Impulse Control for Planar Spring-Mass Running

Devin Koepl and Jonathan Hurst

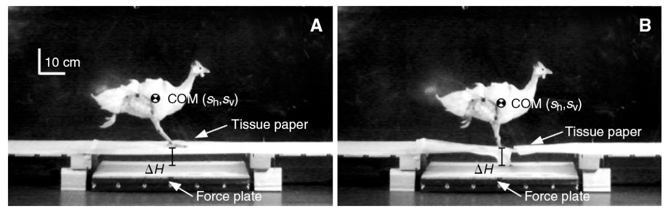
In this paper, we present a novel control strategy for running which is robust to disturbances, and makes excellent use of passive dynamics for energy economy. Our strategy combines two ideas: an existing flight phase policy, and a novel stance phase impulse control policy. The state-of-the-art flight phase policy commands a leg angle trajectory that results in a consistent horizontal center-of-mass velocity from hop to hop when running over uneven terrain, thus maintaining a steady gait and avoiding falls. Our novel stance phase control policy rejects ground disturbances by matching the actuated model's toe impulse profile to that of a passive spring-mass system hopping on flat rigid ground. This combined strategy is self-stable for changes in ground impedance or ground height, and thus does not require a ground model. Our strategy is promising for robotics applications, because there is a clear distinction between the passive dynamic behavior of the model and the active controller, it does not require sensing of the environment, and it is based on a sound theoretical background that is compatible with existing high-level controllers for ideal spring-mass models.

I. INTRODUCTION

We seek to approach the performance of animal running, shown in Fig. 1(a), with robots, such as that shown in Fig. 1(b) and Fig. 1(c) [2]. Existing robots, with behavior determined by the combination of software control and passive mechanism dynamics, are not capable of the combined energy economy and robustness to disturbances observed in animals. Existing running robots that focus on passive dynamics, such as the ARL Monopod II and the Bow Leg Hopper, are capable of energy economy similar to animals, but have demonstrated limited ability to handle disturbances, and to our knowledge, none has handled changes in ground impedance [3], [4]. Robots that rely primarily on active control, such as Boston Dynamics' "BigDog," can demonstrate impressive robustness to disturbances at the expense of energy economy [5]. In this paper, we present a bio-inspired control strategy for actuated spring-mass running robots that combines the robustness to disturbances of actively controlled machines with the energy economy of a passive dynamic walker.

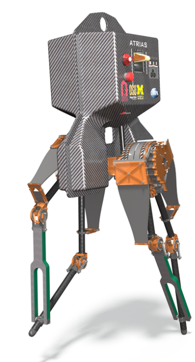
For the purposes of this paper, "running" is defined as the bouncing motion of a spring-mass system, shown in Fig. 2(b), where energy is transferred primarily between leg spring energy and gravitational potential energy. Spring-mass models are pervasive in biomechanics and in robotics literature, and provide a good approximation of animal running behaviors, including everything from Ghost crabs to horses to kangaroos to humans [6], [7], [8], [9], [10]. By basing this work on spring-mass models, we tie this work to the extensive biomechanics work using spring-mass models [11], [12], [13], [14], [15], the history of successful running spring-mass robots [16], [3], [4], and prior theoretical work [17], [18], [19]. The Spring-Loaded Inverted Pendulum, or SLIP model, is among the most widely-used theoretical models, consisting of a point mass connected to a massless spring leg, with no actuators, as shown in Figure 2(a); yet it is the basis for many proposed control methods and theories of animal running[20], [21]. The control methods presented here can be applied to any robot designed with the same proven principles of passive dynamics.

Our controller consists of two parts: First, an existing state-



(a) The guinea fowl is able to accommodate for the unexpected decrease in ground surface without a significant change to its steady-state center of mass motion; image used from Daley et al. [1].

(b) Single ATRIAS leg. Can be used independently as a planar monopod.

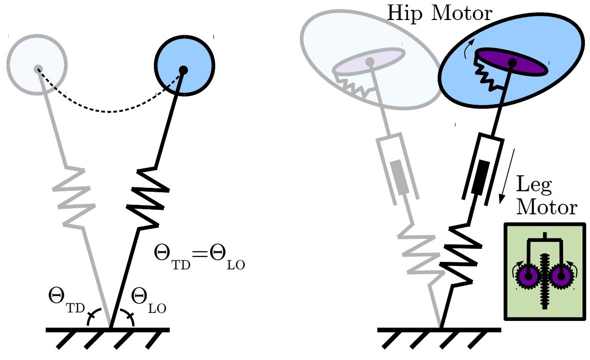


(c) 3-D bipedal ATRIAS.

Fig. 1. Our goal is to engineer control strategies that will allow legged robots to approach the energy economy and robustness of animal running.

This work was supported by the school of Mechanical, Industrial and Manufacturing Engineering at Oregon State University and the Defense Advanced Research Projects Agency. The authors can be contacted by email at:

koepld@onid.orst.edu



(a) SLIP+EGB model. (b) Impulse controlled model.

Fig. 2. Starting with the passive SLIP model, we add a body moment of inertia, and hip and leg motors for active control.

of-the-art flight phase control similar to that of Ernst, Geyer, and Blickan (which we refer to as the EGB method)[22], which specifies the leg angle in flight such that the model touches down with a center of mass trajectory that is symmetric about mid-stance. Symmetrical stance phases have mirror image touchdown and liftoff conditions, as shown in Fig. 2(a), where the velocity vector at liftoff has the same horizontal component as the velocity vector at touchdown and equal and opposite vertical component. Symmetrical stance phases lead to an equilibrium gait, because each stance phase is identical to the last if there are no outside disturbances. In other words, stabilization of an energetically conservative spring-mass model running gait on rigid but uneven ground can be achieved by existing methods.

