AN ABSTRACT OF THE THESIS OF

Devin N. Koepl for the degree of Master of Science in Mechanical Engineering presented on December 2, 2011.

Title: Force and Impulse Control for Spring-Mass Running

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Jonathan W. Hurst

We present a novel control strategy for running which is robust to disturbances, and makes excellent use of passive dynamics for energy economy. The motivation for our control strategy is based on observations of animals, which are able to economically walk and run over varying terrain and ground dynamics. It is well-known that steady-state animal running can be approximated by spring-mass models, but these passive dynamic models describe only steady-state running and are sensitive to disturbances that animals can accommodate. While animals rely on their passive dynamics for energy economy, they also incorporate active control for disturbance rejection. The same approach can be used for spring-mass walking and running, but an active controller is needed that interferes minimally with the passive dynamics of the system. We demonstrate, in simulation, how force or impulse control combined with a leg spring stiffness tuned for the desired hopping frequency provides robustness to disturbances on a model for robot

hopping, while maintaining the energy economy of a completely passive system during steady-state operation. 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.

Force and Impulse Control for Spring-Mass Running

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Devin N. Koepl, Author

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Chapter 1 – Introduction

We propose a novel concept of adding force control to a spring-mass model for excellent energy economy and robustness to disturbances. Because existing force control actuators are schematically similar to the spring-mass model, it is easy to combine the two on a real system, and effective. We show, in simulation, that our force control strategy improves the disturbance rejection of the spring-mass model, while still maintaining most of the energy economy of the completely passive system.

Walking and Running robots, in general, have significant ground to cover before they can approach the abilities of animals. For robots to approach the performance of animal walking and running, they must be able to attenuate significant disturbances, while maintaining excellent energy economy. Existing passive walkers are capable of energy economy similar to animals, but they fall in the presence of small disturbances. In contrast, robots that rely primarily on active control, such as Boston Dynamics' "BigDog," demonstrate impressive robustness to disturbances at the expense of energy economy [1]. Our goal is to combine the robustness to disturbances of actively controlled machines with the energy economy of a passive dynamic walker.

Spring-mass models are able to reproduce the energy economy and some of the robustness of animal walking and running. During undisturbed hopping they are energetically conservative, but they have no way to add or remove energy from their gait, and disturbances affect their toe force profile, center of mass trajectory, and can lead to falls. To approach the robustness of animal walking and running, active control needs to be incorporated that interferes minimally with the existing passive dynamics, but that still attenuates disturbances.

Our models are schematically similar to existing force control actuators, which makes them compatible with existing force control techniques. We use actuated spring-mass models that are suitable for implementation as real systems to demonstrate our force control strategy in simulation, and associated control strategies for vertical and planar hopping. The force controlled models that we present include realistic physical limitations, such as motor torque limits and inertia, approximated from legged robots of our own design and construction. Our force control strategy has similarities to the force control used on the MIT Series Elastic Actuator (SEA). The MIT SEA measures and controls the deflection of its spring, which corresponds to the force applied by the actuator [2]. As an added benefit, the series spring filters impulsive forces, improving the SEA's robustness to shock loads [3]. 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 [4].

Our basic control strategy is to control the toe force profile through active control of the leg length motor. Although 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" [5, 6]. These robots use springs in much the same way as the SEA, as a force sensor and mechanical filter, but not for energy storage. When correctly applied, this approach can result in impressive performance, but at the cost of high energy consumption.

We show in Chapters 2 and 3 that force control in the leg length direction can reject changes in ground stiffness, damping, and surface height for the vertically hopping model with a correctly sized leg-spring. Our force control strategy matches its toe force profile to that of the passive spring-mass model hopping on flat rigid ground, which has the added benefit of roughly maintaining the center of mass trajectory of the undisturbed model. A leg-spring tuned to the desired hopping frequency is important for energy economy, but also robustness to disturbances, which we demonstrate in Chapter 3.

We extend our force control strategy to hopping in the vertical plain in Chapters 4 and 5 by combining it with a state of the art control strategy for the leg touchdown angle that prevents falls when hopping over uneven terrain. Force control in the leg length direction is all the control that is needed for vertical hopping, but planar hopping requires some additional control of the leg touchdown angle to prevent falls. The vertically hopping spring-mass model is insusceptible to falling forwards or backwards, and even the passive vertically hopping spring-mass model can prevent falls in the presence of many disturbances. In contrast, the planar hopping spring-mass model, commonly called the spring loaded inverted pendulum (SLIP), will fall without careful control of the leg touchdown angle. Starting with our force controlled model for vertical hopping, we add a second motor and spring at the hip for control of the leg angle during flight, and for force control in the leg angle direction during stance. Our flight controller than sets a leg touchdown angle during flight that prevents falls and maintains a constant horizontal velocity during flight from one stride to the next. We show that our combined impulse control and leg touchdown angle strategy can reject changes in ground stiffness, damping, and surface height for the planar hopping model. Our force control strategy maintains the toe force profile of the passive spring-mass model hopping on flat rigid ground, and roughly maintains the center of mass trajectory of the passive spring-mass model, because the toe forces are the same.

Finally, in Chapter 5 we present impulse control as an incremental improvement to our basic force control approach that retains all of the benefits we found for force control, but also maintains a more consistent center of mass trajectory and requires less control authority. Our impulse control strategy matches its toe impulse profile to that of the target passive system hopping on flat rigid ground. During steady state operation, our impulse control strategy is able to track the desired toe impulse profile, such that the force profile for our impulse controlled model is the same as for the target passive model. Disturbances cause unavoidable force errors that affect the center of mass trajectory of our force controlled model, but our impulse control strategy is able to correct for any tracking errors by commanding equal and opposite forces. In addition to maintaining a more consistent center of mass trajectory, our impulse control strategy requires less control authority, because its performance is not dependent on how quickly it can regulate force errors and only on whether it can begin tracking the desired toe impulse profile within a single stance phase.

Our force control strategy, and its extensions, are promising for real world walking and running robots, because they do not require any sensing of their environment, are robust to ground disturbances, and are capable of excellent energy economy. We show in simulation that our control strategy handles realistic dynamics consistent with a hopping robot using a commercially available electric motor.

Chapter 2 – Force Control for Spring-Mass Walking and Running

We demonstrate in simulation that active force control applied to a passive spring-mass model for walking and running attenuates disturbances, while maintaining the energy economy of a completely passive system during steady-state operation. It is well known that spring-mass models approximate steady-state animal running, but these passive dynamic models are sensitive to disturbances that animals are able to accommodate. Active control can be used to add robustness to spring-mass walking and running, and most existing controllers add a fixed amount of energy to the system based on information from previous strides. Because spring-mass models are schematically similar to force control actuators, it is convenient to combine the two concepts in a single system. We show, in simulation, that the resulting system can attenuate sudden disturbances during a single stance phase by matching its toe force profile to that of the undisturbed spring-mass model.

2.1 INTRODUCTION

For robots to approach the performance of animal walking and running, they must be able to attenuate significant disturbances, while maintaining excellent energy economy. Existing passive walkers are capable of energy economy similiar to animals, but they fall in the presence of small disturbances. Robots that rely primarily on active control, such as Boston Dynamics' "BigDog," demonstrate impressive robustness to disturbances at the expense of energy economy [1]. Our goal is to combine the robustness to disturbances of actively controlled machines with the energy economy of a passive dynamic walker. We propose a novel concept of adding force control to a spring-mass model. Because existing force control actuators are schematically similiar to the spring mass model, it is easy to combine the two on a real system.

We simulate a motor for active control, in series with a spring in a small modification to the familiar spring-mass system that is schematically similar to existing force control actuators, shown in Fig. 2.1. This simulation makes use of the extensive background in spring-mass running models, but like a number of running robots, also includes actuation, allowing for active control of the existing passive dynamics [7, 8]. However, most controllers of spring-mass running add a fixed amount of energy to the system by adjusting the zero-force leg length or spring stiffness, and can require extensive sensing.

Our simulation results show that active force control can make the spring-mass model robust to ground disturbances with limited sensory input. The controller is based only on the spring deflection, and not on any external sensing, which makes it practical for legged robots that have incomplete knowledge of the world. While the passive dynamics of the system attenuate very high-frequency disturbances, the force controller focuses on the middle-frequency disturbances, leaving any high-level gait choices or stride-to-stride control to a higher-level control system.

This novel concept of combining force control and a spring-mass model is convenient, easy to implement on a real system with dynamic and sensing limitations, and effective. To our knowledge force control has never been used on any running robots or models to compensate for ground disturbances. This paper presents a general method for improving the robustness of spring-mass model walking and running by applying force control.

2.2 BACKGROUND

Our motivation for this work is based on observations of animals, which are able to economically walk and run at varying speeds over varying terrain. The economy and robustness of animal walking and running is attributed to passive dynamics, which allow legs to store and release energy in a cyclic manner, conserving energy [9]. Because our goal is to build robots that can match the performance, economy, and robustness of animal walking and running, our models incorporate passive dynamics similar to those observed in animal walking and running. Spring-mass models provide a good approximation for animal walking and running, we therefore begin with a simple model consisting of a mass bouncing on a spring, similar to the spring loaded inverted pendulum, but restricted to vertical hopping.

Animals make excellent use of passive dynamics, but robots can also benefit from them, if their mechanical system is designed appropriately. All devices have passive dynamics of some sort that can either help or harm the overall performance

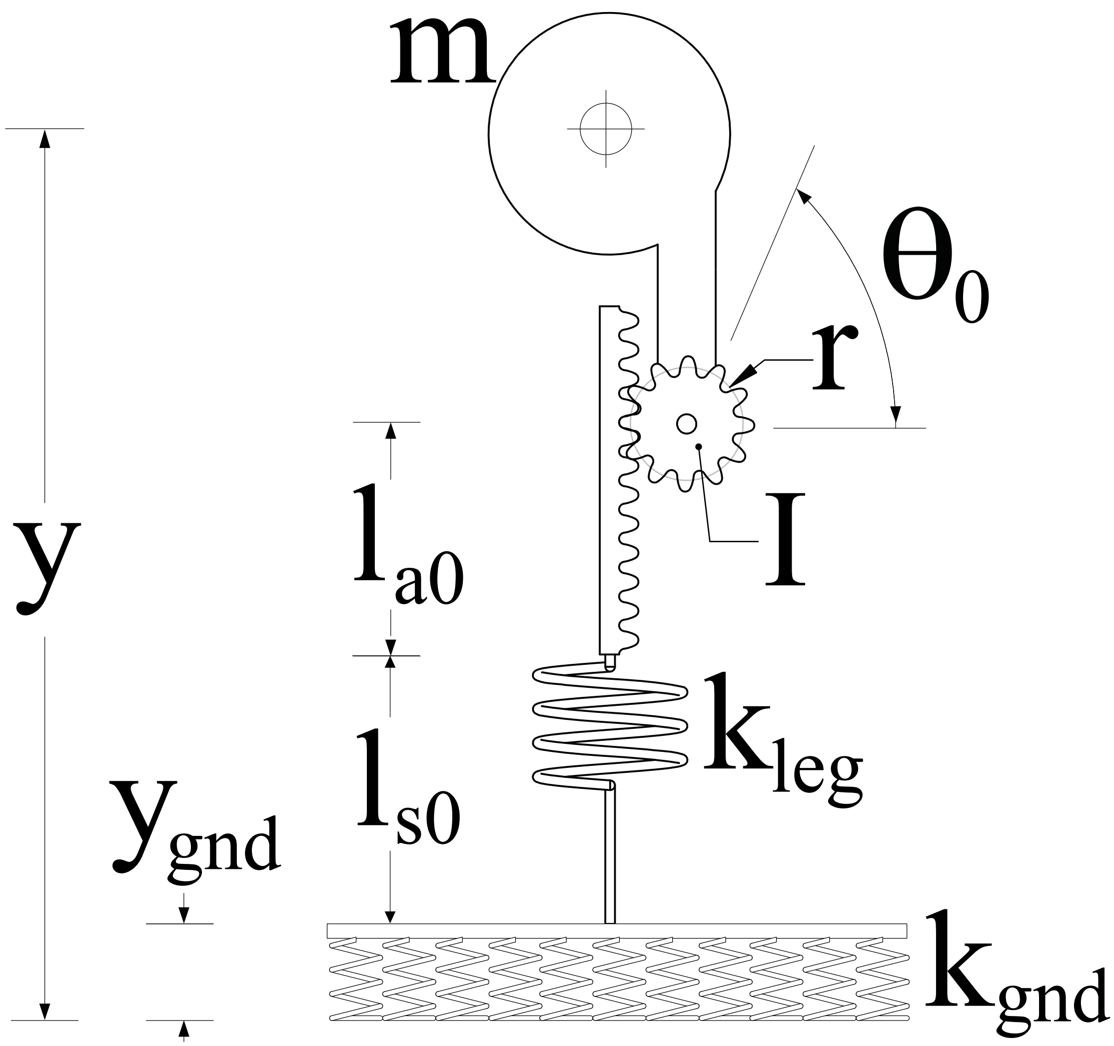


Figure 2.1: Force controlled spring-mass model with reflected motor inertia, shown at the instant of leg touchdown on a compliant surface.

of the system. Robots with mechanical designs that do not consider passive dynamics tend to have a relatively high specific cost of transport, defined as the amount of energy they must expend to move a unit distance, taking their weight into account. For example, Honda's ASIMO has demonstrated stable walking and running gaits, based on ZMP control and careful avoidance of jarring ground impacts, by matching foot speed to relative ground velocity just before leg touchdown. Like most walking robots, ASIMO ignores or overcomes its inherent passive dynamics with active control, and has a relatively high specific cost of transport of 3.23 [10]. In contrast, humans and passive dynamic walkers, such as the Cornell efficient biped, have a specific cost of transport of just 0.2 [11]. This cost of transport is especially important for any tether-free robot. For walking robots that must store their own energy, the specific cost of transport determines the distance a robot may travel before depleting its energy supply.

In addition to passive dynamics, animals also use active control to compensate for disturbances. For example, guinea fowl are able to accommodate for a drop in ground height by rapidly extending their leg into an unexpected disturbance, as shown in Fig. 2.2, resulting in only slight deviation from their undisturbed gait [12]. Compensating for ground disturbances is important on a physical system, since deviations from the undisturbed gait can lead to a loss of stability, falls or springs exceeding their maximum deflection, potentially causing damage. For example, when a spring-mass model encounters a decrease in ground surface, some additional gravitational potential energy is converted into kinetic energy as the model falls into the disturbance. The additional kinetic energy must then be

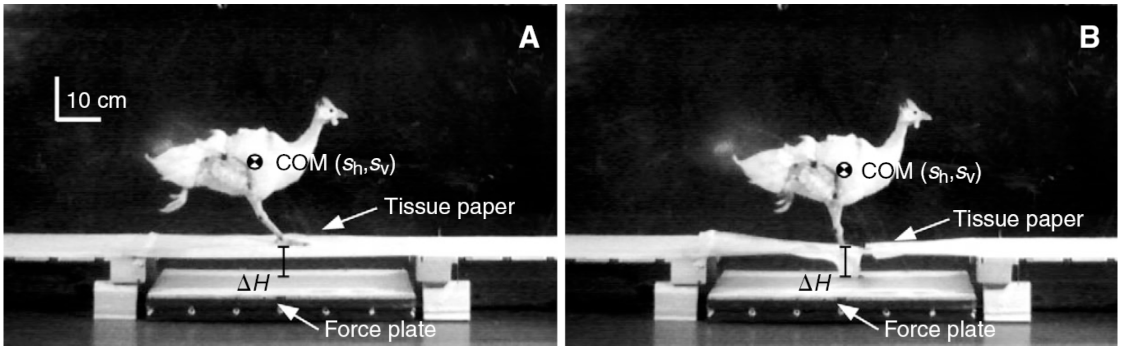


Figure 2.2: Motivation comes from the economy and disturbance rejection ability of animals such as the guinea fowl. The guinea fowl is able to accommodate for the unexpected decrease in ground surface without a significant change to its steady-state center of mass motion.

converted into spring potential energy, which results in increased spring deflection. In addition to higher deflections, disturbances can cause high1er forces. 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 [13].

Our proposed force-control idea is philosophically similar in many ways to previous works including the MIT Leg Lab robots and the ARL Monopod-II. Like our model, these robots utilize passive dynamics, while incorporating active control. Leg Lab robots, such as the Planar Hopper, use springs to facilitate running gaits, and while not designed for energetic economy, are capable of impressive feats such as somersaults [7]. In contrast, the ARL Monopod-II, although mechanically similar to the Leg Lab robots, is designed to minimize its energy cost, and implements the aptly named "controlled passive dynamic running." This robot uses active feedback control to match its hopping trajectory with that of the system's passive dynamics, which are similar to a SLIP. The ARL Monopod-II calculates motor torques based on information from its previous hop, and does not begin to compensate for ground disturbances until later strides [8].

Springs clearly help running gaits by storing and releasing energy, but they are also useful for improving force control. The MIT SEA measures and controls the deflection of its spring, which corresponds to the force applied by the actuator [2]. As an added benefit, the series spring filters impulsive forces, improving the SEA's robustness to shock loads [3]. Although the performance of force controlled actuators has been explored, investigations do not generally relate to legged locomotion [4].

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". These robots use springs in much the same way as the SEA, as a force sensor and mechanical filter, but not for energy storage. When correctly applied, this approach can result in impressive performance, but at the cost of high energy consumption. For example, when "BigDog's" legs touch down, its leg springs deflect and hydraulic actuators absorb energy. This energy is not released to propel "BigDog's" next step, instead the legs are actively raised and relocated. "BigDog" overcomes this inefficiency with a seventeen horsepower gasoline engine, and although it holds the current distance record for legged vehicles at 12.8 miles, its range would be severely limited if it had to rely on batteries for power [1, 5]. Like "BigDog", the "Spring Flamingo" also uses springs for force control, but not for energy storage

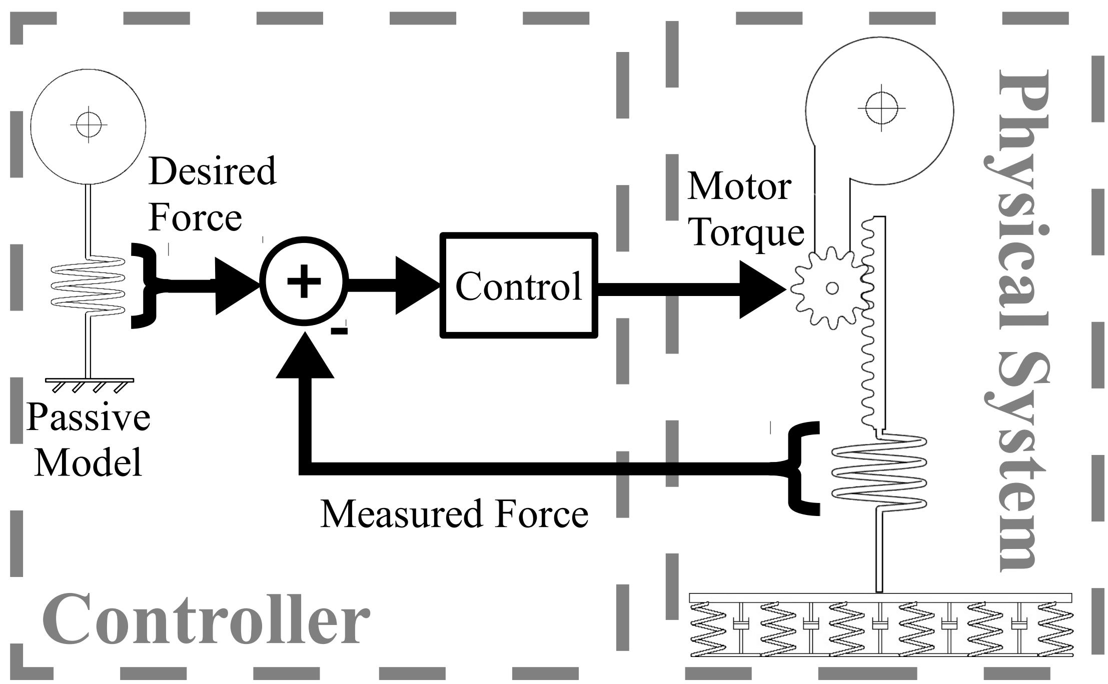


Figure 2.3: Block diagram for control and physical systems. The physical system is the force controlled spring-mass model, shown in Fig. 2.1. Our controller measures the leg-spring displacement and generates motor torques that attempt to match the toe force profile with that of the undisturbed passive spring-mass model.

[6]. The "Spring Flamingo" successfully demonstrated force controlled walking on a slope, but is not a spring-mass model walker, is incapable of running gaits, and has passive dynamics that do not benefit its energy economy.

Biomechanics studies have shown that humans and animals adjust their leg stiffness through a concerted effort of muscles, tendons and ligaments during hopping, walking and running to accommodate for changes in ground stiffness [14]. Based on these observations, 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 [15, 16]. These devices pretension springs to increase their leg's apparent stiffness, but were never successfully implemented on a running robot. In contrast, humans are able to hop, walk, and run on compliant surfaces by adjusting their leg stiffness such that the equivalent stiffness of the series combination of the ground and leg spring is the same for all surfaces [17]. By maintaining an equivalent stiffness, humans are able to maintain a toe force profile, such that their center of mass trajectory does not change in response to changes in ground stiffness. Although our controller may not directly set leg stiffness, our model produces an equivalent result by maintaining a toe force profile.

2.3 MODEL

We add a motor and associated reflected motor inertia to the simple spring-mass model, as shown in Fig. 2.1. With these additions, we arrive at a single degree of freedom vertically hopping model, schematically similar to the MIT SEA [2]. However, in addition to using series elasticity for force control, our model stores energy in its springs. The spring stiffness is tuned to the natural frequency of our desired spring-mass hopper, so the energy will be stored in the spring as the mass decelerates, and recovered as the mass accelerates towards liftoff. In the ideal scenario, the motor does no work, and all of the model's behavior is expressed by the passive dynamics of the system as it bounces up and down. Any disturbance that the model encounters is handled by the actively controlled motor.

We use kinetic equations of motion to simulate our vertically hopping force controlled model. During undisturbed hopping our model behaves like a standard spring-mass model bouncing on a flat, rigid surface, and therefore its center of mass trajectory may be broken into identical periods (bounces). Since we provide our model with some initial height, it simplifies our simulation to break a period into a fall, stance and rise stage, rather than just a flight and stance phase. Each of these stages is well-defined for the standard spring-mass model bouncing vertically on a flat rigid surface, and therefore, analytical solutions for the center of mass motion, toe force and spring work can be found as functions of time. These functions are the same as for a mass in free-fall during the fall and rise stages, but are complicated during stance by the spring force. During stance, the trajectory of the system is found by solving an ordinary differential equation of the form:

$$m \cdot \ddot{y} = F_{spring}(y, \theta) - m \cdot g, \tag{2.1}$$

where F_{spring} is the force of the leg spring. This is similar to the equation for a vertical undamped spring-mass oscillator.

To simulate the behavior of our robot model we solve the kinetic equations for the center of mass height and motor angle. The equation of motion for our robot's center of mass trajectory is the same as for the standard spring-mass model (2.1), although computing values for F_{spring} is complicated by the motor angle.

The motor inertia gives rise to a second equation of motion for the angle of the motor,

$$I \cdot \ddot{\Theta} = F_{spring}(y, \theta) - \tau_{motor}. \tag{2.2}$$

We include significant non-linearities in our model's control functions, such as motor torque limits, so we are unable to find an analytical solution for the center of mass motion of our force controlled robot. However, we are able to generate an approximate numerical solution using MATLAB's ODE15s ordinary differential equation solver. Our intention is to demonstrate a concept with as many implementation details abstracted away as possible, while retaining important features such as motor inertia and torque limits.

2.4 CONTROLLER

The active control system in our model intervenes with the passive dynamics only to accommodate ground disturbances. Our controller attempts to match our model's toe force profile to that of an equivalent undisturbed spring-mass model, such that its center of mass movement approximates that of the undisturbed model.

When our model encounters an unexpected change in ground height or stiffness, the leg extends or retracts such that the toe forces match those of the undisturbed passive dynamics.

