

# MABEL, A New Robotic Bipedal Walker and Runner

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**Abstract**—This paper introduces MABEL, a new platform for the study of bipedal locomotion in robots. One of the purposes of building the mechanism is to explore a novel powertrain design that incorporates compliance, with the objective of improving the power efficiency of the robot, both in steady state operation and in responding to disturbances. A second purpose is to inspire the development of new feedback control algorithms for running on level surfaces and walking on rough terrain. A third motivation for building the robot is science and technology outreach; indeed, it is already included in tours when K-through-12 students visit the College of Engineering at the University of Michigan. MABEL is currently walking at 1.1 m/s on a level surface, and a related monopod at Carnegie Mellon is hopping well, establishing that the testbed has the potential to realize its many objectives.

## I. INTRODUCTION

This paper describes MABEL, a new bipedal testbed at the University of Michigan’s EECS Department. The robot is designed to be a good walker and an even better runner. It seeks to take advantage of compliance in its powertrain to improve the efficiency and agility of legged locomotion.

MABEL grew out of a collaborative effort between the University of Michigan and the Robotics Institute of Carnegie Mellon University; the acknowledgements attempt to summarize the important contributions made by many people to the conception, design and construction of this robotic testbed. As with many collaborative efforts, each group of participants brought different expectations, motivations and skills to the project. The Carnegie Mellon team was primarily interested in the design of the mechanism, with a focus on dynamic behavior; the Michigan team was looking for an exciting platform to inspire new control designs; the primary sponsor, NSF, was as much interested in the potential of the robot for outreach as it was in the new science that would come of the effort.

Section II overviews the general features of the robot; a much more detailed treatment is available in [17]. Section III summarizes the key features of the nonlinear, hybrid dynamic model of the robot for a walking gait. Initial experimental walking results are described in Sect. IV. Conclusions and future directions are provided in Sect. V. The latest information on the robot can be found at [11].

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## II. MECHANISM OVERVIEW

MABEL is a planar bipedal robot comprised of five links assembled to form a torso and two legs with knees; see Fig. 1. The legs are terminated in point feet. The planar nature of the robot is manifested in the hips, which are constrained to revolute motion in the sagittal plane. The robot is attached to a boom and hence walks or runs in a circle; when the radius is sufficiently large, this approximates well locomotion along a straight line. Up to this point, the robot is similar to RABBIT, the French robot on which the Michigan team collaborated from 2001 through 2004 [4], [26], [27].

The novel aspects of MABEL, and there are many, appear in the transmission or powertrain [18], [17]. First of all, all of the actuators (four DC-brushless motors, two for each leg) are located in the torso, so that the legs are as light as possible; this is done for running efficiency. In RABBIT and most other robots, the knee actuators are mounted on the thigh. Secondly, the actuated degrees of freedom of each leg

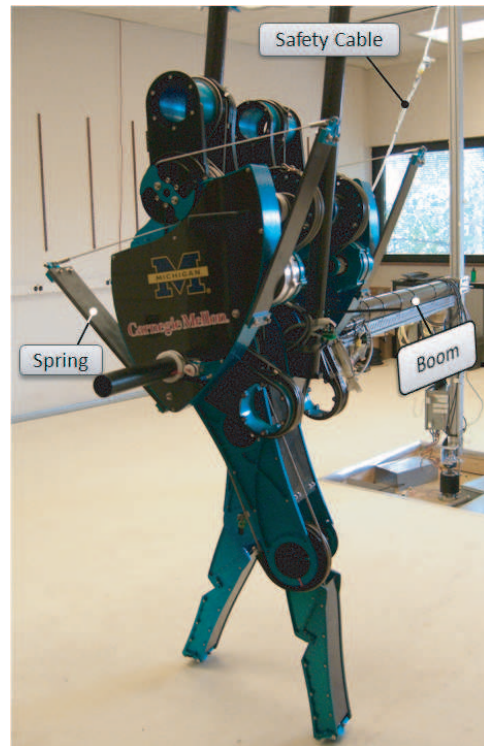


Fig. 1. MABEL, showing the boom that provides stabilization in the frontal plane and a safety cable. The shin and thigh are each 50cm long, making the robot one meter tall at the hip. The overall mass is 56 Kg. The robot’s powertrain incorporates unilateral springs for shock absorption and energy storage; see text and Figs. 2 and 3.

