Three Uses for Springs in Extension in Legged Locomotion*

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***Abstract*— Compliant robot legs are typically used in compression, however in some cases it may be possible and in fact advantageous to use the legs in extension. This work documents three such uses: terrain adaptation, energy storage, and shape change. The general strategies are instantiated in example robot behavioral experiments.**

I. Introduction

Compliance is known to play a variety of important roles in legged locomotion [1], e.g. providing energy storage [2], reducing impact losses [3], and adapting to rough terrain [4]. However, all of these examples have used a physical or virtual spring leg that compresses (shortens) as the ground reaction forces act on it. This is in part because the fundamental challenge of legged locomotion is to resist the gravitational attraction between the robot and the world below. Typically, legs are used to provide an upward force while pushing down on terrain that is more or less upward facing (with reaction forces that have a negative dot product with the gravitational direction). Any elastic compliance must be compressed to produce such a force.

Climbing robots, who live on terrain that is not upward facing (i.e. on vertical or overhanging surfaces), naturally do lead to legs that are used in extension [5, 6]. However, these robots must generally use some sort of attachment mechanism, such as claws, gecko feet, or adhesive pads in order to maintain ground contact while experiencing a negative ground reaction force. Here we will assume that no specialized attachment mechanism is available, and that the leg must maintain a positive ground reaction force or it will simply lift off the ground.

While it is easy to conclude that on average for ground based legged robots a compliant leg must be used in compression most of the time, there is nothing that restricts the leg from occasional use in extension so long as it is able to maintain a positive normal force with the ground.

Why do we care? Any time we can endow a robot with a new locomotion modality it will expand the range of capabilities of that robot. This is demonstrated clearly with the experimental behaviors documented below. But beyond this, the fact that prior uses of leg compliance have had an opposite sign from these modes suggests great opportunity to exploit nonlinear springs – there is no physical reason that the spring constant must be the same in both directions, e.g. [5]. A behavior that uses legs in extension is not restricted to using the same spring force/displacement characteristics of the existing behaviors.

* With apologies to R. McN. Alexander [1].

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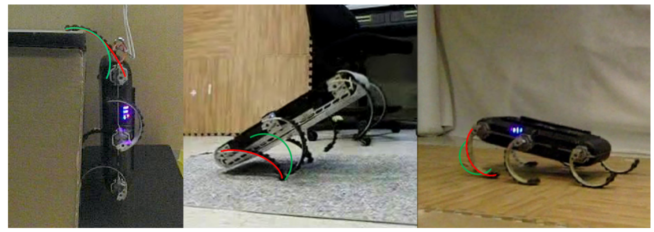

Fig. 1: Three examples of compliant legs used in extension. In each, the green highlight is the leg at rest length at the start of the behavior, and the red highlight is the extended length. (Left) Climbing onto a ledge. (Center) Rapid stop and flip. (Right) Leaping vertically.

This work documents three broad categories of behaviors that are able to use compliant legs in extension for short periods of time: rough terrain adaptation, dynamic energy storage, and passive shape change. Examples of each category, based on [7], are shown in Figure 1.

II. Terrain Adaptation

Uneven terrain provides many opportunities to stretch compliant legs. Once the normal direction of the ground is not smooth or uniformly opposing gravity, it is possible to find configurations of the robot where a leg may maintain ground contact while the gravitational forces extend the leg compliance. As the terrain roughness becomes greater than the length scale of the robot, these configurations start to look more like attachment-free climbing – planting limbs onto patches of terrain that are above, and not below, the robot. For example, in Figure 1 (Left), the robot is using the top legs to pull itself up onto a high ledge.

III. Energy Storage

As with compressive loading, energy storage and return can lead to interesting behaviors with legs in extension. In either direction, one common way to store energy is to plant the distal end of the leg using contact normal or frictional forces while the kinetic energy of the system is stored as potential energy in the spring. In general this is easier to do with a leg in compression as the external ground reaction force will point in towards the robot's center of mass. In extension, the leg must be controlled so that it maintains frictional contact while the inertia of the body pulls the hip away from the toe. The behavior shown in Figure 1 (Center) applies a leg torque to maintain the ground contact while the forward kinetic energy of the system is stored in the leg spring and then returned as rotational energy flipping the robot over.

IV. Shape Change

If a passive spring leg were replaced by an active linear actuator, there would clearly be many new behaviors enabled by this additional controlled DOF. Directly extending a leg would make leaping into the air much easier. With passive compliance, planting or stubbing the toe so that the spring is extended will generate a similar novel robot twist. Doing so requires controlling the rest of the system to ensure the leg will be extended and then released, and as such may come with an energetic cost, but the possibility of moving in an otherwise unachievable direction is worth it in some situations. The robot in Figure 1 (Right) has jammed its rear toe into the ground to force the leg to extend, pushing it in a more vertical direction than a regular leap could achieve. This results in the leg extending by around 25% in length, a 40° different in hip velocity, and a resulting 2cm higher leap, at the cost of about 3% of the total system energy.

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