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Dr. Jonathan Hurst

We present a model for running that combines active control with passive dynamics, in an attempt to approach the economy and robustness of animal running. Our work is inspired by examples of guinea fowl encountering an unexpected drop in ground surface, with little affect on their running gait. Previous investigations have shown that the steady-state center-of-mass motion of animal running and walking may be approximated by a mass bouncing upon a spring, but this approximation does not incorporate disturbance rejection. To approach the robustness of animal running, we add a motor in series with our spring, and use it for closed-loop force control. The active controller maintains the force profile of the vertically hopping spring-mass model in the presence of disturbances, while the series spring does the majority of the mechnical work, maintaining the economy of the purely passive spring-mass system. We show in simulation that our force-controlled model is more resilient to ground disturbances that affect the center-of-mass trajectory, toe-force profile and hopping frequency than the uncontrolled model.

Keywords: dynamic walking, disturbance rejection, force control, passive dynamics, walking model

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Active Control of Passive Dynamics for Ground Disturbance Rejection

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Chapter 1

Introduction

Our goal is to build walking and running robots that can match the performance, economy and robustness of animals. Our approach is to combine the benefits of passive dynamics and active control. Passive dynamics refer to a mechanical system's natural tendency towards certain behaviors. Some robots have demonstrated successful walking gaits using passive dynamics exclusively, with no motors or electronics of any sort [10]. Most robots, such as Honda's ASIMO, rely exclusively on active control through electric motors or other actuators, ignoring or overcoming any inherent passive dynamics.

While passive dynamics are important for energy economy, active control of some sort is important for robustness to disturbances. The purely passive dynamic walking robots do exhibit stable gaits, but they fall very easily with small disturbances.

Our model includes active control of the toe force with the passive spring-mass system, to handle unexpected disturbances while retaining the energy economy of a purely passive system. For the purposes of this paper we constrain the system to vertical hopping, and limit disturbances to changes in ground height and ground stiffness. Changes in ground height occur when the ground surface unexpectedly decreases between stance phases, comparable to stepping into an unseen hole in the ground. Changes in ground stiffness occur when the ground unexpectedly transforms from rigid behavior to ideal spring behavior deflecting proportionately to the toe force, comparable to stepping from pavement to soft grass.

By controlling a robot's toe forces, it is possible to obtain a desired center-of-mass trajectory. If the toe force of a walking system is measured as a function of time, the result is a force profile. To maximize the energetic economy of our actively-controlled spring-mass model, the commanded toe forces match exactly the forces that would be observed from a passive, undisturbed model. Therefore, in the absence of any disturbances, our model behaves indistinguishably to a passive spring mass hopper, with all of the energy economy and no motor work. However, in the event of an unexpected disturbance, active control maintains the same toe forces as the undisturbed system, maintaining the same center-of-mass trajectory. This paper presents our concept for combining the benefits of passive dynamics and active control for legged locomotion gaits, validated in simulation using realistic values. We are now working towards validating our simulation results on robots of our own design and construction. We hope to illustrate the basic concept on a single degree of freedom prototype benchtop actuator, and eventually apply these ideas to a two-joint hopping monopod. These systems are discussed briefly in the section "Conclusions and Future Work".

Chapter 2

Background

Our motivation for this work is based on observations of animal behavior, which are able to walk and run at varying speeds over varying terrain. Guinea fowl are able to accommodate for a drop in ground height by rapidly extending its leg into the unexpected disturbance. Although the guinea fowl's center of mass trajectory diverges slightly from undisturbed steps, it is able to maintain dynamic stability [4]. While animals clearly use active control for running gaits, they also utilize passive springs to store and release energy in a cyclic manner [3]. Tendons stretch during the first part of stance, storing energy that is released during the second part of stance to facilitate lift-off.

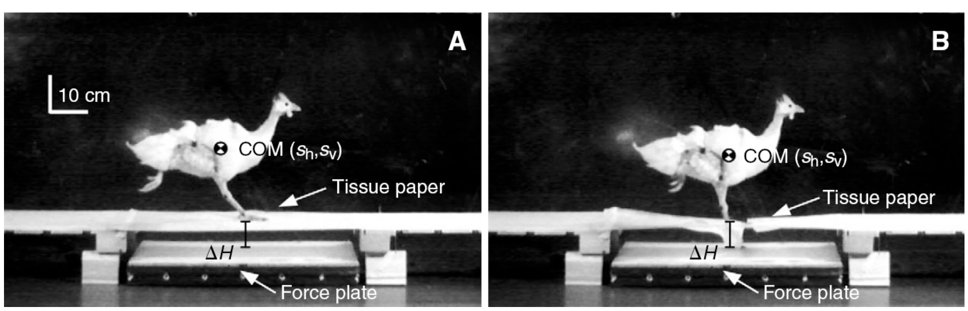

Figure 2.1: Motivation comes from the economy and disturbance rejection ability of animals such as the guinea fowl. The guinea fowl is able to accommodate for the unexpected decrease in ground surface without a significant change to its steady-state center-of-mass motion.

Steady-state animal running can be approximated by simple spring-mass spring models, such as the spring-loaded inverted pendulum (SLIP). It is able to maintain dynamic stability in the presence of ground disturbances, however, disturbances affect the SLIP model's center-of-mass trajectory and toe force profile. The ARL-Monopod II uses controlled passive dynamic running to reduce its energy cost of locomotion [1]. This robot uses active feedback control to match its hopping trajectory with that of the system's passive dynamics, which are modeled as a (SLIP).

When the SLIP model encounters a decrease in ground surface, some amount of gravitational potential energy is converted into kinetic energy as the model falls into the disturbance. The additionally kinetic energy must then be converted into spring potential energy, which results in increased spring deflection. On a physical system, this can lead to springs exceeding their maximum deflection, potentially causing damage to a real system. Disturbances can cause higher forces. Galloping horses are already near peak force on tendons and bones [14], so remianing beneath Force limits can be an important consideration, or small ground disturbances could result in injury.