The second part of our controller, and the primary contribution of this paper, addresses energy addition or subtraction for non-rigid ground surfaces, and control of the stance phase, working seamlessly with the EGB or other method for flight phase leg angle control. Briefly, the leg length actuator is controlled during stance to maintain the robot's center-of-mass impulse as a function of time, regardless of disturbances. Thus, even when running on ground of varying impedance, the behavior of the center of mass is unchanged from running over rigid ground surfaces, within limitations imposed by motor dynamics and other passive dynamics.

We show in simulation that, even with realistic actuator limitations, our combined flight and stance phase controllers enable the spring-mass runner to reject disturbances to ground height and dynamics, while maintaining the energy economy of the passive spring-mass model on flat rigid ground.

A. ATRIAS

The work in this paper is primarily math and simulation, illustrating a set of ideas for control of running gaits on real machines. It has been said that "A simulation is doomed to succeed." In other words, it is possible to show many things in simulation that are not possible in realistic systems. However, the methods described in this paper are intended for real machines which are based on spring-mass models for running, and the simulation results are not an end in themselves, but a tool on the path to demonstration. As such, we seek to capture the relevant dynamics accurately, and the simulations are linked to a physically realistic set of numbers for parameters of the bipedal robot ATRIAS, currently under construction. Parameters such as leg mass, body mass, and motor torques, which limit the acceleration and bandwidth of the actuators are shown in Table I. Although the simulation shows the controller on one example set of parameters, the ideas are general and can be applied to a wide range of spring-mass running machines.

Conversely, ATRIAS is explicitly being designed to match a convenient spring-mass model. This is an important concept for highly dynamic robot design: concurrent design of machine dynamics and machine control, as an integrated system. Figure 3 shows the basic spring-mass model as compared to the mechanical design of ATRIAS. The robot has most of the mass concentrated at the hip, legs of lightweight carbon fiber for negligible leg mass, large fiberglass springs to implement the leg stiffness, and very precise sensing to allow for nearly continuous state information.

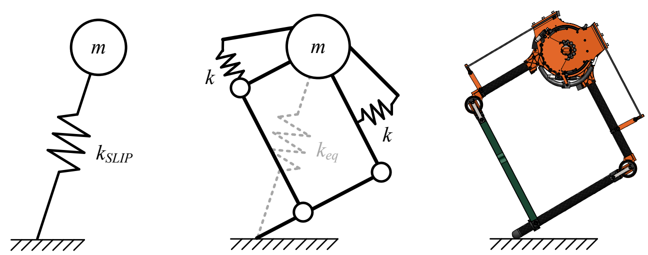


Fig. 3. The spring-mass model behavior is implemented on ATRIAS via a 4-bar linkage. This concentrates the center of mass at the hip and enables very light weight legs. Leg compliance is implemented with fiberglass plate springs.

II. BACKGROUND

The simple spring-mass model with a fixed touchdown leg angle is capable of some passive stability, but with any sizable disturbance it tends to become unstable and fall, as shown in Fig. 4(a) [23]. Adding a simple leg angle controller based on tuples of natural frequency, zero-force leg length, apex hop height, and horizontal velocity may yield stable hopping gaits. Existing methods for selecting leg touchdown angles have included hand-tuned gain based controllers and constant leg retraction velocity control [24]. However, these methods require tuning, and are subject to controller optimality.

A more principled method of selecting a leg touchdown angle for SLIP model running, the previously-mentioned EGB method, controls leg angle during flight to ensure a stance-phase center of mass trajectory that is symmetrical about mid-stance, as shown in Fig. 4(b) [22]. This control method prevents falls when hopping or running over uneven terrain, because the leg angle throughout the flight phase is continually updated to the appropriate angle for touchdown into a symmetrical stance phase at the current velocity of the hopper. However, the EGB method assumes that the ground is rigid, so the leg touchdown angle it chooses may not result in an equilibrium gait on non-rigid ground, and can even result in falls, as shown in Fig. 4(c). Furthermore, it does not maintain a consistent center of mass trajectory or toe force profile in the presence of changes in ground surface height, as shown in Fig. 4(b).

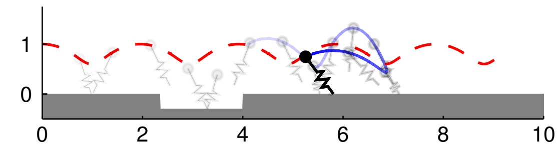
On the SLIP model, the EGB method of setting the leg touchdown angle results in an energetically conservative gait, and all of the work required to make the model hop is passively recycled by the model's leg spring. Setting the leg touchdown angle for a SLIP model does not require any work or a controller, because the SLIP model uses a massless leg. The EGB method must be adapted for use on model-inspired realistic systems with physical limitations. Although these systems may not be capable of energetically conservative gaits, they can still optimize their energy economy by making excellent use of their passive dynamics.

Springs clearly help running gaits by storing and releasing energy, but they are also useful for force control, which can improve the robustness of running gaits. The MIT Series Elastic Actuator (SEA) measures and controls the deflection of its spring, which corresponds to the force applied by the actuator [25]. As an added benefit, the series spring filters impulsive forces, improving the SEA's robustness to shock loads [26]. The performance of force-controlled actuators, such as the SEA, has been explored, and some task-specific criteria for selecting actuator dynamics have been identified, but these investigations are not generally extended to robot walking and running [27]. However, force control using the deflection of series springs has been successfully implemented on legged robots such as Boston Dynamics's walking and running quadruped, "BigDog", and the MIT Leg Lab's walking biped, "Spring Flamingo" [28], [29]. These robots use springs in much the same way as the SEA, as a force sensor and mechanical filter, but not for energy storage. Force control makes these robots robust to disturbances, but at the cost of high energy consumption.

