

Design and Philosophy of the BiMASC, a Highly Dynamic Biped

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Abstract—This paper discusses the design principles and philosophy of the BiMASC, a biped with Mechanically Adjustable Series Compliance which incorporates tuned mechanical leg springs. This robot will be capable of dynamic running using mechanical leg springs, as well as dynamic ballistic walking with human-like passive leg swing behavior. The BiMASC will enable the study of the role of both controllable compliance in running and will serve as a test platform for control strategies that utilize the leg springs and other natural dynamics of the robot.

The mechanism is designed to behave in a dynamically “clean” manner, such that relatively simple mathematical models will accurately predict the robot’s behavior. The availability of simple and accurate mathematical models will facilitate the design of controllers, accurate simulations, and the implementation of accurate model-based control on the robot.

I. INTRODUCTION

The Biped with Mechanically Adjustable Series Compliance, or BiMASC, is being designed and built at the Carnegie Mellon University Robotics Institute, in collaboration with Professor Jessy Grizzle and Benjamin Morris at the University of Michigan. This paper provides an introduction to the design philosophy of this robot, along with some mechanical design details.

The purpose of the BiMASC is twofold. First, we seek to explore the role of compliance in running gaits. This is motivated by evidence from biomechanical studies and from simulations, which indicate that physical leg springs are important for energy efficiency and robustness in the presence of environmental disturbances; however, the problem of choosing the correct leg stiffness for a particular situation remains an open question. Second, the BiMASC will serve as a test platform for exploring control strategies that utilize the mechanical springs in order to achieve more efficient running and walking over smooth surfaces as well as robust locomotion over rough terrain.

Many legged robots have been constructed, each with different research purposes in mind. In this paper, we begin by comparing the BiMASC to existing robots. The BiMASC has a degree of morphological similarity to many of these robots as well as to human legs, but the primary goal of our research is to develop effective locomotion systems, rather than to mimic human locomotion. Our goal is to understand the principles of both running and walking, and to create legged robots that are energetically efficient in addition to being stable and robust to disturbances. Achieving these goals is imperative if a robot is to function effectively with a limited power source in real-world environments.

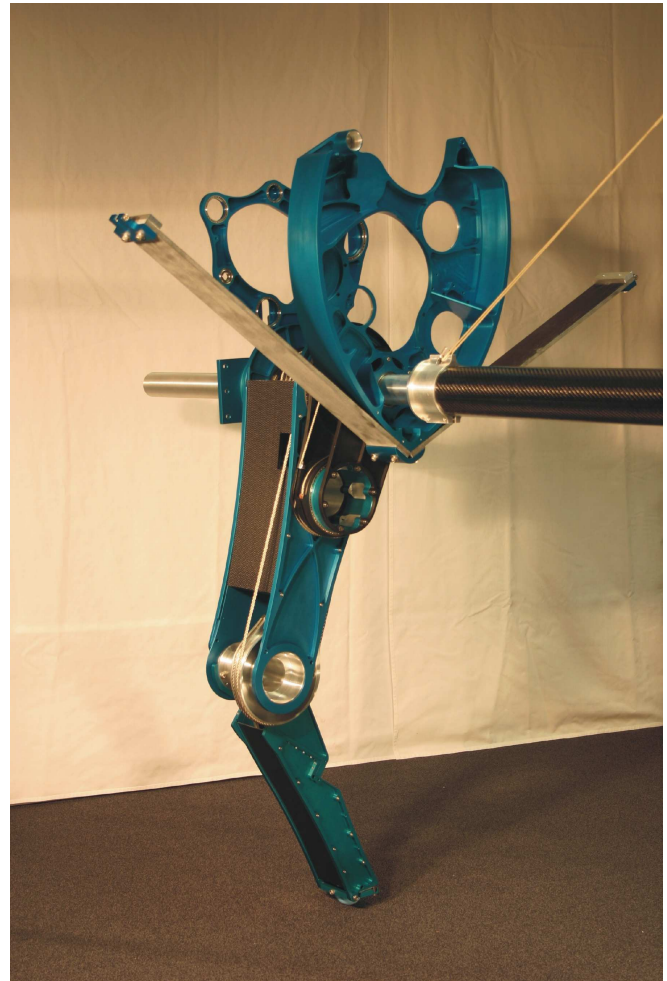


Fig. 1. One of the BiMASC’s legs, partially assembled. There are two joints, one at the hip and one at the knee. The length of the leg, from the toe to the hip, is approximately 1 meter. The long bars protruding from the front and back of the body are fiberglass springs, which will be attached to the pulleys of the robot with a steel cable. There are no gears in this system, all power transmission is accomplished using steel cables wrapped around aluminum pulleys.