When the SLIP model encounters a decrease in ground stiffness, the series combination of the ground stiffness and leg spring decreases. This causes a decrease in the fundamental frequency for the equivalent spring-mass system, and a prolonged stance phase. In contrast, biomechanics studies have shown that humans and animals adjust their leg stiffness during hopping, running and walking to accommodate for this type of change in ground stiffness [6]. Humans and animals are able to set leg stiffness through a concerted effort of muscles, tendons and ligaments [5]. The Actuator with Mechanically Adjustable Series Compliance (AMASC) used this fact to control running gaits by adjusting leg compliance [8]. The AMASC pre-tensions springs to increase its leg's apparent stiffness. When hopping on a compliant surface, humans increase their leg stiffness such that the equivalent stiffness of the series combination of the ground and leg spring is the same for all surfaces. 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 we do not directly control leg stiffness, our model produces an equivalent result by maintaining a toe force profile. There are currently several robots that have successfully taken different approaches to dynamic running and walking. We have already mentioned Honda's ASIMO biped. ASIMO does not make use of passive dynamics, does not include any compliance in its legs and, for these reasons, has a relatively high specific cost of transport [13]. However, ASIMO has demonstrated stable walking and running gaits. ASIMO minimizes jarring, lossy and difficult to control impacts between its motor inertias and the ground by matching foot speed to relative ground velocity just before leg touchdown. By comparison, Raibert's running robots can easily handle regular or even unexpected ground impacts with simple controllers thanks to series elasticity in legs [12]. Boston Dynamics's BigDog holds the current distance record for legged vehicles at 12.8 miles [9]. Unlike ASIMO, BigDog's legs include series compliance. BigDog uses its leg springs only for force control. When BigDog's legs touchdown, its leg springs deflect and absorb energy. This energy is not released to propel BigDog's next step, instead legs are actively raised and relocated. Our goal is to recycle the energy stored in leg springs to reduce the specific cost of transport and to maintain or improve the robustness and stability.

We build upon MIT's Series Elastic Actuator(SEA) [11]. MIT's work demonstrated the effectiveness of using series elasticity for force control. The SEA uses the deflection of a spring to transform the force control problem into a position control problem. The series elasticity reduced impulse forces on the transmission, thereby decoupling the active elements of the robot from the load.

Compliant legs better approximate bipedal walking than vaulting over stiff legs [7]. The addition of series elasticity to the walking model results in the small center-of-mass trajectory vertical amplitudes observed in animal walking. In contrast, the stiff legged model produces large center-of-mass vertical amplitudes. Compliant legs produce the characteristic M-shaped toe force profile of bipedal walking, and provide an accurate model for the stance dynamics of running [2]. The stiff legged model is only valid for walking gaits, and does not reproduce animal walking as well as the compliant leg model. Introducing compliance into walking legs allows the same model and mechanical system to be used for both running and walking gaits. fficiency

Chapter 3

Model

We use kinematic equations of motion to simulate our vertically hopping, force-controlled model. The behavior of a standard spring-mass model bouncing vertically on a flat rigid surface may be broken into identical periods (bounces). Since we provide the model with some initial height, it simplifies our simulation to break a period into three stages, rather than just a flight and stance phase. A bounce is made up of a fall, stance and rise stage. 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 may be found as functions of time. During the fall and rise stages the system behaves as a mass in free-fall. The trajectory of the system during stance was found by solving a ordinary differential equation of the form:

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

which is similar to the equation for a vertical, undamped spring-mass oscillator. We add a motor and associated reflected motor inertia to the simple spring-mass model as illustrated in Fig. 3.1. With these additions we arrive at a single-degree of freedom, vertically hopping model schematically the same as MIT's Series Elastic Actuator [11]. We use a much larger leaf spring with a higher energy density then the torsional spring used on MIT's SEA. Our robot uses series elasticity for both force control and energy storage. We attempt to recover the energy used to decelerate the robot mass after touchdown and use it to re-accelerate the mass leading up to liftoff without expending motor work.

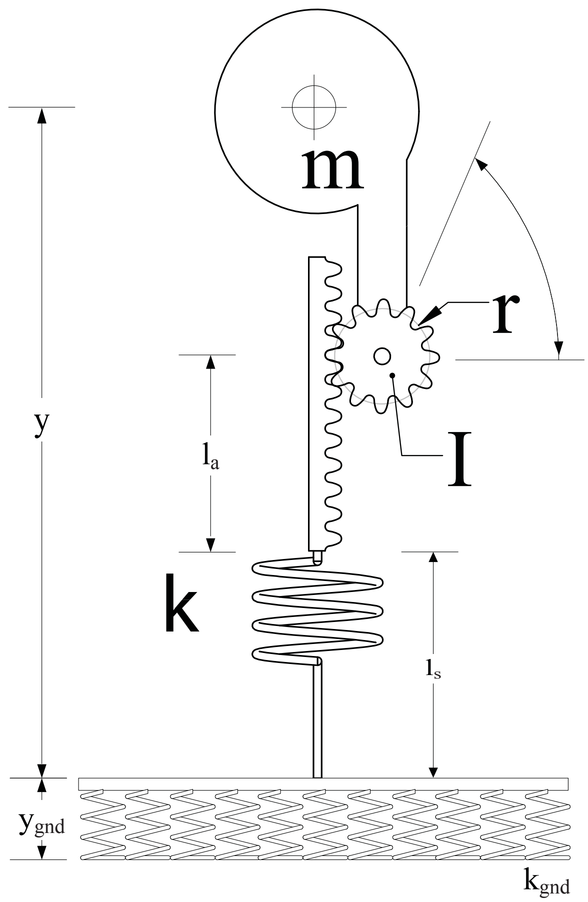

Figure 3.1: Force-controlled spring-mass model with a small reflected motor inertia at the instant of leg touchdown on a compliant surface.