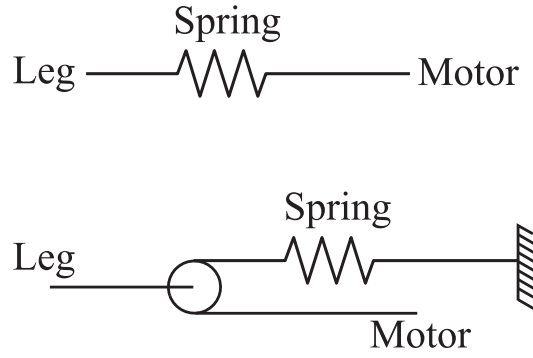


Fig. 2. The top figure shows a series elastic element without a differential: the entire spring moves back and forth. The bottom figure illustrates that with a differential, the spring can remain grounded at one end. MABEL’s powertrain is based on the second configuration.

do not correspond to the knee and the hip angles (the hip angle being the relative angle between the torso and thigh). Instead, for each leg, a collection of differentials is used to connect two motors to the hip and knee joints in such a way that one motor controls the angle of the *virtual leg* consisting of the line connecting the hip to the toe, and the second motor is connected—in series with a spring—in order to control the *length or shape* of the virtual leg; see Figs. 2, 3 and 4.

Roughly speaking, the rationale for this design is that it makes the robot a hybrid of RABBIT, a robot that walks extremely well, but never achieved a stable running gait [19], and a Raibert Hopper [24], a robot that “runs” remarkably well<sup>1</sup>. The springs in MABEL serve to isolate the reflected rotor inertia of the leg-shape motors from the impact forces at leg touchdown and to store energy in the compression phase of a running gait, when the support leg must decelerate the downward motion of the robot’s center of mass; the energy stored in the spring can then be used to redirect the center of mass upwards for the subsequent flight phase, when both legs will be off the ground [1], [2], [3], [5], [10]. Both of these properties (shock isolation and energy storage) enhance the energy efficiency of running and reduce overall actuator power requirements. This is also true for walking on flat ground, but to a lesser extent, due to the lower forces at leg impact and the reduced vertical travel of the center of mass. The robotics literature strongly suggests that shock isolation and compliance will be very useful for walking on uneven terrain [13], [25], [7], [6], [12], [20].

The third novelty in MABEL’s powertrain is that the springs in series with the leg shape motors are *unilateral* in the sense that they compress, but do not extend beyond their nominal rest length; instead, once a spring reaches its rest length, the position of the leg-shape motor and the shape of the virtual leg are rigidly connected (i.e., directly, through a gear ratio, and no longer through a compliant element); see Fig. 3 for how this is achieved. This is a big advantage in walking where at leg exchange, when the former stance leg must be lifted from the ground, this motion does not have to

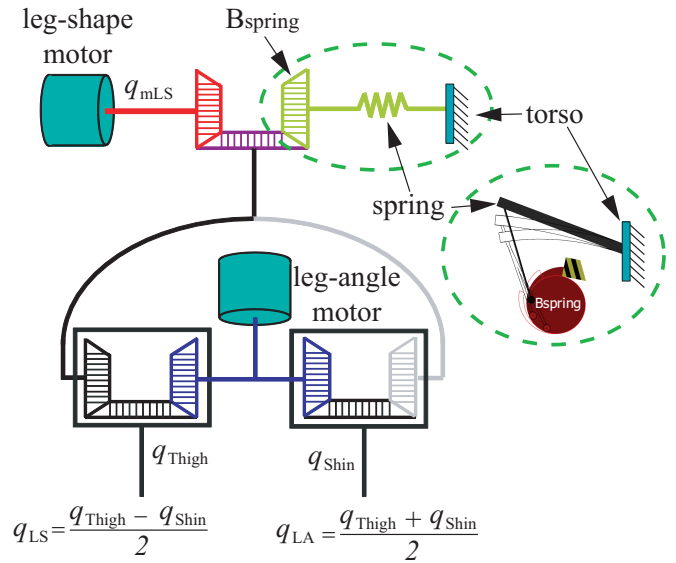


Fig. 3. MABEL’s powertrain (same for each leg), all housed in the torso. Two motors and a spring are connected to the traditional hip and knee joints via three differentials. On the robot, the differentials are realized via cables and pulleys [17] and not via gears. They are connected such that the actuated variables are leg angle and leg shape, see Fig. 4, and so that the spring is in series with the leg shape motor, see Fig. 2. The effect of a torsional spring is realized as shown in the expanded view. The base of the spring is grounded to the torso, and the other end is connected to the differential via a cable. Because the spring is connected via cables, it is unilateral. When the spring reaches its rest length, the pulley hits a hard stop, formed by a very stiff damper. When this happens, the leg shape motor is, for all intents and purposes, rigidly connected to leg shape through a gear ratio.