Next, we explore our philosophical approach to the design of the BiMASC. Our guiding principle is dynamic simplicity. The passive dynamics are intentionally designed to match a simple, biomechanically-inspired mathematical model, such that a model-based control system will behave in a predictable manner. We have attempted to create a “clean” system, with measurable and predictable torques and forces,

low friction, conveniently located mass concentrations, more than sufficient motor power, ample proprioceptive sensing, minimal backlash in the transmission, and no loose wires or components which can vibrate.

Finally, we discuss details of the mechanical design. We have spent considerable time and effort on the high-level mechanical design of the BiMASC as well as on the design details, because the mechanical system is the most fundamental part of the machine’s dynamic behavior. We use a system of five cable differentials to transmit power between the three motors, two springs, and the thigh and shin associated with each leg. Each motor does not correspond to a single leg joint, but instead to specific combinations constrained by the differentials, so that the complete set of components behaves like a simple and predictable system.

II. BACKGROUND

The BiMASC is designed to exhibit dynamic behavior that closely matches a simple mathematical model. This model, in turn, is based on approximations of animal running behavior. The BiMASC incorporates ideas from the field of biomechanics, from direct observations of animal behaviors, and from existing running robots.

A. Spring-like behavior

A common theme among all runners is spring-like behavior. Runners follow an approximate center-of-mass motion similar to that of a bouncing ball. Spring-mass models such as the Spring Loaded Inverted Pendulum (SLIP) model have been developed as a tool to describe this center-of-mass motion [1], [2], [3].

Although adjustable leg stiffness is generally not implemented on running robots, prior theoretical and biomechanics research indicates that varying the leg stiffness is one effective method for controlling a running gait. Only three terms are required to describe a cyclic running gait based on the SLIP model, and leg stiffness affects one or more of the three terms [1]. Hodgins and Raibert used a planar hopping robot to demonstrate control of foot placement using leg stiffness, as well as hopping height and leg angle at touchdown [4]. To our knowledge, this is the sole example of robotic leg stiffness control in a running gait.

It is well understood that animals adjust their leg stiffness, and vary it to control running and hopping in certain situations [5], [6], [7], [8], [9]. Most research suggests that animals prefer to maintain leg stiffness over a range of running speeds [10], but do change leg stiffness to accommodate disturbances or when other methods of gait control are constrained. For example, hopping in place with varying frequency [2], hopping or running on a surface of changing stiffness [11], [12], or running at different speeds with constant stride length [13].

B. Creating Spring-Like Behavior

All running animals (and most running robots) store mechanical spring energy during a running gait [14], [15], [16], [17]. The basic definition of running is linked to the

use of leg springs, as depicted in the SLIP model — energy is transferred from kinetic energy in the flight phase to spring energy in the stance phase, and vice versa [18].

Physical compliance is virtually necessary for achieving a successful running gait. Simulating compliance using a rigid actuator such as an electric gearmotor is not feasible for three reasons: bandwidth limitations, power output limitations, and energetic efficiency [19]. The bandwidth limitation of an electric motor is due, in large part, to the high reflected inertia linked rigidly to the robot leg, which makes a correct dynamic response to impacts impossible. The power density of a physical spring can be arbitrarily high, depending on its stiffness, which makes a compelling argument for combining the relatively high work capacity of a motor and power source with the high power density of a physical spring. Springs are particularly useful in rhythmic systems, because energy can be stored and released much more efficiently through a spring than if it were passed through the motor, transmission, and power electronics with each transfer.

C. Actuator with Mechanically Adjustable Series Compliance (AMASC)

The Actuator with Mechanically Adjustable Series Compliance (AMASC) was developed specifically for the purpose of actuating a running robot [20], [21], [19]. It actuates a single degree of freedom, with a large spring in series between the electric motor and the output of the device. The spring is sized to store the energy of a running gait, so the robot may bounce on the spring much like a rider on a pogo stick, or like any animal in a regular running gait. The spring stiffness is mechanically adjustable; therefore, leg stiffness can be tuned for a particular gait or ground surface.