To simulate the behavior of our robot model we solve the kinematic equations for the center-of-mass height and motor angle. The equation for the center-of-mass acceleration is the same as for the standard spring-mass model

$$\ddot{y} = \frac{1}{m} F_{spring}(y, \theta) - g.$$

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

$$\ddot{\Theta} = \frac{r}{I} F_{spring}(y, \theta) - \frac{1}{I} \tau_{motor}.$$

Because of non-linearities in the control functions, such as motor torque limits, 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 ordinary differential equation solver. The parameter values chosen for these experiments make calculating a numerical solution slow when using ODE45, so we simulate our experiments using MATLAB's ODE15s solver, which is designed for differential equations too stiff for the ODE45 solver. Our intention is to demonstrate a concept with as many implementation details abstracted away as possible. During simulation we switch between flight and stance models. Control is embedded within these models such that motor torques are generated synchronously with solver iterations. This prevents our model from being limited by a realistic sampling frequency. Although we partition a bounce into three stages, the fall and rise stages are described by the same model of a mass in free-fall. Event detection is used to determine instants of leg touchdown, liftoff and maximum height. As events occur, our simulation transitions from fall-to-stance, from stance-to-rise and from rise to the next hop respectively. Along the way, output from the ODE15s solver is accumulated. After three simulated hops, the center-of-mass trajectories, toe-force profile and motor movement are plotted as functions of time.

Chapter 4

Controller

We take the idea behind the ARL-Monopod II, a SLIP model hopper, a step further by actively controlling the passive dynamics of our system to accommodate for ground disturbances. Our proposed model simplifies upper level control by maintaining a regular cyclic center-of-mass trajectory during external disturbances as if the model were hopping vertically on a flat rigid surface. Disturbances are handled by low level controllers, leaving the upper-level controller free to concentrate on other tasks.

In general, our simulation behaves like a simple spring-mass model without interference from active controllers. The only time active control plays a role in our simulation's performance is when a ground disturbance is encountered.

During undisturbed hopping we expect our model's motor to perform zero work. Our model behaves like its equivalent passive spring-mass system under ideal conditions. Our model's spring exerts the work required to decelerate and re-accelerate the system after leg touchdown at no cost to our system. We actively actuate our leg in the presence of ground disturbances. This allows our robot to follow the toe force profiles, and maintain the same center-of-mass movement as its equivalent passive system bouncing on a flat, rigid surface.

Toe force is determined from the deflection of the series spring. The controller generates motor torques by combining closed-loop feed-back torques. Our robot attempts to match its toe force profile with the toe force profile of its ideal, undisturbed passive dynamics, which we model as a point mass bouncing on a spring.

Force control using series elastic elements, provides disturbance rejection. Our force-controlled, spring-mass model is schematically the same as MIT's Series Elastic Actuator[11]. However, we use a much larger spring that is used for both energy storage, and as part of the natural dynamics of the system. Since we attempt to match our model's toe force profile to that of an equivalent undisturbed spring-mass model, its center of mass movement approximates that of the undisturbed model. When our model encounters an unexpected change in ground height, the leg quickly extends or retracts such that the phase and amplitude of the toe force profile match those of the undisturbed passive dynamics. When our model encounters an unexpected change in ground stiffness, the leg extends gradually during stance.

We actively control spring deflection, which corresponds to toe force. In simulation we assume an ideal linear spring with known spring coefficient, such that the spring force may be easily calculated from the spring deflection. Although our physical robot uses fiberglass leaf springs with non-linear performance, we can generate lookup tables to approximate spring force as a function of spring deflection. The relationship between spring force and deflection is of no significance to our controller, as long as the spring force can be determined from measuring the spring deflection.

The controller attempts to match the model's toe force with the force profile that would be generated by an ideal, undisturbed spring-mass system. To accomplish this goal, the motor torque is calculated by combining torques from three independent controllers. This way, the leg spring exhibits all of the robot behavior, and the motor does no work, when there are no external disturbances. The motor torque, τ_{motor}, is calculated as follows,

$$\tau_{motor} = \tau_{compensate} + \tau_{error} + \tau_{retract}.$$

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. 4.1. This allows the second controller to treat the motor as an independent inertia and control its position through basic PD control, applying τ_{error} based on the error between a desired motor position and its measured position. A third controller generates a torque, $\tau_{retract}$, that returns the leg to its initial length by resetting the motor position after liftoff.

When our model senses that it has left the ground, this third controller uses a second PD controller to return the leg to its original length. Our model responds to ground disturbances by actuating its leg, which leads to changes in leg length and motor velocity at lift-off. Without active motor position control during flight, our model could touchdown unexpectedly, or with the motor already spinning. If either of these scenarios occur, the result is a large amount of wasted energy and deviation from the equivalent passive model. Large motor torques are needed to rapidly actuate the leg when an unexpected touchdown or touchdown with motor velocity occurs.