“fight” a spring that is trying to extend due to the non-zero mass of the shin. Similarly, a unilateral spring also makes it easier to initiate take-off in running (i.e., transition from stance phase to flight phase). *Roughly speaking, the springs are present when they are useful for shock attenuation and energy storage, and absent when they would be a hindrance for lifting the legs from the ground.* The springs can be easily changed from one experiment to another in order to study the relation of spring stiffness to gait efficiency or robustness to perturbations, for example. An optional pre-load is easily established on the springs as well, so that compliance only comes into play when sufficiently large forces are present; this is convenient for testing simplified walking strategies while debugging the electronics and software.

A fourth novel feature of the robot is that it is constructed from two monopods joined at the hip. By removing six bolts, half of MABEL’s torso and one leg can be removed, yielding a monopod. In fact, Thumper at CMU is literally the left half of MABEL [16].

**Remark:** The springs in MABEL may seem similar to the MIT series elastic actuator [14], [23], [21], [22]. Any resemblance is superficial. The MIT actuator is designed for force control and cannot store significant amounts of energy. MABEL’s springs can easily absorb 150 J of energy (the equivalent of dropping the robot from a height of 30 cm).

<sup>1</sup>A bipedal version of the hopper work is reported in [13].

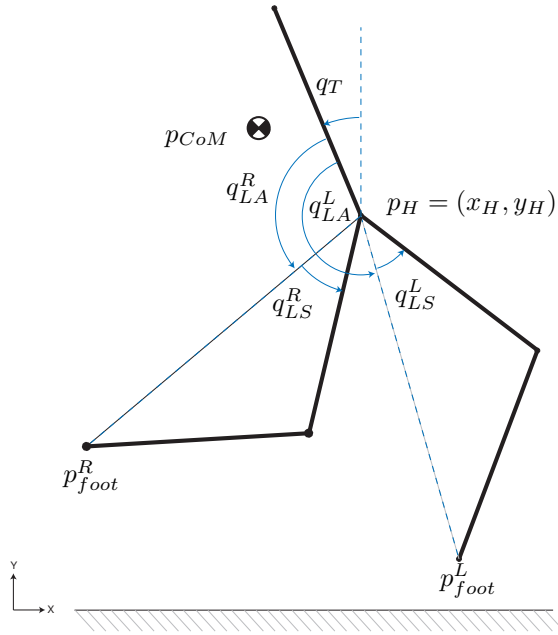


Fig. 4. Coordinate definitions used on the robot are indicated on the figure. The virtual legs are given by the dashed lines connecting the leg ends and the hip. The actuated variables  $q_{LA}^R$ ,  $q_{LA}^L$  (leg angles) and  $q_{LS}^R$ ,  $q_{LS}^L$  (leg shapes) correspond to the virtual legs. The length of a virtual is given by  $\cos(q_{LS})$ . The springs in the transmissions (*c.f.* Fig. 3) make the virtual legs “compliant” in the radial direction, that is, along the dashed lines. The compliance provides both shock absorption and energy storage. Ongoing work is seeking to take advantage of this capability in the control law design.

### III. OVERVIEW OF THE MATHEMATICAL MODEL

Walking is modeled as a hybrid system corresponding to the alternation of phases of single support (one leg in contact with the ground) and double support (both legs in contact with the ground), where the double support phase is instantaneous, and no slipping occurs during the single support phase. The most general form of the robot model is discussed first. Important special cases, such as those arising when ground contact conditions create holonomic constraints at the leg ends, are presented next, followed by the impact model. The components are then assembled into an overall hybrid model.