D. Comparable Robots

Many robots have been built for the purpose of walking and running. There are generally two classes: robots that utilize mechanical springs to store and release kinetic energy during a running gait (much like animals), and robots that do not. The planar biped from MIT’s Leg Lab [4] is an example of a spring-mass robot, using air springs for energy storage. Because this robot was tethered to a large hydraulic compressor and air compressor, it was capable of high performance behavior such as back flips. In contrast to the high power of many of Raibert’s machines, the Bowleg Hopper from Carnegie Mellon University and the ARL Monopod II from McGill University both have defensible claims to being the most efficient running robots [22], [23]. Both gain their efficiency by utilizing leg springs to effectively store and release energy during each stride, so the electric motors do relatively little work during a normal running gait.

The MIT Leg Lab’s Spring Flamingo does use springs, but not for energy storage. The springs on the MIT-style Series Elastic Actuator (MIT-SEA) are primarily for force sensing and mechanical filtering purposes [24], [25]. An important distinction between the MIT-SEA and the AMASC is that although both systems consist of springs in series between the motor and the output, the springs in a MIT-SEA are at

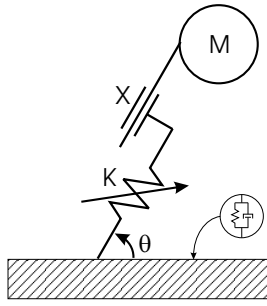


Fig. 2. The spring-loaded inverted pendulum model

least an order of magnitude smaller and stiffer. The springs of a MIT-SEA are essentially a soft load cell, acting as a force sensor for the low-level controller. At low frequencies, the MIT-SEA acts as a more sensitive and robust force actuator than a gearmotor and load cell. While the AMASC can behave as a MIT-SEA, the purpose of the adjustable spring in the AMASC is to store energy during a running gait and to create desirable natural dynamics for a range of gaits.

Recent bipeds have also been constructed which can change the stiffness of their joints [26], [27]. However, these bipeds are not designed for running, and are similar to the MIT-SEA in that they do not store significant amounts of energy in their springs. Additionally, when using pneumatic actuators for the joint stiffness control [27], the resulting system can be difficult to model and control precisely.

Robots with rigid transmissions such as Rabbit and Asimo do not use springs [28]. This is an important difference. If these robots are capable of an aerial phase, it is only at the expense of great motor power output and high energetic cost, with relatively unpredictable dynamic behavior at ground impact.

III. PHILOSOPHY

Our goal is to understand the principles of running, and to then leverage those principles to enable the creation of robots that effectively locomote in real-world environments. We seek to capture the essence of the physics and dynamics exhibited by a locomoting animal, rather than merely mimic the motion. By understanding the underlying dynamics, we hope to attain the stability, efficiency, and robustness required to achieve effective running and walking. Our goal is not necessarily to create a robot that appears to run like an animal, although we believe that if the principles of running are understood and implemented properly, this may be the outcome.

Determining which aspects of the behavior should be implemented in hardware and which aspects may be implemented through software control is a significant challenge of the robot design. The software can determine the robot behavior only within the limits of the mechanical system. For example, a gearmotor with a rigid connection to the leg cannot accurately simulate a spring during an impact event. This is a crucial factor, since impacts are common in running.

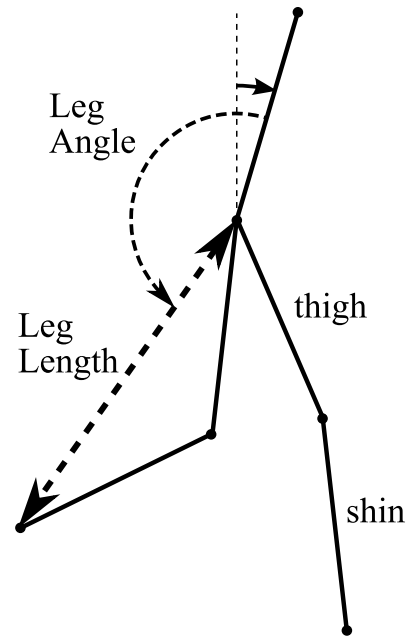


Fig. 3. The basic configuration of the robot is a familiar humanoid leg shape. The thigh and shin are equal length, and the foot ends in a point contact. The leg length and leg angle are actuated through a series of differentials, rather than direct actuation of the hip and the knee.

We treat the behavior of the robot as an integrated system of mechanical, electrical, and software control components. The dynamics of the mechanism, sometimes referred to as the natural dynamics, are critical; properly tuned mechanical springs and close attention to leg mass and actuator dynamics (such as inertia) are as much a part of the control system as the software. The natural dynamics of the mechanism can create a basic cycle, analogous to a mechanical clock, and the software controller nudges the system to change speed or step length. The controller can also aid in recovery from disturbances. However, when the gait is undisturbed and cyclic, little influence is required from the software control system.