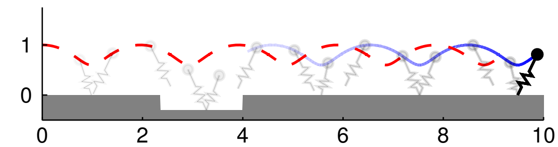
Humans and animals make excellent use of passive dynamics, but also use active control to compensate for disturbances. For example, guinea fowl are able to accommodate a drop in ground height by rapidly extending their leg into an unexpected disturbance, as shown in Fig. 1(a), resulting in only slight deviation from their undisturbed gait [1]. Furthermore, biomechanics studies suggest that humans and animals adjust their leg stiffness during hopping, walking, and running to accommodate changes in ground stiffness and speed [30]. These types of active responses to ground disturbances are important on physical systems, where deviations from the undisturbed gait can lead to a loss of stability, falls, or springs exceeding their maximum deflection, potentially causing damage. For example, galloping horses are already near peak force on tendons and bones, so remaining below force limits is an important consideration, or small ground disturbances could result in injury or damage [31].

In previous publications we showed how simple PD force control can make the vertically hopping actuated spring-mass model and planar actuated spring-mass models robust to changes in ground height and ground stiffness [32], [33]. In these works, we attempted to match the toe force profiles of our force controlled models to those of equivalent passive spring mass models hopping on flat rigid ground. As a result of maintaining a consistent toe force profile, our control strategy adjusts its leg length during flight in response to changes in ground surface height. During undisturbed hopping the motors in our models do zero work on their environment, and all of their behavior is generated by the passive dynamics of their leg springs.

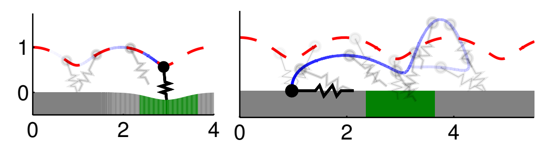
Our force control strategy provides a simple control policy for robot running that reproduces key characteristics of human and animal running without attempting to match them directly, which makes our approach fundamentally different from other works that seek to duplicate experiments in biology without concern for the underlying control policies. For example, the Musculoskeletal Athlete Robot has demonstrated a 3-D running gait by matching muscle activation and kinetic data gathered from human experiments [34]. This work is exciting for several reasons; it shows the potential to build machines with significant dynamic similarity to humans, and for human generated control signals to be captured and adapted for use on a dynamic mechanical



(a) The passive SLIP model falls after encountering a pothole.



(b) The SLIP model with EGB control successfully maintains an equilibrium gait through an encounter with a pothole.



(c) The SLIP model with EGB control falls after encountering a decrease in ground stiffness.

Fig. 4. The EGB control method is the current state-of-the-art for SLIP model control. It prevents falls when hopping over uneven terrain, but relies on a rigid ground assumption, and can fall after encountering a change in ground impedance.

system. However, this type of work does not provide insight into the underlying control laws that humans and animals use to generate muscle activation commands.

The control policies used by running humans and animals are unknown, but force control produces results that resemble disturbance rejection observed in animals [33]. Biomechanics studies have shown that humans and animals accommodate changes in ground stiffness through a concerted effort of muscles, tendons and ligaments during hopping, walking and running [30]. One hypothesis is that humans and animals adjust their leg stiffness, such that the equivalent stiffness of the series combination of the ground and leg spring is the same for all surfaces [14]. Based on this idea, a number of actuation systems have been devised to vary leg compliance, including the Actuator with Mechanically Adjustable Series Compliance (AMASC) and the MACCEPPA actuator [35], [36]. These devices pre-tension springs to increase their leg's apparent stiffness, but were never successfully implemented on a running robot. We showed that force control produces an equivalent result without directly controlling the leg stiffness. Furthermore, animals accommodate for changes in ground surface height by adjusting their leg length during flight, as shown in Fig. 1(a). We showed that by attempting to maintain the toe force profile of a passive model hopping on flat rigid ground that we could produce a similar result without engineering a specific leg length control strategy.

Force control alone cannot maintain a consistent center of mass trajectory in the presence of ground disturbances when actuator limitations are included. Actuator limitations make errors in the toe force profile unavoidable, because they limit the acceleration of the zero force leg length. For example, when our force controlled model encountered an unexpected decrease in ground height, there was a limit on how quickly it could extend its leg, and then when ground contact did occur, additional time was needed to decelerate the leg motor [32]. Planar hopping added more complexity to the problem, because it became important to simultaneously control both the hip and leg spring forces, and small errors in the force profile began affecting the forward velocity as well as the hopping height [33].

III. MODEL

Starting with the simple spring-mass model, shown in Fig. 2(a), we add hip and leg actuation as well as body moment of inertia to arrive at a model for robot running that incorporates the most significant dynamics of a spring-leg robot, as shown in Fig. 2(b). The parameters are derived from the ATRIAS single-leg design, and shown in Table I. Our actuators include a motor with a torque limit and rotor inertia. By controlling the deflection in their series springs, the actuators are able to control the rate of change of the toe impulse profile. We chose to omit leg mass from our model, to keep the system as simple as possible. For ATRIAS, shown in Figures 1(b) and 1(c), our eventual target robot for this control method, leg mass composes less than one percent of total robot mass. The leg actuator makes use of the existing leg spring, while we add a second rotational spring to the model for the hip actuator. The hip actuator sets the leg angle during flight and maintains zero moment about the hip during stance, such that the force-controlled model behaves like the passive model during undisturbed hopping.

