Energy efficient control of a 1D hopper through tunable damping

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Introduction

In this paper, we report on accurate and efficient deadbeat control of a serially-actuated vertical hopper platform. Our control approach is based on virtually tuning the damping coefficient of the elastic leg by controlling the ground reaction force through the position of the series actuator.

In previous work, we demonstrated on a simulated vertical hopper that modulating leg damping performs considerably better than changing leg stiffness during stance, a commonly used method for controlling energy for the Spring-Loaded Inverted Pendulum (SLIP) model [3]. In this context, our findings indicated that tuning the damping coefficient instead of the stiffness i) substantially reduces actuation power requirements, ii) achieves more than four-fold increase in positive actuator work, and iii) achieves more accurate and agile deadbeat control performance since it preserves the accuracy of analytic approximations to the passive SLIP dynamics during stance due to less aggressive actuator usage. In subsequent work, we have extended these controllers based on the virtual modulation of leg damping to planar hopping and proposed a hierarchical template/anchor framework to realize them on platforms with more complex dynamics [4].

In this paper, our focus is mainly on the experimental validation of our simulation results summarized above for damping-based deadbeat control of vertically constrained hopping. To this end, we conducted extensive experiments, yielding results that were in agreement with our simulation results. We have also extended our proposed control approach, maximizing performance by eliminating negative work altogether and achieving more effective embedding of SLIP dynamics.

Control of Platform

Our hopper platform consists of a vertically constrained mass, connected serially to a pair of helical linear springs through a ball screw actuated with a brushless DC motor as shown in Fig. 2. Kinematic and dynamic parameters of the platform were found through system identification experiments, yielding the spring rest length $l_0 = 0.2m$, unsprung distance of COM to the toe $r_0 = 0.375m$, the body mass $m_b = 3.81kg$, the actuator mass $m_a = 1.01kg$, the toe mass $m_t = 0.7kg$, the spring stiffness $k_p = 6200N/m$, radial damping coefficient of the leg $d_p = 3.75Ns/m$, and the vertical damping of the linear guide $d_f = 1.5Ns/m$.

As suggested in our earlier work [4], we consider an extended version of the SLIP model (SLIP+) shown in Fig. 2 as a template model for hopping. SLIP+ has three adjustable leg parameters, the spring constant k, the damping coefficient d and a constant force f in parallel with the spring. We model the control problem as a once-per-step selection of these parameters for SLIP+. This approach can be formalized as the single-step deadbeat control problem

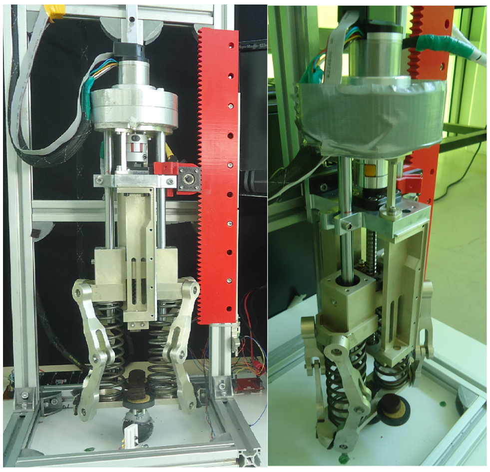

Figure 1: Vertically constrained hopper platform with series elastic actiation.

$$[k_i, d_i, f_i] = \underset{[k,d,f]}{\arg\min} ||z^* - P(z_k, k, d, f)||^2 ,$$

where z^* denotes the desired height of the hopper at the apex of a jump, and $P(z_k, k, d, f)$ denotes the apex Poincaré return map for SLIP+ consisting of the composition of flight and stance maps. Analytic approximations to this return map allow effective implementation of this controller [2]. We restrict $k = k_p$ for tunable damping control by following our previous approach. On the other hand, traditional variable stiffness control can be obtained by restricting $d = d_p$ and $f = 0$. After choosing virtual leg parameters, we map the desired template to the physical anchor, and realize its vector field on the Center-Of-Mass coordinates for the platform by controlling the position of the series elastic actuator to follow

$$u^* = \frac{m_b + m_a}{m_b} \left(\frac{d_p - d}{k_p} \dot{r} + \frac{k_p - k}{k_p} (r - r_0) - \frac{f}{k_p} \right) . \tag{1}$$

Unfortunately, traditional linear controllers cannot achieve this position control task with sufficient accuracy due to nonlinearities and low mechanical transparency of our actuator. To this end, we use a robust 2DOF controller based on [1], consisting of three components: a feedforward friction and spring force compensator, a disturbance observer based on velocity estimations, and a PD position feedback controller.