#### A. 9 DOF model

A planar mechanism consisting of five rigid links connected via revolute joints in a tree structure with *no contacts or constraints* has seven DOF: a degree of freedom associated with the orientation of each link, plus two DOF associated with the horizontal and vertical displacement of the center of mass within the sagittal plane. The springs present in MABEL’s powertrain provide two additional degrees of freedom, taken here as the leg-shape motor positions, measured relative to the torso, for the left and right legs,  $q_{mLS}^L$  and  $q_{mLS}^R$ , for a total of nine DOF. The state vector of the dynamical model is thus 18-dimensional: there are nine configuration variables required to describe the position of the robot, plus the associated velocities.

A convenient choice of link configuration variables is depicted in Fig. 4, namely, the left and right *leg angles* (the relative angles between the torso and the virtual legs connecting the hip to the toes),  $q_{LA}^L$  and  $q_{LA}^R$ , the left and right *leg shape angles* (the relative angles of the virtual leg with respect to the thigh),  $q_{LS}^L$  and  $q_{LS}^R$ , the angle of the torso with respect to the vertical,  $q_T$ , and the cartesian position of the hips,  $(x_H, y_H)$ . The overall generalized configuration  $q_e$  is formed by appending to this  $q_{mLS}^L$  and  $q_{mLS}^R$ .

The dynamic model is easily obtained with the method of Lagrange<sup>2</sup> if the springs in the powertrain are replaced with generalized forces, which can then be specified in a second step. Denoting the Lagrangian as  $L = K - V$ , a second order dynamical model immediately follows

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_e} - \frac{\partial L}{\partial q_e} = \Gamma_e,$$

where  $\Gamma_e$  is the vector of generalized forces and torques applied to the robot. It is standard to write the model in the form

$$D_e(q_e)\ddot{q}_e + C_e(q_e, \dot{q}_e)\dot{q}_e + G_e(q_e) = \Gamma_e \quad (1)$$

where,  $D_e$  is the inertia matrix, the matrix  $C_e$  contains Coriolis and centrifugal terms, and  $G_e$  is the gravity vector.

The vector of generalized forces and torques can be expressed as

$$\Gamma_e = B_e u + E_e(q_e) F^{ext} + \tau_{fric}(q_e, \dot{q}_e) + \tau_{spr}(q_e, \dot{q}_e), \quad (2)$$

where the matrices  $B_e$  and  $E_e$  are derived from the principle of virtual work and define how the joint torques,  $u$ , and external forces at the leg end,  $F^{ext}$ , enter the model, and  $\tau_{fric}$  represents joint friction. These terms are standard [9] and are not discussed further for reasons of space.

The term  $\tau_{spr}(q_e, \dot{q}_e)$  is the vector of torques acting on the left and right spring differentials. The following discussion applies to each side of the robot. Let  $B_{spring}$  denote the angular position of the differential to which the spring is attached, which can be expressed in terms of  $q_{mLS}$  and  $q_{LS}$ ; see Fig. 2. Assume  $B_{spring} = 0$  corresponds to the rest position of the spring. Then,

$$\tau_{spr}(q_e, \dot{q}_e) = \begin{cases} K_{sp} B_{spring}, & \text{if } B_{spring} \geq 0 \\ K_{damp} B_{spring} + D_{damp} \dot{B}_{spring} & \text{otherwise,} \end{cases} \quad (3)$$

where  $K_{sp}$  is the effective radial spring stiffness, and the coefficients of the damper forming the “hard stop” are  $K_{damp}$  and  $D_{damp}$ .

**Remark:** We sometimes also model the  $B_{spring}$  pulley hitting the hard stop as a rigid impact.

<sup>2</sup>The model of the differentials in the powertrain is somewhat involved. A symbolic file that computes the Lagrangian will be made available online at [11]. The inertias of the motor rotors as well as the pulleys in the differentials and the effective gear ratios achieved by passing cables over pulleys of varying radii are all accounted for in this model.

### B. Lower DOF models

When the robot is in single support, that is, one leg is on the ground and it is neither slipping nor rebounding, the foot acts like a pin joint. In this case, the hip coordinates are no longer independent of the other coordinates and can be eliminated, resulting in a seven DOF model. This is standard and is not discussed further.