Selected ATRIAS single-leg Specifications	
Leg Length	1m
Mass	24kg
Actuators	Brushless Frameless motors
Transmission	50:1 Harmonic Drive
Peak Torque	302Nm
Reflected Motor Inertia	$1kgm^2$
Body Moment of Inertia	$1kgm^2$
Leg Stiffness	3000N/m
Hip Stiffness	500Nm/rad
Leg Mass	Negligible compared to rotor inertia

TABLE I

PHYSICALLY REALISTIC SPECIFICATIONS USED IN THE SPRING-MASS SIMULATIONS. OTHER PARAMETERS SHOWED SIMILAR RESULTS FOR THE FUNDAMENTAL CONTROL IDEAS.

IV. CONTROL STRATEGY

Our control strategy uses separate flight and stance phase controllers, which are shown in Fig. 5(a) and Fig. 5(b).

A. Flight Phase Control Strategy

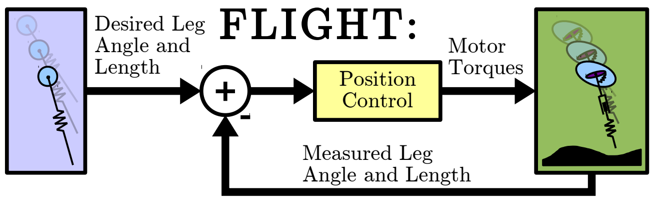
During flight, we control the leg angle in a manner similar to the EGB method, such that the model touches down in an equilibrium gait regardless of when the toe contacts the ground. It has been proven that there is no closed form solution for SLIP model running, so we use a numerical approximation along with a gradient descent algorithm to generate a lookup table for the equilibrium gait leg angle [37]. By providing continuous state information to our leg touchdown angle lookup table during flight, our controller numerically estimates a leg angle trajectory that will ensure an equilibrium gait. Because there is some stance phase control that can change leg length, our flight leg angle controller must also consider the zero-force leg length as an input to our leg angle lookup table; this is a difference from the EGB method.

Our control strategy references the target passive model hopping on flat rigid ground, and uses it to make decisions about how to actuate the motors on our actuated model. While our controller expects to be in flight, it regulates the actuated model's toe impulse, and at the instant our controller expects ground contact, it switches to the stance phase control strategy.

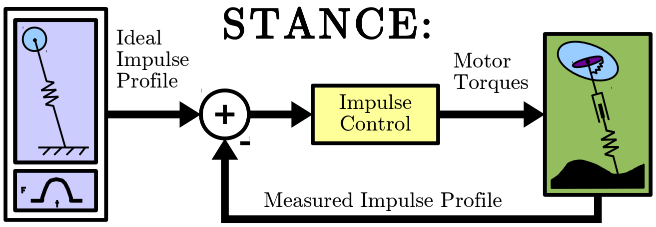
B. Stance Phase Control Strategy

In stance, the motor controls the impulse applied on the ground by the leg, at each instant of time, to match the leg impulse profile of the passive undisturbed SLIP model. The impulse $I(t)$ is defined as:

$$I(t) = \int_0^t F_L(s)\mathrm{d}s$$



(a) The EGB method defines a desired leg angle trajectory during flight, which can be implemented on with actuators using standard control methods.



(b) Our novel idea is a stance phase control strategy that controls the toe impulse to reject disturbances. During stance our control strategy matches the toe impulse profile of the active model to that of the passive model hopping on flat rigid ground.

Fig. 5. Our approach switches between flight and stance controllers according to when it expects to be in contact with the ground. Because it always expects flat ground, the runner will switch to stance phase control before touching the ground when there is a step down. As a result, the leg will extend into the hole in the ground as it attempts to apply the desired force.

where time $t = 0$ is the beginning of stance, and t progresses through to the end of a single stance phase. This control is implemented through a concerted effort of the hip and leg motors. The leg motor controls the radial toe impulse, and the hip motor controls the tangential toe impulse. By tracking the target impulse profile, our controller also maintains the desired toe force profile. Controlling the impulse is analogous in many ways to using an integral controller on the toe force; any errors at the beginning of stance are compensated later. Therefore, the leg motor torque, τ_L, is obtained as follows:

$$\tau_L = \frac{r_L \cdot F_L^d(t)}{G_L} + \bar{K}_S \cdot \bar{F}_L + \bar{K}_E \cdot \left(\bar{F}_L^d(t) - \bar{F}_L\right),$$

where r_L is the transmission output radius, G_L is the gear ratio, and F_L^d is the desired leg force derived from the undisturbed SLIP model behavior. The vector $\bar{F}_L$ is constituted of the impulse, force and derivative of the force:

$$\bar{F}_L = \begin{bmatrix} \int F_L(t)\,\mathrm{d}t \\ F_L(t) \\ \frac{d}{dt}F_L(t) \end{bmatrix}.$$

The state and gain matrices $\bar{K}_S$ and $\bar{K}_E$ are defined by the following equations:

$$\bar{K}_S = \begin{bmatrix} K_{SI} & K_{SP} & K_{SD} \end{bmatrix}$$

and

$$\bar{K}_E = \begin{bmatrix} K_{EI} & K_{EP} & K_{ED} \end{bmatrix}.$$

The entries in the above matrices are the integral, proportional and derivative gains of $\bar{K}_S$ and $\bar{K}_E$.

The hip actuator approximates an ideal hinge by regulating its impulse to zero, such that the impulse-controlled model behaves like a SLIP model in stance with a point-mass body. When hip forces do occur, our impulse control strategy corrects for them by commanding equal and opposite forces that return the hip impulse to zero. Although our model's hip joint may not behave like an ideal hinge at every instant during stance, it is able to maintain the desired net impulse, such that over the course of a stance phase it closely approximates the desired behavior.