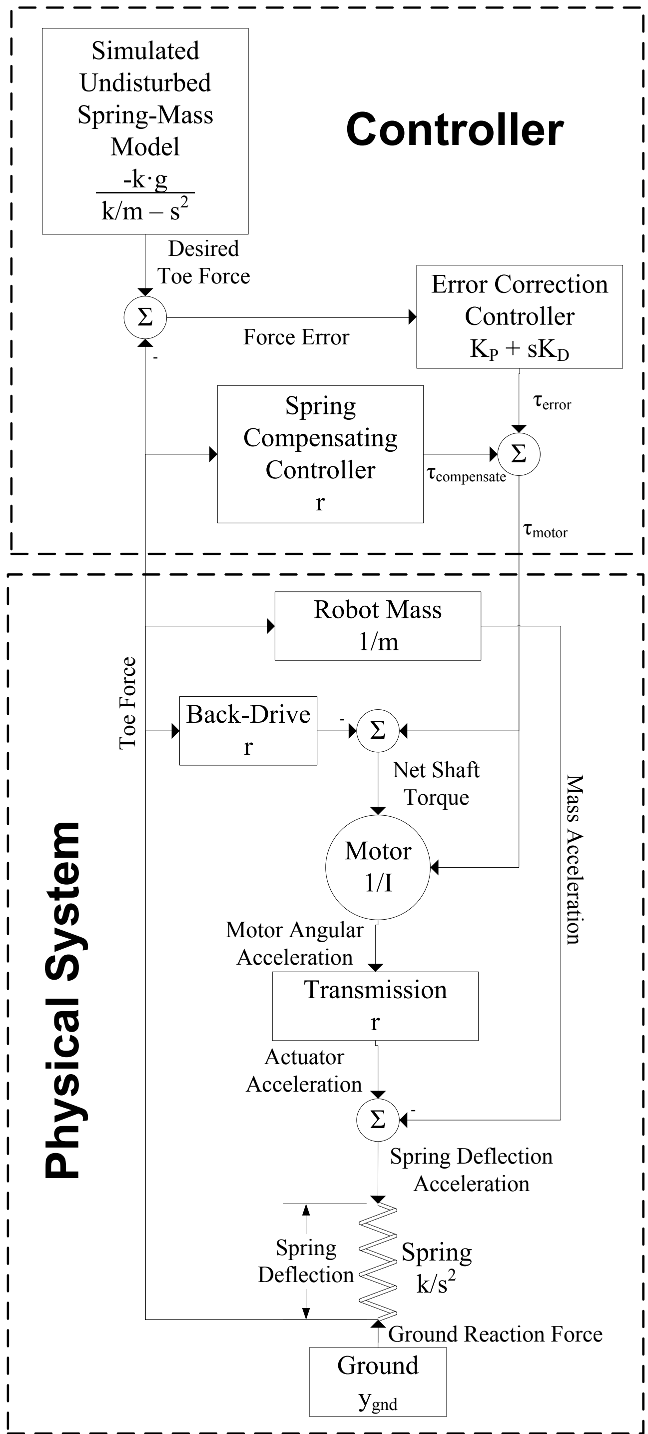

Figure 4.1: System block diagram for stance phase. Although three independent controllers working in parallel generate the motor torque, we omit the leg retraction PD controller because it only becomes active during the flight phase after a disturbance, and is never active in concert with another controller.

Chapter 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. We expect the actively controlled system to show better disturbance rejection, while still utilizing passive dynamics to minimize necessary motor work. On a rigid, flat surface the passive dynamics of our model give it the same behavior as the simple spring-mass model. However, in the real world the ground is rarely ideal, and we therefore introduce active control to accommodate for ground disturbances. The ground disturbances we investigate are unexpected drops in ground height and changes in 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.

The first type of disturbance we investigate is a sudden decrease in ground surface during the flight phase. For this experiment the ground height unexpectedly drops by 5cm after one undisturbed hop. There are no "sensors" that allow the model to change its control strategy, it has no forewarning of this change in ground surface. The model then takes one hop on the lower ground surface, before the ground surface 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. We subject the standard spring-mass model to the same disturbance, and use its performance as a baseline for comparison to evaluate the disturbance rejection ability of our force-controlled model.

The second type of ground disturbance we investigate is a decrease in ground stiffness. For this experiment the ground unexpectedly changes from being perfectly inelastic to behaving like an ideal spring, with a spring coefficient of 10kN/m. 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.

parameter	**value**	**description**
y_0	$22.75cm$	initial CoM height
$y_{gnd}(t)$	0 or $-5cm$	ground heights
m	$10kg$	robot mass
I	$1\frac{rad}{N \cdot m \cdot s^2}$	reflected motor inertia
r	$40cm$	transmission output radius
G	$17.25 : 1$	transmission gearing ratio
τ_{lim}	$\pm 25N \cdot m$	motor torque limits
θ_0	0	initial motor position
k	$10\frac{kN}{m}$	robot spring coefficient
$k_{gnd}(t)$	$10\frac{kN}{m}$ or ∞	ground spring coefficients
l_s	$10cm$	unstretched robot spring length
l_a	$5cm$	initial actuator length

Chapter 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.

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 illustrated in Fig. 6.2 and Fig. 6.1 respectively. 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 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