During undisturbed hopping our simulation behaves like a simple spring-mass model without interference from active controllers. Our model's spring exerts all of the work required to decelerate and re-accelerate the system after leg touch down. Active control plays a role in our simulation's performance only when a ground disturbance is encountered.

Force control, using series elastic elements, provides disturbance rejection. To control toe forces during stance, the motor torque, τ_{motor}, is calculated by combining torques from two independent controllers:

$$\tau_{motor} = \tau_{compensate} + \tau_{error} \tag{2.3}$$

The first controller generates a torque, $\tau_{compensate}$, to exactly balance the torques applied by the spring on the motor shaft, as shown in Fig. 2.3. This allows the second controller to treat the motor as an independent inertia and control its position through PID control, applying τ_{error} based on the error between a desired motor position and its measured position. If the desired motor position cannot be determined, because the toe is not in contact with the ground, our controller commands maximum motor torque until toe touch down. During flight, another controller returns the leg to its initial length by resetting the motor position after liftoff.

The controller we demonstrate in simulation may not be optimal, but demonstrates our idea for using force control with limited tuning on a platform in simulation with realistic parameter values. Some other approach might improve the performance of our model, however, we are only interested in demonstrating a concept, and not in choosing simulation parameters.

2.5 EXPERIMENTS

We compare, in simulation, a passive spring-mass model, hopping vertically, with our force controlled spring-mass model. Both are subject to disturbances in ground height and ground stiffness. On a flat rigid surface, the passive dynamics of our model match the simple spring-mass model. In the presence of unexpected decreases in ground height and changes in ground stiffness, our active controller applies motor torques to maintain a consistent center of mass trajectory. To better demonstrate the feasibility of disturbance rejection on our model in simulation, we choose the following, somewhat arbitrary, but realistic values for a moderately-sized robot using a commercially available motor:

Parameter	Description	Value
y_0	initial CoM height	$27.75cm$
y_{gnd}	ground surface	0 or $-10cm$
l_{s0}	unstretched spring length	$15cm$
l_{a0}	initial actuator length	$5cm$
θ_0	initial motor angle	0
τ_{lim}	maximum motor torque	$\pm 25N \cdot m$
I	motor rotor inertia	$1\frac{rad}{N \cdot m \cdot s^2}$
r	transmission output radius	$2.3188cm$
m	robot mass	$10kg$
k_{leg}	leg spring stiffness	$2.5\frac{k \cdot N}{m}$
k_{gnd}	ground spring stiffness	$5\frac{k \cdot N}{m}$ or ∞

The first type of disturbance we investigate is a sudden decrease in ground surface during the flight phase. There are no “sensors” that allow the model to change its control strategy, and it has no forewarning of this change in ground height. The model takes its second hop on the lower ground surface, and the ground surface then returns to its regular height for a third hop. The model is restricted to movement on the vertical axis, and simulation results are plotted as functions of time.

The second type of ground disturbance we investigate is a decrease in ground stiffness. For this experiment the ground unexpectedly changes from being perfectly rigid to behaving like an ideal spring. As the model touches down the ground depresses proportionately to the model's toe force. The net result is that the model experiences a spring stiffness equal to the series combination of its leg spring with the ground stiffness.

2.6 SIMULATIONS

We test the disturbance rejection ability of our force controlled model against the standard spring-mass model in simulation. We expect ground disturbances to result in a temporary change in hopping height and a permanent shift in hopping phase for the standard spring-mass model. However, we expect our force controlled model to accommodate for ground disturbances and to closely follow the toe force profiles and center of mass trajectory of the undisturbed system.

2.6.1 Ground Height Disturbance

For the standard spring-mass model, variations in ground height affect the toe force profile and center of mass trajectory, as shown in Fig. 2.4 and Fig. 2.5. When the spring-mass model encounters a drop in ground height, it remains in free-fall for longer than if the ground had been at its previous height. Since the system remains in free-fall for longer, it touches down with greater velocity and the toe force profile exceeds that of the undisturbed model.

During stance the model behaves like a spring-mass oscillator. The natural frequency for a spring-mass oscillator is independent of initial conditions, and

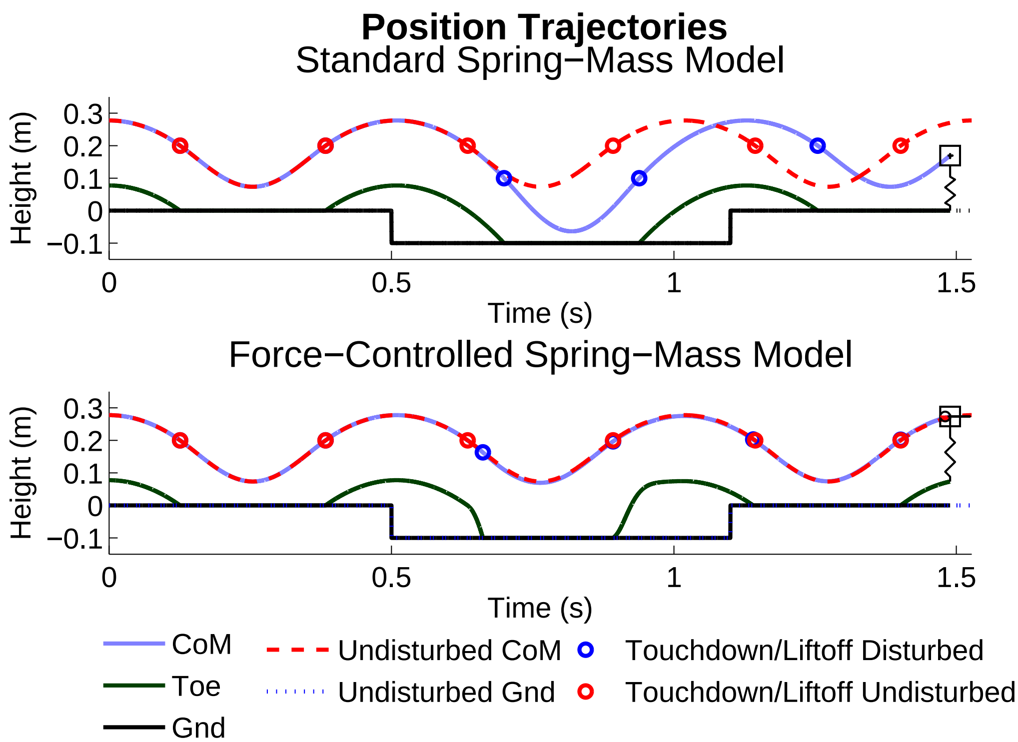


Figure 2.4: Comparison between the center of mass trajectories of the standard vertically hopping, spring-mass and force controlled models encountering an unexpected decrease in ground surface. Our force controlled model roughly maintains the center of mass trajectory of the passive undisturbed spring-mass model.

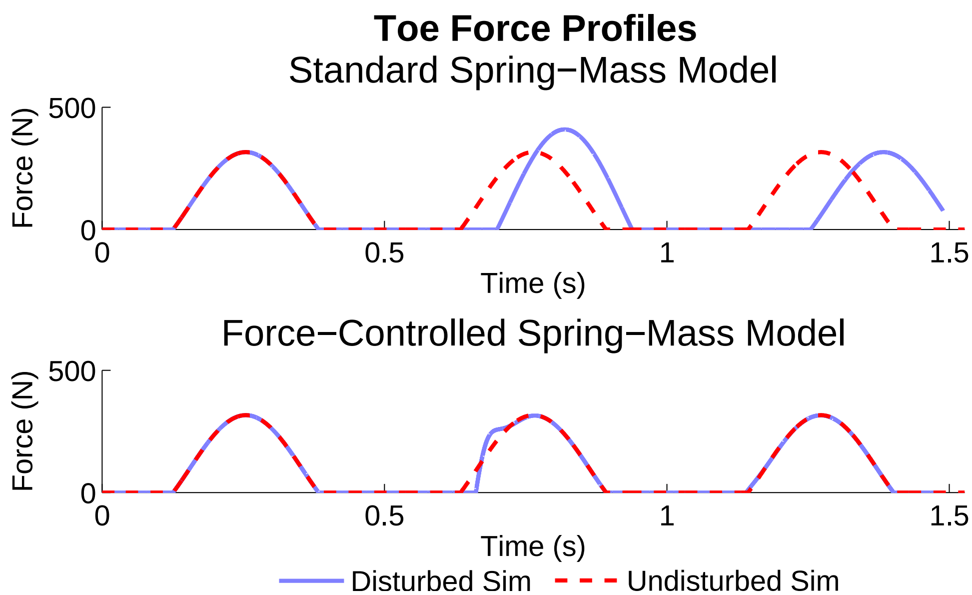


Figure 2.5: Comparison between the toe force profiles of the standard vertically hopping spring-mass and force controlled odels encountering an unexpected decrease in ground surface. Our force controlled model roughly maintains the toe force profile of the assive undisturbed spring-mass model.

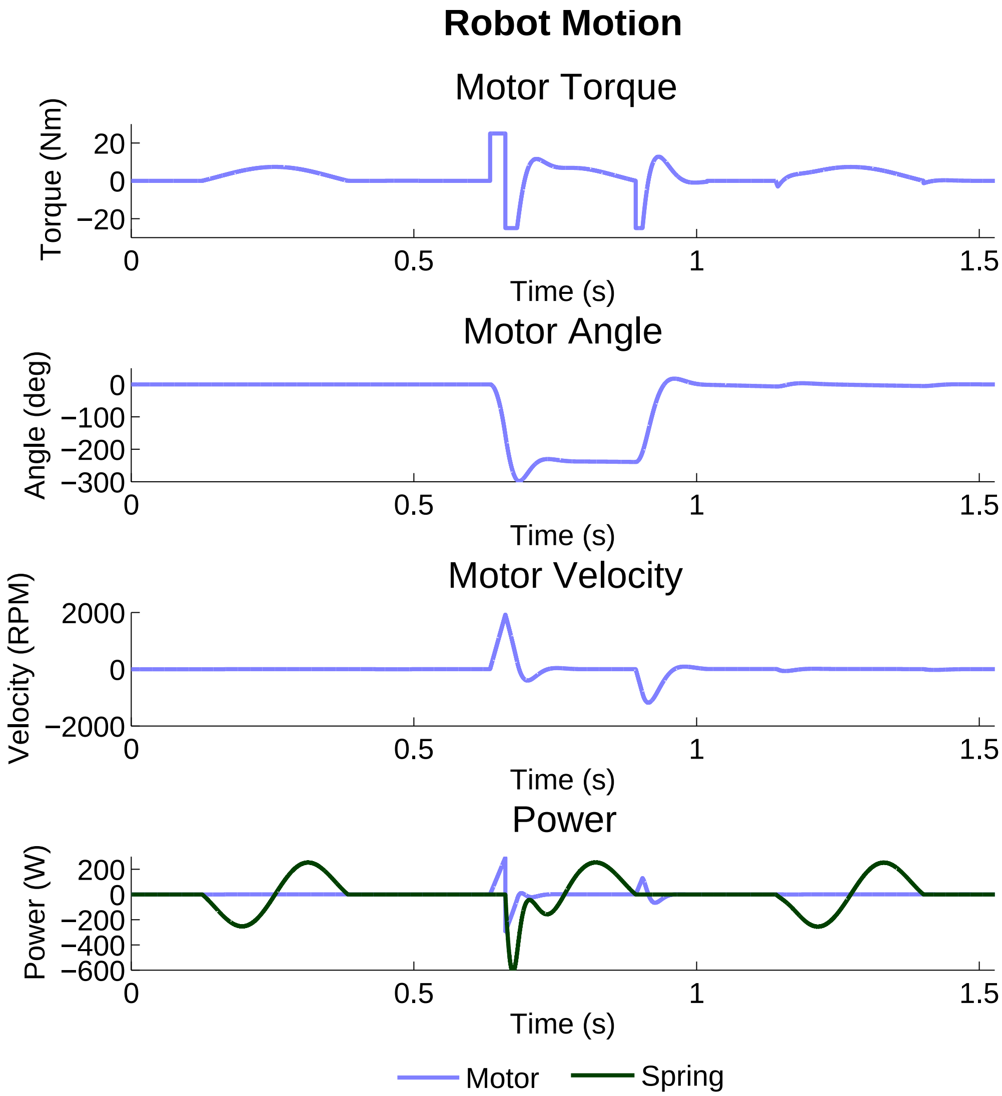


Figure 2.6: Motor torque, angle, velocity, power and spring power for the vertically hopping force controlled model encountering an unexpected decrease in ground surface. Notice that our motor only exerts work in response to the ground disturbance.

therefore, the duration of the stance phase is not affected by changes in ground height. However, the passive model touches down later when it encounters a drop in ground height, so it must also lift-off later. The net result of a temporary drop in ground height is a permanent shift in hopping phase for the simple model.

In contrast to the uncontrolled spring-mass model, the toe force profile for the force controlled spring-mass model is roughly maintained despite changes in ground height. The active control system begins to follow a force trajectory at the time of expected toe impact. Because the ground is lower than expected and does not come into contract with the toe, it provides no reaction force. The leg accelerates towards the ground until it makes contact, as shown in Fig. 2.6. This control strategy maintains a relatively consistent toe force profile, even in the presence of unexpected changes in ground height. Because the center of mass trajectory is determined solely by toe forces, our force controlled hopper maintains a more consistent center of mass motion than the purely passive spring-mass model subjected to the same disturbance.

2.6.2 Ground Stiffness Disturbance

For the standard spring-mass model variations in ground stiffness affect the center of mass trajectory, as shown in Fig. 2.7. When the spring-mass model encounters a decrease in ground stiffness, its spring combines in series with the ground spring. The equivalent leg stiffness is less than the leg stiffness of the model alone, so the natural frequency for the equivalent spring-mass oscillator decreases. The duration

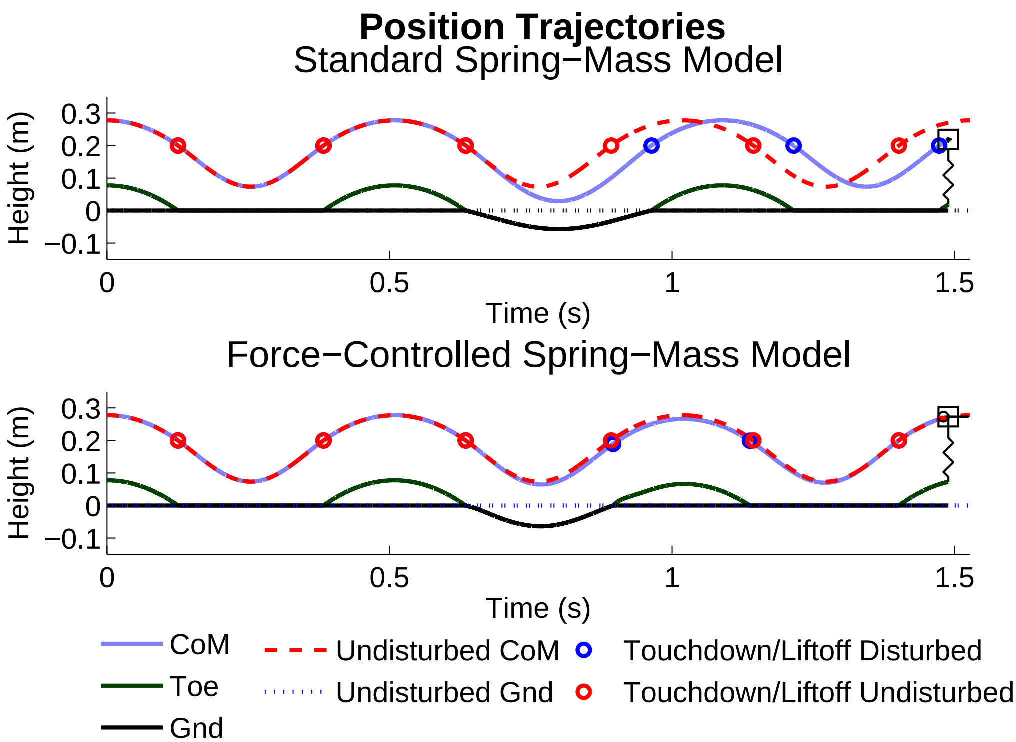


Figure 2.7: Comparison between the center of mass trajectories of the standard vertically hopping spring-mass and force controlled odels encountering an unexpected decrease in ground stiffness. Our force controlled model roughly maintains the center of mass trajectory of the passive undisturbed spring-mass model.

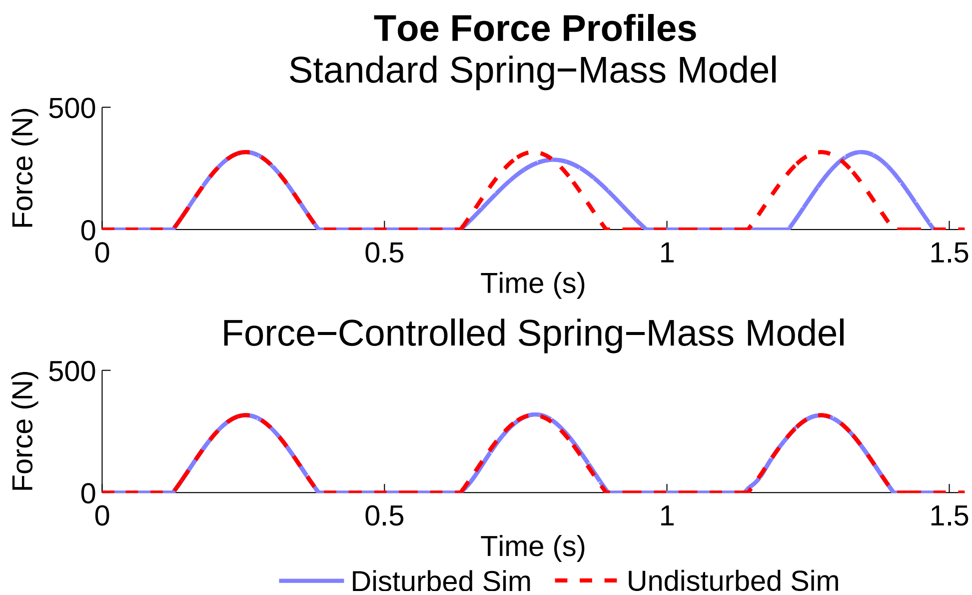


Figure 2.8: Comparison between the toe force profiles of the standard vertically hopping spring-mass and force controlled odels encountering an unexpected decrease in ground stiffness. Our force controlled model roughly maintains the toe force profile of the assive undisturbed spring-mass model.

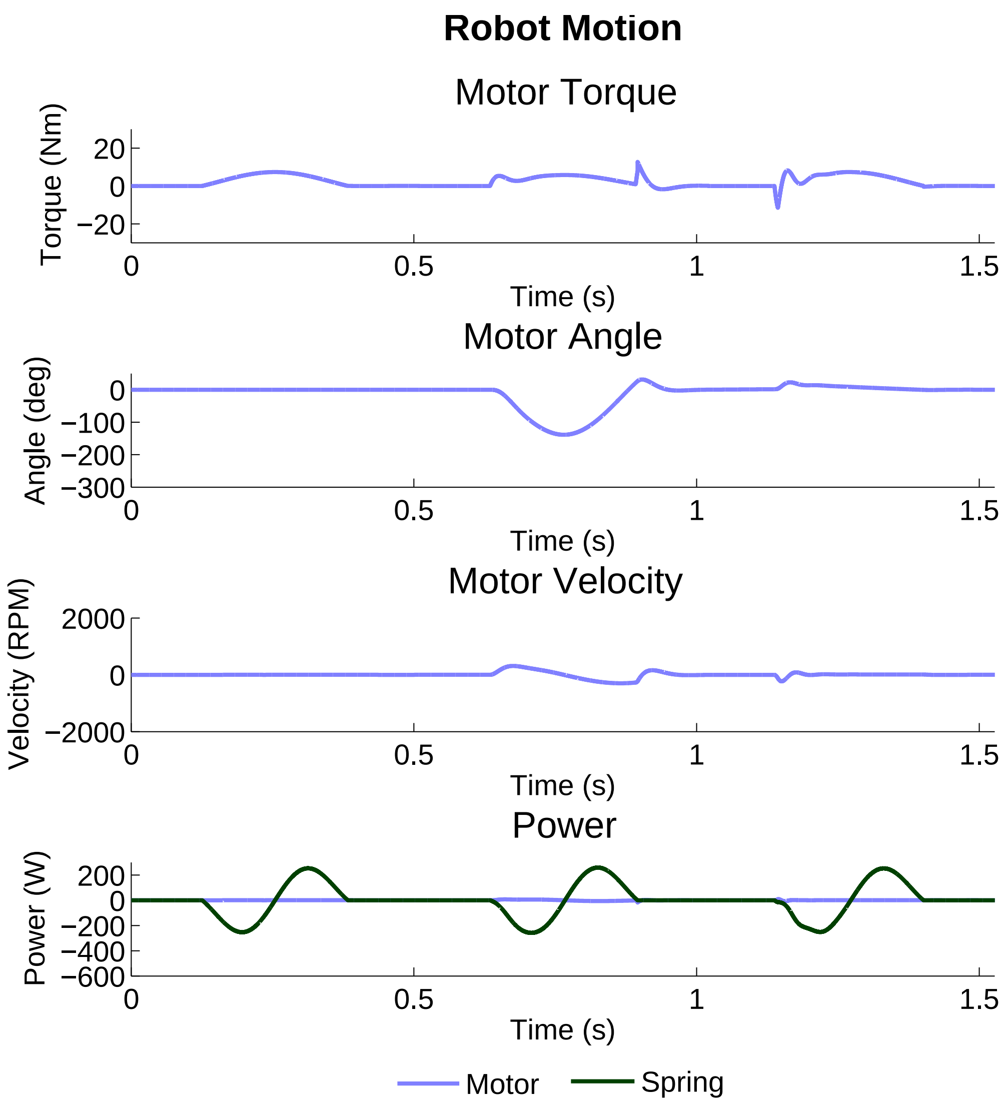


Figure 2.9: Motor torque, angle, velocity, power and spring power for the vertically hopping force controlled model encountering an unexpected decrease in ground stiffness. Notice that the spring is responsible for most of the work required to maintain the center of mass otion.

of the stance phase therefore increases when the ground compliance increases. However, the spring work over the stance phase remains constant, so the peak force decreases, as shown in Fig. 2.8, as the length of stance increases.

In contrast, the force controlled model maintains the toe force profile of the equivalent undisturbed spring-mass model despite changes in ground stiffness. The force controlled model compensates for the decrease in its equivalent leg stiffness by actuating the leg during the stance phase, as shown in Fig. 2.9. During the first half of the stance phase, the leg gradually extends, increasing the rate of spring compression. The leg is then gradually retracted during the second half of the stance phase, causing the spring to decompress more rapidly. The result of this leg actuation is a toe force profile that approximates the toe force profile of the passive, undisturbed model, at the cost of additional motor work. As with the ground height disturbance experiment, unexpected changes in ground stiffness do not significantly affect the center of mass trajectory, because the center of mass trajectory is directly related to the toe force.

2.7 CONCLUSIONS AND FUTURE WORK

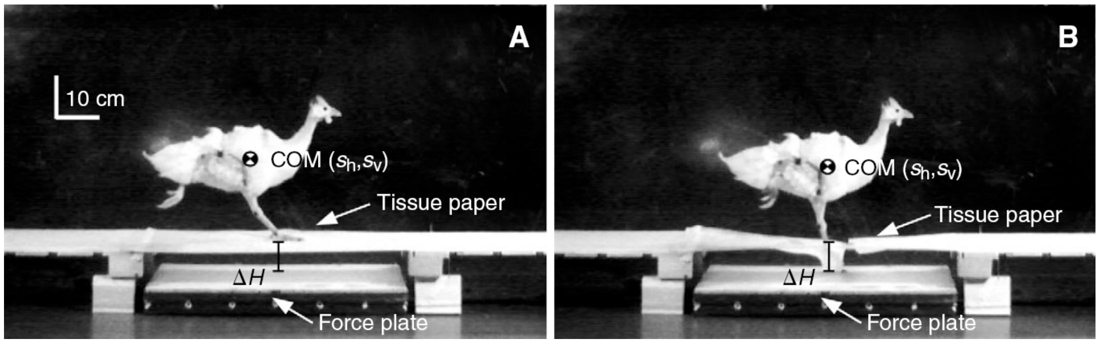
We have shown in simulation that active force control combined with a correctly sized leg spring yields good disturbance rejection, while maintaining the energy economy of a completely passive system during steady-state vertical hopping. In the presence of disturbances, we are able to match the toe force profile to that of a passive spring-mass model on a flat rigid surface. Because the toe force profiles are identical, the model's center of mass movement follows that of the ideal passive system.