The springs in the robot have to be stiff enough to support the weight of the robot, reflected through the leg joints and transmission. The mass of the shins is small in relation to the overall mass of the robot. Consequently, the spring of the swing leg deflects very little during the stance phase, and it is computationally advantageous to eliminate this degree of freedom when designing walking motions for the robot, resulting in a six degree of freedom model when in single support. Denote the resulting configuration variables by  $q$ . Letting  $x = (q, \dot{q})$  and  $u$  the motor torques, the stance-phase model is then easily expressed in state variable form

$$\dot{x} = f(x) + g(x)u. \quad (4)$$

### C. Impact model and leg swapping

Due to the rigid links used in MABEL, a rigid impact model is appropriate when the swing leg end touches the walking surface [8], [15]. It is assumed that the contact of the swing leg end with the ground results in no rebound and no slipping of the swing leg, and the stance leg lifting from the ground without interaction (see [28, pp. 49] for a complete set of hypotheses). This results in the double support phase being instantaneous. The ground reaction forces are represented by impulses, leading to an instantaneous change in the velocity coordinates, but there is no instantaneous change in the positions.

Following the development in [28, pp. 55], the nine degree of freedom dynamic model (1) is used to determine an expression for  $\dot{q}^+$ , the vector of angular velocities just after impact, in terms of the configuration of the robot at impact and  $\dot{q}^-$ , the vector of angular velocities just before impact [8], [15]. The post-impact velocity is then used to re-initialize the stance-phase model for the next step. The stance-phase model must make a choice of the stance leg (i.e., left or right). In order to re-use the same model, a change of coordinates is used so that the former swing leg becomes the stance leg and vice versa [28, pp. 57]. It is convenient to include this coordinate swap as part of the impact map. The final result is an expression for  $x^+ = (q^+, \dot{q}^+)$  in terms of  $x^- = (q^-, \dot{q}^-)$ , which is written as

$$x^+ = \Delta(x^-). \quad (5)$$

**Remark:** Just before impact, the spring of the stance leg is still supporting the weight of the robot and hence the  $B_{spring}$  pulley position is non-zero. As part of the impact and leg swapping map,  $B_{spring}$  is set equal to zero. This represents energy loss (typically small on a well-designed gait) and, in any case, approximates the negative work that the leg shape motor would have to do in order to begin leg retraction.

**Remark:** Due to the springs in the powertrain, the reflected inertias of the leg shape motors are effectively isolated from the impact. They are only coupled to the impact through the relatively small inertia of the spring differentials; see Fig. 3.

### D. Hybrid model of walking

The dynamic model (4) and the impact model (5) together yield a nonlinear system with impulse effects [29], [28, pp. 57]

$$\begin{cases} \dot{x} &= f(x) + g(x)u, & x^- \notin S, \\ x^+ &= \Delta(x^-), & x^- \in S, \end{cases} \quad (6)$$

where  $S$  is the surface of points where the swing leg height above the ground is zero and the swing leg is strictly in front of the stance leg.

## IV. INITIAL WALKING GAIT DESIGN

This section presents an elementary walking gait. Its purpose is simply to demonstrate that the testbed is functional. The control law is not sophisticated enough to properly take advantage of the compliance in the powertrain. That is a subject of ongoing work, which will be presented elsewhere.

A walking gait was designed using the method of virtual constraints. Virtual constraints are holonomic constraints among the generalized coordinates of the robot that are dynamically imposed through feedback control. Their function is to coordinate the evolution of the various links throughout a step, with the goal of achieving a closed-loop mechanism that naturally gives rise to a periodic walking gait. Because parameter identification of the dynamic model had not been completed at the time of these experiments, the virtual constraints were designed by hand instead of being designed on the basis of the dynamic model (6), as in [28] and [26].

