Skippy: A Versatile 3D Hopper

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1 Introduction

This paper describes the ideas behind a new robot, in the process of being designed, that explores the limits of simplicity in a versatile and energetic 3D hopping and balancing machine. Whereas Raibert's original 3D hopper had three actuators, the new robot has only two. This reduction in mechanical complexity, together with modern powerful electric motors and lightweight batteries, opens the possibility to create a robot that is considerably more athletic than an animal of similar size. On the other hand, the increased degree of under-actuation makes the control problem more difficult.

2 The Mechanism

Figure 1 shows a conceptual design of the new mechanism, called Skippy. It consists of a springy leg, a torso and a crossbar at the head. The leg is driven by a powerful DC servo motor via a ballscrew, a series elastic element, and a mechanism that is, in principle, two wheels rolling over each other. (In practice this mechanism could be implemented using cables, gears or an isogram linkage.) Sensors and battery pack are not shown. The crossbar is driven by a smaller motor and planetary gearbox. The purpose of the crossbar is to rotate the plane containing the torso and the leg. Mostly, this means keeping the plane vertical. The leg and torso can then act substantially as a planar hopping machine.

Despite its simplicity, this mechanism is theoretically capable of a variety of activities, such as: hopping forward, backward and sideways; hopping around curved paths; climbing and going down stairs; somersaults; sitting down, standing up and balancing; falling over and getting back up again; and bowing, pirouetting and turning on the spot. Assuming a mass of 2kg and a leg length of 50cm, the mechanism is theoretically capable of a 4m leap using a 60W motor pulsed at 200W, assuming a 50–50 split between new energy from the motor and energy recovered from the previous bounce via the springs.

3 Balance Control

Unlike Raibert's original hoppers, Skippy is expected to be able to balance on a point, to perform various movements while balancing, and to make transitions between hopping and balancing activities. This raises the question of whether such behaviours are possible on a machine with only two actuators. To answer this question, [1] demonstrated (in simulation) a control system capable of balancing a planar inverted double pendulum while simultaneously following a commanded trajectory of the controlled joint. The control system was further developed in [2], which demonstrated isolated single hops that begin and end in a balanced configuration, and yet further developed in [3], which demonstrates balancing and trajectory-following in 3D.

The above are all simulation studies with perfect sensors and actuators. However, Azad's forthcoming Ph.D. thesis describes some more realistic simulations in which the planar balance controller is shown to work well in the presence of modelling errors, sensor noise and actuator dynamics, including saturation limits.

The 3D balance controller introduces a new idea that is highly relevant to Skippy: balancing in bend and swivel space. According to this idea, balancing in 3D can be decomposed into two subtasks: balancing within a plane, and ensuring that this plane remains vertical. The former is accomplished by means of bending movements and the latter by swivelling movements. When applied to Skippy, the bend plane is defined by the central axes of the leg and torso, and swivelling is accomplished by rotating the crossbar.

4 Physical Ability to Balance

For Skippy to hop high, it is best to put most of the mass near the head, so that the robot can achieve the greatest possible velocity of its centre of mass at take-off. However, this is not necessarily a good mass distribution for balancing. Quantitative measures of a robot mechanism's physical ability to balance were introduced in [5], and express the ratio of a small balance error to the amount of motion needed to correct that error. If this ratio is too small, then tiny errors in the IMU's estimate of the vertical (for example) will cause large corrective movements of the robot, or even a loss of balance. The particular measure introduced in [5] is a dimensionless number called the velocity gain. It is independent of the overall mass and size of a robot mechanism, but it is sensitive to the mass distribution. The simplest form of velocity gain is shown in Figure 2. The actual mass distribution of Skippy will have to be a compromise between what is good for hopping and what is good for balancing.

Past research on balancing has tended to treat it as a control problem; but the upper limit to a robot's ability to balance is set by the dynamic properties of the mechanism, together with the strength and speed of the actuators and the quality of the sensor signals. If the mechanism has a velocity gain close to zero then no control system can remedy it.

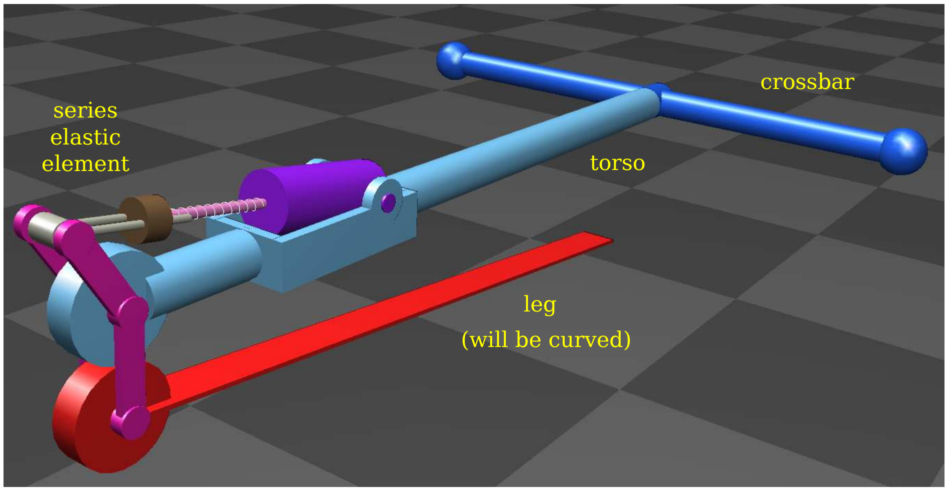

Figure 1: Conceptual design of a 3D hopping and balancing machine called Skippy

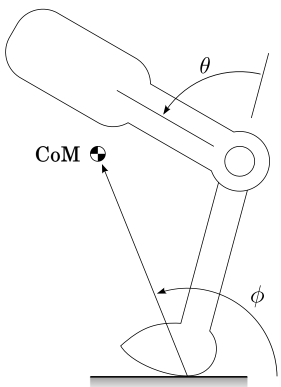

Figure 2: Velocity gain: $\Delta\dot{\phi}/\Delta\dot{\theta}$ where both velocity changes are caused by an impulsive torque at the actuated joint

5 Trajectory Following

The ability to balance and perform commanded movements at the same time is an essential skill for a legged robot. However, the control systems mentioned above do something special: they use the same actuator for both tasks.[1] The situation is clearest in the planar case: the robot consists of two rods connected by a single actuated revolute joint, and the lower rod is connected to a fixed pivot via a passive revolute joint. The trajectory specifies the angle of the actuated joint as a function of time, and is chosen without regard to the need of the robot to keep its balance. (In other words, it is not a special balance-preserving trajectory such as those described in [4].)

One can easily prove that it is physically impossible for the robot to accomplish both tasks simultaneously: the trajectory cannot be followed without losing balance, and the balance cannot be maintained without deviating from the trajectory. Yet the control system successfully accomplishes both tasks simultaneously. The key to understanding this result is to realise that neither task is being followed exactly: the robot necessarily wobbles a little as it follows the trajectory, and it necessarily deviates slightly from the trajectory in order to keep itself balanced.

[1] They are not the first control systems to achieve this.

This phenomenon is of some theoretical significance, since it presents us with an example where the number of tasks to be performed exceeds the number of control inputs to the plant. This is something that cannot be expressed in Khatib's operational-space formalism for whole-body control, and therefore highlights a deficiency in our present state of knowledge on how to express and implement complex whole-body motions.

References

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