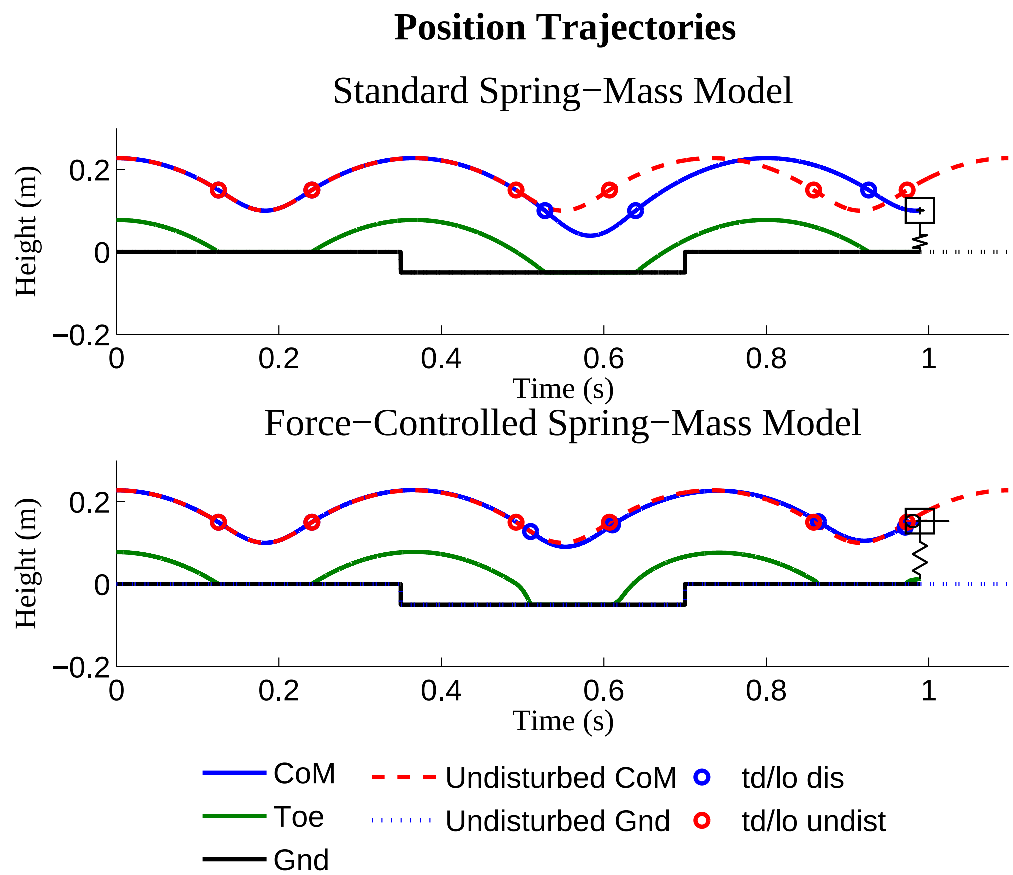

Figure 6.1: Comparison between the center-of-mass trajectories of the standard, vertically-hopping, spring-mass and force-controlled models encountering an unexpected decrease in ground surface.

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. When the force-controlled spring-mass model encounters an unexpected drop in ground height it begins to follow a force trajectory. Because the ground provides no reaction force against the toe, the leg accelerates towards the ground until it makes contact, as shown in Fig. 6.3. The center of mass trajectory depends upon the force profile through the double integral of the toe force. Unexpected changes in ground height do not significantly affect the toe force profile, and therefore, reduce deviation between the center-of-mass trajectory for the

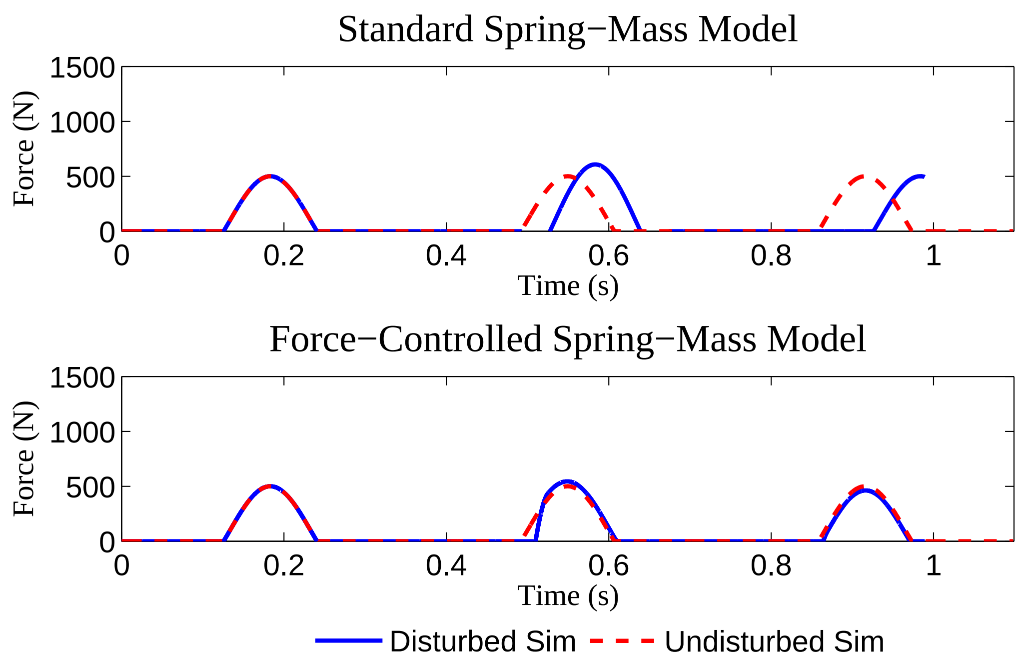

Figure 6.2: Comparison between the toe force profiles of the standard, vertically-hopping, spring-mass and force-controlled models encountering an unexpected decrease in ground surface.

force-controlled model and the equivalent, undisturbed, passive system as compared to the uncontrolled spring-mass model subjected to the same experiment.