The simulation illustrates some system limitations caused by the motor's torque limit. When the force controlled model encounters a drop in ground height, there is a delay between when toe touchdown is expected to occur, and when it actually does. The delay depends on the magnitude of the disturbance and physical limitations of the system, such as the motor inertia, motor torque limit, transmission ratio, and leg inertia. During this delay the motor gains angular momentum causing the actual toe force to exceed the desired toe force in the moments following toe touchdown. The simulated motor has a realistic inertia that can only be decelerated as quickly as the motor's torque limit allows. The error in the toe force profile can be minimized by tuning control constants, but the controller does not know the position of the ground or any other information about the world, so we presume that it cannot be eliminated without additional sensory input. Despite this sensor limitation, it is able to perform well, with only a small and brief discrepancy between the actual and desired toe force profiles, even in the presence of a substantial change in ground height.

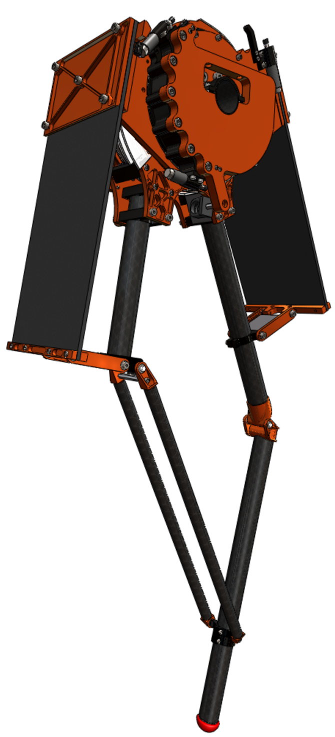
The long-term goal of this work is to build a biped with excellent energy economy capable of robust walking and running gaits. As an intermediate step towards this goal, we are extending the single degree of freedom model presented in this paper to a two degree of freedom monopod in simulation. We will then demonstrate our concept of adding force 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. With these real-world devices we hope to approach the performance of animal walking and running.

Chapter 3 – Force Control for Vertical Spring-Mass Hopping

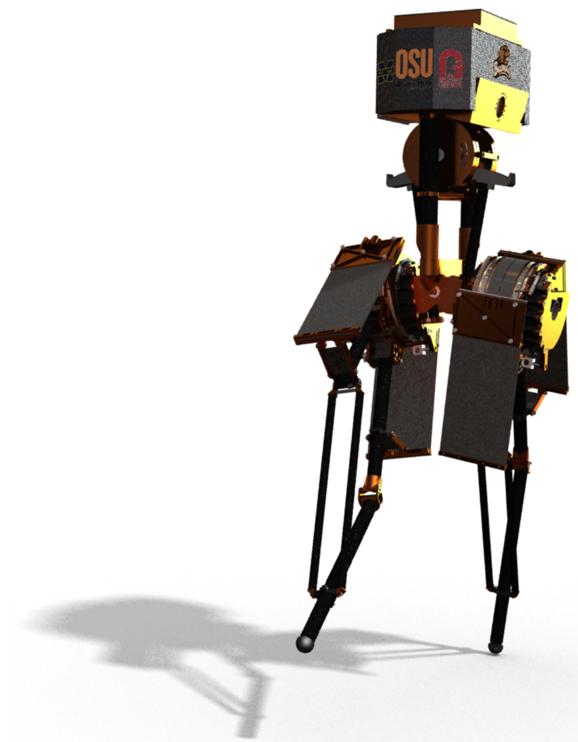
In this chapter we present a novel control strategy for spring-mass hopping that combines force control with a tuned leg-spring stiffness. The motivation for this work is based on observations of animals, which are able to economically walk and run over varying terrain and ground dynamics. It is well-known that steady-state animal running can be approximated by spring-mass models, but these passive dynamic models describe only steady-state running and are sensitive to disturbances that animals can accommodate. While animals rely on their passive dynamics for energy economy, they also incorporate active control for disturbance rejection. The same approach can be used for spring-mass walking and running, but an active controller is needed that interferes minimally with the passive dynamics of the system. We demonstrate, in simulation, how force control combined with a leg spring stiffness tuned for the desired hopping frequency provides robustness to disturbances on a model for robot hopping, while maintaining the energy economy of a completely passive system during steady-state operation.



(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. [12].

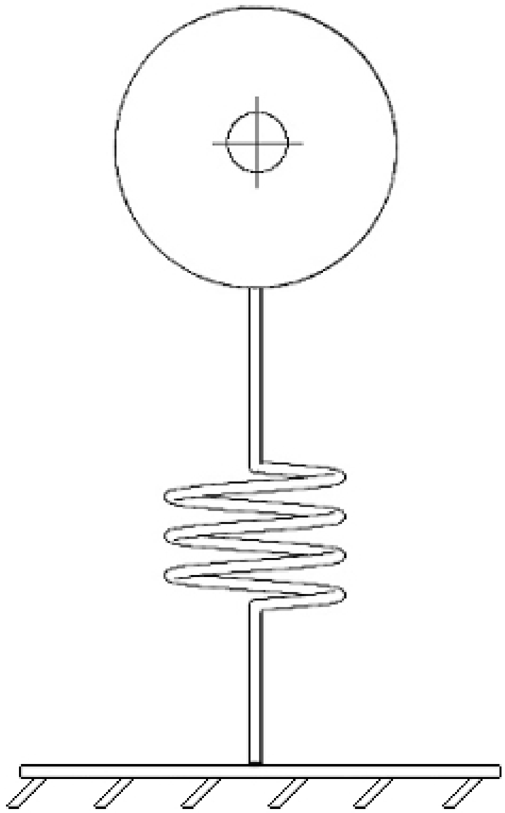


(b) Bio-inspired planar monopod ATRIAS (under construction).

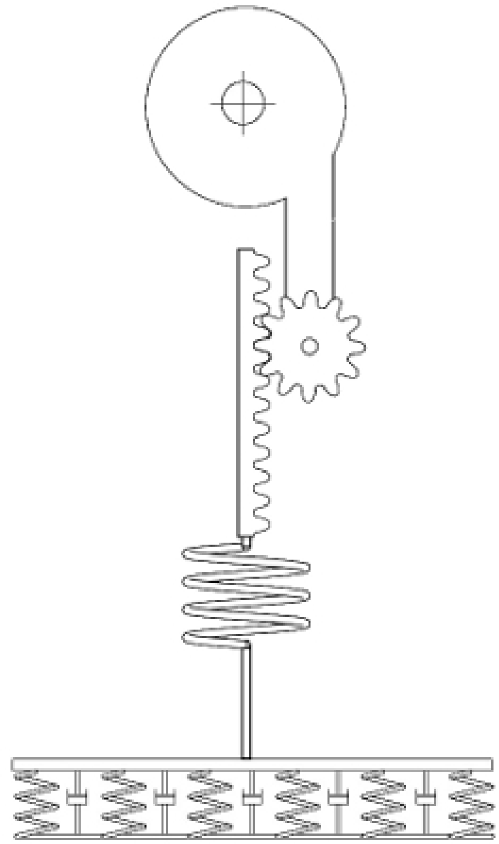


(c) 3-D bipedal ATRIAS.

Figure 3.1: Force control, as presented in this paper, describes observed behavior in animals and can be implemented on a robot.



(a) The passive spring-mass model.



(b) Force controlled spring-mass model.

Figure 3.2: Starting with the passive spring-mass model, we add a series motor for active force control with a torque limit and reflected rotor inertia.

3.1 INTRODUCTION

We seek to build machines that approach the performance of animal walking and running, as shown in Fig. 3.1. Existing robots are not capable of the energy economy or disturbance rejection observed in animals. For robots to approach the performance of animal walking and running, they must be able to attenuate significant disturbances, while maintaining excellent energy economy. Existing passive walkers are capable of energy economy similar to animals, but they fall in the presence of small disturbances [18]. Robots that rely primarily on active control, such as Boston Dynamics' "BigDog," demonstrate impressive robustness to disturbances at the expense of energy economy [1]. Our goal is to combine the robustness to disturbances of actively controlled machines with the energy economy of a passive dynamic walker.

We propose combining force control with the spring-mass model to achieve efficient and robust running. The simple spring-mass model, shown in Fig. 3.2a, is capable of energetically conservative hopping and approximates key aspects of animal running [9]. Because existing force control actuators are schematically similar to the spring-mass model, it is easy to combine the two on a real system. We add a series motor with a torque limit and associated reflected inertia to the passive spring-mass model for active control, as shown in Fig. 3.2b, and then use force control to match the toe force profile of our actuated model to a target passive spring-mass model hopping on flat rigid ground. This combination of controller and model makes use of the extensive work in the field of spring-mass running, but also includes actuation, allowing for active control of the existing passive dynamics [7, 8].

We demonstrate for vertical hopping, in simulation, that our combination of a leg-spring stiffness tuned for the desired hopping gait and active force control attenuates disturbances in ground surface height and impedance, such as those shown in Fig. 3.3, within a single stance phase. In addition, our combined strategy utilizes passive dynamics exclusively during steady state running, which results in excellent energy economy. Our controller is based only on the spring deflection, and not on any external sensing, which makes it practical for legged robots that have incomplete knowledge of the world.

This concept of combining force control and a spring-mass model is convenient, easy to implement on a real system with dynamic and sensing limitations, and effective. Our force control strategy is designed to reject disturbances and maintain a consistent running gait; this leaves any higher-level gait decisions such as changes in hopping height or velocity to a stride-to-stride controller. We believe the results we present for vertical hopping can be extended to realistic running gaits.

3.2 BACKGROUND

Our motivation for this work is based on observations of animals, which are able to economically walk and run at varying speeds over varying terrain. The energy economy of animal walking and running is attributed to passive dynamics, which allow legs to store and release energy in a cyclic manner, conserving energy [9]. Because our goal is to build robots that can match the performance and energy economy of animal walking and running, our models incorporate passive dynamics similar to those observed in animal walking and running. Spring-mass models provide a good approximation for animal walking and running, so we begin with such a model, but restrict it to vertical hopping.

Animals make excellent use of passive dynamics, and robots can benefit from them too, if their mechanical system is designed appropriately. All devices have passive dynamics of some sort that can either help or harm the overall performance of the system. Robots with mechanical designs that do not consider passive dynamics tend to have a relatively high specific cost of transport, defined as the amount of energy they must expend to move a unit distance, taking their weight into account [19]. For example, Honda's ASIMO has demonstrated stable walking and running gaits, based on ZMP control and careful avoidance of jarring ground impacts, by matching foot speed to relative ground velocity just before leg touchdown. Like most walking robots, ASIMO ignores or overcomes its inherent passive dynamics with active control, and has a relatively high specific cost of transport of 3.23 [10]. In contrast, humans and robots that rely on their passive dynamics, such as the Cornell efficient biped, have a specific cost of transport of just 0.2 [11]. This cost of transport is especially important for any tether-free robot. For walking robots that must store their own energy, the specific cost of transport determines the distance a robot may travel before depleting its energy supply.

In addition to passive dynamics, humans and animals also use active control to compensate for disturbances. 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 [20, 21]. Another investigation showed that guinea fowl are able to accommodate for a drop in ground height by rapidly extending their leg into an unexpected disturbance, as shown in Fig. 3.1a, resulting in only slight deviation from their undisturbed gait [14, 12].

Compensating for ground disturbances is important on physical systems, because deviations from the undisturbed gait can lead to a loss of stability, falls, or springs exceeding their maximum deflection, potentially causing damage. For example, when a spring-mass model encounters a decrease in ground surface, some additional gravitational potential energy is converted into kinetic energy as the model falls into the disturbance. The additional kinetic energy must then be converted into spring potential energy, which results in increased spring deflection. In addition to higher deflections, disturbances can cause higher forces. 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 [13].

Springs clearly help running gaits by storing and releasing energy, but they are also useful for improving force control. The MIT Series Elastic Actuator (MIT-SEA) consists of a motor and transmission for active control, and a series spring for force control. The MIT-SEA measures and controls the deflection of its series spring, which corresponds to the force applied by the actuator [2]. As an added benefit, the series spring filters impulsive forces, improving the MIT-SEA's robustness to shock loads [3]. Although the performance of force controlled actuators has been explored, investigations do not generally relate to legged locomotion [4].

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" [1, 6]. These robots use springs in much the same way as the MIT-SEA, as a force sensor and mechanical filter, but not for energy storage. The natural frequency of these systems are much higher than those that appear in human-scale running, because they use very stiff leg springs, along with high force low inertia hydraulic actuators that make them ideal for high bandwidth force control. When correctly applied, this approach can result in impressive performance, but at the cost of high energy consumption. For example, when "BigDog's" legs touch down, its leg springs deflect and hydraulic actuators absorb energy. This energy is not released to propel "BigDog's" next step; instead the legs are actively raised and relocated. "BigDog" overcomes this inefficiency with a gasoline engine, and although it has currently walked as far as 12.8 miles on a single tank of fuel, its range would be more limited if it had to rely on batteries for power [1, 5]. Like "BigDog", the "Spring Flamingo" also uses springs for force control, but not for energy storage [6]. The "Spring Flamingo" successfully demonstrated force controlled walking on a slope, but is not a spring-mass model walker, is incapable of running gaits, and has passive dynamics that do not benefit its energy economy. We show, in simulation, that a leg-spring chosen for the desired running gait can provide similar disturbance rejection, while improving energy economy.

A leg-spring stiffness tuned to a realistic human-scale hopping frequency makes a good compromise between high-bandwidth force control and robustness to disturbances. For force control on realistic actuators, stiffer springs are able to track higher frequency and amplitude force profiles than softer springs, because they limit the spring deflections needed to generate a specific force output profile [4]. For a similar reason, softer springs provide better robustness to disturbances, such as unexpected impacts, because errors in the spring deflection result in smaller force errors than with stiffer springs. Existing robots that use force control for walking and running use stiff leg-springs that are well-suited to controlling a force profile against a static load, but these robots require very low inertia actuators or an accurate ground model to prevent jarring ground impacts [22]. In contrast, we choose a softer leg-spring stiffness tuned for a realistic human-scale hopping frequency. The bandwidth for tracking a varying force profile is lower for this softer spring compared to a stiffer spring, but allows our force controlled model to accommodate larger disturbances with less force error. To illustrate the trade-off between force tracking and disturbance rejection we compare the performance of our tuned leg-spring against a “soft” leg-spring, with one fifth of the stiffness of our tuned leg-spring, and a “stiff” leg-spring, with five times the stiffness of our tuned leg-spring for each of these two fundamental force control tasks, as shown in Fig. 3.4. Only the tuned leg spring provides both the force tracking bandwidth and disturbance rejection needed for the hopping experiments presented in this paper.

Our proposed force-control idea is philosophically similar in many ways to previous works including the MIT Leg Lab robots and the ARL Monopod-II [6, 23]. Like our model, these robots utilize passive dynamics, while incorporating active control. Leg Lab robots, such as the Planar Hopper, use springs to facilitate running gaits, and while not designed for energetic economy, are capable of impressive feats such as somersaults [7]. In contrast, the ARL Monopod-II, although mechanically similar to the Leg Lab robots, is designed to minimize its energy cost, and implements the aptly named "controlled passive dynamic running." This robot uses active feedback control to match its hopping trajectory with that of the system's passive dynamics, which are similar to a spring-mass model. The ARL Monopod-II calculates motor torques based on information from its previous hop, and does not begin to compensate for ground disturbances until later strides [8].

This paper builds upon our previous publication in which we first presented our novel force control strategy for improving the robustness of spring-mass model walking and running [24].

3.3 MODEL

We add a motor and associated reflected motor inertia to the simple spring-mass model, as shown in Fig. 3.2b. With these additions, we arrive at a single degree-of-freedom vertically-hopping model that includes realistic dynamics and limitations. Our model for robot hopping is schematically similar to the MIT-SEA, but in addition to using series elasticity for force control, our model also uses its spring for energy storage [2]. The spring stiffness is tuned to the natural frequency of our desired spring-mass hopper, so the energy will be stored in the spring as the mass decelerates, and recovered as the mass accelerates toward liftoff. In the ideal scenario, the motor does no work, and all of the model's behavior is expressed by the passive dynamics of the system as it bounces up and down. Any disturbance that the model encounters is handled by the actively controlled motor.

To demonstrate the benefit of a leg-spring stiffness tuned to the desired hopping frequency, we test our force controlled model against a schematically identical leg with five times the leg stiffness of our target model and similar to the MIT-SEA. For brevity, we henceforth refer to our force controlled model with tuned leg-spring as the FCM+TS, and our force controlled model with stiff leg-spring as the FCM+SS.

3.4 CONTROL STRATEGY

Our force control strategy maintains the toe force profile of the target passive system hopping on flat rigid ground, shown in Fig. 3.5. At the expected instant of ground contact our controller begins tracking the desired force profile regardless of whether touchdown actually occurred and any changes in ground dynamics. Although our force control strategy does not directly control the resting leg length, it may extend or retract the leg actuator to achieve the desired force profile. In simulation, our force control strategy measures the force in the leg and has no sensing of its environment, but is able to automatically respond to disturbances by regulating errors in the toe force profile.

3.5 SIMULATIONS AND RESULTS

We compare, in simulation, a passive spring-mass model, hopping vertically, against the FCM+TS and the FCM+SS. Each model is subject to disturbances in ground height, ground stiffness and ground damping. On flat rigid ground, the passive dynamics of the FCM+TS match the simple spring-mass model, so the motor does no work. In contrast, the FCM+SS must use active control to create an apparent leg-spring stiffness equal to that of the spring already in place on the passive model and the FCM+TS. In the presence of unexpected decreases in ground height and impedance, the active controller applies motor torques to maintain the toe force profile of the passive system. To better demonstrate the feasibility of our force control strategy in simulation, we choose somewhat arbitrary, but realistic values for a moderately-sized robot using a commercially available motor. We expect that the FCM+TS will provide better disturbance rejection than the passive spring-mass model, and a better combination of robustness to disturbances and energy economy than the FCM+SS.

We use kinetic equations of motion to simulate the vertically-hopping force controlled models. The hybrid passive dynamics of the systems are simple. In flight the models behave like masses in free-fall, and on the ground they resemble spring-mass oscillators with additional dynamic effects from their motors and non-rigid ground dynamics. It would be straightforward to develop closed-form solutions for the uncontrolled models, but motor torque limits add non-linearity to the system dynamics. Therefore, we use a numerical solver to compute an approximate solution for the models' dynamics.

There are no "sensors" that allow the FCM+TS or FCM+SS models to change their control strategy, and the models have no forewarning of ground disturbances. In each experiment, the models take one undisturbed hop on a rigid ground surface, a second hop on the disturbed ground surface, and a final hop back on rigid ground at the regular height. We consider vertical hopping in this paper, and our simulation results are plotted against time.

3.5.1 Ground Height Disturbance

The first type of disturbance we investigate is a sudden decrease in ground surface height during the flight phase, as shown in Fig. 3.3a.

For the standard spring-mass model, variations in ground height affect the center of mass trajectory and toe force profile, as shown in Fig. 3.6a and Fig. 3.7a. When the spring-mass model encounters a drop in ground height, it remains in free-fall for longer than if the ground had been at its previous height. Since the system remains in free-fall for longer, it touches down with greater velocity and the toe force profile exceeds that of the undisturbed model. The net result is that a temporary decrease in ground surface height causes a permanent shift in the center of mass trajectory of the passive model, and causes a higher peak force for the disturbed stride.

In contrast, the FCM+TS rejects the unexpected decrease in ground height by maintaining the toe force profile of the target passive system, as shown in Fig. 3.6b and Fig. 3.7b. The active control system begins to follow a force trajectory at the time of expected toe impact. Because the ground is lower than expected, and does not come into contact with the toe, it provides no reaction force, causing the leg to accelerate towards the ground until it makes contact. This control strategy maintains a relatively consistent toe force profile, even in the presence of unexpected changes in ground height. The force error that exists could be reduced with controller tuning, but some force error is unavoidable, and arises from actuator limitations. Because the center of mass trajectory is determined solely by toe forces, our force controlled hopper maintains a more consistent center of mass motion than the purely passive spring-mass model subjected to the same disturbance.

The FCM+SS, in some ways, handles the unexpected decrease in ground surface height worse than the passive spring-mass model. Neither model is able to maintain the desired center of mass trajectory, as shown in Fig. 3.6a and Fig. 3.6c, but the passive spring-mass model at least returns to its original hopping height. The electric motor that we simulate does not have the control authority to get out of the way of the stiff leg-spring, resulting in jarring ground impacts, especially when the ground surface height unexpectedly decreases. The stiff leg-spring is such a detriment to disturbance rejection that the FCM+SS actually experiences a higher peak force on the decreased ground surface than the passive spring-mass model, as shown in Fig. 3.7a and Fig. 3.7c.

The FCM+TS makes excellent use of its leg-spring for mechanical work, while the FCM+SS relies on active control for most of the work required to hop, as shown in Fig. 3.8. Both the FCM+TS and FCM+SS must expend roughly the same amount of work extending their leg into the decrease in ground surface height, as shown in Fig. 3.8b, but the FCM+SS must also use motor work to try and force the desired toe force profile, because it does not occur naturally. In contrast, the FCM+TS uses motor work only to accommodate the change in ground height, during undisturbed hopping all of the work comes from the tuned leg spring, as shown in Fig. 3.8b.

3.5.2 Ground Stiffness Disturbance

The second type of disturbance we investigate is a decrease in ground stiffness. In this experiment, the ground goes from rigid in the first stance phase to behaving like a linear spring in the second stance phase, as shown in Fig. 3.3b. As a model touches down the ground depresses proportionately to the model's toe force. The net result is that the model experiences a spring stiffness equal to the series combination of its leg spring with the ground stiffness.

For the standard spring-mass model, variations in ground stiffness affect the center of mass trajectory, as shown in Fig. 3.9a, and toe force profile, shown in Fig. 3.10a. When the spring-mass model encounters a decrease in ground stiffness, the combined ground and leg stiffness is less than the leg stiffness
of the model alone, so the natural frequency for the equivalent spring-mass oscillator decreases. The duration of the stance phase therefore increases when the ground compliance increases. However, the spring work over the stance phase remains constant, so the peak force decreases, as shown in Fig. 3.10a, as the length of stance increases. Since the stance phase duration is longer for the passive model on the decreased ground surface stiffness, liftoff occurs later than for the target passive model, and a temporary decrease in ground stiffness results in a permanent shift in center of mass trajectory for the passive spring-mass model.

In contrast, the FCM+TS maintains the toe force profile of the equivalent undisturbed spring-mass model despite changes in ground stiffness, as shown in Fig. 3.10b, such that a consistent center of mass trajectory is maintained, as shown in Fig. 3.9b. As a result of controlling the toe force profile, the FCM+TS seems to maintain its apparent leg stiffness without modeling the ground dynamics or directly adjusting its leg stiffness.

The springy ground surface helps the FCM+SS maintain a consistent center of mass trajectory, as shown in Fig. 3.9c, by making it possible for it to track the target force profile on the section of decreased ground stiffness, as shown in Fig. 3.10c. Jarring ground impacts prevent the FCM+SS from maintaining the target force profile on rigid ground, because the toe force increases faster than our controller can pull its motor out of the way. However, on the springy ground surface, the series combination of the leg and ground springs results in an apparent leg stiffness that is closer to the target passive dynamics, and improves the ability of the FCM+SS to maintain the desired force profile. Although the FCM+SS is able to track the target force profile on the springy ground, it still requires more motor work than the FCM+TS encountering the same disturbance. The FCM+TS does a better job of maintaining the target force profile and center of mass trajectory than the FCM+SS while expending less energy through motor work.

