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# THE DESIGN OF ATRIAS 1.0
# A UNIQUE MONOPOD, HOPPING ROBOT*

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ATRIAS 1.0 is a spring-legged, monopod robot designed and built as a prototype towards a human-scale 3D biped. The monopod has to meet certain requirements concerning locomotion dynamics and energy efficiency to meet the goal of a biped that can autonomously walk and run efficiently and robustly outdoors, untethered over realistic (non-ideal) terrain. The design of ATRIAS 1.0 includes adequate control authority for robust locomotion as well as incorporating the idea of passive dynamics for high energy economy. Towards this effort, the passive dynamics of ATRIAS 1.0 are designed to match the key features of the Spring Loaded Inverted Pendulum model: a massless leg, mass centered at the hip joint, and a series spring between the ground and the mass at the hip joint. In this paper the authors discuss the key features of this unique robot design.

*Keywords*: robot; legged; monopod; hopping; walking; running.

## 1. Introduction

ATRIAS is a prototype spring-legged monopod robot designed as a precursor to a human-scale biped that is intended to efficiently and robustly walk and run outdoors, untethered, over realistic (non-ideal) terrain. Legged robots that can currently locomote outdoors do so at significant energy expense.[1,2] Conversely, robots that walk or run efficiently do so at the expense of robustness.[3] Although no robot currently realizes both features, we believe these are not mutually exclusive goals, and that ATRIAS will bridge the gap.

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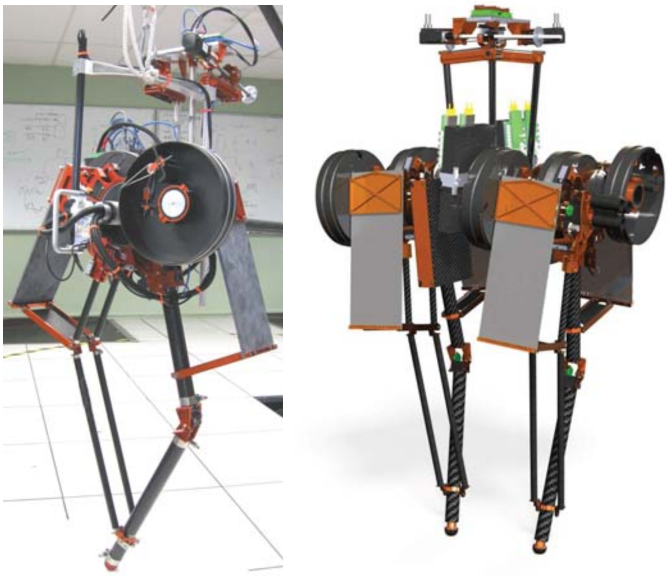

Fig. 1. **Left:** ATRIAS version 1.0, a Monopod prototype for a bipedal walking, running robot. **Right:** CAD model of the biped configuration.

ATRIAS is designed to match a simple mathematical model called the Spring Loaded Inverted Pendulum (SLIP), a model that approximatly describes the steady-state legged locomotion for most legged animals.[4] By matching this established model, we can take advantage of existing robust and efficient control theory that is built on this foundation.[5–7] Successful application of these controllers on ATRIAS relies on close approximation of the SLIP model's passive dynamics. The key elements of the SLIP that we have approximated in ATRIAS are a massless leg, mass centered at the hip joint, and a series spring between the mass and the ground.

## 2. Background

Big Dog and LS3 are quadruped robots representing the state of the art in legged locomotion.[1,8] These robots can walk outside in a wide range of non-ideal, real world environments. Utilizing gasoline engines to power hydraulic actuators, these robots have ample power to allow for their controllers to be developed and implemented. Each have a cost of energetic transport rating of over ten times that of a human. Legged robots that currently locomote effectively outdoors do so at high energy cost.

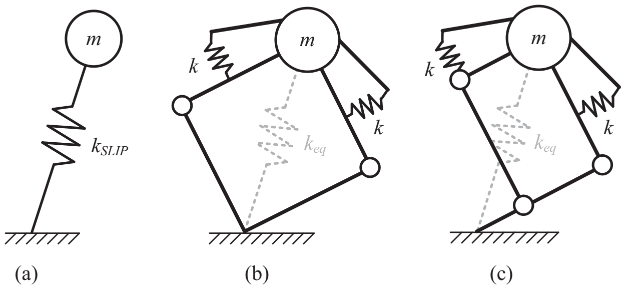


Fig. 2. **A:** Spring Mass model **B:** Simplified ATRIAS model **C:** ATRIAS model. This figure shows the similarity between the Spring Mass model and the ATRIAS model. The dynamics of the SLIP and ATRIAS are equivalent. The equivalent SLIP model is superimposed over the ATRIAS models.