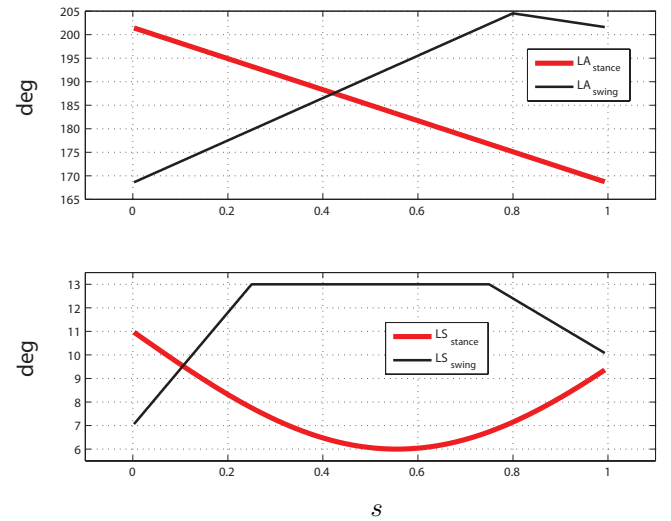


Fig. 5. The virtual constraints used in the walking experiment, expressed as a function of  $s$ , the normalized quantity used to parameterize the robot's position within each step. There are four constraints because the robot has four actuators. The value of  $s$  is computed from the measured values of leg angle and leg shape of the stance leg and the angle of the torso with respect to the world frame.



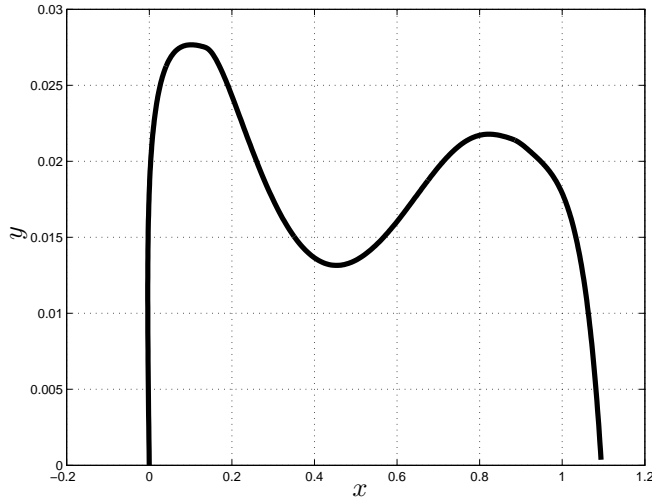


Fig. 6. Vertical toe position (m) versus horizontal toe position (m) of the swing leg that result from the virtual constraints of Fig. 5.

Results from the current version of the model are shown below nevertheless, for comparison purposes.

Virtual constraints were designed for leg angle and leg shape, for both the stance phase and swing phase of the gait. The virtual constraints were parameterized by (a linear approximation of) the angle of the line connecting the stance toe to the robot's center of mass; this angle is normalized to the interval  $[0, 1]$  and called  $s$ . The constraints used are depicted in Fig. 5. The purpose the stance leg angle constraint is to regulate the horizontal position of the torso center of mass throughout the step; this has a large affect on walking speed. The constraint on swing leg angle brings the leg forward, preparing it for impact with a desired step length. The swing leg shape is responsible for lifting the swing leg from the ground and avoiding foot scuffing. The stance leg

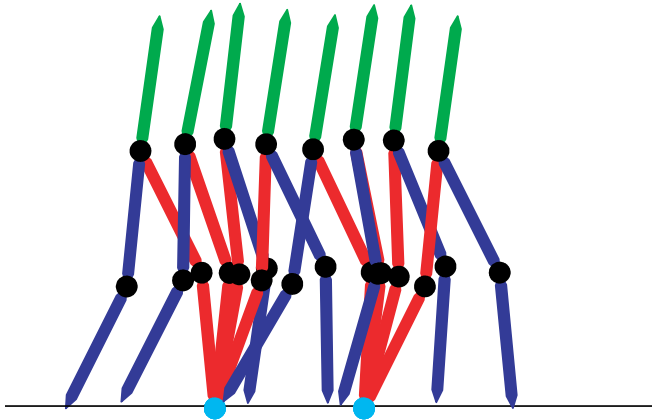


Fig. 7. Stick figure of the robot walking at 0.89 m/s, on the basis of the virtual constraints of Fig. 5.