The decrease in ground stiffness improves the energy economy of the FCM+SS, but the FCM+SS does not get more work out of its leg-spring, as shown in Fig. 3.11a. During undisturbed hopping the FCM+SS relies on active control for most of its dynamic behavior, and it uses its leg-spring mostly as a force sensor. On springy ground the FCM+SS does not make better use of its own leg-spring, but it expends less energy through active control, because the ground dynamics provide a part of the energy required to hop. Even with this help from the springy ground, the FCM+SS requires more motor work than the FCM+TS hopping on the same ground surface.

3.5.3 Damped Surface Disturbance

The final type of disturbance we investigate is a decrease in ground damping, as shown in Fig. 3.3c. For this experiment the ground unexpectedly changes from being perfectly rigid to behaving like an ideal viscous damper. Viscous dampers provide a good model of realistic dissipative ground surfaces such as sand or mud [25]. In this experiment, ground reaction forces cause permanent ground deformation, but we choose to reset the ground surface height during each flight phase. We believe that this decision provides a better representation for planar hopping and 3-D running, where there is some horizontal velocity and toe contact occurs at a new location during each stride.

The passive spring-mass model loses energy when it encounters damped ground, causing an inconsistent center of mass trajectory and loss of hopping height, as shown in Fig. 3.12a and Fig. 3.13a. The passive spring-mass model has no way to re-add energy dissipated by the ground dynamics, so hopping on damped ground can stop the model from hopping.

The FCM+TS is able to successfully reject unexpected ground damping by maintaining the toe force profile of the target passive system. Our force control strategy replaces the energy dissipated by the ground disturbance without directly sensing or controlling the system energy by maintaining the toe force profile of the equivalent passive system hopping on flat rigid ground, as shown in Fig. 3.13b. On damped ground our force controlled model's toe force causes the ground to depress. As the ground depresses our controller increases the zero force leg length to maintain the target force profile. Since the ground continues to depress through stance, our control strategy does not retract the leg to its nominal length until after liftoff from the depressed ground.

The unexpected decrease in ground damping disrupts the center of mass trajectory of the FCM+SS, as shown in Fig. 3.12c, because it does not have the control authority or correct passive dynamics to maintain the target force profile, as shown in Fig. 3.13c. The FCM+SS cannot maintain the desired force profile on rigid ground, because of jarring ground impacts that arise from its stiff leg spring. The problem is exasperated for hopping on damped ground, because in addition to being unable to track the target force profile, some of the system energy is dissipated.

The FCM+TS relies on its leg-spring for most of the work needed to make the model hop, and uses active control only to re-add energy dissipated by the ground surface and correct for the resulting disturbance to the center of mass trajectory. Whereas, the FCM+SS relies predominantly on active control to "fake" the desired dynamic behavior. Hopping on rigid ground already requires more control authority for the FCM+SS than we make available to our actuated models, and damped ground disturbances add additional control effort requirements, because the energy dissipated by the ground surface must be re-added through active control. The net result is that the FCM+SS does not expend significantly more motor work on the damped surface, because it is already running at maximum capacity on the rigid ground surface, and has no hope of maintaining the target force profile or center of mass trajectory when additional work is required. In contrast, the FCM+TS expends no motor work on flat rigid ground, leaving the model plenty of control authority to replace energy dissipated by the damped ground surface.

3.6 DISCUSSION

The force control strategy that we demonstrate in this paper is optimized for temporary ground disturbances, and we choose to leave any gait decisions to a higher-level stride-to-stride controller. Our controller is not aware of upcoming ground disturbances, it does not need to be; force control is sufficient to attenuate disturbances within a single stride without identifying or adjusting for them in any way. Disturbances cause our force controlled model to adjust its zero force leg length, although our controller does not directly control the zero force leg length. When our force controlled model encounters a disturbance there is some force error that our controller regulates with motor torques. These motor torques affect the motor angle and zero force leg length, and we therefore find it helpful to add a simple PD position controller on top of our force control strategy to reset the zero force leg length during the first part of flight. For a physical system, this added control would require a sensor on the motor angle, and although our force control approach could work without this leg length resetting, it would prevent the motor from drifting during flight when there is no spring force present. By resetting the zero force leg length, our controller limits the effect that one stride has on the next, and sets itself up for a step on flat rigid ground, regardless of what was encountered in the previous stride.

Our force control strategy is not specific to a low-level control law, it only requires that its controllers are able to track a desired force profile. In this paper, we chose to use simple PD controllers and minimal hand-tuning, but many other controllers could also work.

Our simulations illustrate some system limitations caused by motor torque limits and inertia. For example, when the force controlled model encounters a drop in ground height, there is a delay between when toe touchdown is expected to occur, and when it actually does. The delay depends on the magnitude of the disturbance and physical limitations of the system, such as the motor inertia, motor torque limit, transmission ratio, and leg inertia. During this delay the motor gains angular momentum causing the actual toe force to exceed the desired toe force in the moments following toe touchdown. The simulated motor has a realistic inertia that can only be decelerated as quickly as the motor's torque limit allows. The error in the toe force profile can be minimized by tuning control constants, but the controller does not know the position of the ground or any other information about the world, so we presume that it cannot be eliminated without additional sensory input. Despite this sensor limitation, it is able to perform well, with only a small and brief discrepancy between the actual and desired toe force profiles, even in the presence of a substantial change in ground height. Despite these physical limitations, our force control strategy is able to attenuate ground disturbances by matching its toe force profile to that of an undisturbed passive system.

Although its stiff leg-spring benefited the FCM+SS on springy ground, it was otherwise a detriment to the model's performance. In this paper, we found that decreases in ground stiffness improved the FCM+SS's ability to maintain the target force profile, because they resulted in an apparent leg stiffness that was closer to the desired passive dynamics. However, the FCM+SS did not have the control authority to maintain the target force profile during steady state hopping, and its ability to track the target force profile on the springy ground required more motor work than for the FCM+TS. Reducing the motor inertia or increasing control authority could improve force control, but would not increase energy economy. This is in effect what Boston Dynamics does by using hydraulics on "BigDog" [1].

Ground damping disturbances offer a special challenge, because unlike the other types of disturbances presented which were energetically conservative, ground damping disturbances dissipate energy. For vertical hopping, sufficiently large changes in ground surface height can result in our leg spring exceeding its maximum deflection, but only the damped ground can stop the vertically-hopping model. When our force controlled model encounters a damped ground surface, its motor must do work to replace the energy dissipated by the ground surface. By matching our force controlled model's toe force profile to that of the passive spring-mass system hopping on flat rigid ground, our control strategy re-adds the dissipated energy, without directly controlling or sensing it.

3.7 CONCLUSIONS AND FUTURE WORK

In this paper we introduced a novel strategy for controlling legged robots that combines tuned passive dynamics with active force control. We started with a simple energetically conservative model for animal walking and running, and then added a motor for active force control. The underlying passive dynamics provide all of the work required to hop on flat rigid ground, and force control attenuates any ground disturbances encountered.

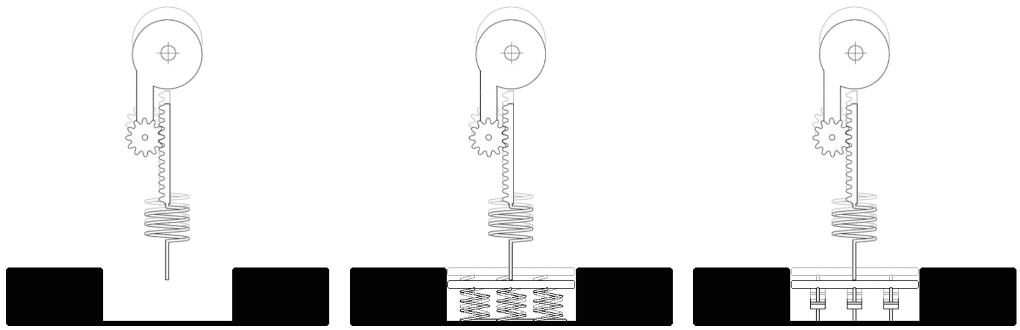
Force control is convenient to combine with a spring-mass model, and the combination responds to disturbances in a way that resembles disturbance rejection observed in animal and human experiments. Guinea fowl accommodate a decrease in ground surface height by extending their leg into the unexpected disturbance, and although our approach does not directly control leg length, it produces a similar result by attempting to maintain the target force profile. Similarly, humans and animals attenuate changes in ground stiffness through a concerted effort of tendons and muscles, and our force control strategy arrives at a similar result [20, 21]. The control policies used by humans and animals are still unknown, but the disturbance rejection of our force control strategy is at least qualitatively similar to that observed in biomechanics research.

We showed in simulation that our force control strategy makes the FCM+TS robust to unexpected changes in ground height and impedance. We subjected our model for robot walking and running to significant decreases in ground height, stiffness, and damping, and found that it was able to maintain the force profile of the passive model hopping on flat rigid ground. We believe that our results will extend to real world disturbances that incorporate a combination of the three disturbances investigated in this paper, in addition to other dynamics.

Our force control strategy is also promising for legged robots to approach the energy economy of animal walking and running. The active control system in our model intervenes with the passive dynamics only to accommodate ground disturbances, which leads to excellent energy economy in normal steady-state locomotion. All of the work required for steady state hopping is done by our model's tuned leg-spring.

Our control strategy is practical for walking and running robots that have limited control authority, sensing, and that must carry there own energy supply. We used simulation parameters, such as torque limits and body mass, estimated from a robot of our own design and construction using a commercially available electric motor, shown in Fig. 3.1b. Our force control strategy only requires sensing of the leg-spring deflection, and not of the environment, and because it is capable of excellent energy economy, it could increase the range of walking and running robots.

The long-term goal of this work is to build a biped with excellent energy economy capable of robust walking and running gaits. As an intermediate step towards this goal, we are extending the single degree of freedom model presented in this paper to a two degree of freedom monopod in simulation. We will then demonstrate our concept of adding force control to the spring mass model on physical systems, including a single degree of freedom benchtop actuator, a two degree of freedom monopod, shown in Fig. 3.1b, and eventually on a tether-free biped, shown in Fig. 3.1c. With these real-world devices we hope to approach the performance of animal walking and running.

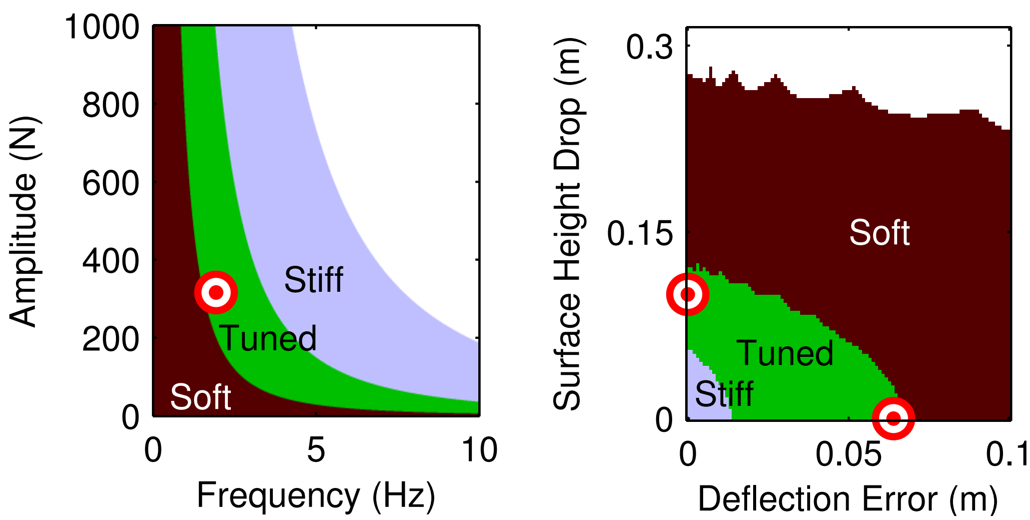


(a) Ground surface height disturbance.

(b) Ground stiffness disturbance.

(c) Ground damping disturbance.

Figure 3.3: We subject our force controlled model to disturbances in ground surface height and impedance.



(a) Regions where tracking a force profile is possible. The target represents our desired gait.

(b) Regions where a constant force can be maintained. The targets approximate the experiments we present.

Figure 3.4: Stiffer springs can track higher frequency and amplitude force profiles, shown in Fig. 3.4a, but softer springs provide better robustness to disturbances, shown in Fig. 3.4b. A leg-spring stiffness tuned to the desired gait is necessary for energetically economical hopping, but is also a good compromise between these two disparate tasks.

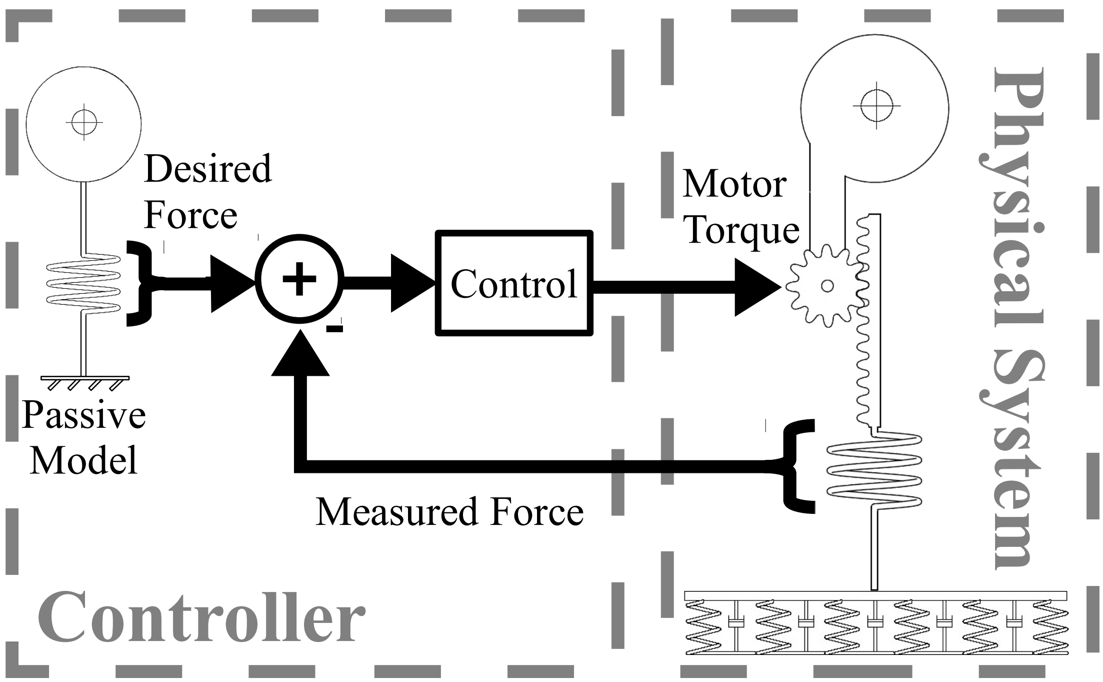
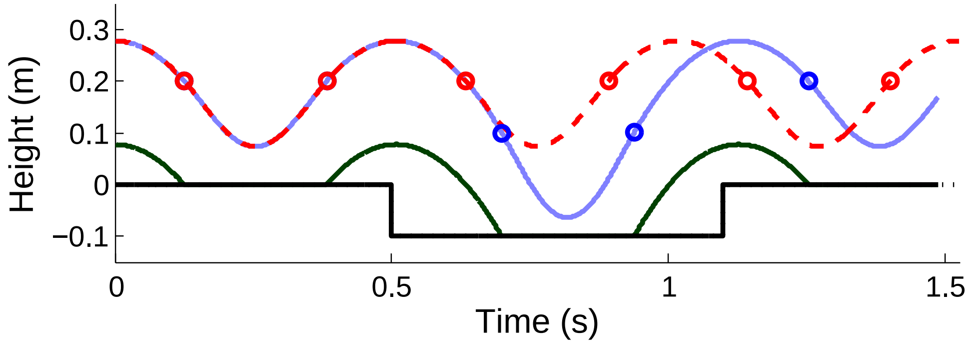
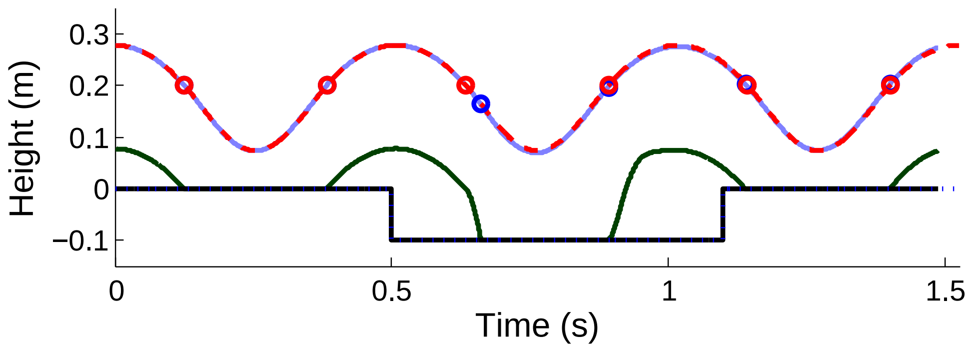


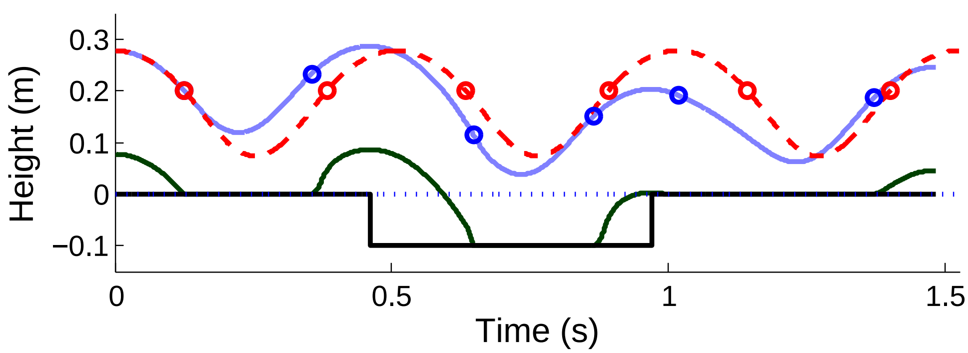
Figure 3.5: Our controller matches the toe force profile of the physical system hopping on realistic ground surfaces, in simulation, to that of an equivalent, but passive spring-mass model hopping on flat rigid ground.



(a) Temporary changes in ground surface height cause a permanent shift in the center of mass trajectory for the passive spring-mass model.



(b) FCM+TS maintains a consistent center of mass trajectory despite unexpected changes in ground surface height.



(c) FCM+SS cannot maintain the center of mass trajectory of the target passive dynamics.

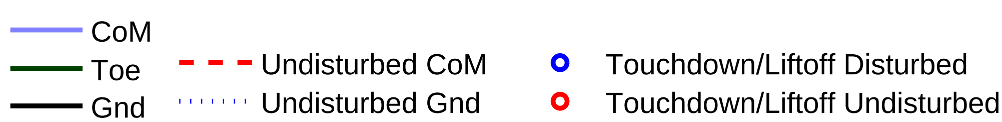
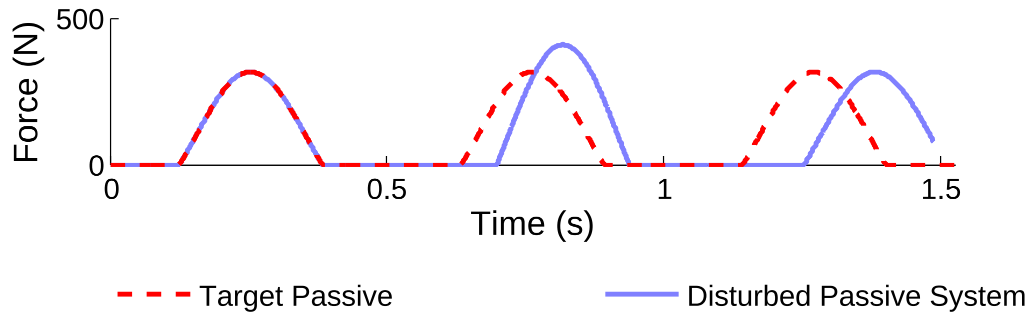
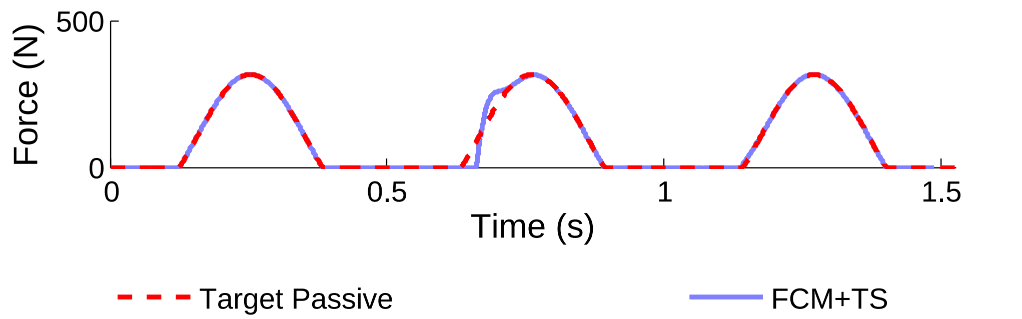


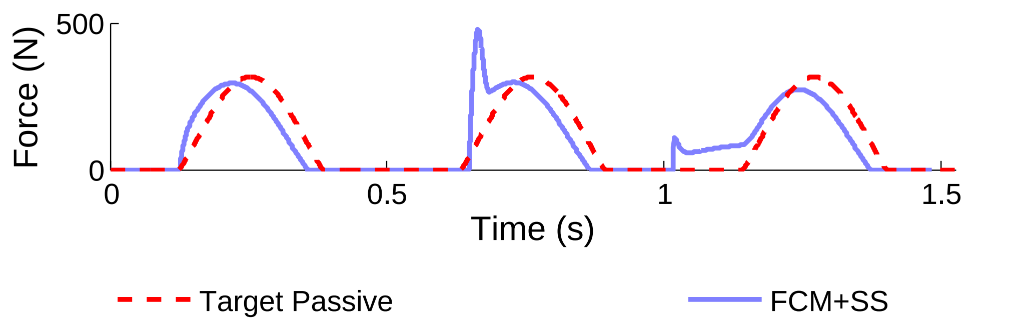
Figure 3.6: Our force control strategy combined with a leg-spring stiffness tuned to the desired passive dynamics rejects unexpected changes in ground surface height.



(a) The toe force profile of the passive spring-mass model increases when the ground surface height decreases.

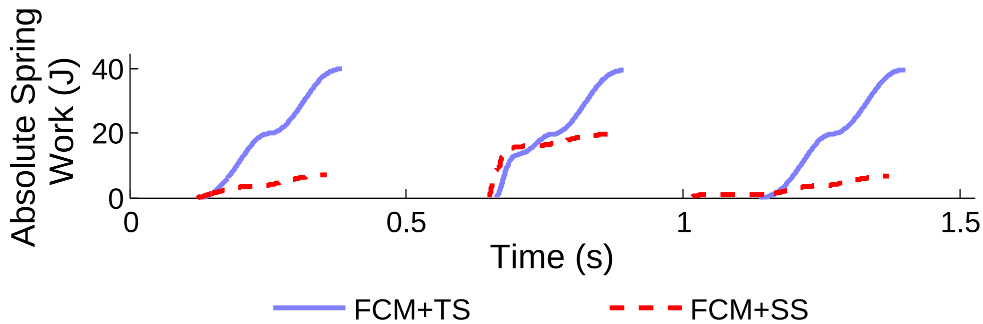


(b) The FCM+TS maintains the toe force profile of the target passive system. Actuator limitations make some toe force error unavoidable.

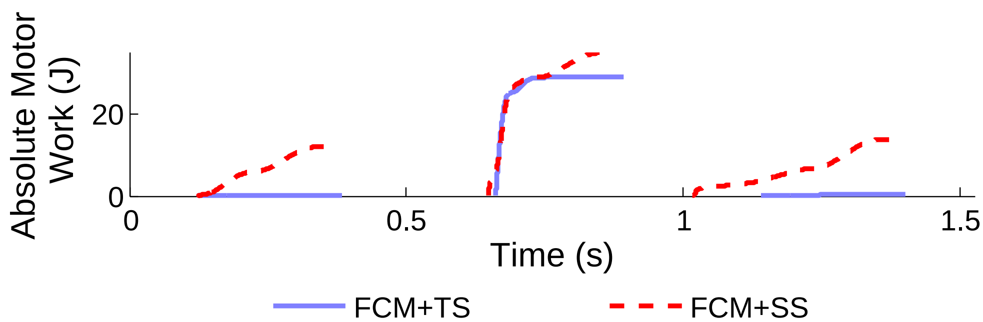


(c) The FCM+SS cannot control ground impact forces.