Efficient legged robots locomote at the expense of robustness. Robots like Cornell Biped, Ranger and T.U. Delft's Denise use little or no actuation and rely on the mechanism design to achieve a stable walking gait.[3] They rely largely on their passive dynamics showing us that an understanding of this concept can lead to greater energy economy in legged robotics.

A combination of the two approaches, combining active control with passive dynamics, can result in an energetically efficient and robust legged robot. As an example MABEL is a planar biped built with passive dynamics to match the SLIP model and has proven to be a robust walker with a cost of transport of about twice that of a human.[7]

## 3. Robot Model and Mechanical Design

The goal of the mechanical design of our robot is to closely match the key features of the SLIP model. As with the SLIP model, our robot operates in a plane, constrained by a support boom allowing the robot to run in a circle in our laboratory while allowing un-restricted vertical motion.

A four-bar mechanism composed of lightweight carbon fiber tubes is used to meet the requirement of a massless leg as close as physically possible. This leg follows the same idea of high-speed pick-and-place robots featuring low-inertia limbs with simple pin joints, driven by motors placed above the limbs.[9] While a massless leg is impossible, this four-bar leg is only 10% of the total full monopod robot weight.

Placement of the motors at the hip joint also helps to match the SLIP-model feature of robot mass concentrated at the hip joint. These two brushless DC motors paired with low-friction, zero-backlash cable pulley

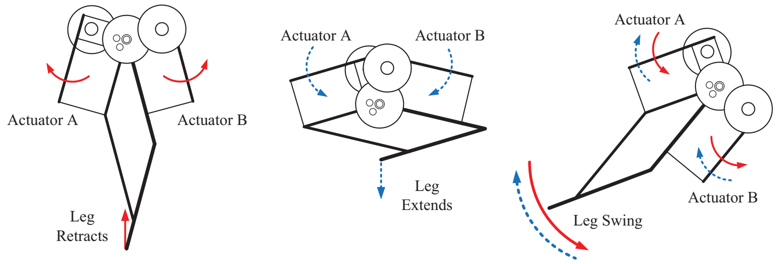


Fig. 3. Reaction torque is canceled during leg extension and retraction but not for leg swing. Both motors contribute to the torque for leg extension, in contrast to a design with one motor controlling leg length and second for leg angle. **Right:** Solid, red arrows indicate leg swing in one direction; dashed, blue arrows indicate leg swing in the opposite direction.

transmissions drive the two topmost members of the four-bar leg through a large series spring.[7,10] Figure 3 shows this configuration where both motors contribute to the leg length and the leg angle, combining torques to extend the leg. Both motors contribute to the large forces exerted by the leg during the stance phase of running or jumping. This allows the motors to be smaller and lighter compared to a configuration where one motor drives the leg length and the other the leg angle.[a]

A series spring is placed between each motor and its driven carbon fiber linkage in the form of a fiberglass leaf spring. Figure 5 shows deflection in the springs, which is measured with high resolution absolute encoders allowing for very precise force control.

The configuration of the four-bar leg, with the mass centered at the hip joint and series springs pictured in Fig. 2c, is dynamically equivalent to the SLIP model. The SLIP model generally has a linear spring stiffness, $k_{SLIP}$ (Fig. 2a), but this is primarily for mathematical convenience. Due to ATRIAS's leg configuration, linear leaf springs result in an overall leg stiffness, $k_{eq}$ (Fig. 2c), that is a non-linear, softening spring. To make ATRIAS a 3D-capable robot, a hip actuator is included to control the angle of the leg to the sagittal plane of the robot, allowing the robot to side step. This is a divergence from the 2D SLIP model but is a necessary extension for a 3D biped configuration, and is also useful to counter the angular changes imposed on the monopod by the robot support boom. This actuator is composed of a considerably smaller motor from the leg motors, includes a series spring and ball screw, driving the leg with respect to the body. The robot's

[a]MABEL is an example of this configuration.[7]