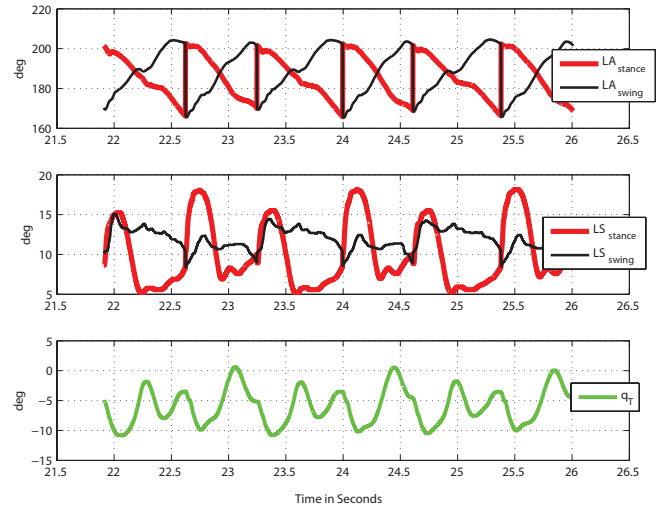


Fig. 8. Joint positions (degrees) versus time (seconds) for steps 30 to 36 of the experiment. The vertical lines in the LA plots mark the impact points, that is, the transition from one stance leg to the other. There is a notable amount of asymmetry in the gait with respect to left and right legs of the robot, with this most clearly showing up in the trace of the torso angle. The large deviations in torso angle are occurring when the right leg is stance.

shape was selected so as to achieve an approximate parabolic trajectory for the vertical height of the hip. The exact values chosen were arrived at on the basis of experience with a related robot, RABBIT [4], and a modest amount of trial and error. The swing leg profile is shown in Fig. 6. A stick figure representation of the gait is shown in Fig. 7. For videos of MABEL walking, see [11].

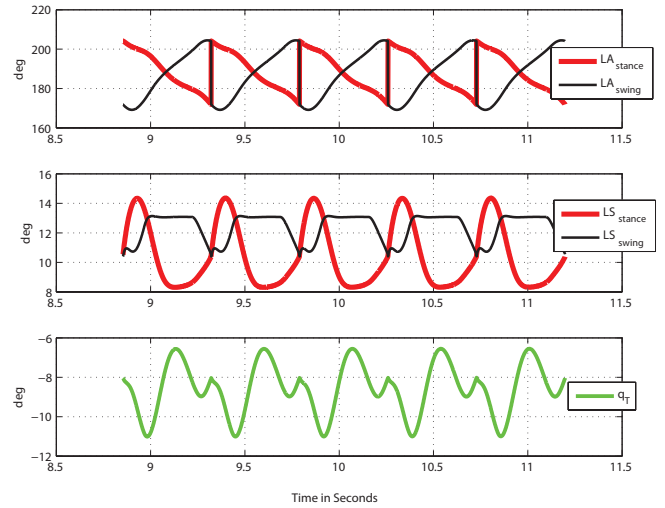


Fig. 9. Joint positions (degrees) versus time (seconds) for steps 20 to 25 of the simulation model. The vertical lines in the LA plots mark the impact points, that is, the transition from one stance leg to the other. The traces correspond reasonably well to the experimental values, with the exception of the torso trace when the right leg is in stance.

The virtual constraints were applied to the robot in an approximate manner, as in [27], via PD controllers. The controllers on leg angle acted on the error of the measured leg

angle and the desired angle given by the virtual constraint, while the controllers for leg shape, due to the presence of the springs, used an inner-outer loop configuration, with the inner loop applied to leg shape motor position and the outer loop to leg shape. The result was a stable gait in which MABEL took 45 steps before being stopped by the experimenters.

The experiment began with MABEL elevated in the air. The legs were servoed to a nominal double support position corresponding to  $s = 0$ . The robot was then placed on the ground. The closed-loop system is asymptotically stable in double support with zero forward velocity ( $\dot{s} \equiv 0$ ). To initiate walking, an external force was applied to MABEL by means of pushing on the boom which provides its support in the frontal plane. Application of this force provided the robot with an initial forward velocity sufficient to enter the basin of attraction of the controller. The result was a stable walking gait with average forward speed of 0.89 m/s.

Figure 8 depicts a snapshot the evolution of the robot's links through out the gait. For comparison purposes, the evolution predicted by the simulation model is shown in Fig. 9. The comparison is made further in Fig. 10. An important difference between the simulation and experiments is the left-right asymmetry that is currently present in the physical mechanism. If this cannot be eliminated on the testbed, then it will have to be captured by the model.