Figure 3.7: The FCM+TS prevents jarring ground impacts and returns to the target toe force profile.

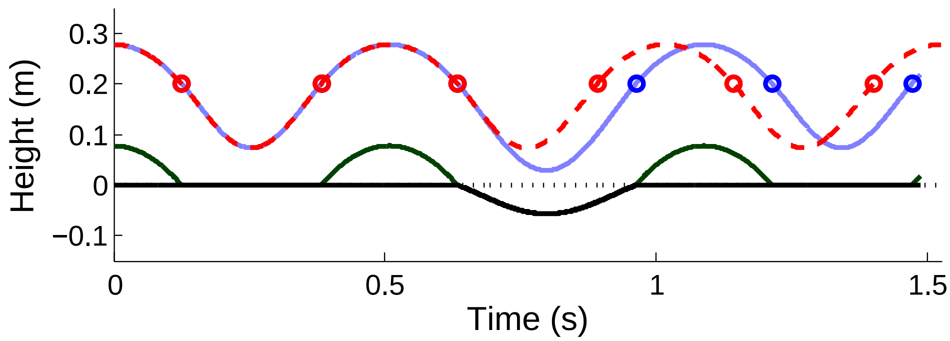


(a) The FCM+TS uses its leg-spring to do most of the work required to make the model hop.

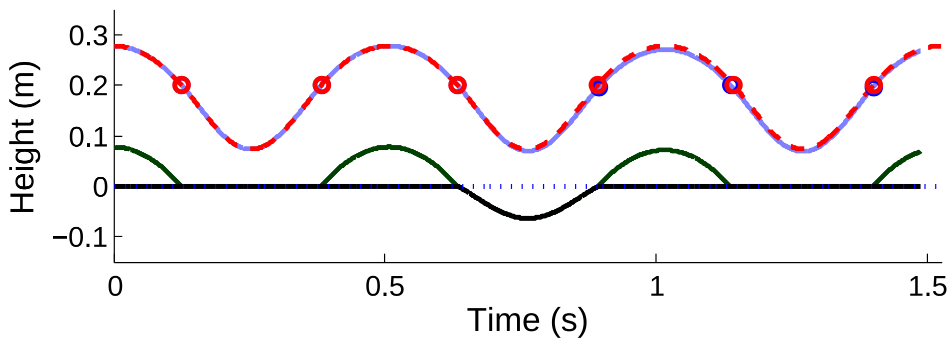


(b) The FCM+TS uses motor work only to reject the unexpected decrease in ground surface height. In contrast the FCM+SS relies on motor work even during steady-state hopping.

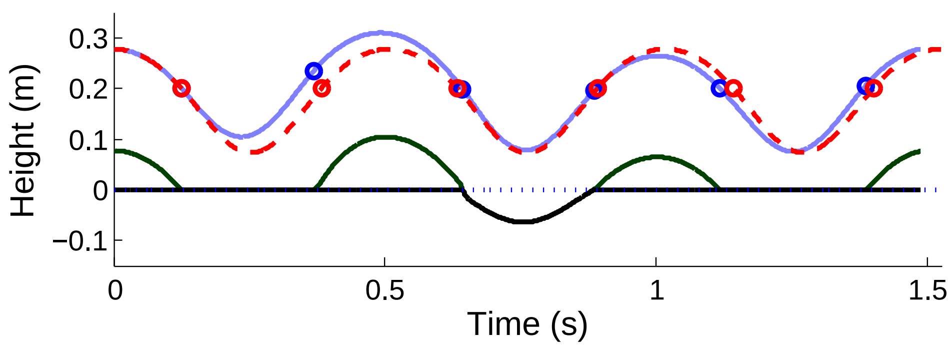
Figure 3.8: Both the FCM+TS and FCM+SS require motor work to accommodate the unexpected decrease in ground surface height, but the FCM+TS makes much better use of its leg-spring and does no motor work during undisturbed hopping.



(a) A temporary decrease in ground surface stiffness causes a permanent shift in center of mass trajectory for the passive spring-mass model.

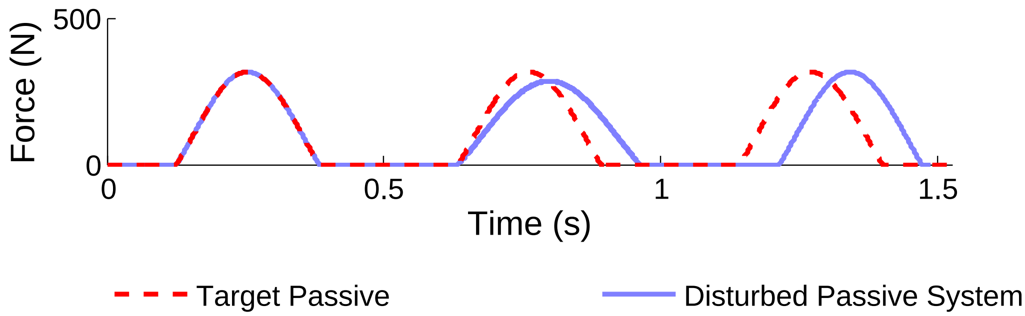


(b) The FCM+TS maintains a consistent center of mass trajectory despite an unexpected decrease in ground stiffness.

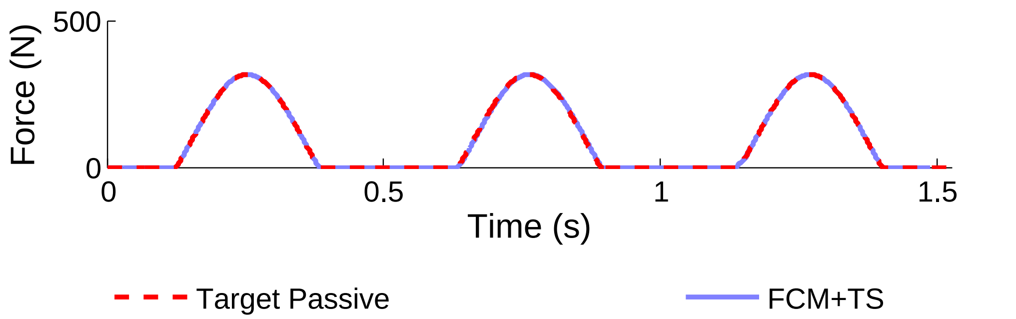


(c) The FCM+SS is also able to accommodate an unexpected decrease in ground stiffness, although its center of mass trajectory is not as consistent as with the tuned spring.

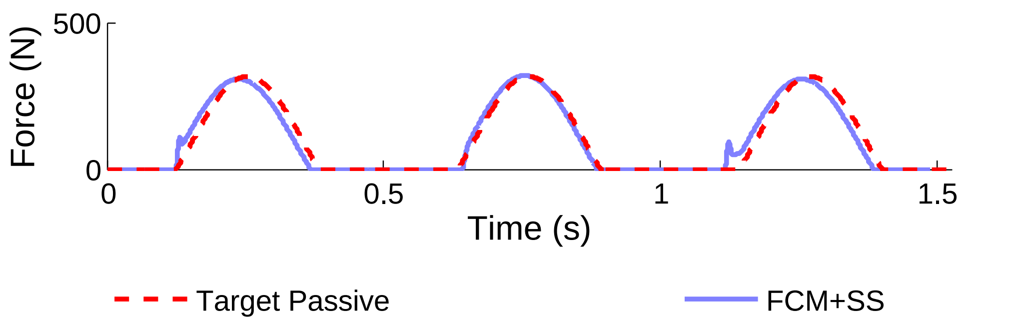
Figure 3.9: The force controlled models are able to maintain a more consistent center of mass trajectory in the presence of ground disturbances then the passive spring-mass model.



(a) The toe force profile of the passive spring-mass model is disrupted by an unexpected decrease in ground stiffness.

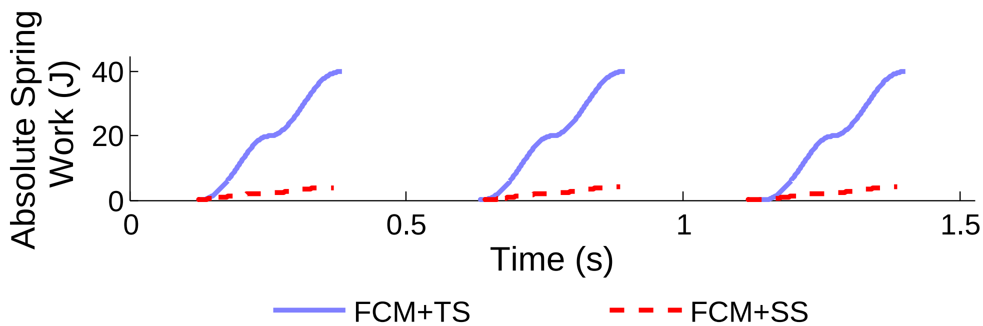


(b) The FCM+TS maintains the toe force profile of the target passive system.

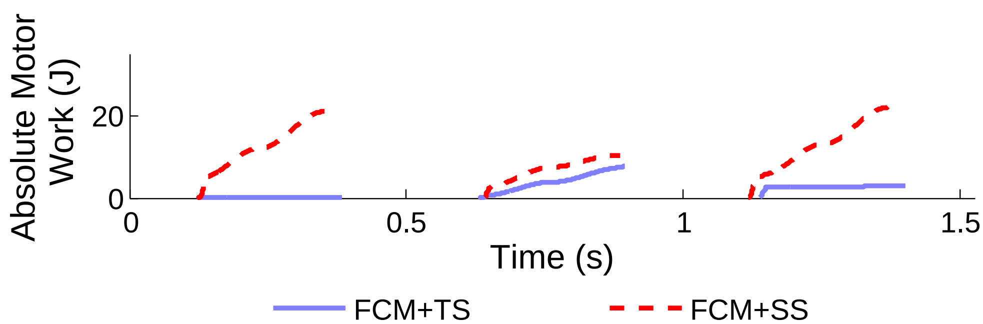


(c) The FCM+SS is assisted by the unexpected decrease in ground stiffness, because it reduces the apparent leg stiffness bringing it closer to the tuned leg stiffness.

Figure 3.10: Our force control strategy maintains a toe force profile in the presence of changes in ground stiffness.

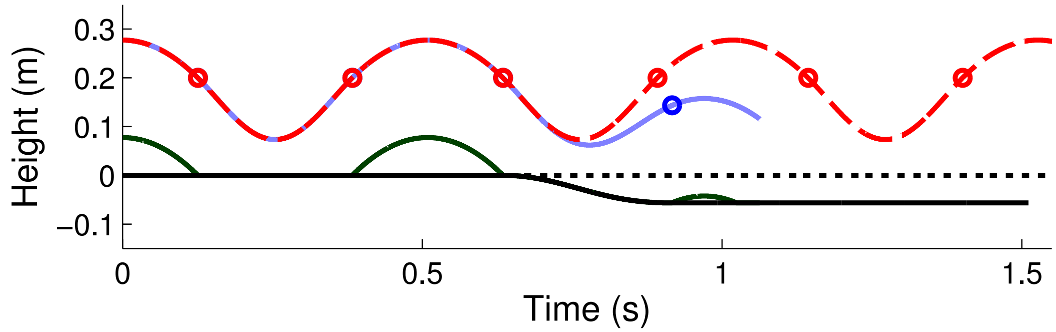


(a) The FCM+TS gets more work out of its leg spring then the FCM+SS, which leads to better energy economy.

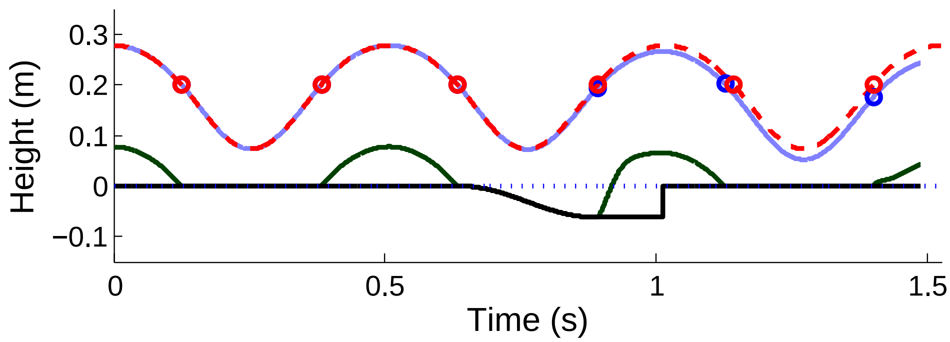


(b) The FCM+TS uses motor work only to accommodate for the unexpected decrease in ground stiffness, and the resulting center of mass trajectory disruption.

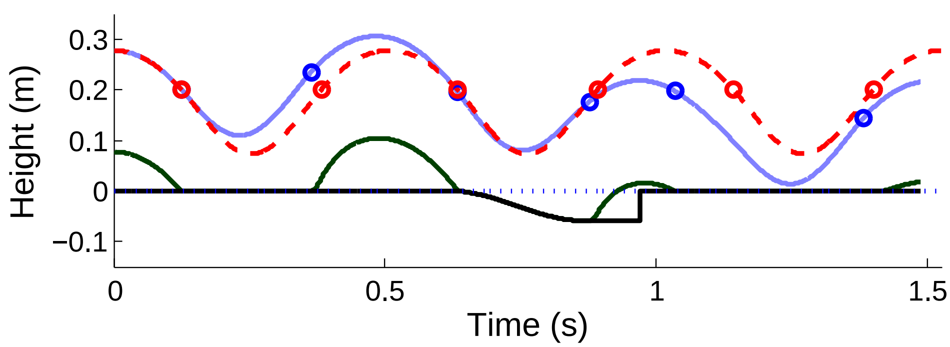
Figure 3.11: The FCM+TS makes excellent use of its leg-spring for energy economy. In contrast the FCM+SS gets very little work out of its leg spring, and most of the energy required to make the model hop must come from the active controller emulating spring.



(a) The passive spring-mass model loses a large part of its energy to the damped ground.



(b) The FCM+TS re-adds most of the energy dissipated by the disturbance such that a consistent center of mass trajectory is roughly maintained.



(c) An unexpected decrease in ground damping disrupts the center of mass trajectory of the FCM+SS.

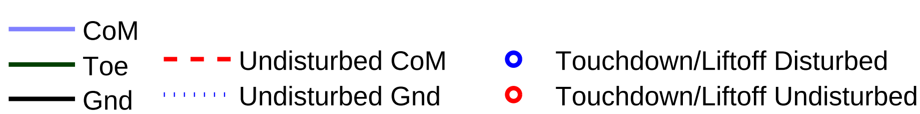
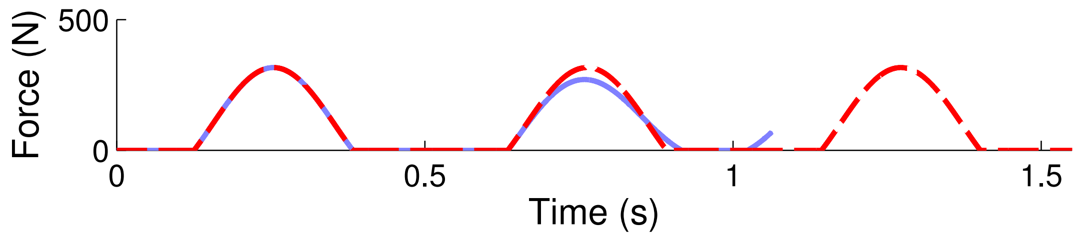
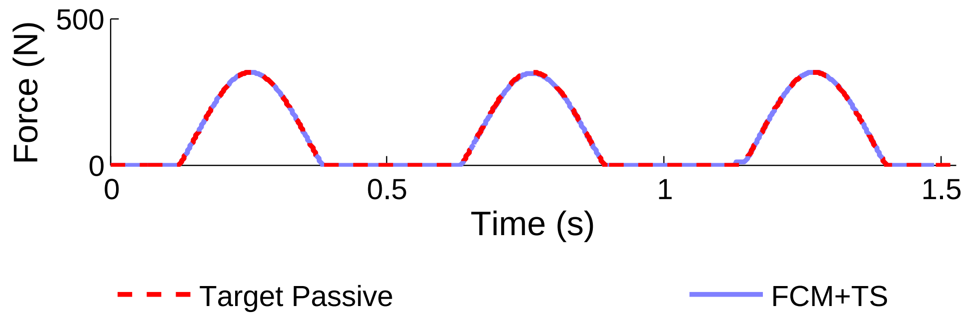


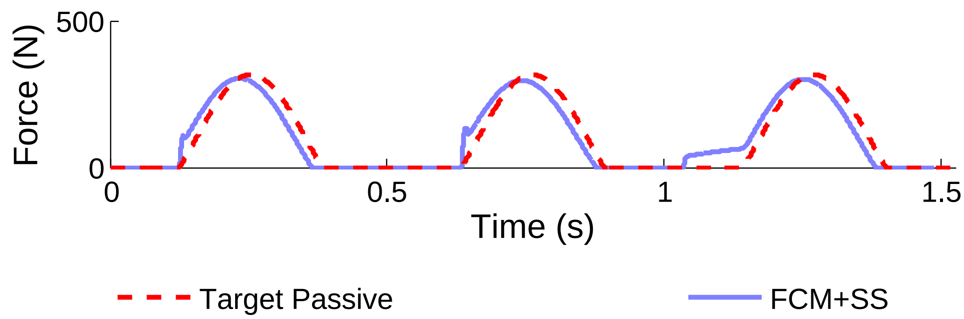
Figure 3.12: The passive spring-mass model and FCM+SS are unable to reject an unexpected decrease in ground damping. The combination of force control with a tuned leg-spring, the FCM+TS, is able to accommodate the disturbance better than force control, or a tuned leg-spring alone.



(a) The toe force profile of the passive spring-mass model is permanently disrupted by a temporary decrease in ground damping.

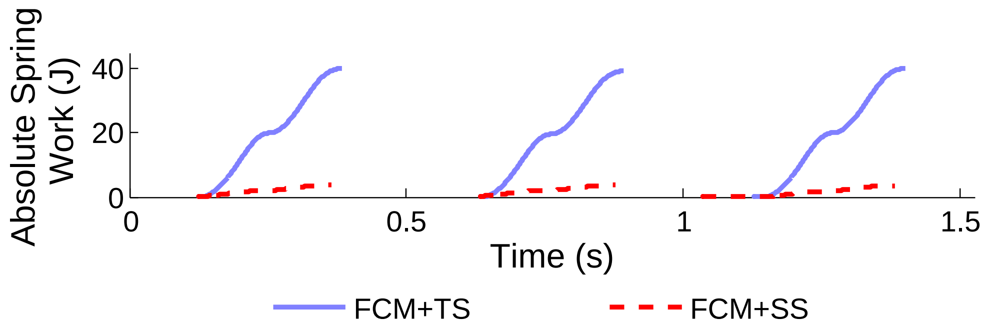


(b) The FCM+TS maintains the toe force profile of the target passive system despite an unexpected decrease in ground damping.

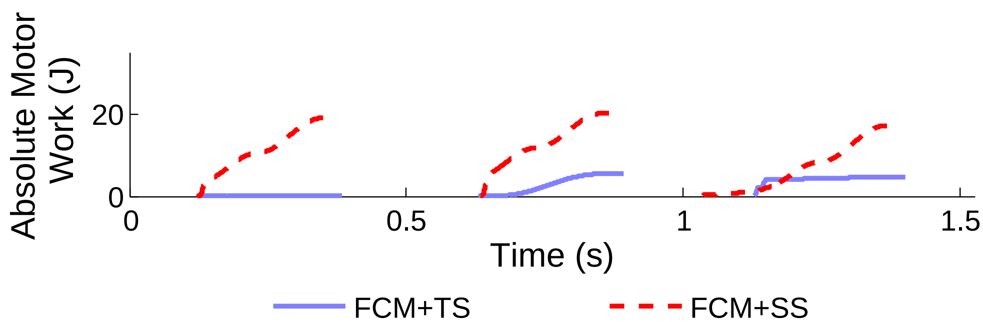


(c) The FCM+SS struggles to match its toe force profile to that of the target passive system.

Figure 3.13: The FCM+TS does a better job of maintaining a toe force profile in the presence of a ground damping disturbance than the passive spring-mass model or the FCM+SS.



(a) The FCM+TS gets a lot of work out of its leg-spring compared to the FCM+SS.



(b) The FCM+TS uses motor work only to accommodate for the unexpected decrease in ground damping, and the resulting center of mass trajectory disruption.

Figure 3.14: The FCM+TS makes excellent use of its leg-spring during undisturbed hopping, but it also helps the model reject unexpected changes in ground damping. The FCM+SS must use active control to simulate a softer leg spring, while re-adding energy dissipated by the ground surface.

Chapter 4 – Force Control for Planar Spring-Mass Running

In this chapter, we present a novel control strategy for spring-mass running gaits which is robust to disturbances, while still utilizing the passive dynamic behavior of the mechanical model for energy economy. Our strategy combines two ideas: a flight phase strategy, which commands a hip angle trajectory prior to touchdown, and a stance phase strategy, which treats the spring-mass system as a force-controlled actuator and commands forces according to an ideal model of the passive dynamics. This combined strategy is self-stable for changes in ground height or ground impedance, and thus does not require an accurate ground model. Our strategy is promising for robotics applications, because there is a clear distinction between the passive dynamic behavior 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.

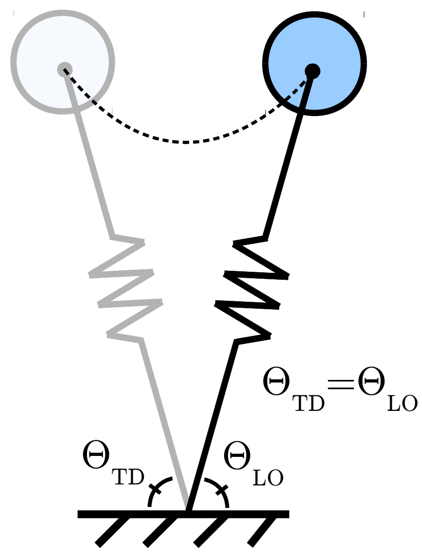
4.1 INTRODUCTION

Walking and Running robots, in general, have significant ground to cover before they can approach the abilities of animals. Walking and running animals are able to attenuate significant disturbances, such as uneven ground, while maintaining excellent energy economy. Existing passive walkers, such as the Cornell Walker, are capable of energy economy similar to animals, but will fall in the presence of small disturbances [26]. Robots that rely primarily on active control, such as Boston Dynamics' "BigDog," can demonstrate impressive robustness to disturbances at the expense of energy economy [1]. Our goal is to create robots that combine the robustness to disturbances of actively controlled machines with the energy economy of a passive dynamic walker.

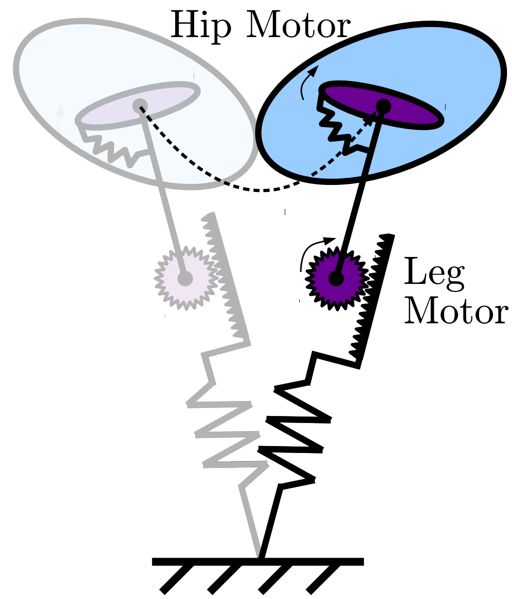
In this paper, we present an actuated spring-mass model that is suitable for implementation as a real system, shown in Fig. 4.1b, and an associated control strategy for planar running. The control strategy works in conjunction with our model to utilize the passive dynamics where possible for energy economy, and to add or remove energy only when necessary via actuation. We show in simulation that the combined model and controller is energetically conservative like the completely passive spring-mass model during steady-state running, but is self-stable in the presence of disturbances in the ground height or impedance. In other words, our model and controller combine the benefits of passive dynamics and active control, producing an efficient and robust running gait.