The BiMASC is designed to behave in a dynamically simple manner, closely following the SLIP model. While the complex dynamics of an animal may not be perfectly represented through simple models such as the SLIP, such simplifications are important to enable a useful understanding of the system behavior. Many existing mathematical models and control strategies are based on the SLIP model, and if the robot behavior closely matches that of the SLIP model, then model-based controllers can be applied directly to the robot. This attempt at dynamic simplicity has led to mechanical complexity and non-traditional mechanical design, with more moving parts than would normally be required for so few degrees of freedom.

IV. MECHANICAL DESIGN

The BiMASC will be a highly dynamic running and walking planar robot. This project represents a challenging mechanical design problem, in part because there will be

regular impacts between the toe and the ground, positive and negative torques about the joints that will accentuate any backlash, and high power density requirements for lifting the robot off the ground repeatedly. These issues are addressed through careful attention to the natural dynamics, as well as some uncommon design choices.

A. Design Choices

There are a number of decisions made at the beginning of the design that determine the basic morphology of the robot. Following our design philosophy, the BiMASC is intended to be a dynamically simple system, which can be modeled and controlled using the simple spring-loaded inverted pendulum (SLIP) model. This means the robot should have point feet, a prismatic leg spring with controllable stiffness that is large enough to store gait energy, control of hip angle and spring set point, low friction, and low leg mass. Practical considerations include low or zero backlash, and clean mechanical design with no freely oscillating parts or loose wires.

We have chosen to add knees to the BiMASC, so that it may walk with dynamic gaits that are similar to human walkers. This choice is somewhat arbitrary—successful walkers and runners have bird-like legs, human-like legs, or even prismatic joints [29]. We have also chosen to include onboard computing, to reduce the length of control wires and to gain experience towards building autonomous machines in the future.

To achieve the goals of low backlash, low leg mass, and low friction, nearly all of the mechanical power transmission is implemented through highly efficient cable drives [30]. Cable drives are rarely utilized, but are ideal for this particular application. Unlike gears or timing belts, they do not allow for continuous rotation; however, this is unnecessary for a legged robot. More importantly, cable drives have no backlash, because cables are tensioned against each other or against the antagonistic springs. They are lightweight for their torque capacity, because they can use lightweight thin shells for pulleys. The torque capacity is limited primarily by the strength of the cable, which can be quite high. Cable drives can be very efficient (up to 96%) if properly implemented [31]. In addition, the cables can transmit power across lengths of the leg, so the motors (and their mass) can be placed inside the body of the robot, with the legs remaining largely free of components.

The basic actuation is based on the AMASC, using fiberglass springs and electric motors to implement a mechanically adjustable leg stiffness. In addition, the AMASC can use software control to accurately simulate zero torque at a joint, enabling passive leg swings for walking gaits.

Although we have knees, the leg spring in the AMASC acts in the leg length direction, rather than acting on a particular joint. This is implemented through the use of a series of five differentials, explained in detail in the following section.

B. Layout of Differentials

A differential is a special connection of three components (A , B , and C), and an internal, unobserved idler (D). The

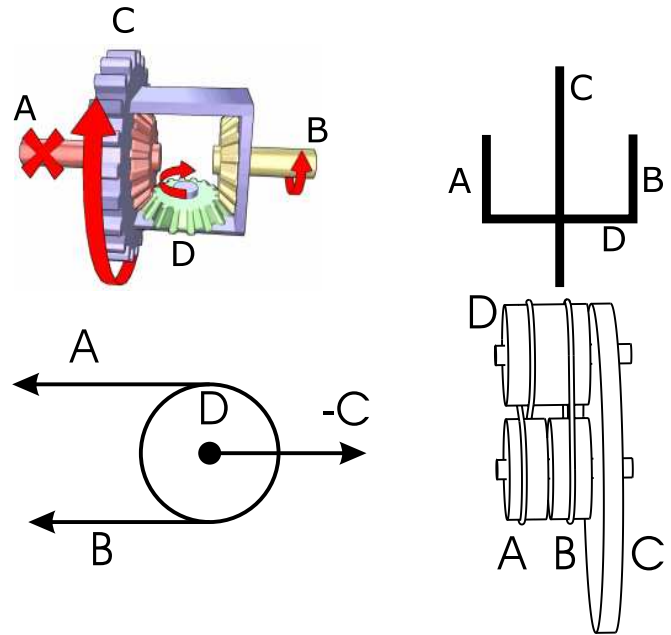


Fig. 4. Different implementations of a differential. The AMASC uses the implementation shown in the lower left, while The BiMASC uses the implementation in the lower right. The symbol shown at the upper right is a simplified drawing of the mechanism in the upper left.

kinematic equation for a differential is given by $\frac{A+B}{2} = C$. The components are constrained such that the average motion of two of the components (A and B) is equal to the motion of the third (C). Consequently, A and B can move in opposite directions if C is held stationary, and the motion of C will be half the speed of A if B is held stationary.