V. Control Laws

The robot model's flight phase dynamics are a ballistic trajectory, and thus are linear and time invariant. During flight, the hip and leg dynamics are independent from one another, allowing the use of disparate control laws for the hip and leg motors. The leg angle was controlled to follow the equilibrium gait leg angle trajectory, while the leg length motor was controlled to follow a trajectory that simply reset its length from the previous step, and then held a position.

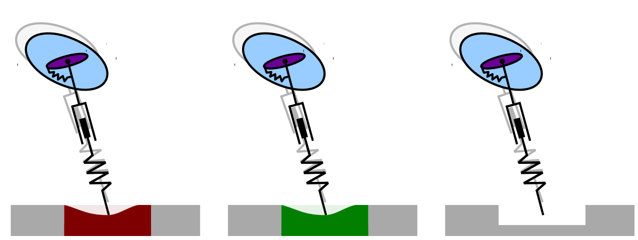
During stance, we controlled either our robot model's toe force or impulse profile by using output tracking controllers that referenced the toe force profile of the passive spring-mass model hopping on flat rigid ground.

Following a desired trajectory can be done many ways, and our methods (drawn from textbooks such as page 238 of [38]) merely worked well enough to implement the flight phase and stand phase control strategies that are the primary contribution of this paper. Other controllers could achieve similar results; the specific parameters of the model will determine the best control laws.

VI. Simulation Results

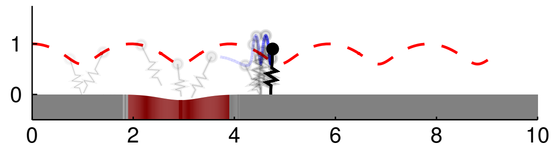
We subject the SLIP+EGB and our impulse controlled model to changes in ground damping, stiffness, and surface height, and expect that our impulse controlled model will be able to better reject these unexpected disturbances. Neither model is able to sense the ground dynamics or adjust for them in any way, but our impulse controlled model should attenuate them within a single stance phase by matching its toe impulse profile to that of the passive SLIP model hopping on flat rigid ground.

We use kinetic equations of motion, solved numerically, to simulate the SLIP+EGB and our impulse controlled models hopping in the vertical plane.

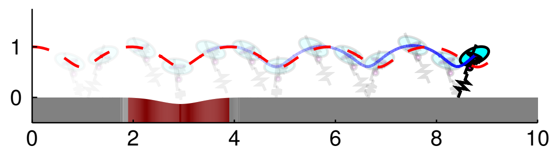


(a) Ground damping disturbance. (b) Ground stiffness disturbance. (c) Ground surface height disturbance.

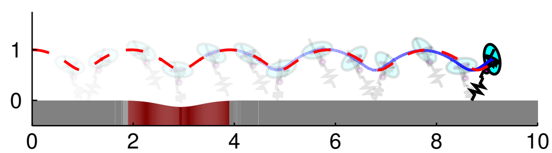
Fig. 6. We subject our force controlled model to ground disturbances in simulation.



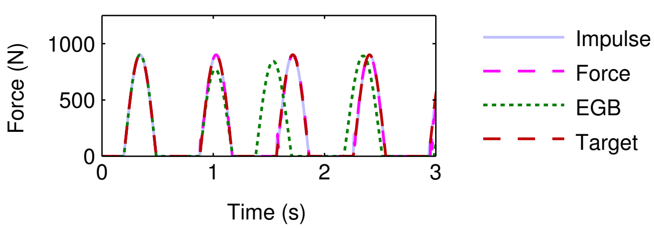
(a) The SLIP+EGB model is greatly disturbed by the unexpected damped ground.



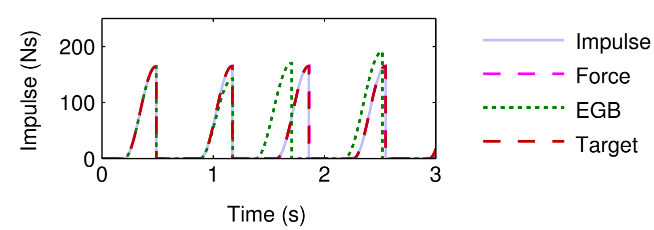
(b) Force control accomodates the damped ground, but the center of mass trajectory is affected.



(c) Impulse control rejects the damped ground, and maintains a consistent center of mass trajectory.



(d) Force and impulse control maintain the target force profile.



(e) Our impulse controlled model maintains a consistent toe impulse profile.

Fig. 7. Force control can accommodate the decrease in ground damping, but errors in the force profile, caused by actuator limitations, accumulate disturbing its center of mass trajectory. Our impulse controlled model corrects for errors in the force profile.

A. Ground Damping Disturbance

The first type of ground disturbance that we investigate is a decrease in ground damping, shown in Fig. 6(a). In this experiment, the ground unexpectedly changes from being rigid (i.e. no deflection under any force) during the first stance phase to behaving like a viscous damper in all directions for the second stance phase. For all ground disturbances, we assumed zero toe-slip upon contact with the ground. The change in ground damping can be described in Cartesian coordinates as follows, where $\odot$ denotes element-wise vector multiplication:

$$\bar{F}_{gnd} = -\bar{b}_{gnd} \odot \bar{v}_{toe}$$

where

$$\bar{b}_{gnd} = \langle 1250, 1250 \rangle \frac{N \cdot sec}{m}.$$

Damped ground dissipates a portion of the system energy during stance, which must be re-added by active controllers in order to maintain a consistent gait and prevent falls.