The control strategy in this paper combines two concepts: control of the leg angle position during flight, similar to that described by Seyfarth et al., and active force control in the leg length direction during the stance phase, described in our earlier publication for vertical hopping [27, 24].

Our leg angle controller is based on maintaining a symmetrical stance phase,



(a) The passive spring loaded inverted pendulum (SLIP) model.



(b) Our actuated spring-mass model.

Figure 4.1: Starting with the passive SLIP model, we add hip and leg motors for active control, and body moment of inertia.

where the velocity vector of the center of mass at liftoff will be a perfect mirror of the velocity vector at touchdown; the horizontal component will be identical, and the vertical component will be equal and opposite, as shown in Fig. 4.1a. A symmetrical stance phase leads to an equilibrium gait, because each stance phase is identical to the last if there are no outside disturbances. For a given spring-mass model, with a particular center-of-mass velocity vector at touchdown, there is a particular leg angle at touchdown that will result in a symmetrical stance phase. We calculate this leg angle for each instant of time during the flight phase, as the velocity vector changes, such that the spring-mass model will have a symmetrical stance phase no matter when its foot makes contact with the ground.

Controlling the leg angle for a symmetrical stance phase will ensure an energetically optimal, stable gait on unpredictable, uneven terrain. However, changes in ground impedance, such as changes in ground stiffness or damping, will destabilize the gait. To handle such disturbances, we implement stance phase force control. The actuators control the deflection of the leg spring as a function of time, and thus the toe force as a function of time, to match the ideal force profiles of the undisturbed passive spring-mass system. In the absence of disturbances the result is that the motor holds its position, and the spring does all the work. By maintaining a specific force profile, the leg appears to automatically adjust its stiffness to accommodate changes in ground stiffness, to adjust its zero force leg length to attenuate changes in ground surface height, and to add energy to accommodate increased ground damping.

Our simulation results show that our control strategy can make the spring-mass model, hopping in the vertical plane, robust to ground disturbances with limited sensory input. Our strategy is based only on the spring deflections, center of mass velocity, motor, and body angles, and not on any external sensing, which makes it practical for legged robots, such as ours, shown in Figures 4.8a and 4.8b, that have incomplete knowledge of the world. While the passive dynamics of the system attenuate very high-frequency disturbances, the force controller focuses on the middle-frequency disturbances, leaving any high-level gait choices or stride-to-stride control to a higher-level control system. This novel concept of combining force control and a spring-mass model is convenient, easy to implement on a real system with dynamic and sensing limitations, and effective.

4.2 BACKGROUND

Because our goal is to build robots that can match the performance, economy, and robustness of animal running, our models incorporate passive dynamics similar to those observed in animals. Spring-mass models provide a good approximation for animal running, we therefore begin with a simple model consisting of a mass bouncing on a spring, as shown in Fig. 4.1a [28].

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. 4.2, resulting in only slight deviation from their undisturbed gait [29]. 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 [14]. 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 [13].

The simple spring-mass model is capable of some passive stability, but without careful control of the leg angle at touchdown it tends to become unstable and fall [30]. A simple leg angle controller based on tuplets of natural frequency, zero-force

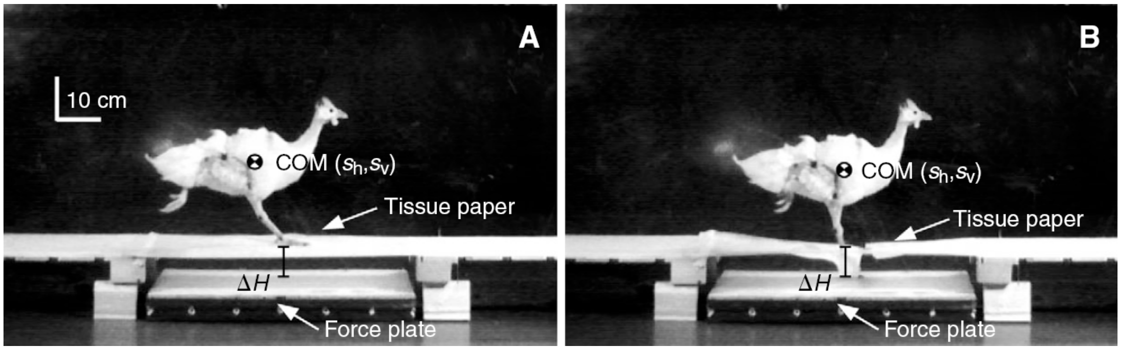


Figure 4.2: Motivation comes from the economy and disturbance rejection ability of animals such as the guinea fowl. The guinea fowl is able to accommodate for the unexpected decrease in ground surface without a significant change to its steady-state center of mass motion.

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 [27]. However, these methods require tuning, and are subject to controller optimality.

A more reliable method of selecting a leg touchdown angle for SLIP model running, presented by Ernst et al., prevents falls by ensuring a center of mass trajectory during stance that is symmetrical about midstance [31]. We call this type of gait an equilibrium gait, because its strides are equal, and in the interest of brevity, will henceforth refer to Ernst et al.'s method of selecting the leg touchdown angle as the Ernst-Geyer-Blickhan (EGB) method.

Equilibrium gaits are desirable for applications such as ours, where a consistent center of mass trajectory and toe force profile are desired. We therefore adopt the EGB method as a baseline for comparison and use it on our force-controlled model for setting the flight phase leg angle to the equilibrium gait leg touchdown angle.

Controlling the leg angle in this way requires a method for finding the equilibrium gait leg touchdown angle, but since the stance phase dynamics of the spring-mass model hopping with non-zero horizontal velocity in the vertical plane are non-integrable, analytically computing this equilibrium gait leg touchdown angle is not possible [32]. This limits us to numerical solutions or analytical approximations such as those presented by Geyer et al. [33]. For the purposes of this paper, we generate a three input look up table, but a trained neural network was also considered, and other approximations could yield similar results.

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 SEA measures and controls the deflection of its spring, which corresponds to the force applied by the actuator [2]. As an added benefit, the series spring filters impulsive forces, improving the SEA's robustness to shock loads [3]. 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 [4]. 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" [5, 6]. These robots use springs in much the same way as the SEA, as a force sensor and mechanical filter, but not for energy storage. When correctly applied, this approach can result in impressive performance, but at the cost of high energy consumption.

4.3 MODEL

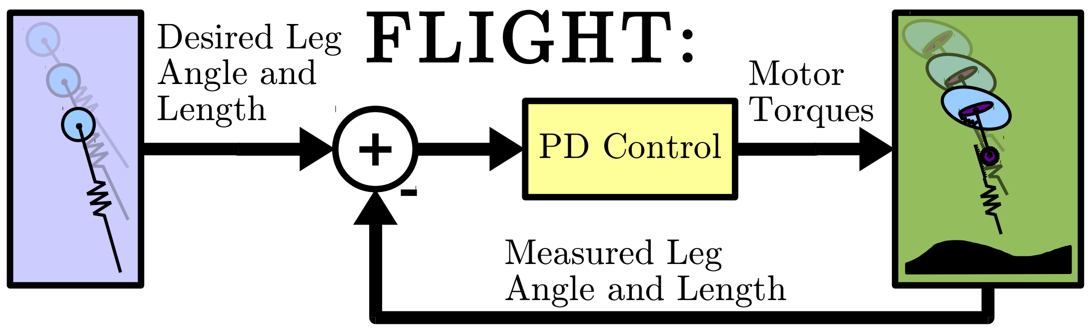
Starting with the simple spring-mass model, shown in Fig. 4.1a, we add hip and leg actuation as well as body moment of inertia to arrive at a realistic model for robot running, as shown in Fig. 4.1b. The actuators include a motor with a torque limit and rotor inertia. We chose to omit a leg mass, because it composes less than one percent of our total target robot mass, shown in Figure 4.8b. 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.

We use kinetic equations of motion to simulate our force-controlled model hopping in the vertical plane. Although developing these non-linear equations is straightforward for both the standard spring-mass model and the force-controlled model, finding a closed-form solution for the trajectories of either is impossible [32]. However, we are able to generate approximate numerical solutions using ordinary differential equation solvers.

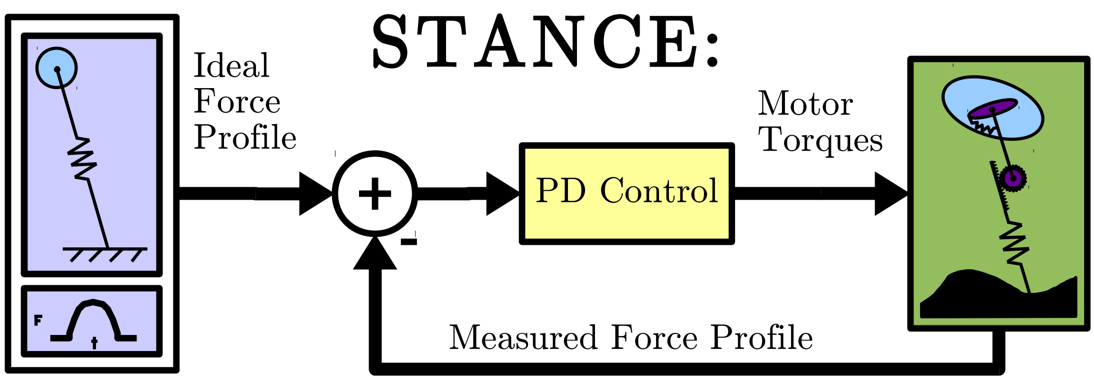
4.4 CONTROL STRATEGY

Our controller attempts to match the force-controlled model's toe force profile to that of an equivalent undisturbed spring-mass model, such that the center of mass movement is roughly the same for both.

During flight, we use PD position control of the hip motor and the EGB method



(a) In flight we set the leg angle using the Ernst-Geyer-Blickhan method, and the zero force leg length such that it remains equal to that of the equivalent passive model, unless there is a change in ground height.



(b) During stance we command the toe force profile of the passive model hopping on flat rigid ground.

Figure 4.3: Our approach switches between flight and stance controllers according to whether force is present in the model's springs.

to set a leg angle trajectory, such that the model touches down in an equilibrium gait regardless of when the toe contacts the ground. We use a numerical solution for the SLIP model along with a gradient descent algorithm to generate a lookup table for the equilibrium gait leg angle, in much the same way as presented by Ernst et al., but we also consider the zero-force leg length as an input to our leg angle lookup table, since it varies in response to ground surface disturbances [31].

In stance, we use PD torque control of the hip actuator to approximate an ideal hinge, such that the force-controlled model behaves like a SLIP model in stance with a point-mass body. The hip motor must track the motion of the leg in stance to maintain zero deflection of the hip spring; this task is equivalent to maintaining constant force against a moving load, a task which has been approached analytically in previous works [4]. Although optimal performance for a force control task would require very low motor inertia and spring stiffness, we use realistic values from the design of a legged robot we are currently constructing, shown in Fig. 4.8a. The limitations imposed by these realistic passive dynamics are represented in our results.

The leg actuator attenuates ground disturbances by controlling the force in the leg spring. The leg spring stiffness is tuned to the natural frequency of our desired spring-mass hopper, so energy will be stored in the spring during the first part of stance, and then recovered as the body mass accelerates towards liftoff. In the ideal scenario, the leg motor does no work, the hip motor is only responsible for moving its own inertia and does no work on the environment, and all of the model's behavior is expressed by the passive dynamics of the system as it bounces forward. In the presence of disturbances, critically damped PD force control of the leg motor generates torques such that a toe force profile can be followed provided that the motor's torque limits are not exceeded. As a result of attempting to control the force when the toe is not in contact with the ground, our controller adjusts the leg length during flight when toe contact is not achieved at the time predicted by the undisturbed ideal passive model.

Our active control strategy maintains the passive dynamics of the equivalent spring-mass system, and intervenes with the passive dynamics of the simple model only to accommodate ground disturbances. When our model encounters an unexpected change in ground height or stiffness, the leg extends or retracts such that the toe forces match those of the undisturbed passive dynamics. During undisturbed hopping our simulation behaves like a simple spring-mass model with minimal interference from active controllers. Aside from setting the leg touchdown angle, active control does work only when a ground disturbance is encountered.

4.5 SIMULATIONS

We compare, in simulation, three models: a passive spring-mass model with constant leg angle at touchdown, a spring-mass model that adjusts its leg angle in flight according to the EGB method, and our force-controlled model that combines the EGB method with force control. The three models are subjected to changes in ground height and ground stiffness. To better demonstrate the feasibility of disturbance rejection on our model in simulation, we choose somewhat arbitrary, but realistic values for a moderately-sized robot using a commercially available motor, such as our ATRIAS monopod, shown in Fig. 4.8a.

The unactuated spring-mass models are not subjected to any of the physical limitations that we impose on our force-controlled model. They are able to instantaneously set their leg angle, their hip behaves like an ideal hinge during stance, and they do not have motors that can hit their torque limit, accumulate angular momentum, or be backdriven.

We expect ground disturbances to result in permanent shifts in hopping phase and height for the standard spring-mass models, if not a loss of stability and falls. However, we expect our force-controlled model to accommodate ground disturbances and to closely follow the toe force profiles and center of mass trajectory of the undisturbed system.

4.5.1 Ground Height Disturbance

The first type of disturbance we investigate is a decrease in ground height. There are no "sensors" that allow the model to change its control strategy, and it has no forewarning of the change in ground height. After its first hop on the flat rigid surface, the model takes its second hop onto the lower ground surface, and the ground surface then returns to its original height for a third hop. We choose a ground height disturbance of sufficient magnitude to cause the passive model with constant leg touchdown angle to become unstable and fall.

For the standard spring-mass models, variations in ground height affect the toe force profile and center of mass trajectory, as shown in Fig. 4.4a, 4.4b, and 4.5. When these models encounter a drop in ground height, they touchdown with greater velocity and the toe force profile exceeds that of the undisturbed model. The spring-mass model with constant leg touchdown angle becomes unstable in the example we present, and falls soon after the disturbance, as shown in Fig. 4.4a, but the spring-mass model using the EGB method hops through the disturbance without losing stability. The decrease in ground height disturbance causes the model with constant leg touchdown angle to lose horizontal velocity, making its leg touchdown angle too shallow, whereas the model using the EGB method maintains a constant horizontal velocity.

In contrast to the passive spring-mass models, the toe force profile of our force-controlled model is roughly maintained despite changes in ground height, such that the peak force does not increase from the undisturbed gait. The active control system extends the leg as quickly as possible, given the leg motor torque limit, at the time of expected toe impact. When toe impact occurs, the leg actuator begins to track the force profile of the equivalent passive system hopping on flat rigid ground. The result is a small phase shift in the center of mass trajectory and toe force profile, as shown in Fig. 4.5, that is caused by the leg motor torque limit and inertia. These physical limitations and the lack of sensing of the environment makes some deviation inevitable, but we note that we can greatly reduce the deviation using the approach we describe.

4.5.2 Ground Stiffness Disturbance

The second type of ground disturbance we investigate is a decrease in ground stiffness. For this experiment, the ground unexpectedly changes from being perfectly rigid to behaving like an ideal spring in all directions. 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 standard spring-mass models, 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. 4.7a, 4.7b, and 4.6. When these models touchdown on a non-rigid surface, their apparent leg stiffness becomes the series combination of their leg spring and the ground stiffness, and their leg touchdown angle, which would have produced an equilibrium gait on rigid ground, is too steep for the decrease in stiffness. Even for small decreases in ground stiffness, the standard spring-mass model with constant leg touchdown angle becomes unstable and falls. The standard spring-mass model with EGB leg touchdown angle can avoid falls due to ground stiffness perturbations by adjusting its leg touchdown angle to compensate for the higher horizontal velocity and lower hopping height that result from the disturbance. However, the EGB method will fail if a disturbance is severe enough that liftoff does not occur or an equilibrium gait touchdown angle cannot be found, as shown in Fig. 4.7b.

In contrast, the force-controlled model maintains the toe force profile of the equivalent undisturbed spring-mass model despite changes in ground stiffness. Controlling the toe force profile results in the leg extending into the soft ground during the first half of stance and retracting during the second half, such that the toe force profile and apparent leg stiffness are roughly the same as for the undisturbed model hopping on flat rigid ground, as shown in Fig. 4.7c. As with the ground height disturbance, there is a slight deviation away from the undisturbed center of mass trajectory that results from motor limitations. This is because at the instant of touchdown, infinite motor torque is required to instantaneously give the leg motor the angular velocity necessary to perfectly match the toe force profile of the undisturbed system, but we limit the motor torque to that of a commercially available motor.

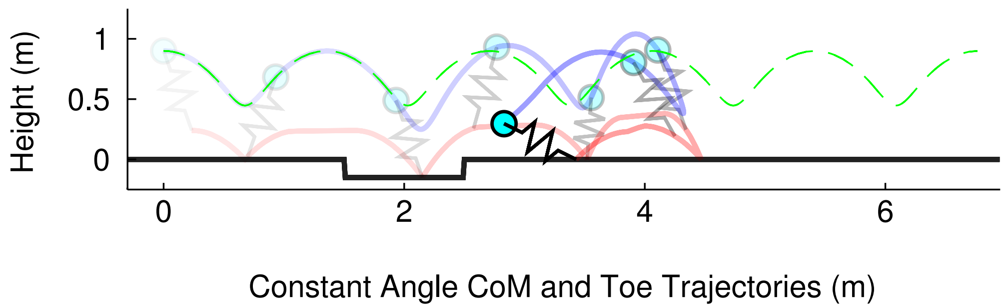
4.6 CONCLUSIONS AND FUTURE WORK

We have shown in simulation that active force control combined with careful control of the leg touchdown angle yields good disturbance rejection for spring-mass model running, while requiring little sensory feedback and minimal active control. An untethered robot using our control strategy would require only joint position sensors, and an inertial measurement unit for sensing the center of mass velocity during flight. During steady state hopping, the model predominantly relies on its passive dynamics as it hops forward, maintaining much of the energy economy of the entirely passive system. In the presence of disturbances, we use active motor control to approximate the toe force profile of the passive spring-mass model on a flat rigid surface. The deviation that exists is due to motor limitations, and diminishes with greater control authority. Because the toe force profiles are close, the model's center of mass movement follows that of the undisturbed ideal passive system.

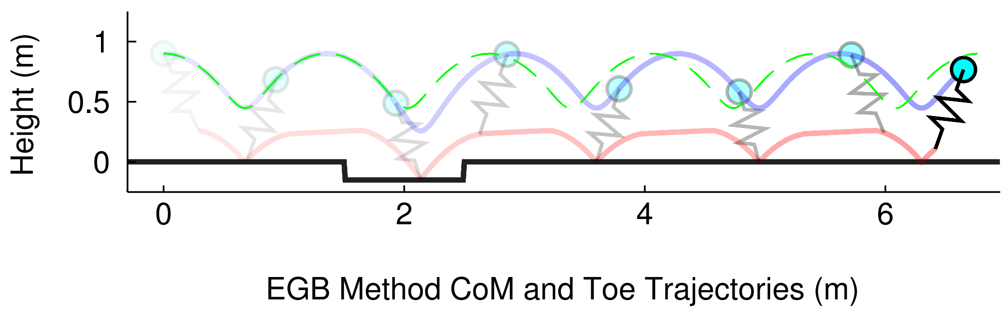
The simulation illustrates some system limitations caused by the motors' torque limit and inertia. When the force-controlled model encounters a drop in ground height, there is a delay between when toe touchdown is expected to occur, and when it actually does. The delay depends on the magnitude of the disturbance and motor limitations. During this delay, the motor gains angular momentum, causing a slight asymmetry in the stance of the force-controlled model. The simulated motor has a realistic inertia that can only be accelerated and decelerated as quickly as the motor's torque limit allows. The error in the toe force profile can be minimized by tuning control constants, but the controller does not know the position of the ground or any other information about the world, so we presume that it cannot be eliminated without additional sensory input. Despite this sensor limitation, our force controlled model outperforms the idealized un-implementable SLIP model using the EGB method to set its leg touchdown angle. It is able to perform well, with only a small discrepancy between the actual and desired toe force profiles, even in the presence of a substantial change in ground height.

Sensory and physical limitations affect the ability of the model to remain in an equilibrium gait. The performance of the in-flight leg touchdown angle controller is dependent on the accuracy of force and angle measurements during stance, the accuracy of the approximation method, the angular momentum of the leg motor at touchdown, and the control authority of the the hip motor. On a physical system with sensory, computing, and physical limitations, this dependency is unavoidable, and while such limitations could easily be lifted from our simulation, we chose to include them to better illustrate the feasibility of taking our force control approach on a physical system.

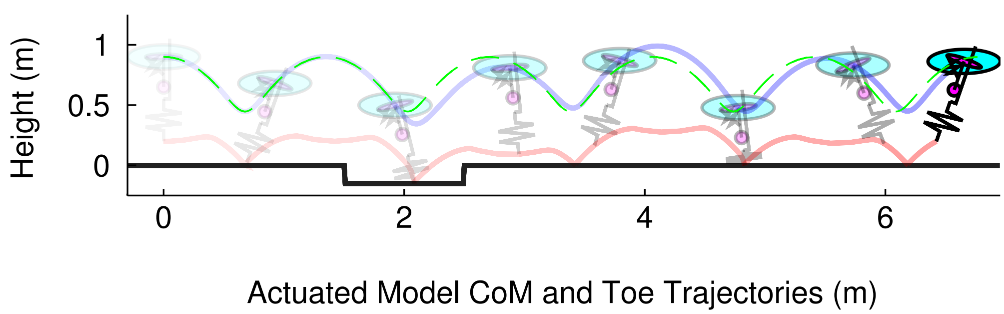
The long-term goal of this work is to build a model and bio-inspired biped capable of robust walking and running gaits. Previously we showed how force control could be used to add disturbance rejection to a vertically hopping force-controlled spring-mass model [24]. We have now shown how this idea can be extended to the vertical plane in simulation on a model with similar limitations to a physical system we are building, shown in Fig. 4.8a. We are now working to demonstrate our concept of adding force 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. Our biped will maintain as much of the energy economy of the equivalent passive system as possible by making excellent use of its passive dynamics, while limiting the need for sensory feedback and active control. With these real-world devices, we hope to approach the performance of animal walking and running.



(a) The passive spring-mass model with constant leg touchdown angle encountering a decrease in ground surface height. The model falls shortly after the disturbance.



(b) A standard spring-mass model using the EGB method to select the leg touchdown angle encountering a decrease in ground surface height. Although the model does not fall, its center of mass trajectory is affected by the disturbance.



(c) The force-controlled model encountering a decrease in ground surface height. The center of mass trajectory is affected, but the deviation that occurs is a result of motor limitations.

Figure 4.4: Center of mass and toe trajectories for the standard spring-mass models and the force-controlled model encountering an unexpected decrease in ground surface. The dashed line represents the center of mass trajectory of the passive undisturbed model.