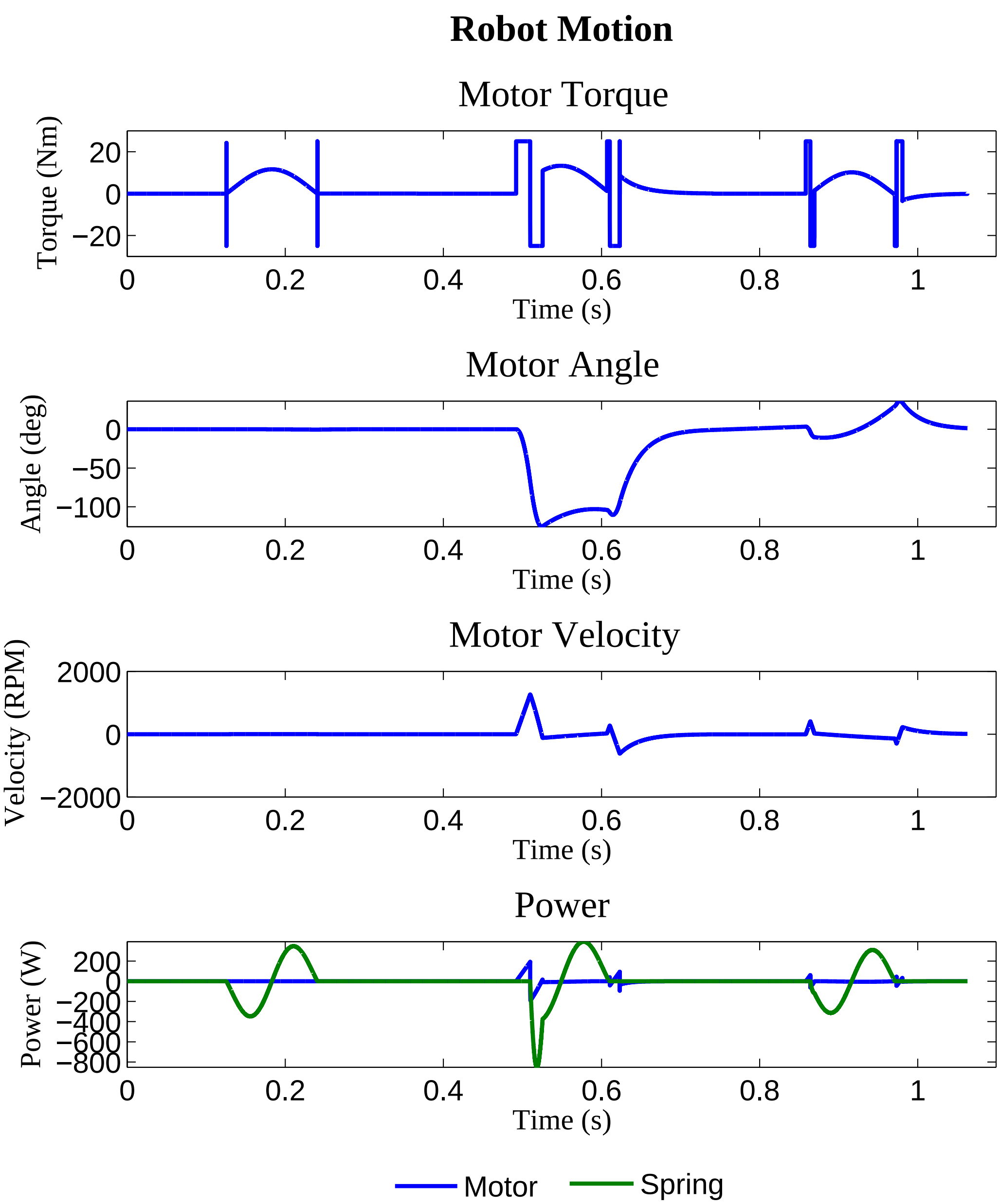

Figure 6.3: Motor torque, angle, velocity, power, and spring power for the vertically-hopping, force-controlled model encountering an unexpected decrease in ground surface.

6.2 Ground Stiffness Disturbance

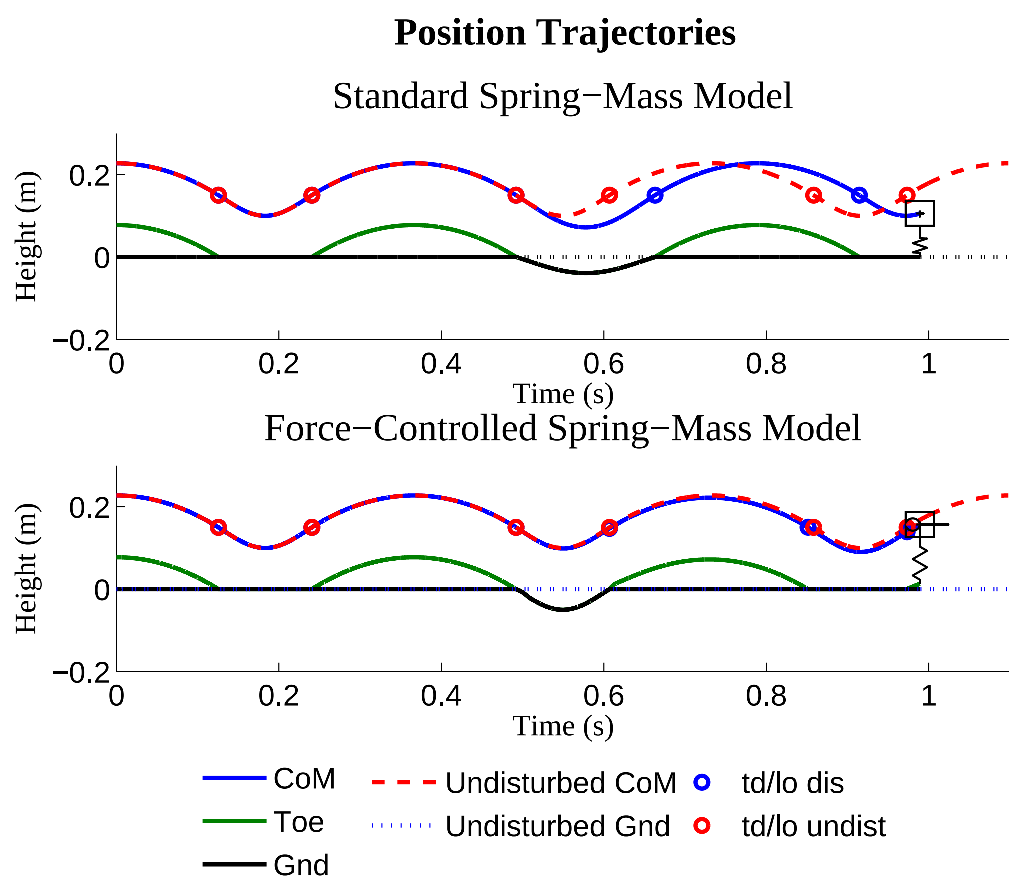

Figure 6.4: Comparison between the center-of-mass trajectories of the standard, vertically-hopping, spring-mass and force-controlled models encountering an unexpected decrease in ground stiffness.