The differentials in the BiMASC are implemented through the cable drive, as depicted in Figure 4. Figure 5 illustrates the cable drive layout of one leg of the BiMASC. The cable drive system is made up of five cable differentials and three motors.

1) *Leg Length and Leg Angle*: As discussed in Section III, the leg spring acts in the direction of the leg length. Although the BiMASC has knees, the leg spring is connected to the thigh and shin through a pair of differentials in the hip (shown at the bottom of Figure 5), such that the leg spring acts in the desired direction. Notice that if the thigh angle and shin angle move by the same amount, the leg angle changes while the leg shape stays the same. In addition, because the thigh and shin are the same length, if the thigh angle and shin angle are changed by opposite amounts, the leg length changes while the leg angle stays the same. As a result, the hip differential is a transmission with leg length and leg angle as inputs, and thigh angle and shin angle as outputs. By connecting the leg length pulley to the AMASC made up of the top three differentials, the spring in the AMASC acts only along the leg length direction.

2) *Adjustable Spring Function*: To adjust the spring stiffness, which acts along the leg length direction, we use two opposing springs. After creating a desired nonlinear spring function using the fiberglass spring and shaped spiral pulleys,

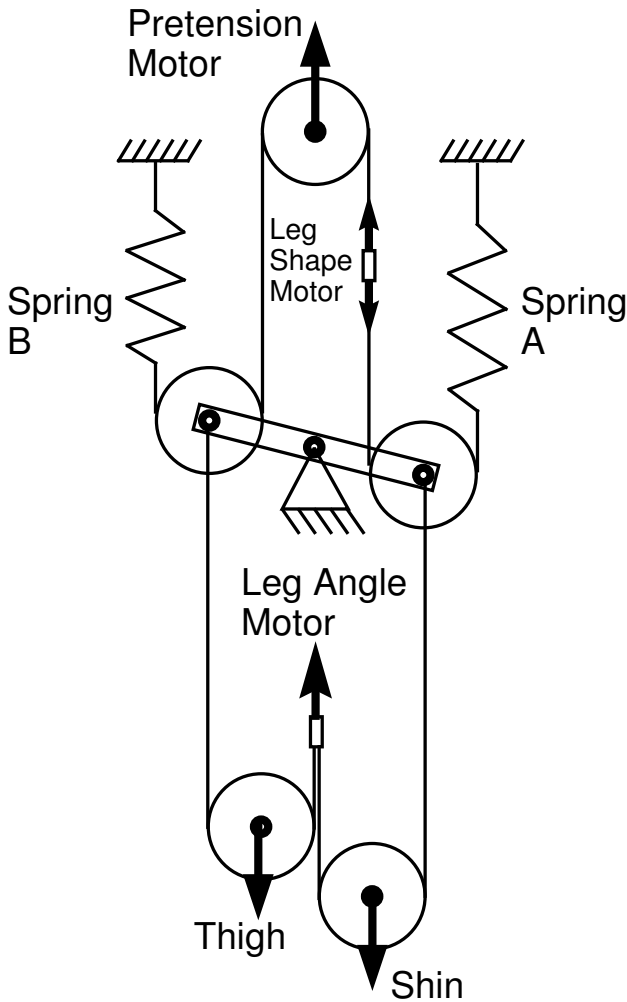


Fig. 5. Conceptual diagram of differential placement in the BiMASC. If the shin and thigh move in the same direction, the leg angle changes. If the shin and thigh move in opposite directions, the leg shape changes or the springs deflect differentially.

placing two such spring/pulley systems in direct opposition results in a single effective torsional spring whose stiffness is determined by the pretension on each individual nonlinear spring.

To prevent the need for the entire spring to move when the set point changes, we connect the springs between the motor and leg length via a differential, as shown in Figure 6. This configuration allows one end of the spring to remain grounded on the torso at all times. These two differentials (one for each spring) are shown in the middle of Figure 5.