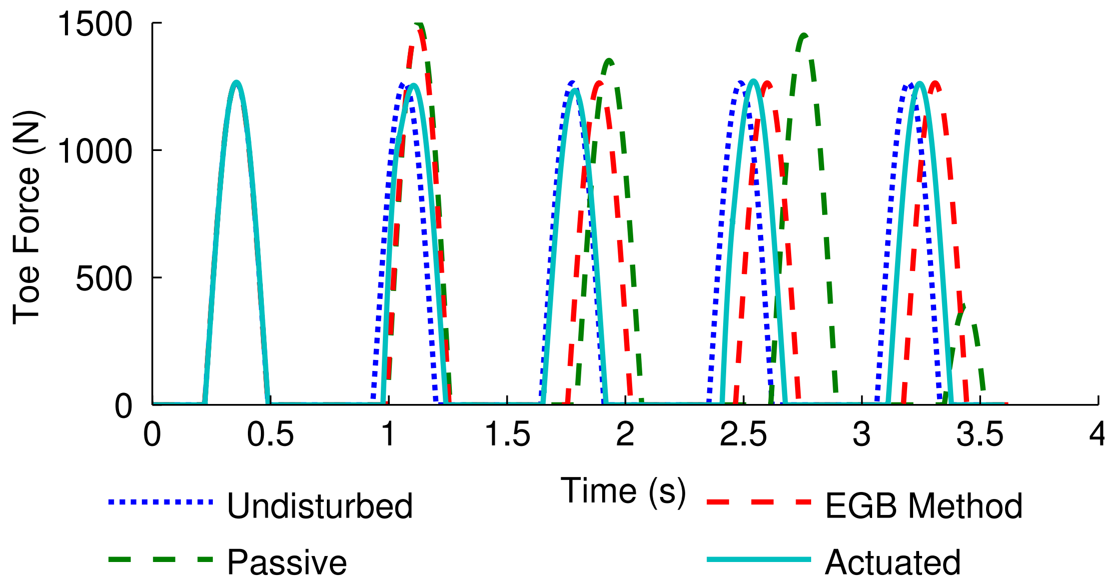


Figure 4.5: Toe force profiles for the passive undisturbed, passive disturbed, passive with Ernst-Geyer-Blickhan leg touchdown angle, and force-controlled models encountering a decrease in ground surface height. Our force-controlled model is nearly able to maintain the toe force profile of the undisturbed model, and most importantly, is able to limit the peak forces. In contrast, both passive models show a significant change in the force profile, and an increase in peak forces.

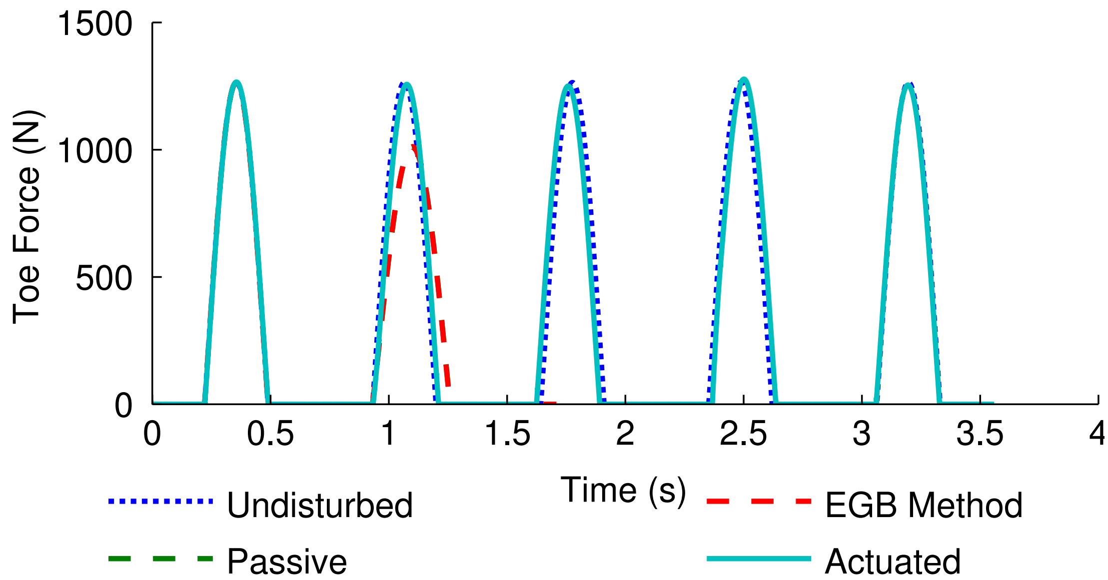
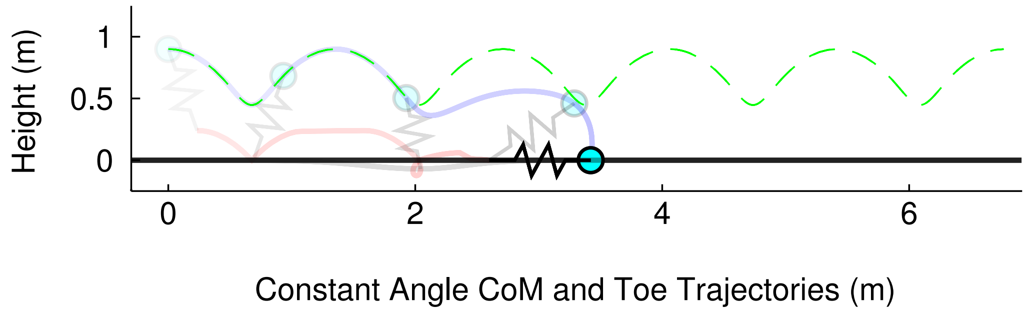
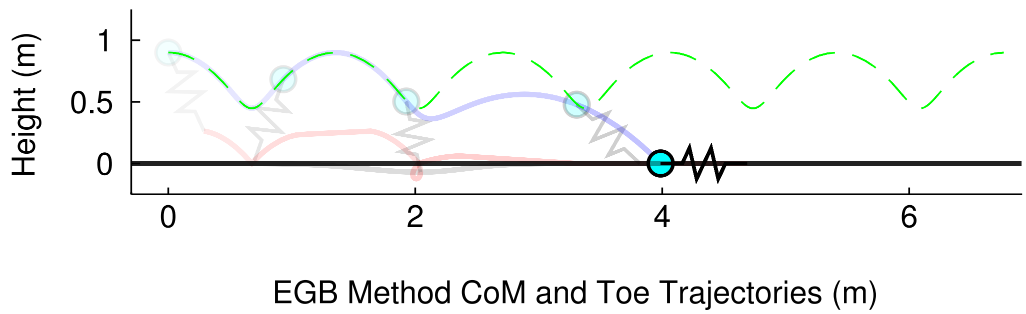


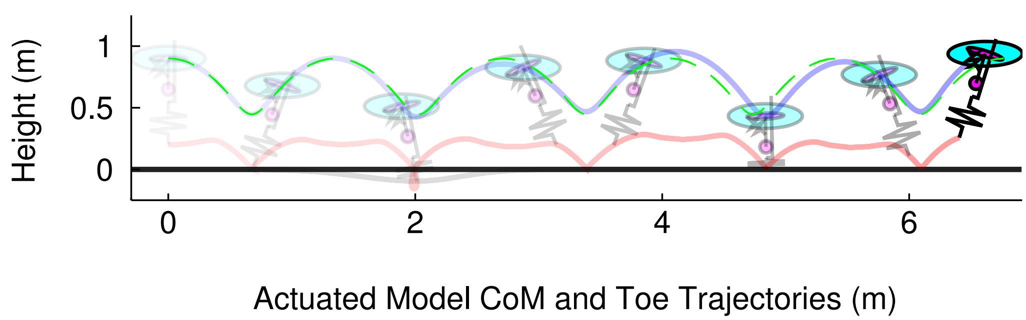
Figure 4.6: Toe force profiles for the passive, passive with Ernst-Geyer-Blickhan leg touchdown angle, and force-controlled models compared to the undisturbed passive model encountering a decrease in ground stiffness. The toe force profiles of the passive models encountering the disturbance exceed and deviate away from the toe force profile of the force-controlled model, which is able to maintain the toe force profile of the undisturbed passive model, aside from a small phase shift caused by motor limitations.



(a) The passive spring-mass model with constant leg touchdown angle encountering a decrease in ground stiffness. The model falls in the presence of the disturbance.



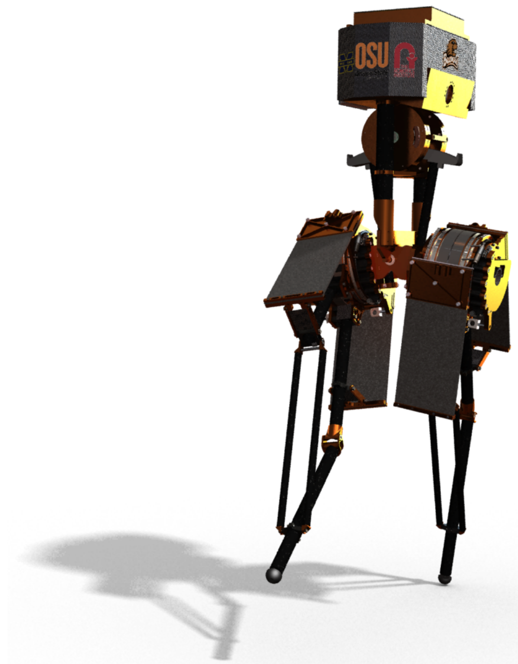
(b) The passive spring-mass model using the EGB method to set the leg touchdown angle encountering a decrease in ground stiffness. The model bounces out of the disturbance at such a low trajectory that there is no leg touchdown angle that will prevent a fall.



(c) The force-controlled model is able to attenuate the unexpected decrease in ground stiffness by maintaining the ground force profile of the ideal model. The center of mass trajectory is scarcely affected by the unexpected disturbance.

Figure 4.7: Simulation results for our robot model and spring-mass models encountering an unexpected decrease in ground stiffness. The dashed line represents the center of mass trajectory of the passive undisturbed model.

(a) A monopod version of ATRIAS, with hip and leg series elasticity.



(b) Bipedal ATRIAS, including onboard power and computing.

Figure 4.8: We are currently working toward validating our simulation results on purpose-built machines of our own design and construction.

Chapter 5 – Impulse Control for Planar Spring-Mass Running

In this chapter, 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 prevents falls by maintaining a constant horizontal flight phase velocity over uneven terrain. 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.

5.1 INTRODUCTION

We seek to approach the performance of animal walking and running, shown in Fig. 5.1a, with a robot, shown in Fig. 5.1b and Fig. 5.1c, existing robots are not capable of the combined energy economy and robustness to disturbances observed in animals. Existing passive walkers, such as the Cornell Walker, are capable of energy economy similar to animals, but will fall in the presence of small disturbances [26]. Robots that rely primarily on active control, such as Boston Dynamics' "BigDog," can demonstrate impressive robustness to disturbances at the expense of energy economy [1]. Our goal is to engineer a control strategy for appropriately designed running robots that combines the robustness to disturbances of actively controlled machines with the energy economy of a passive dynamic walker.

We present a novel model and bio-inspired control strategy that allows a simple model for robot running, shown in Fig. 5.2b, to run with excellent energy economy and robustness. The control strategy works in conjunction with our model to utilize the passive dynamics where possible for energy economy, and to use active control to reject disturbances. We show in simulation that the combined model and controller is energetically conservative like the completely passive spring-mass model during steady-state running, but is self-stable in the presence of disturbances in the ground height or impedance. In other words, our model and controller combine the benefits of passive dynamics and active control, producing an efficient and robust running gait. We believe these results can be extended to physical systems.

Our control strategy uses an existing state-of-the-art method for controlling a spring-mass running model, which is effective at maintaining an energetically conservative gait over uneven terrain without falling. This method was presented by Ernst et al., and in the interest of brevity, we will henceforth refer to Ernst et al.'s method of selecting the leg touchdown angle as the Ernst-Geyer-Blickhan (EGB) method, and the SLIP model using the EGB method to set its leg touchdown angle as the SLIP+EGB model. The EGB method controls 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. 5.2a, 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.

For a given spring-mass model, with a particular center-of-mass velocity vector at touchdown, there is a particular leg angle at touchdown that will result in a symmetrical stance phase. We calculate this leg angle for each instant of time during the flight phase, as the velocity vector changes, such that the spring-mass model will have a symmetrical stance phase no matter when its foot makes contact with the ground. Controlling the leg angle for a symmetrical stance phase ensures an energetically optimal, stable gait on unpredictable, uneven terrain, but is limited to an ideal model hopping on rigid ground.

This state-of-the-art method falls easily in the presence of any non-rigid ground dynamics, and is not designed to deal with physical limitations such as motor torque limits or motor inertia. Some additional control is needed to accommodate physical limitations and changes in ground impedance, such as changes in ground stiffness or damping, which will destabilize the gait. The EGB method can be adapted for use on a physical system by designing a controller to track the desired leg angle trajectory, but some additional stance phase control is needed to reject ground impedance disturbances.

In this paper, we show that adding actuators with realistic limitations, shown in Fig. 5.2b, and using impulse control during stance enables 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. Furthermore, we show that the combined controller can be implemented on a system with realistic limitations, and is not constrained to an ideal spring-mass model.

5.2 BACKGROUND

Because our goal is to build robots that can match the performance, economy, and robustness of animal running, our models incorporate passive dynamics similar to those observed in animals. Spring-mass models provide a good approximation for animal running, and so we begin with a simple model consisting of a mass bouncing on a spring, as shown in Fig. 5.2a [28]. For hopping in the vertical plane, the simple spring-mass system is called a SLIP model.

The simple spring-mass model is capable of some passive stability, but without careful control of the leg angle at touchdown it tends to become unstable and fall, as shown in Fig. 5.4a [30]. 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 [27]. 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, presented by Ernst et al., prevents falls when hopping over uneven terrain by ensuring a center of mass trajectory that is symmetrical about mid-stance, as shown in Fig. 5.4b [31]. Symmetrical stance phases result in an equilibrium gait, where every stride is the same as the last. We find an equilibrium gait useful for demonstrating our impulse control strategy, because it helps our impulse controlled model to run along as if the ground were flat.

The EGB method prevents falls when hopping over uneven terrain, but can lose stability in the presence of non-rigid ground dynamics, as shown in Fig. 5.5, and 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. 5.4b. 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. 5.5.

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 SEA measures and controls the deflection of its spring, which corresponds to the force applied by the actuator [2]. As an added benefit, the series spring filters impulsive forces, improving the SEA's robustness to shock loads [3]. 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 [4]. 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" [5, 6]. 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. 5.1a, resulting in only slight deviation from their undisturbed gait [29]. 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 [14]. 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 [13].

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 [24, 34]. 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 [35]. 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 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 [34]. 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 [14]. 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 [17]. 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 [15, 16]. 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. 5.1a. 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 does not 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 [24]. 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 [34].

5.3 MODEL

We keep our model as simple as possible, but no simpler to capture only the most significant dynamics of a real system. Starting with the simple spring-mass model, shown in Fig. 5.2a, 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. 5.2b. 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 5.1b and 5.1c, our eventual target robot for this control method, toe 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.

5.4 CONTROL STRATEGY

Our control strategy uses separate flight and stance phase controllers, which are shown in Fig. 5.6a and Fig. 5.6b.

5.4.1 Flight Phase Control Strategy

During flight, we use the EGB method to set a leg angle trajectory, 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 [32]. 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. This implementation is similar to that presented by

Ernst et al., but we also consider the zero-force leg length as an input to our leg angle lookup table, since it varies in response to ground surface disturbances [31].

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.

5.4.2 Stance Phase Control Strategy

In stance our controller maintains the toe impulse profile of the passive undisturbed model 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 when there is zero tracking error. When impulse errors do occur, they cause error in the toe force profile. By regulating errors in the impulse profile, our controller simultaneously regulates any toe force errors.

Active impulse control of the leg motor attenuates ground disturbances by matching the impulse through its leg spring to a SLIP model hopping on flat rigid ground. When our impulse control strategy is able to track the target impulse profile, it also maintains the desired toe force profile. Force tracking errors cause error in the impulse profile. Our impulse control strategy regulates any errors that appear in the impulse profile by commanding leg motor torques. By regulating impulse errors, our strategy corrects for any errors in the force profile.

The hip actuator approximates an ideal hinge by regulating its impulse, 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.

5.5 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 to simulate the SLIP+EGB and our impulse controlled models hopping in the vertical plane. Although developing these non-linear equations is straightforward for both the SLIP+EGB model and our impulse controlled model, finding a closed-form solution for the trajectories of either is impossible [32]. However, we are able to generate approximate numerical solutions using ordinary differential equation solvers.

5.5.1 Ground Damping Disturbance

The first type of ground disturbance that we investigate is a decrease in ground damping, shown in Fig. 5.3a. In this experiment, the ground unexpectedly changes from being rigid during the first stance phase to behaving like a viscous damper in all directions for the second stance phase. 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. 5.7a. 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. 5.6d and 5.6e. 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. 5.7b.

Our impulse control strategy, a small extension to force control, corrects for unavoidable errors in the toe force profile, and maintains a consistent center of mass trajectory, as shown in Fig. 5.7c. 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. 5.6d and 5.6e.

5.5.2 Ground Stiffness Disturbance

The second type of ground disturbance we investigate is a decrease in ground stiffness, shown in Fig. 5.3b. 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 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. 5.7a. 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 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. 5.7a.

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. 5.7b. Our impulse controlled model closely follows the desired toe force and impulse profiles, as shown in Fig. 5.6c and 5.6d, 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, outside observations of force and position would suggest that it does, much like published observations of animals do [36].

5.5.3 Ground Height Disturbance

The final type of ground disturbance we investigate is a decrease in ground surface height, shown in Fig. 5.3c. 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. 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.

The SLIP+EGB model prevents falls in the presence of changes in ground surface height, as shown in Fig. 5.7a, 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. 5.6c.

Our impulse controlled model extends its leg during flight as a result of attempting to achieve a toe impulse profile, and is able to reject the ground height disturbance, as shown in Fig. 5.7b. 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. 5.6c, 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. 5.6d.

5.6 DISCUSSION

Our hip control during stance is an extension of a fundamental force control task, maintaining a constant force against a moving load, which has been approached analytically in previous works [4]. Although low actuator inertia and large control authority are desirable for maintaining a constant force on a moving load, we choose values from a commercially available motor that we plan to use on ATRIAS, shown in Fig. 5.1b.

A stride-to-stride controller can be used on top of force control to correct errors in the center of mass trajectory that arise because of small errors in the force profile, but impulse control can correct for toe force profile errors within a single stride. Force control alone can maintain the toe force profile of the equivalent completely passive system, but some additional control is needed to maintain a specific center of mass trajectory in the presence of large disturbances. By using impulse control, we effectively maintain the toe force profile of the undisturbed system. As long as our impulse output tracking controller settles within a stance phase, it will ensure that a specific impulse has been in-parted to our model's center of mass.

Small toe force errors are unavoidable, even during steady-state hopping, because our model's hip inertia does not necessarily have the correct velocity at touchdown to track the leg angle. With force control, toe force error can be minimized by stiffening controller gains, which also increases control authority requirements, but can never be completely eliminated. In contrast, we can use softer controller gains with impulse control, since we do not rely on our controller converging to the desired leg force profile quickly, we require only that it is able to converge to a specific toe impulse profile within a single stance phase.

Our basic impulse control strategy is not confined to a specific low-level controller, and while the low-level controllers used to implement it affect the performance of our robot model, our strategy only requires that its low-level controllers are able to control the impulse through a spring and a motor angle.

Our impulse output tracking controller follows from our basic force output tracking controller implementation, which controlled the toe forces in the leg angle and length directions. It is possible that better disturbance rejection could be achieved by controlling the toe impulse in the horizontal and vertical directions, but this type of control could require greater control authority, more mathematical complexity, and greater shear forces on the ground. We found that controlling the toe impulse profile in the leg angle and length directions was more intuitive, yet still very effective at rejecting ground disturbances.

5.7 CONCLUSIONS AND FUTURE WORK

We have shown in simulation that impulse control combined with careful control of the leg touchdown angle yields good disturbance rejection for spring-mass model running, while requiring little sensory feedback and minimal active control. Our impulse control strategy maintains the passive dynamics of the equivalent spring-mass system, and intervenes only to accommodate ground disturbances. Our strategy combines the robustness to disturbances of active control, while maintaining most of the energy economy of a completely passive system.

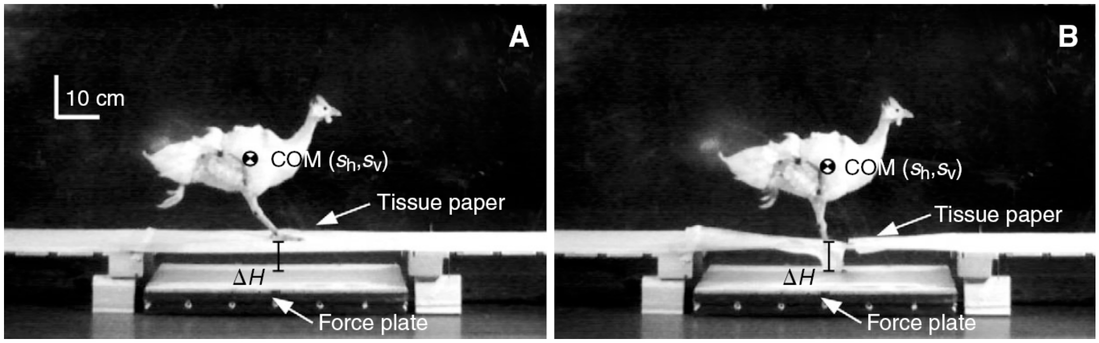
Our impulse control strategy extends and improves the force control strategy for a vertically hopping single actuator spring-mass system that we presented in our previous work [34]. We found that a leg-spring tuned to the desired passive dynamics is important for energy economy, but also disturbance rejection and good output tracking, just as it was for vertical hopping. Our impulse control strategy maintains a consistent toe force profile, similar to the force control strategy that we presented for vertical hopping, but also corrects for unavoidable errors in the force profile that arise from actuator limitations. For planar hopping, in addition to impulse control during stance, control of the leg angle during flight becomes important for preventing falls. We chose to use the existing state-of-the-art control strategy for SLIP model running in flight, the EGB method, because it is effective at preventing falls and convenient to combine with impulse control.

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. 5.7. 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.

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 do not attempt to duplicate the disturbance rejection observed in biomechanics studies, our impulse controlled model accommodates disturbances in a way that resembles disturbance rejection observed in humans and animals without attempting to match the behavior of either. The control policies used by humans to accommodate disturbances are unknown, but our impulse control strategy rejects changes in ground stiffness and damping in a way that resembles disturbance rejection observed in humans [21, 37]. 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 [29].

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. 5.1c. 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 limiting the need for sensory feedback and active control.

With these real-world devices, we hope to approach the performance of animal walking and running.

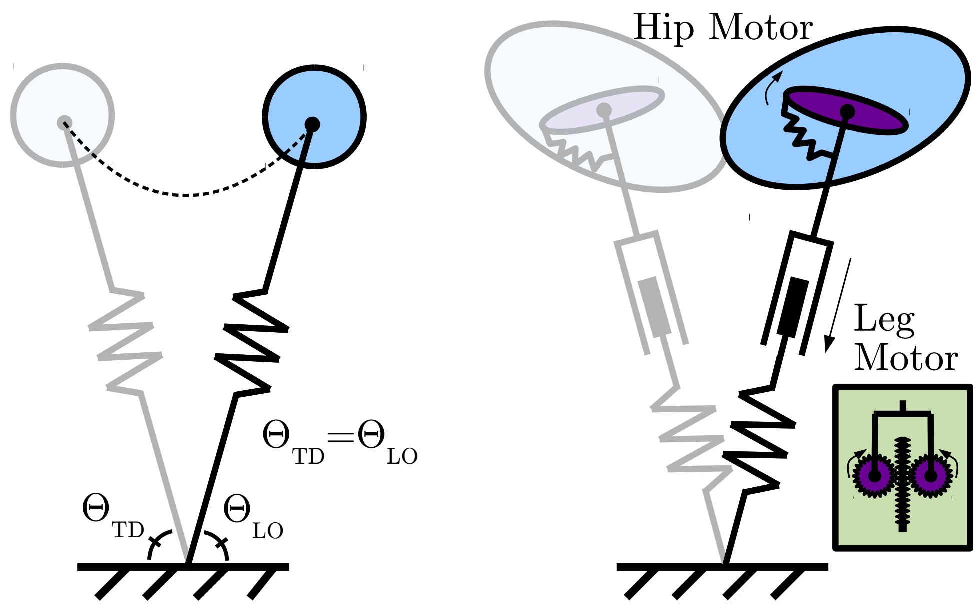


(a) The guinea fowl is able to accommodate for the unexpected decrease in ground surface without a significant change to its steady-state center of mass motion; image used from Daley et al. [29].

(b) Planar monopod ATRIAS.