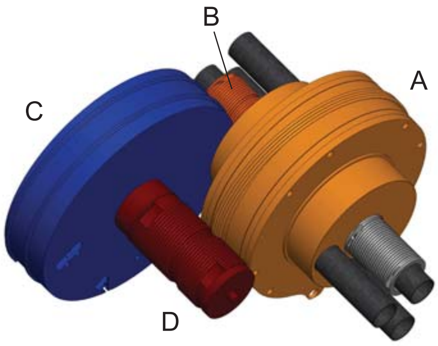


Fig. 4. ATRIAS 1.0 Cable Drive Transmission for one motor (transmission for second motor is removed for clarity). Four Pulleys make up the planetary gear system for one of the two force controlled actuators on the robot. D: Motor housing, fixed to body (non-rotating) A: Motor output spindle (input to transmission) A & C First stage of transmission, 5.38:1 C & D Second stage of transmission 3.73:1 C: Pulley, rotates around motor housing (D) with the transmission output. An overall transmission ratio of 20:1 is achieved.

body is composed of this actuator and a battery pack arranged such that the center of mass of the body is located at the hip joint. This maintains the desired mass concentration of the robot and the requirement set by the SLIP model.

## 4. Discussion and Future Work

While the cable pulley transmission is highly efficient, its system of pulleys require a large workspace when moving the leg. This is problematic when the leg has a large range of motion including that which is necessary for side stepping. The robot necessarily becomes very bulky in order to keep the pulley workspaces from intersecting.

The four-bar leg is a lightweight, low-inertia physical approximation of the massless leg on the SLIP model. Because one motor applies torques between the body and the thigh, and the other motor applies torques between the body and the shin, both motors must work together for coordinated leg movements. This has two implications: the reaction forces of the motors accelerating, and how they apply force and work.

Due to the counter-rotation of the motors during leg extension, motor reaction torques are canceled; however, co-rotation of the motors during leg swing these torques are added. For a monopod configuration this can cause undesired pitching of the robot body, but, for a biped configuration these

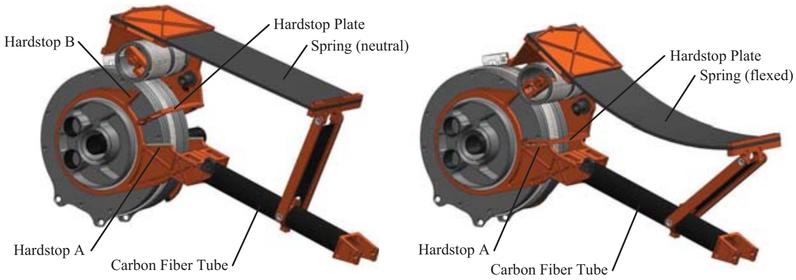


Fig. 5. Section view of one of ATRIAS's leg actuators. The carbon fiber tube is driven by the motor through the leaf spring and linkage forming a series elastic actuator.

reaction torques can be canceled by counter-rotating the two legs. This divergence from the SLIP model must be accounted for in any dynamic modeling, as a modification of the actuated SLIP model.

The four-bar leg has a distinct advantage in the application of force, and a disadvantage in conservation of work. For force application, both motors apply opposing torques to lift the robot off of the ground. However, when running forward at speed, both motors are moving in the same direction as the leg sweeps through the stride. Because the forces are applied in opposite directions while the speed is in the same direction, one motor is doing positive work while the other is doing negative work. In effect, energy is cycling between the motors and repeatedly encountering losses in the transmissions. This effect will reduce the robot's energy economy when running at high speeds, and whether or not it is a worthwhle tradeoff depends on the specfic gaits or behaviors.

The large leaf springs provide excellent energy storage and series compliance for the two leg actuators responsible for extending, retracting and swinging leg. However, series compliance in the hip actuator, responsible for side stepping, allows for good force application during stance but leads to complications in controlling the system during flight. The complication arises when the hip actuator transitions from applying forces during stance to supporting the leg during flight. This immediate change in controller goals results in undesirable oscillations during flight phase, complicating the task of orienting the leg for touchdown. With our monopod prototype, we essentially ignored the springs and the forces, and did a rough position control based on the kinematics of the boom, to keep the leg upright as it hopped. This design will not work well for a 3D, tether-free biped.

Toward the goal of making a biped robot walk and run in a realistic, non-ideal, 3D environment using SLIP model controllers, ATRIAS 1.0 is an important first step in the design process. With a very basic, intuitive controller, this robot has achieved a hopping gait. We demonstrated that the four-bar linkage leg configuration will work well, the leaf springs work well, and the kinematic structure of ATRIAS is good. In addition, of course, the software and electronics and many small engineering details were tested. Some things will change, including the hip actuator for lateral stepping, and the cable drive transmission, due to the large size. With what we have learned from ATRIAS 1.0, future revisions of ATRIAS paired with proper controllers will be capable of truly efficient, robust 3D walking and running.

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