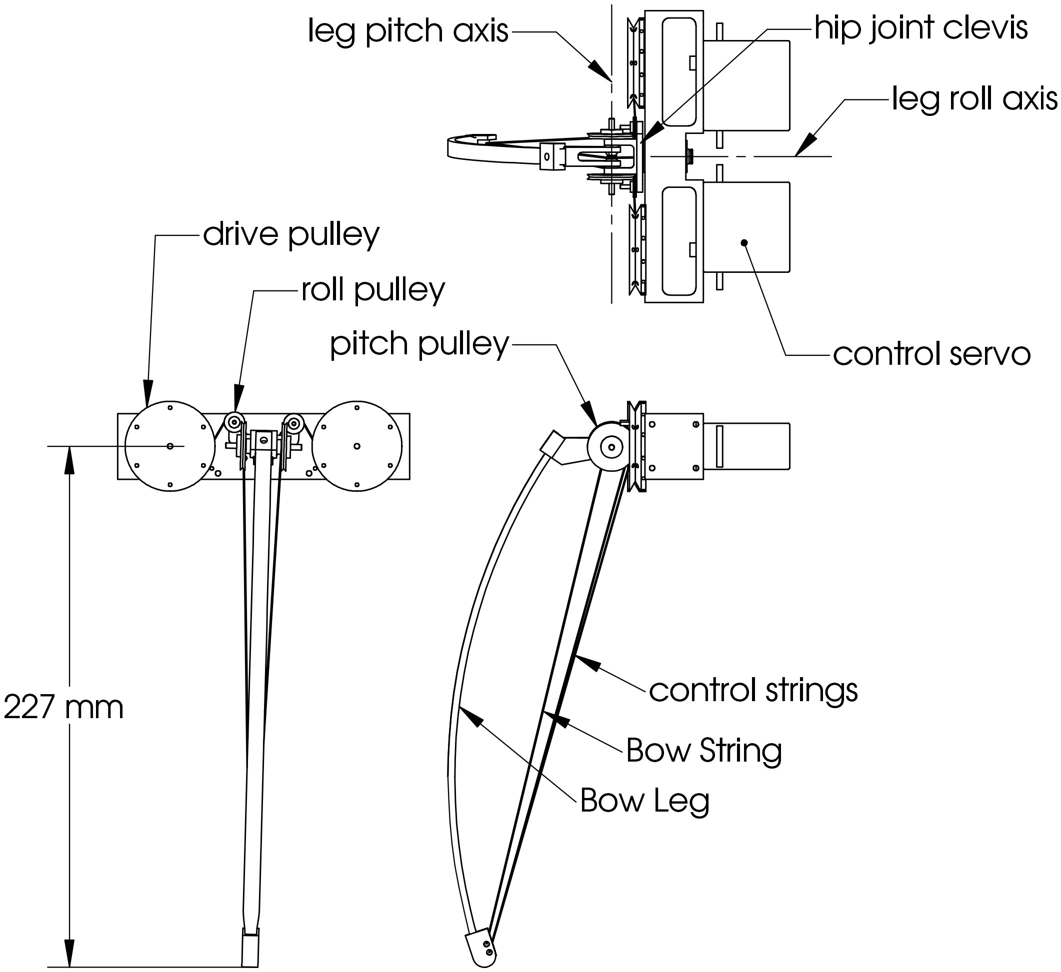

Figure 2: Three views of 3D Bow Leg Hopper chassis.

The machine comprises a rigid body and a flexible leg. The leg is connected to the body by a two-axis gimbal (universal) joint. This is the hip joint, which is operated during flight by three strings that act upon the foot. During stance, the leg is compressed by dynamic forces and the strings become slack; since the hip is freely pivoted the leg and body form a passive spring-mass system.

The three strings are asymmetrically configured so that one of them, the “Bow String,” counters 80% of the leg spring extension force; it is used to compress the leg and hold it in flexion during flight. The Bow String runs from the foot around a tiny 4 mm diameter pulley on the pitch axle, then through the roll axle and out toward the front of the body to the thrust drive mechanism. The other pair of strings operate differentially to control the leg angle; each control string runs from the foot attachment to wrap around a pulley on the hip pitch axis, then around a pulley parallel to the roll axis, and then onto a drive pulley. When the drive pulleys move in the same direction, the leg moves side to side, and when they turn in opposite directions, the leg moves fore and aft.

During flight, the thrust actuator operates to compress the leg by rotating the output disk 180° (see Figure 3). This action drives the eccentric drive pulley sideways into the Bow String, pinching it between the drive pulley and the two pairs of guide pulleys. The final position is statically stable and holds the leg in a shorter, compressed position. The rotation of the drive pulley is powered by the spinning flywheel via reduction gears and a clutch. When the Bow String becomes slack during stance, it is automatically released from the eccentric drive pulley, allowing the leg to extend to full length during takeoff, releasing the energy stored during flight.