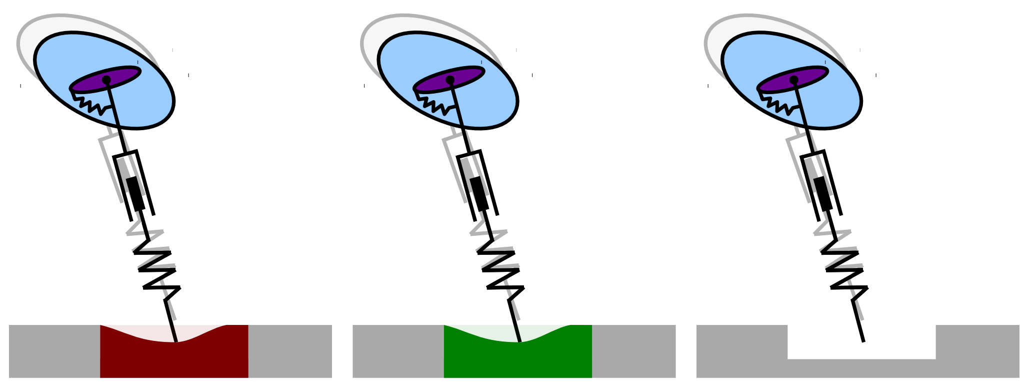
(c) 3-D biped ATRIAS.

Figure 5.1: Our goal is to engineer control strategies that will allow legged robots to approach the energy economy and robustness of animal running.



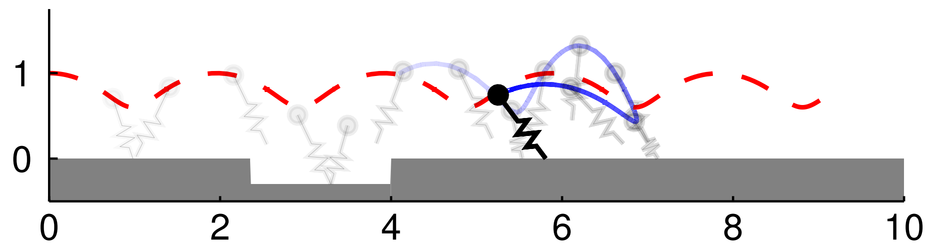
(a) SLIP+EGB model. (b) Impulse controlled model.

Figure 5.2: Starting with the passive SLIP model, we add hip and leg motors for active control, and body moment of inertia.

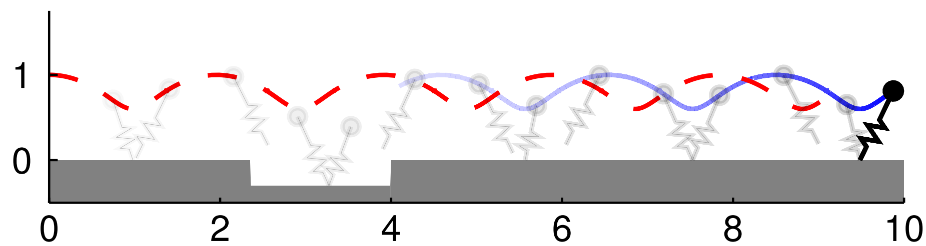


(a) Ground damping disturbance. (b) Ground stiffness disturbance. (c) Ground surface height disturbance.

Figure 5.3: We subject our force controlled model to ground disturbances in simulation.



(a) Passive SLIP model.



(b) SLIP+EGB model.

Figure 5.4: The SLIP+EGB is the current state-of-the-art for SLIP model control. It prevents falls when hopping over uneven terrain.

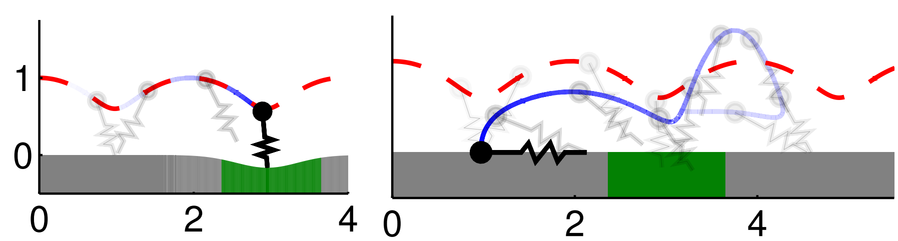
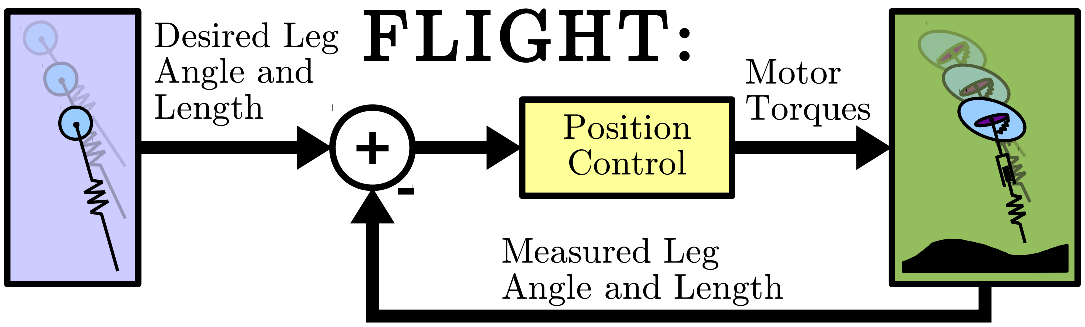
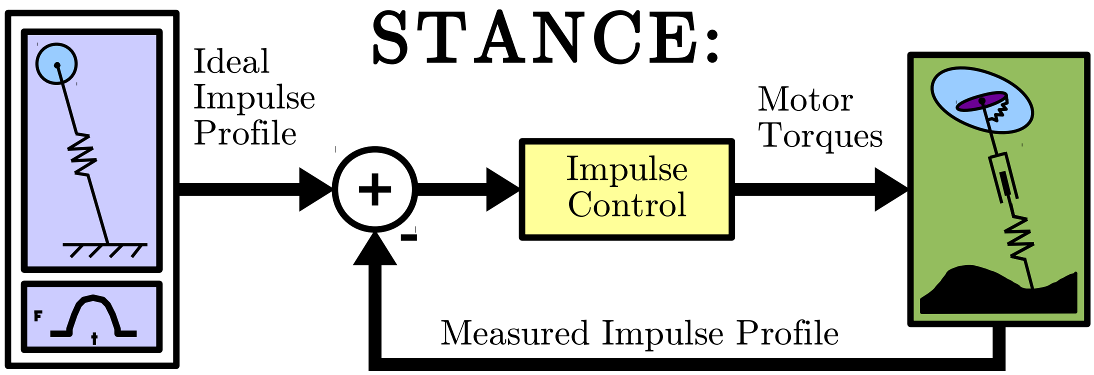


Figure 5.5: The SLIP+EGB falls after encountering a decrease in ground stiffness, because it relies on the ground being rigid.

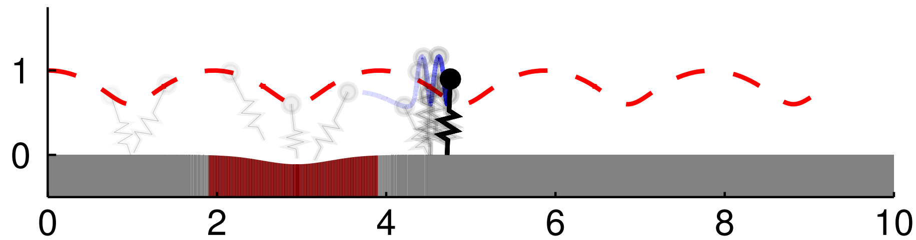


(a) We use an existing control strategy to set the leg angle during flight, such that our model remains equal to the target passive model, unless there is a change in ground height.

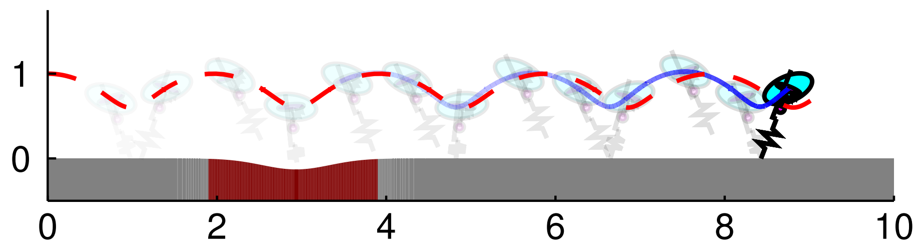


(b) Our novel idea is a stance phase control strategy that controls the toe impulse to reject disturbances. During stance our control strategy matches the toe impulse profile of the active model to that of the passive model hopping on flat rigid ground.

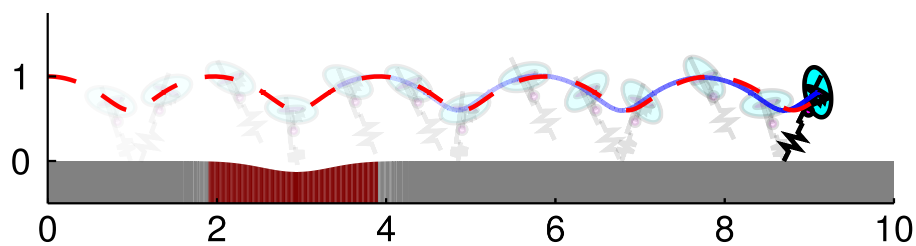
Figure 5.6: Our approach switches between flight and stance controllers according to whether it expects to be in ground contact.



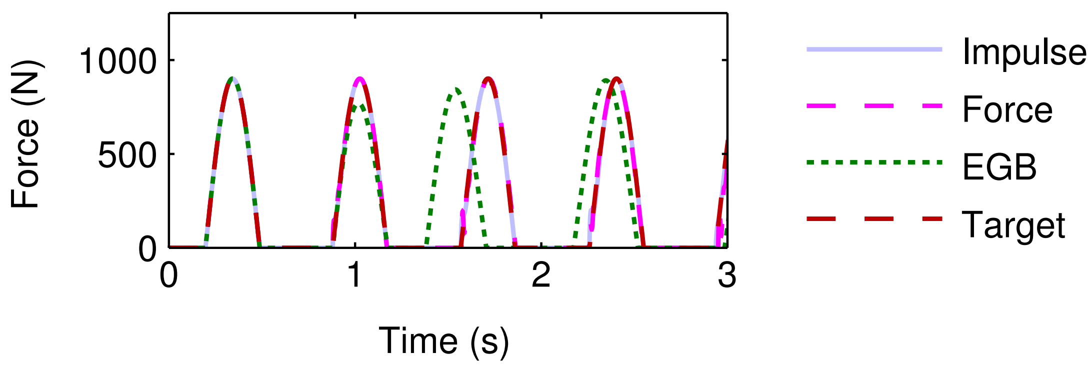
(a) The SLIP+EGB model is greatly disturbed by the unexpected damped ground.



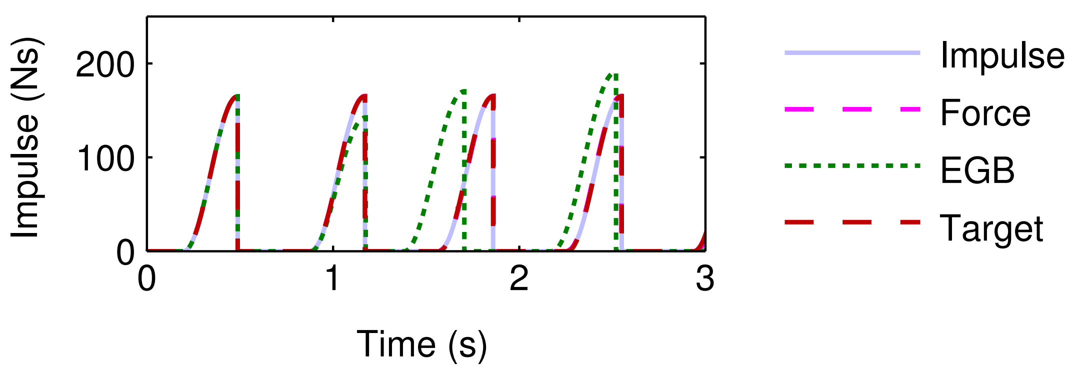
(b) Force control accomodates the damped ground, but the center of mass trajectory is affected.



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

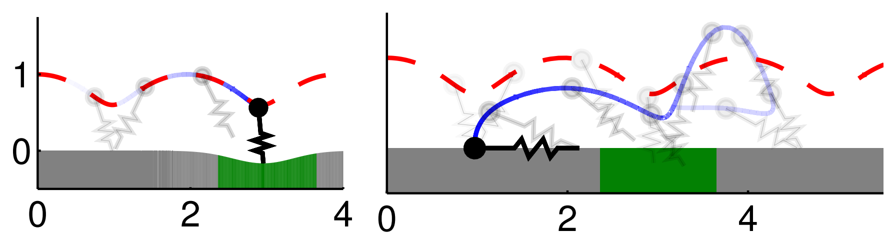


(d) Force and impulse control maintain the target force profile.

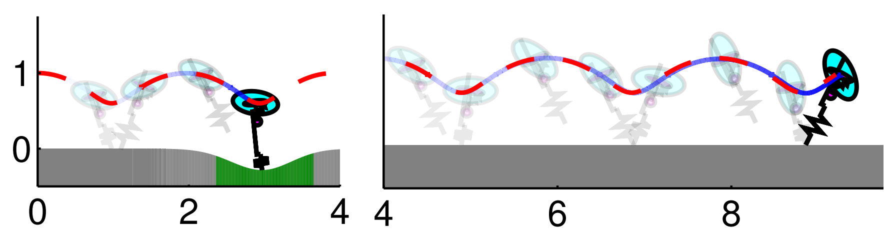


(e) Our impulse controlled model maintains a consistent toe impulse profile.

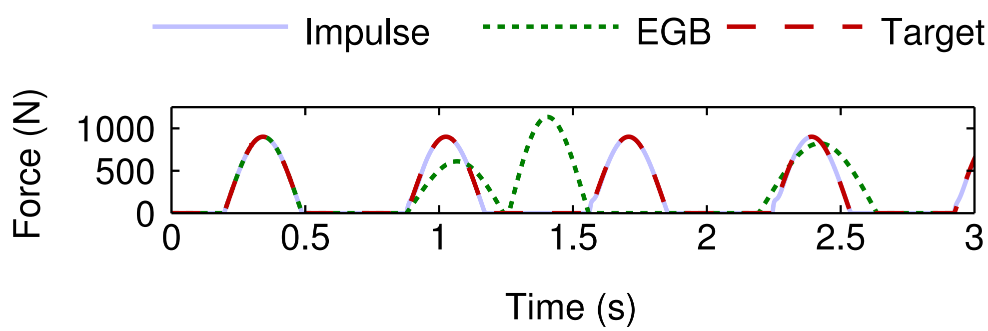
Figure 5.6: Force control can accommodate the decrease in ground damping, but errors in the force profile, caused by actuator limitations, accumulate disturbing its center of mass trajectory. Our impulse controlled model corrects for errors in the force profile.



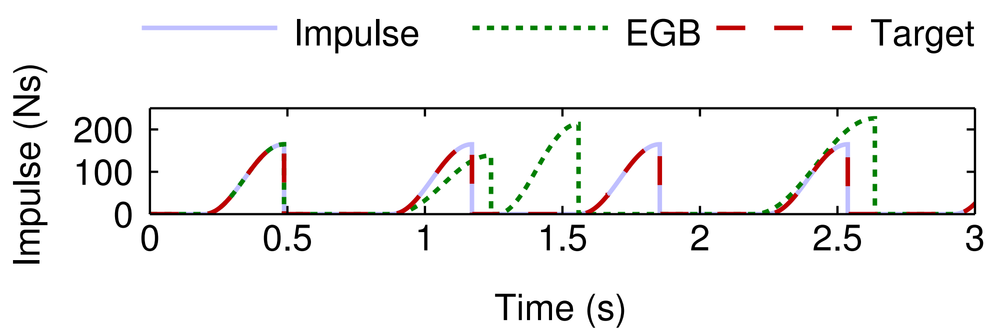
(a) A decrease in ground stiffness causes the SLIP+EGB to fall.



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

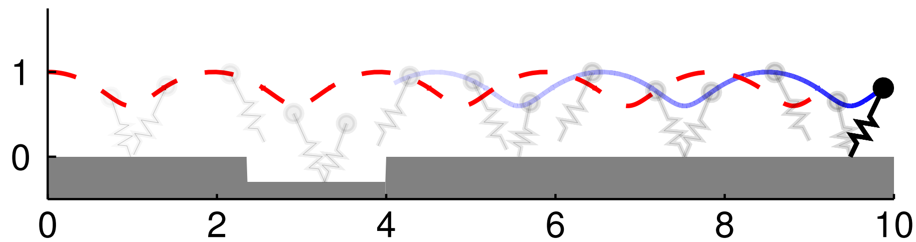


(c) The toe force of the passive model exceeds the target peak force, but our impulse controlled model limits its peak force.

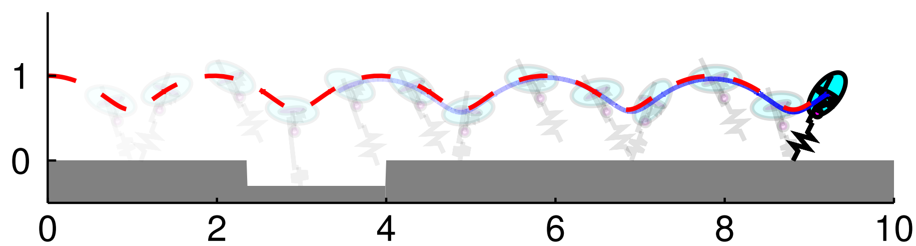


(d) Our impulse controlled model maintains the target toe impulse profile.

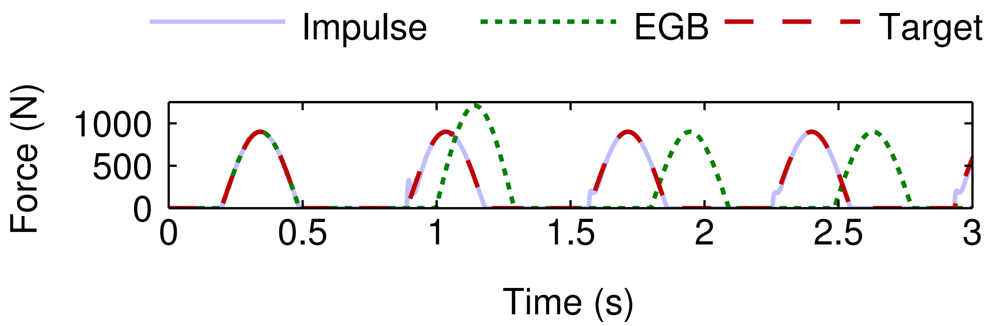
Figure 5.6: Our impulse controlled model is able to reject unexpected changes in ground stiffness by matching its toe impulse profile to that of the target passive system.



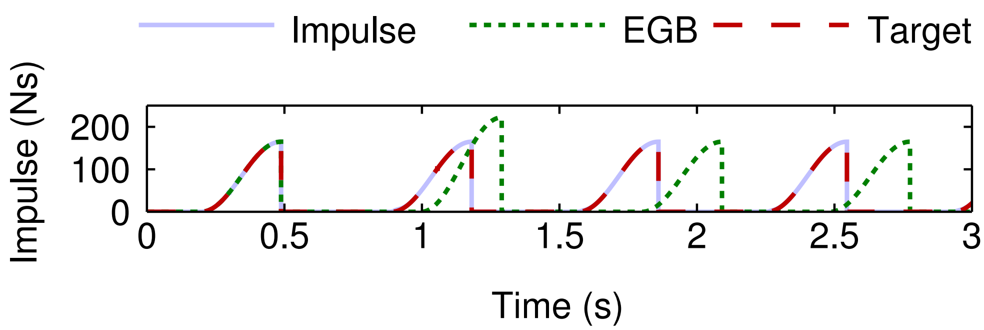
(a) The SLIP+EGB accomodates a decrease in ground surface height, but its center of mass trajectory is affected.



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



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



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

Figure 5.6: Our 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.

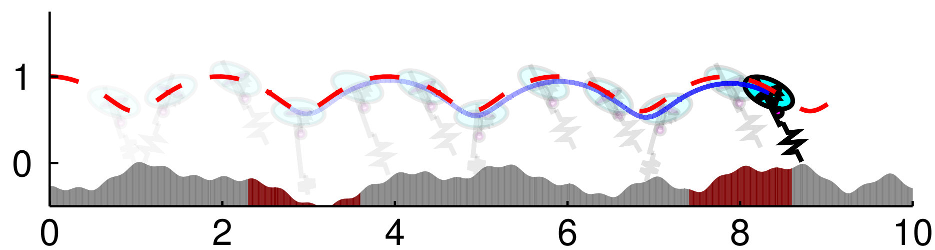


Figure 5.7: Our impulse controlled model can reject disturbances in even the most rugged of environments.

Chapter 6 – Conclusion

We have introduced a novel force control strategy for spring-mass model running that maintains a consistent toe force profile in the presence of disturbances. Our force control strategy makes the spring-mass model robust to ground disturbances, while maintaining most of the energy economy of a completely passive system by making excellent use of its existing passive dynamics. During steady state hopping our control strategy expends zero motor work on the world, and all of the behavior is captured by our model's passive dynamics. Our control strategy intervenes with the passive dynamics only to accommodate disturbances.

The spring-mass model is capable of some passive stability, but may fall even in the presence of small disturbances, as shown in Chapter 5. Restricting the spring-mass model to vertical hopping prevents it from falling forwards and backwards, but disturbances still affect the toe force profile and center of mass trajectory, as shown in Chapters 2 and 3. Active control is important for robustness to disturbances.

Our approach accommodates realistic limitations, such as motor torque limits and inertia, which are inevitable on any physical system. Physical limitations make tracking errors unavoidable, but our force control strategy reduces the affect that errors have on the toe force profile and center of mass trajectory. This frees up any high-level stride-to-stride controller to focus its resources on tasks such as path planning, because our force control strategy ensures a consistent gait regardless of changes in ground surface height and dynamics.

Small improvements can be made to our basic control approach to improve force output tracking and to maintain a more consistent center of mass trajectory. Our force control strategy does not require specific low-level controllers, but its performance is affected by the ability of its controllers to track the desired toe force profile and leg angle trajectory. We show in Chapters 2, 3, and 4 that simple PD loops can achieve impressive disturbance rejection with minimal hand-tuning. In Chapter 5, we show that an output tracking controller can give slightly better performance, by eliminating steady state errors that are unavoidable with PD control.

We show that our basic control approach can be easily extended into impulse control, which simultaneously maintains a consistent toe force profile and center of mass trajectory, as we showed in Chapter 5. Our impulse control strategy works in the same way as our force control strategy, but instead of controlling the toe force profile, it controls the toe impulse profile. By matching the toe impulse profile of the target passive system, our impulse controlled model corrects for unavoidable errors in the toe force profile that could accumulate and affect the center of mass trajectory of our force controlled model. Our impulse control strategy is more robust to errors in the toe force profile than our force control strategy, which makes its performance less dependent on the physical system and the low-level control laws used to implement it. To maintain a consistent center of mass trajectory, our impulse control strategy only needs to begin tracking the target toe impulse profile before liftoff. This ensures that the correct impulse is imparted on the body mass during stance.

The long-term goal of this work is to build an untethered model and bio-inspired biped with excellent energy economy capable of robust walking and running gaits. Our control strategy is practical for this type of real world application, because it has the potential to achieve the desired energy economy, robustness to disturbances, and does not require any external sensing of its environment, which may be unavailable or limited on a physical system. The only sensing that our force controlled model requires is the spring deflections, and for planar hopping, the center of mass velocity. On a physical system, these sensing requirements could be fulfilled by encoders on the spring deflections and an inertial measurement unit when the center of mass velocity is required. Towards our goal of a robust and energy efficient biped, we are working to validate our simulation results on physical systems of our own design and construction, including a 1-D benchtop actuator, a planar hopping monopod, and a 3-D biped. We believe that our force control strategy will prove useful for robots such as ours that include suitable passive dynamics.

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