The SLIP+EGB model prevents a fall in the damped ground experiment that we present in this paper by setting its leg touchdown angle as close to the equilibrium gait angle as possible, as shown in Fig. 7(a). However, the SLIP+EGB model has no mechanism to re-add energy dissipated by the ground dynamics, and its center of mass trajectory, toe force, and impulse profiles are greatly affected by the unexpected disturbance, as shown in Fig. 7(d) and 7(e). Ground damping removes enough energy that the SLIP+EGB model stops moving forward, and just barely hops in place without achieving liftoff. The ground damping disturbance dissipates so much of the EGB+SLIP model's vertical energy that an equilibrium gait leg touchdown angle is not possible for the flight phase following the disturbance, and the SLIP+EGB model must just choose the leg touchdown angle closest to the desired equilibrium gait leg touchdown angle.

Force control alone can accommodate ground disturbances by maintaining a toe force profile. However, toe force errors arise from actuator limitations and can accumulate, causing an inconsistent center of mass trajectory, as shown in Fig. 7(b).

Our impulse control strategy corrects for unavoidable errors in the toe force profile, and maintains a consistent center of mass trajectory, as shown in Fig. 7(c). Energy dissipated by the ground dynamics is continuously re-added to the system by our active control strategy as the impulse controlled model hops forward. Although our impulse controlled model does not sense or attempt to control the system energy, it maintains a constant system energy by maintaining the toe force and impulse profiles of the target passive system, as shown in Fig. 7(d) and 7(e).

B. Ground Stiffness Disturbance

The second type of ground disturbance we investigate is a decrease in ground stiffness, shown in Fig. 6(b). In this experiment the ground unexpectedly changes from being rigid during the first stance phase to behaving like a linear spring in all directions for the second stance phase. As for all ground disturbances, we assume no toe slip, and the change in ground stiffness can be describes as follows:

$$\bar{F}_{gnd} = \bar{k}_{gnd} \odot (\bar{x}_{toe} - \bar{x}_{TD}) - \bar{b}_{gnd} \odot \bar{v}_{toe}$$

where

$$\bar{k}_{gnd} = \langle 3000, 3000 \rangle \, \frac{N}{m}$$

and

$$\bar{b}_{gnd} = \langle 10, 10 \rangle \, \frac{N \cdot sec}{m}.$$

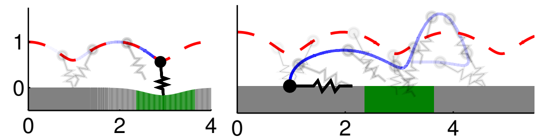
As a model touches down, the ground depresses proportionately to the model's toe force. The net result is that the model experiences a leg spring stiffness equal to the series combination of its leg spring with the ground spring, and the hip stiffness is similarly affected.

For the SLIP+EGB model, variations in ground stiffness lead to immediate falls or, at best, a large change in center of mass trajectory and toe force profile, as shown in Fig. 8(a). When the SLIP+EGB model touches down on a springy surface, it experiences a decreased apparent leg stiffness, and its leg touchdown angle, which would have produced an equilibrium gait on rigid ground, is too steep for the decrease in stiffness. The SLIP+EGB model can avoid falls due to ground stiffness perturbations by continuously adjusting its leg touchdown angle to compensate for the higher horizontal velocity and lower hopping height that result from the disturbance. However, the SLIP+EGB model will fall if a disturbance is severe enough that liftoff does not occur or an equilibrium gait touchdown angle cannot be found, such as the example in Fig. 8(a).

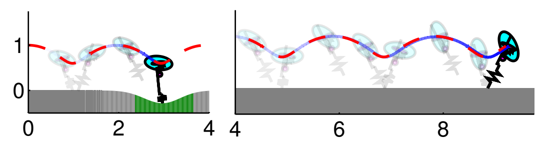
Our impulse controlled model is able to correct for the decrease in its apparent leg stiffness without directly controlling it, by matching its toe impulse profile to that of the passive model hopping on flat rigid ground, as shown in Fig. 8(b). Our impulse controlled model closely follows the desired toe force and impulse profiles, as shown in Fig. 8(c) and 8(d), but small errors in the toe force profile at touchdown are unavoidable. Although our impulse controlled model does not directly adjust its leg stiffness or even sense changes in ground stiffness, measurements of force and position are indistinguishable from changes in stiffness, raising the possibility that animals may use force control rather than direct stiffness changes as well [39].

C. Ground Height Disturbance

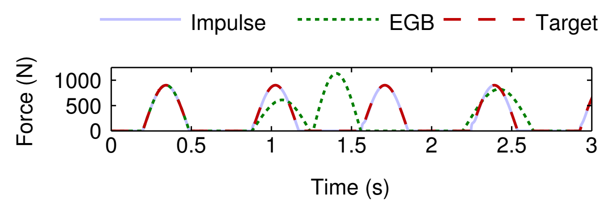
The final type of ground disturbance we investigate is a decrease in ground surface height, shown in Fig. 6(c). In this experiment the ground surface height unexpectedly decreases before the second stance phase. There are no "sensors" that allow the SLIP+EGB or our impulse controlled models to change their control strategy, and they have no forewarning of the change in ground height, like an unexpected step down in a sidewalk. After their first hop on the flat rigid surface, the SLIP+EGB and our impulse controlled models take their second hop onto the lower ground surface, and the ground surface then returns to its original height for subsequent hops.



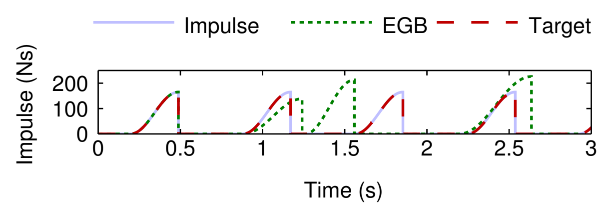
(a) A decrease in ground stiffness causes the SLIP+EGB to fall.