For the standard spring-mass model, variations in ground stiffness affect the center-of-mass trajectory, as shown in Fig. 6.4. 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 is decreased. 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. 6.5, as the length of stance increases, such

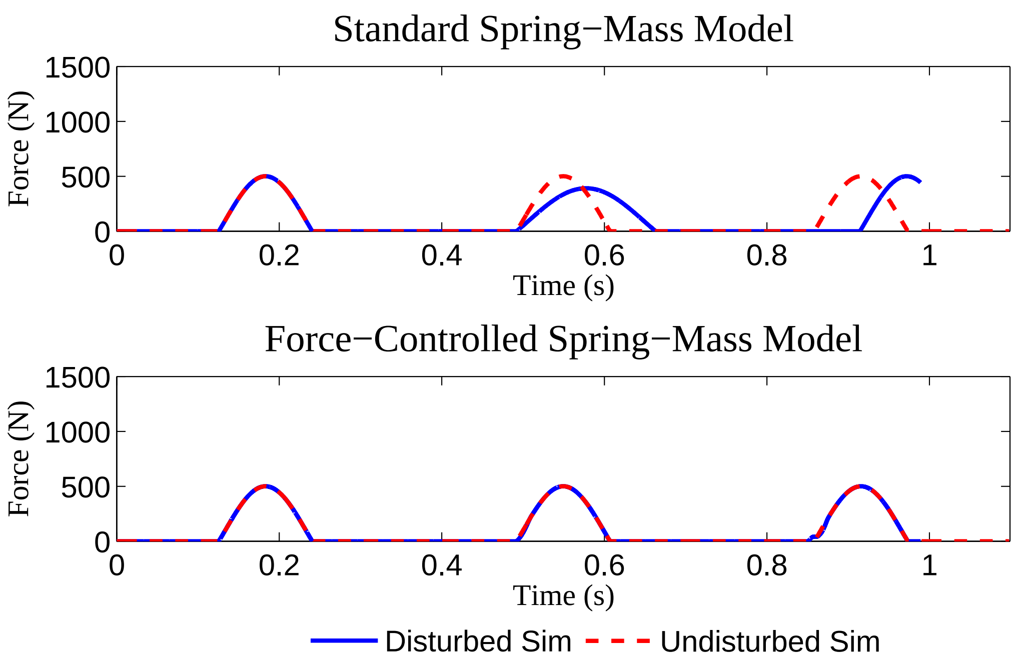

Figure 6.5: Comparison between the toe force profiles of the standard, vertically-hopping, spring-mass and force-controlled models encountering an unexpected decrease in ground stiffness.

that the total energy of the system remains constant.

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, refer to Fig. 6.6. 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. 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.