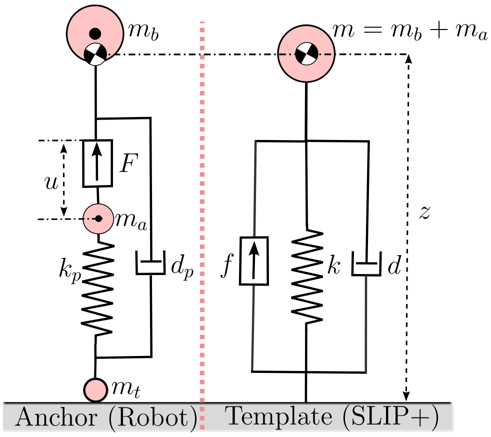

Figure 2: Series elastic actuator based 1D hopper platform.

Experimental Protocol

We performed comprehensive experiments to assess the single-step performance of our damping-based controller in comparison with a variable-stiffness control strategy. We measured the performance of each control strategy for 10 different initial conditions with $z(0) - r_0 \in [0.02, 0.14]m$, each followed by 20 different apex height difference commands with $z^* - z(0) \in [-0.1, +0.1]$. Each experiment was repeated three times to ensure the reliability of the dataset. Fig. 3 illustrates an example test run with the tunable damping controller, showing trajectories of actual robot (solid blue) and the desired template with $d = -94.6Ns/m$ and $f = 59.8N$.

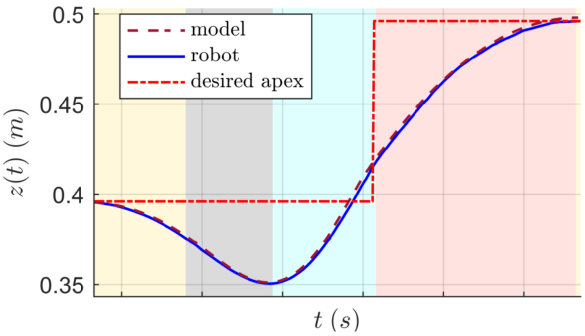

Figure 3: An example test run with $z(0) = 0.395m$, $z^* = 0.515m$. Plots show the desired apex height (dash-dotted red), actual robot (solid blue), and desired template (dashed brown) trajectories with the tunable damping controller. Yellow, grey, light blue, and pink areas correspond to descent, compression, decompression, and ascent phases, respectively.

Results and Discussion

Based on experimental data collected according to the protocol defined above, we compared tunable damping and stiffness controllers with respect to their single step accuracy and actuator power consumption.

First, we evaluate accuracy with a *percentage error* computed as $PE := \|z^* - z(t_a)\|/z^*$ where t_a denotes the time of apex reached at the end of the stride. For the power consumption, we consider both average and peak values during stance. Fig. 4 shows a comparison of these performance metrics as a function of different apex height differences. Tunable damping control has the best overall performance, confirming our previous results [3, 4]. Actuator commands for tunable damping has no discontinuities as opposed to the variable stiffness strategy that requires a step change at bottom. This is one of the main reasons behind the accuracy of the damping control strategy as shown in Fig. 3. In summary, our controller's accurate control capability with small actuation power is an indication of balanced coordination between active control and passive SLIP dynamics and accurate embedding performance.

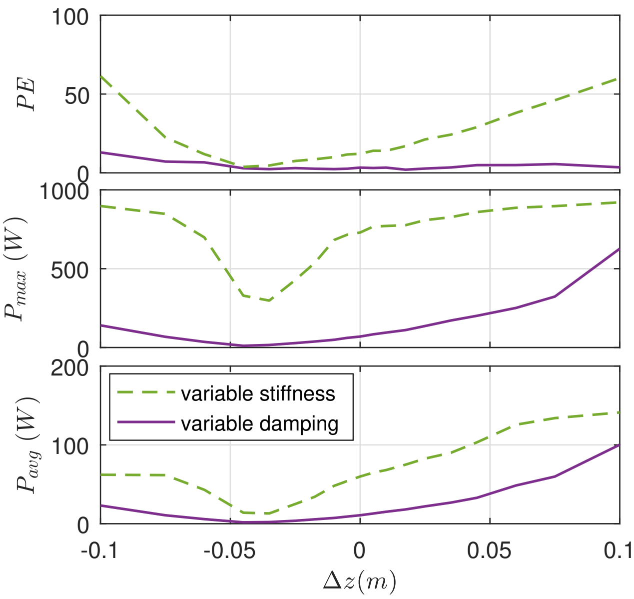

Figure 4: Dependence of percentage height tracking error (top) and average (middle) and peak (bottom) actuator power during stance on the commanded height difference for variable damping and variable stiffness controllers visualized with solid purple and dashed green lines.

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