(b) The impulse controlled model accommodates a decrease in ground stiffness.



(c) The toe force of the passive model exceeds the target peak force, but the impulse controlled model limits its peak force appropriately.

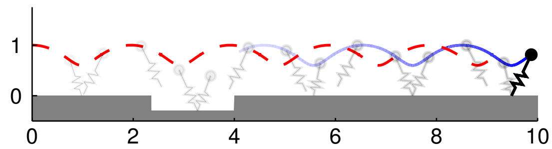


(d) The impulse controlled model maintains the target toe impulse profile.

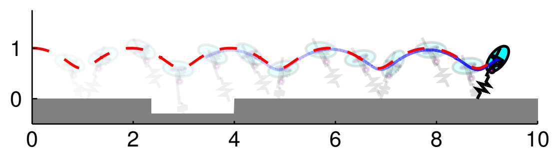
Fig. 8. The impulse controlled model is able to reject unexpected changes in ground stiffness by matching its toe impulse profile to that of the target passive system.

The SLIP+EGB model prevents falls in the presence of changes in ground surface height, as shown in Fig. 9(a), but its center of mass trajectory and toe force profile are permanently affected by these types of disturbances. When the SLIP+EGB model encounters a decrease in ground surface height, it remains in flight for longer and touches down later than it would have on flat ground. This delayed instant of ground contact causes a shift in the center of mass trajectory, which the SLIP+EGB model has no mechanism to correct. In addition to remaining in free-fall for longer, the SLIP+EGB touches down with greater velocity on the decreased ground surface and its toe force profile exceeds that of the passive model hopping on flat rigid ground, as shown in Fig. 9(c).

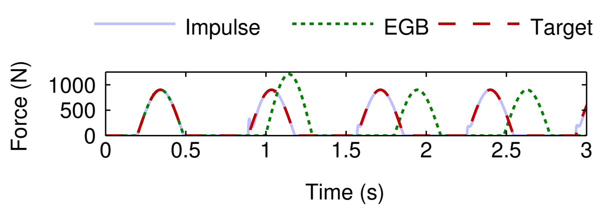
Our impulse controlled model extends its leg during flight



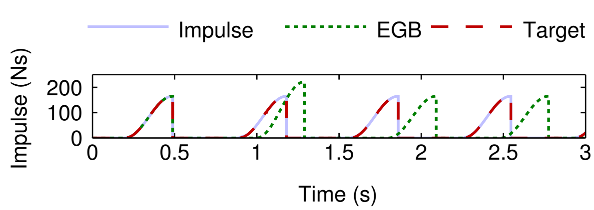
(a) The SLIP+EGB accomodates a decrease in ground surface height, but its center of mass trajectory is affected.



(b) The impulse controlled model rejects a decrease in ground surface height.



(c) The toe force of the passive model exceeds the target peak force, but the impulse controlled model limits its peak force appropriately.



(d) The impulse controlled model maintains the desired toe impulse profile.

Fig. 9. The impulse controlled model is able to reject unexpected changes in ground surface height by matching its toe impulse profile to that of the target passive system.

as a result of attempting to achieve a toe impulse profile, and is able to reject the ground height disturbance, as shown in Fig. 9(b). At the instant of expected ground contact our impulse controlled model begins commanding the toe impulse profile of the target passive model. For a decrease in ground surface height, ground contact does not occur at the expected instant, and so our model rapidly extends its leg into the unexpected disturbance until it is able to begin tracking the desired toe impulse profile. The result is a small phase shift in the center of mass trajectory and toe force profile, as shown in Fig. 9(c), that arises from actuator limitations. Our impulse control strategy corrects for the errors that arise from actuator limitations by maintaining the target toe impulse profile, as shown in Fig. 9(d).

VII. DISCUSSION

The flight and stance phase control policies in this paper are effective at dealing with disturbances to the system imposed by realistic limitations such as motor inertia, leg mass, and torque limits that other spring-mass control methods are not. However, they would have no advantage over many other strategies when implemented on an ideal actuated model, with no actuator limitations, in a simulated world with all information known ahead of time. To demonstrate this robustness to realistic passive dynamics, we chose carefully which realistic parameters to model and which to ignore for the sake of computational simplicity; based on our experience with ATRIAS, for example, it is clear that motor inertia and torque limits are major effects. However, our simplified model did not include leg mass, in part because the motor inertia on ATRIAS is significantly higher than the leg mass, and thus dominates the effect on performance. Adding leg mass to the simulation model would primarily result in some additional energy loss upon toe touchdown at the end of each flight phase - however, this would be addressed as a disturbance, much as if the robot landed on damped ground. The impulse controller would regulate the desired impulse, and the center of mass motion would be much as if the robot were an ideal, undisturbed SLIP model; to an outside observer, it would appear as if the robot calculated the energy lost to collision and added it back in through active control of its motors.