4.2 Mechanical design issues

The basic requirements for using the Bow Leg in a 3D design are as follows: the leg must freely pivot at the hip during stance; the leg must be positioned during flight; energy must be stored in leg compression during flight; and the center of mass of the system must be placed slightly below the hip joint. In practice this has involved some tricky mechanical questions, chiefly the problem of creating a gimbal joint that can be actuated during flight but move with minimal disturbance torques during stance.

Other design considerations include the following: positioning the foot irrespective of the changes in leg curvature resulting from thrust compression; protecting the control servos from the string shock at takeoff as the strings become taut; minimizing the torques applied to the body during takeoff; and separating the control and thrust actuation so the control servos can position the leg without performing significant work.

4.2.1 Control actuation

Like the planar machine, our 3D design uses strings that drive the foot. A big advantage of using tension elements for position control is the automatic clutching action that arises from the strings becoming slack during stance. Another is that they position the foot with respect to the body independent of the details of the leg flexion.

The planar prototype used redundant string connections to separate leg positioning and leg compression functions. However, this required an extra pulley and take-up spring to keep the control strings tight as the tension string compressed the leg. For the 3D prototype, it was decided to use a non-redundant string drive. However, it is desirable to separate the control and thrust forces to avoid large static loads on the positioning actuators. This led to the asymmetric drive arrangement in which the control tensions are kept low by the use of longer lever arms for a control string pair opposing the higher-tension Bow String. One negative consequence of this is that the leg positioning stiffness is very asymmetric.

The Bow String layout nearly eliminates parasitic roll torques from thrust tension, and also provides a location for the thrust mechanism at the front of the machine. It is also desirable to keep the positioning actuators rigidly mounted on the body to minimize the inertia of the leg assembly; this led to the differential drive idea.

One problem with the current arrangement is precisely that the strings become slack, and so have a tendency to slip off the pulleys. To counter this we added elastic bands in parallel with the control strings to maintain a minimal string tension.

But the chief disadvantage of this scheme is the kinematic coupling: the two control strings are driven differentially to move the leg laterally, and must be moved in coordination with the Bow String during thrust. Also, the strings cause asymmetric torques at takeoff as they come under tension. Part of the solution is limiting the forces applied to the positioning motors; they are almost guaranteed to be shock loaded at liftoff, and possibly during collisions. Each drive

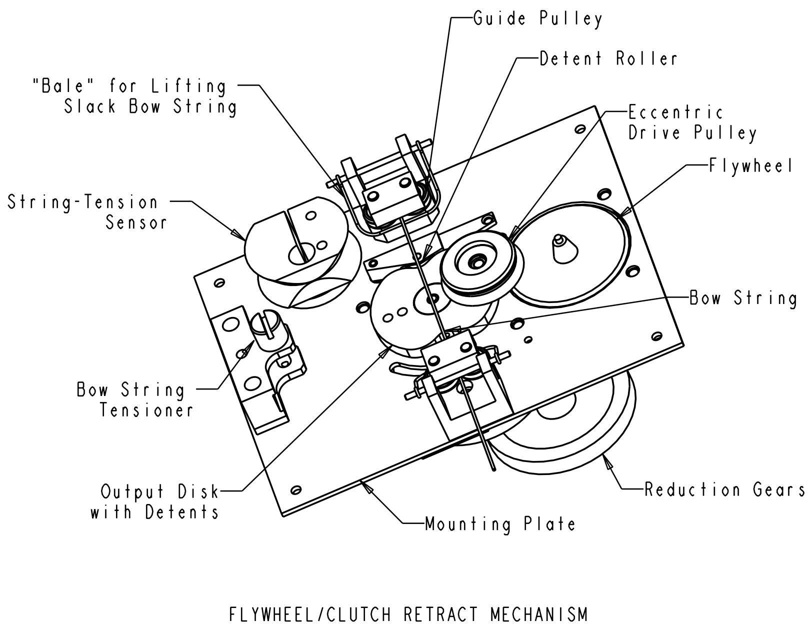

Figure 3: Diagram of thrust drive mechanism.

pulley incorporates a preloaded "overload protection spring" in series with each actuator that limits the forces. The force limit protects the motor and limits the body torques. As in the planar machine, the control actuators are high-speed hobby servos, chosen for low weight and easy interfacing.