3) *Control of Set Point and Stiffness:* Similar to the mechanism in the AMASC, one BiMASC motor controls the set point of the leg length, and another BiMASC motor controls the leg stiffness. This allows different sizes and capabilities to be chosen for the two motors, in contrast to many other stiffness-changing mechanisms that use two identical antagonistic motors. The particular design is shown in the top differential of Figure 5. Due to a mechanical design simplification, both motors must move for the pretension to

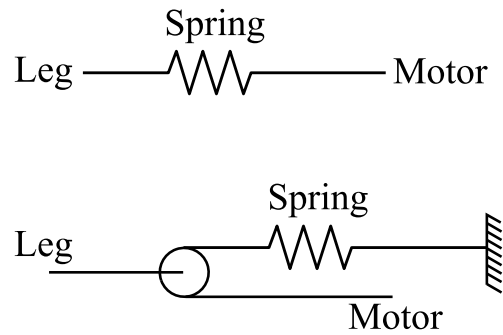


Fig. 6. *TOP:* Series elastic element without differential. The entire spring moves back and forth. *BOTTOM:* With the differential, the spring can remain grounded at one end.

adjust without affecting the leg length set point; however, the set point motor applies no torque, and thus does no work on the system. The two motors remain effectively independent from one another, one controlling leg length set point, and the other controlling stiffness.

V. DISCUSSION AND FUTURE WORKS

The BiMASC is designed to further the high-level goal of robust and efficient robotic legged locomotion. It will run over obstacles and artificial rough terrain, but the primary goal will be exploration of principles for application to future machines. With its directly controllable leg stiffness, the BiMASC will be used to optimize leg stiffness and help understand the role of leg stiffness in running, validating or contradicting theorized principles. We will explore control strategies that cooperate with the carefully constructed natural dynamics of the BiMASC, or with any machine that is also based on the same mass-spring model.

Designing the BiMASC for dynamic simplicity led to some unusual and novel mechanical solutions. For example, there are no gears in the entire robot, most of the transmissions are implemented with steel cables wrapped around aluminum pulleys. The motors are connected to the joints through a system of cable differentials, so forces from a single motor (or a spring) can be applied in directions that are unrelated to a single joint. We hope these ideas will be applied to future robotic systems with similar constraints.

As the BiMASC is a first prototype, we have started with as simple a model as possible to satisfy the goals of the project. Future work, after the performance and behavior of the basic BiMASC has been explored, will involve addition of potentially interesting complexities. For example, hip springs have been shown to be useful for improving efficiency in robotic legged locomotion. The ARL Monopod was first built with only a leg spring, and the ARL Monopod II incorporated a hip spring, with significant energy savings [22]. We do not currently use hip springs, but they could be added in the future. Adding feet will allow the robot to stand in one place, and may also lead to efficiency and stability gains. The legs of the BiMASC are light weight compared to the overall robot mass, and

adding leg weights to tune the natural dynamics may be advantageous for ballistic walking gaits. Of course, 3D running in real-world environments is our eventual goal, although the current mechanism will remain constrained to the cylindrical coordinate system of its boom.

Although the BiMASC will be a biped, two legs is not our final goal or limitation. We are studying legged locomotion in general, beginning with a single monopod prototype, and then immediately building a biped after some debugging (but no major design changes). A monopod is the simplest possible runner, and a biped is the simplest possible walker. More legs may be beneficial, and this may be a significant aspect of future work.

We hope that the technology developed in research with the BiMASC can be applied to biological systems as well as robotic systems. Understanding and implementing tuned leg stiffness will be important when designing human exoskeletons for assisted mobility. By using tuned springs, the mechanism can work together with the wearer's muscles, rather than in place of them. Low power motors might be used to reduce the metabolic cost of transportation for the wearer.

As we submit this paper for publication, the BiMASC is being assembled and debugged in the laboratory. The design is complete, the electronics are in hand, a software architecture for control and simulation is nearly ready, all parts have been fabricated, and assembly is under way. The BiMASC is significantly different from other robots, but based on many proven ideas. We hope to make a significant contribution to the field through the demonstration of new mechanical design ideas and through exploration of basic principles of legged locomotion.

VI. ACKNOWLEDGMENTS

This work is supported in part by an NSF IGERT traineeship, award number 0333420, held by the first author. Additional support is provided through Professor Jessy Grizzle at the University of Michigan, NSF grants ECS-0322395 and ECS-0600869, and by the Robotics Institute of Carnegie Mellon University.

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