In this paper, we do not address body pitch control, which is a significant challenge for 3D locomotion. As the leg swings forward during the flight phase of running, any leg mass or reflected rotor inertia will cause a reaction torque, and the body will pitch backwards. The issue can be addressed many ways; the most obvious is to correct for body pitch errors during stance, when forces may be applied to the ground. Our impedance controller applies forces only in the leg length direction, and thus will not interfere with an additional controller used to apply hip torques and control body pitch during stance. For simple monopod robots, the problem has been minimized in the past by adding body inertia via weights at the end of a long beam attached horizontally to the torso, reducing the effect of the leg inertia [4], [3], [40]. Body pitch has also been controlled via reaction torques from a tail moving equal and opposite directions to the leg, much like that of a kangaroo [41]. For multi-legged machines or animals, the swing legs can move at an equal and opposite speed to the stance leg, thereby canceling the inertial effects and avoiding any effect on the pitch of the body. If these solutions do not completely control the body pitch in a single stride, the gait can still remain stable if the leg angle is calculated relative to the ground rather than relative to the body. Finally, it should be stated that different actuators on a real machine may have very different properties; for example, a hydraulic actuator such as that used on Big Dog [42] will have sufficiently low inertia to be considered negligible.

In evaluating the significance of this work, it is difficult to compare "performance" of the impulse control strategy described in this paper as compared to other control methods, because there is no agreed-upon metric for performance in legged locomotion. However, we can compare to controllers that manage the energy level in spring-mass running, such as the control methods described in Marc Raibert's book, and a feed-forward position trajectory by Clarke and Schmitt [16], [43]. Both of these controllers stabilize the gait over several steps, rather than regulating a ground reaction force and impulse profile during a single stance phase. The Raibert controllers begin with a regular impulse applied at mid-stance, imparted by venting a compressed air cylinder. If the apex height is higher than desired, the pressure (and resulting impulse) is reduced for the subsequent step; if the apex height is not sufficiently high, the pressure in increased. A simple proportional term relates the height to the pressure/impulse. The Clark and Schmitt controller does not measure the apex height or much of anything; instead, it relies on a clock-driven feed-forward leg length position control, in series with the leg spring. They showed mathematically that this will stabilize the hopping height, and then demonstrated on a simple planar spring-mass robot. The impulse control described in this paper is able to handle changes in ground impedance sufficiently well that the flight phase controllers may assume hard ground at all times; this is a significant departure from the state-of-the-art for robots, and even describes many observed animal behaviors such as changing leg "stiffness" on different surfaces.

The ground models used in this simulation were relatively simple, implementing only a linear damping and a linear stiffness. Clearly, real-world dynamics do not match these linear models. However, the impulse control method does not rely on any particular model, and was able to handle a damped ground and a springy ground equally well, even with no prior information about the type of ground it would encounter. This suggests, and it is our belief, that any real-world ground impedance changes would be well handled by this impedance control approach, including sand, grass, pavement, or mud.

VIII. CONCLUSIONS AND FUTURE WORK

We have shown in simulation that impulse control combined with careful control of the leg touchdown angle yields self-stable spring-mass locomotion with no look-ahead sensing. By self-stable, we mean there is good disturbance rejection, while requiring only state information of the runner, and no information about the terrain. In addition, our impulse control strategy maintains the passive dynamics of the equivalent spring-mass system, and intervenes only to accommodate disturbances. This strategy combines the robustness to disturbances of active control, while maintaining most of the energy economy of a completely passive system.

Our impulse control strategy extends and improves the force control strategy for a vertically hopping single actuator spring-mass system that we presented in our previous work [33]. Impulse control follows the desired force profile in the absence of disturbances, but in the presence of disturbances from external or internal sources such as modeling inaccuracy, regulates the accumulated forces over time (impulse) to follow a desired trajectory. Aspects of the gait behavior such as center-of-mass position trajectory will show significant errors resulting from accumulated force errors; if the force is slightly too low during the entire stance phase, the hopper may lift off in a significantly lower trajectory. The impulse controller is able to regulate the center of mass motion more effectively, guaranteeing liftoff in the appropriate speed and direction.

Our impulse control strategy shows promise for hopping in real world environments that include a variety of unexpected ground disturbances. To demonstrate the robustness of our impulse control strategy, we subjected our impulse controlled model to a rugged environment with uneven terrain and changes in ground dynamics, as shown in Fig. 10. Despite these disturbances, our impulse controlled model is able to simultaneously maintain a consistent center of mass trajectory and toe force profile, which can be important considerations for preventing falls and damage on a physical system. For example, race horses break their legs during a race more often than people would prefer; and in the 2012 Olympics, U.S. runner Manteo Mitchell broke his leg during the course of a relay race. If animals can be injured when running on flat ground, it seems clear that limiting peak forces on disturbances so they do not exceed the forces seen on flat ground is an important consideration.

The long-term goal of this work is to build a model and bio-inspired biped capable of robust walking and running gaits. Although we are not attempting to mimic the exact behaviors observed in biomechanics studies, and the control policies used by humans and animals to accommodate disturbances are unknown, our impulse control strategy rejects changes in ground stiffness and damping in a way that resembles disturbance rejection observed in human and animal studies [44], [45]. Furthermore, our impulse controlled model adjusts its leg length in response to changes in ground surface height, similar to how guinea fowl accommodate for an unexpected decrease in ground surface height [1].

We are now working to demonstrate this concept of adding impulse control to the spring-mass model on physical systems, including a single degree of freedom benchtop actuator, a two degree of freedom monopod, and eventually on a tether-free biped, as shown in Fig. 1(c). ATRIAS will maintain as much of the energy economy of the equivalent passive system as possible by making excellent use of its passive dynamics, while exhibiting strong self-stability in unknown terrain. We hope to approach the performance of animal walking and running with robots and controllers founded in strong concepts, so our success can be replicated on future machines.

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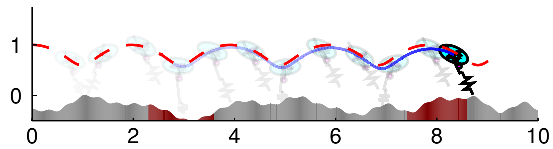

Fig. 10. Our impulse controlled model can reject disturbances in even the most rugged of environments.

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