4.2.2 Thrust actuation

The thrust actuator must pull the Bow String to compress the leg, but release the string when it becomes slack to allow the leg to extend. The planar machine featured a three-pulley mechanism that reliably released the string, but the speed of operation was limited by the maximum actuator torque.

As shown in Figure 3, the same basic arrangement was chosen for the 3D machine, but the servo actuator was replaced by a system with a motor, flywheel, reduction gears, and clutch. Compressing the leg requires a known amount of energy; if a greater amount is stored in flywheel rotation, then the flywheel can be guaranteed to perform a complete operational cycle. The flywheel can generate very large instantaneous torques to overcome the non-uniform torques of the non-linear spring and the three-pulley system. A small motor continually accelerates the flywheel back up to the nominal speed. Thus the flywheel efficiently delivers the short bursts of energy for "charging" the Bow Leg while the motor can run efficiently at nearly constant speed.

The advantage of this system is that it can rapidly compress the leg to keep pace with a hopper bouncing at low altitudes. The disadvantage is that it is binary: it delivers either zero energy or a fixed amount into the leg on each bounce, which limits the precision of the system energy control.

5 EXPERIMENTS

The experiments on the machine thus far have been simple operational tests recorded on video; no attempt has yet been made to transmit telemetry or record trajectories using ground truth sensors. However, a few anecdotal comments can be presented.

The first tests involved bouncing on the leg with the machine partially supported via a long rubber spring, while an operator remotely controlled leg angle (with no thrust mechanism installed). The rubber band both slowed the vertical oscillation and restricted lateral motion. These tests demonstrated that the differential string drive could position the leg. These were followed by “free-flying” tests without the rubber constraint. Although the leg positioning system functioned, the fast hopping rate made control difficult and runs were limited to just a few bounces. At attempt was made to include a stabilizing gyroscope on the body. This appeared to add some rotational stability, but added a great deal of mass.

After a body redesign, the thrust mechanism was added and experiments performed with remote control of leg position, while thrust energy was automatically added on each bounce. However, this test exposed how the differential string drive suffers from the coupling between angular positioning and leg length. Sometimes the leg does not complete a cycle of compressing and settling into a stable configuration before contact, leading to erratic bounce angles. This was partly addressed in follow-on work with sensor feedback that is outside the scope of this paper.

6 RELATED WORK

The important roles of elasticity and negative work in animal locomotion is well-recognized[3][4]. However, the first legged robot with flexible leg structure was a planar monopod built at Raibert’s Leg Lab[5] that used revolute joints at the hip and ankle and a flexible fiberglass leaf spring for a foot. The foot provided the compliance for hopping, and was actuated hydraulically through a rigid tendon. Another machine with passive stance phase was the Ringrose hopping monopod, which was stabilized using purely mechanical feedback[6].

Buehler’s group at McGill addressed the leg sweep problem in a different way by adding compliance in series with the hip actuator of a monopod to create a passive oscillation to help sweep the leg[1]. But the leg most superficially similar to the Bow Leg appears on the walking machine RHex[7]. This hexapod uses lightweight, compliant legs with only a single DOF each. Although the basic gait is a walk, the project aims to implement dynamic running. However, the leg is simply a curved spring, without the energy storage possible with a Bow String.

7 COMMENTARY AND FUTURE WORK

Legged robots are inspired by biological examples, but must still be built from mechanical rather than biological materials. However, robots can mimic the essential biological aspects of running—i.e., travel using a leg to bounce off the ground—but use dynamics compatible with the properties of mechanical components. The Bow Leg demonstrates a solution that reworks the dynamic cycle of running to reduce forces by taking the actuators out of the load path. Since energy storage and control take place during flight, the motors need never carry the weight of the machine and can thus be low-power.

Clearly, this work doesn’t address fundamental practical issues such as getting up from falls, or even yet fully demonstrate successful hopping in 3D. However, it indicates that the Bow Leg idea can be implemented on a 3D platform, and that the planar string drive can be adapted to the new constraints.

We are encouraged by the limited experimental results, but cannot yet determine the success of passive body stability. The freely pivoting hip decouples the body from ground torques and largely minimizes the body rotations. However, the string drive still transmits small torque impulses at takeoff and landing. We have several ideas for mechanisms to produce small control torques to damp out body oscillations, including adding a movable mass to the body to reconfigure the center of mass position during the flight phase. This would allow the normal ground forces to produce controlled correction torques on the body. Other ideas include aerodynamic or gyroscopic stabilization.

The flywheel-driven thrust design has proven to be fast enough for full gravity operation. However, a significant limit on performance has been the precision of the leg positioning system. Further work to improve performance includes refining an on-board attitude sensor, a foot position sensor, and switching to a redundant string drive with separated thrust and position control.

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