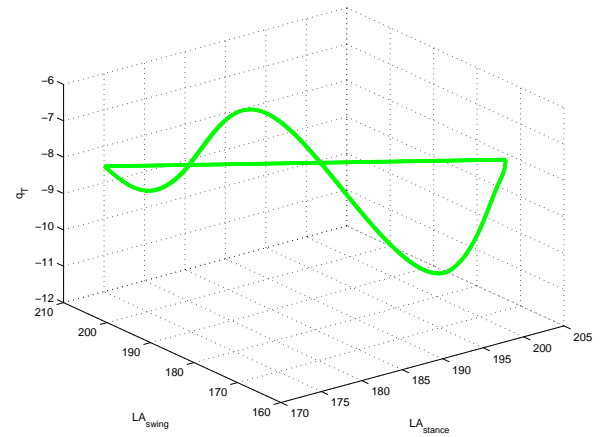
Other gaits have been implemented on the robot, ranging in speed from 0.48 m/s to 1.1 m/s.

## V. CONCLUSIONS AND FUTURE CHALLENGES

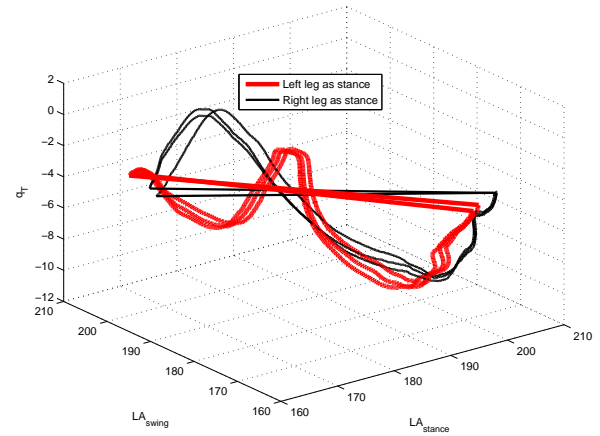
MABEL, a planar, bipedal robot testbed has been installed at the University of Michigan. The robot has a novel powertrain, based on cable differentials and springs, so that the virtual legs represented by the lines connecting the hip to the toes are compliant in the radial direction. This design seeks to improve power efficiency and augment the ability of the robot to absorb shocks at leg impact.

MABEL is currently walking at 1.1 m/s on a level surface. The utility of the testbed will be best proven when the robot is able to run well on flat ground and walk well on uneven ground. We are working hard to develop the control laws that will allow the robot to meet these ambitious performance objectives.

**ACKNOWLEDGMENT:** In Fall of 2004, J.W. Grizzle and A. Rizzi (then of the Robotics Institute, CMU, currently with Boston Dynamics) initiated an NSF-supported project to build a bipedal walker and runner incorporating compliance. The general features of the robot (morphology, dimensions, target mass and motor sizing) were set by J.W. Grizzle, J. Hurst, B. Morris, and A. Rizzi, on the basis of preliminary modeling and control law studies. The detailed mechanical design of the biped, MABEL, and of the associated monopod, Thumper, was done solely by J. Hurst, who also oversaw the machining of the robots' parts. J. Chestnutt led the real-time control platform development, with valuable support provided by C. Haynes and P. Velagapudi. B. Morris initiated the transition of software support from CMU to



(a) simulation



(b) experiment

Fig. 10. A 3-D projection of the limit cycle predicted by the model in (a) versus the limit cycle achieved in the experiment (b). The lower plot highlights the left-right asymmetry present in the current set up of the testbed. The source of the asymmetry is unknown at the moment.

Michigan and expanded the coding scope to address both Acromag IO driver interfaces and the realtime software-in-the-loop evaluation of potential control algorithms. G. Buche, J. Chestnutt, B. Kirby, J. Hurst, and P. Velagapudi contributed to the design of the electronics, power supply and safety interlock system. The assembly of MABEL at Michigan, the development of the laboratory housing the robot, the commissioning and debugging of the overall system, and the development and implementation of the control laws demonstrated here were conducted by H.W. Park, K. Sreenath, and J.W. Grizzle, with the help of G. Buche, L. Dicken, J. Koncsol, B. Morris, S. Platt, I. Poulakakis, and S. Zhang.

The work of J.W. Grizzle, B. Morris, H.W. Park, and K. Sreenath was supported in part by NSF grant ECS-0600869, and in part by the University of Michigan College of Engineering. The work of J. Hurst was supported by an NSF fellowship, an IGERT fellowship, and by Carnegie Mellon University.

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