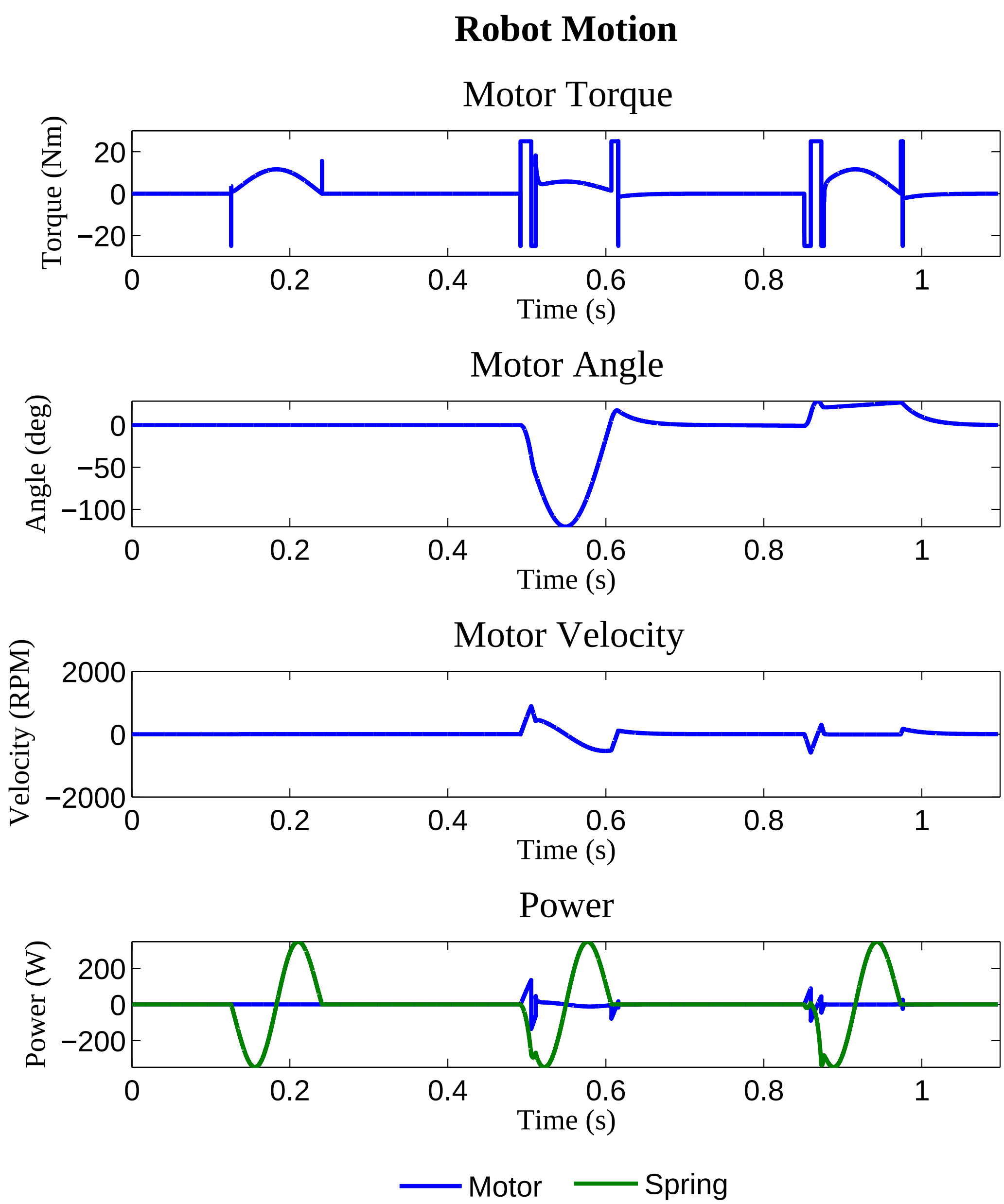

Figure 6.6: Motor torque, angle, velocity, power, and spring power for the vertically-hopping, force-controlled model encountering an unexpected decrease in ground stiffness.

Chapter 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 economy of a completely passive system. The toe force profiles for our force-controlled spring-mass model closely follow those predicted for the equivalent spring-mass system bouncing vertically on a flat rigid surface. Because our simulated robot closely replicates the toe force of its inherent passive dynamics, its center-of-mass movement approximately follows that of the ideal system bouncing vertically on a flat, rigid surface, despite unexpected changes in ground height and ground stiffness. The uncontrolled spring-mass model does not actively respond to unexpected ground disturbances, but our force-controlled model is able to compensate for external perturbations. When the uncontrolled spring-mass model encounters a decrease in ground surface, more of the model's gravitational potential energy is converted into kinetic and finally spring potential energy. In contrast, our robot extends its leg rapidly at the expected instant of leg touchdown maintaining a toe force profile and center-of-mass trajectory that is the same as for the standard spring-mass model. When the uncontrolled spring-mass model encounters unexpected ground compliance, the peak force decreases, while the duration of the stance phase is prolonged, such that the total energy of the system remains constant. Our force-controlled model is able to compensate for ground stiffness disturbances by gradually extending its leg during the first part of stance, and then retracting it during the second part such that a toe force profile and center-of-mass trajectory are maintained.

Our simulation has uncovered some unexpected control issues related to using a PD controller on spring force. When our robot encounters a drop in ground height, there is a delay between when toe touchdown is expected to occur, and when ground contact is actually achieved. As the leg accelerates towards the ground, the actual toe force of our robot overshoots the desired toe force, despite our efforts to critically damp the system.

Without an integral controller there is some steady state error that decreases, but is never eliminated, as the proportional control coefficient is increased. This error causes the magnitude of the actual toe force profile to never quite reach the desired level. This small error in the toe force integrates over the stance phase of a hop for the ground stiffness experiment causing a gradual loss in center-of-mass height. This can be compensated for by measuring the lost energy and adding it back by scaling the force profile, or some other method.

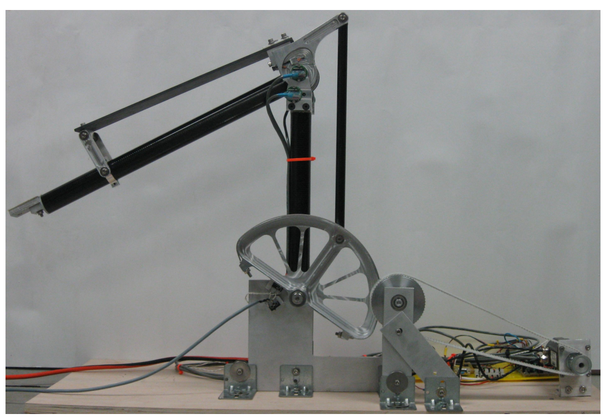

Figure 7.1: Single-joint force controlled actuator with rotating arm.

We will validate these simulation results on a new prototype. We have designed and built a rotating arm, force-controlled actuator, Fig. 7.1. We are constructing a fixture that will convert the torque output of this rotational system into a linear force. We will then attempt to replicate the hopping behavior and disturbance rejection demonstrated in simulation.

We have begun working on a design of a two-joint monopod named ATRIAS, see Fig. 7.2, adapted from the single joint platform. The goal of this two degree-of-freedom system will be to add disturbance rejection capability to the already proven SLIP model. Once we have demonstrated our design in simulation, we will attempt to extend our controller to the physical system. The parameter values chosen for simulations included in this paper roughly match values taken from our design for ATRIAS.

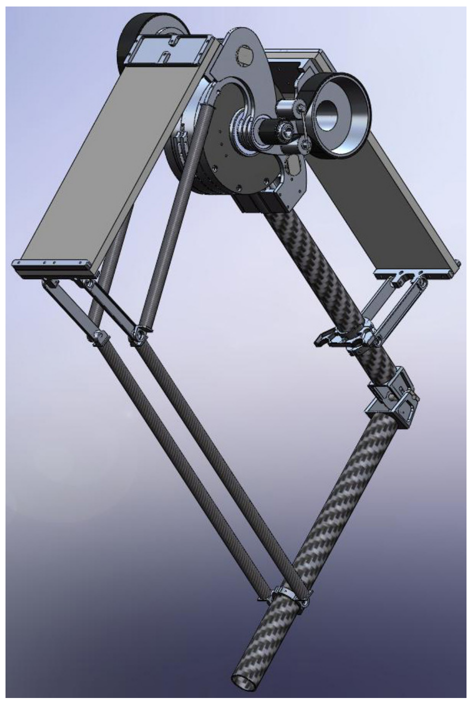

Figure 7.2: Current ATRIAS design. Rendering of monopod with two force-controlled joints and series compliance.

The long-term goal of this work is to design, simulate and build a biped capable of efficient and robust dynamic walking and running gaits. Our biped will be composed of two ATRIAS legs joined at the hip. We hope to be able to match the ground disturbance rejection performance of the single-legged platform.

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