# Design and Control of a Clutch for a Minimally-Actuated Biped Based on the Passive-Dynamic Simple Walker

by

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Submitted to the Department of Mechanical Engineering on May 12, 2006
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## Abstract

Passive-dynamic walking robots are remarkable mechanical devices capable of maintaining dynamically stable walking gaits with no actuation or control. These systems, however, depend on ideal environmental conditions for stability. Robustness and control capabilities are increased with actuation, but so is the power consumption. Such actuated robots are designed to minimize the actuation requirement by exploiting the system natural dynamics system, but still need actuation to compensate for energy dissipated by friction and collision events, as well as for more control capabilities.

A simple clutch mechanism is developed for such systems to allow intermittent control of otherwise passive joints, allowing controllers to exploit the passive or actuated control when desired. The clutch is tested on a hip actuated simple 3D walker to evaluate the performance capabilities of clutched control. Preliminary tests of several control strategies suggest the clutched actuation may provide good performance at a higher efficiency compared to fully actuated systems.

This paper describes the development of the clutch device and the hip-actuated biped on with which the clutch is tested, and evaluates the performance of intermittent clutch-control for several control strategies.

Thesis Supervisor: Russell L. Tedrake
Title: Assistant Professor, Department of Electrical Engineering and Computer Science

# Acknowledgements

I would like to first thank Russ Tedrake, my thesis advisor and mentor during my senior year at MIT, for the opportunity to work in his lab and be part of the Locomotion team. More importantly, I thank him for his enthusiasm about his work and dedication to his students. I deeply appreciate his interest in my learning and willingness to let me "own" this project.

To the members of the Locomotion Group: thank you for always being ready to lend a helping hand. Everyone in this lab has contributed to this project either directly or though his or her own interest, reminding me through a frustrating time that this stuff it fun! It was my experience working in this lab that convinced me to continue school after I graduate.

A special thank you is reserved to Katie Byl, who has been an incredible role model and mentor for me and many other women in Course 2 at MIT. Katie is the perfect combination of genius, teacher and "cool," and I feel proud that I was able to work alongside her.

Finally, I thank my parents for their guidance and support over four tough years at MIT. I may have been "too busy" to let you know what I have been up to lately, so here it is. This thesis is dedicated to you.

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# Chapter 1

# Introduction

This project involves the design and control of a joint mechanism developed for efficient actuation in robots based on passive-dynamic models. Although specifically designed for the walking bipeds of Russ Tedrake's Locomotion Group in the Computer Science and Artificial Intelligence Lab at MIT, the goal is to show that this joint can be implemented in a variety of configurations to improve the actuation efficiencies of robots designed to exploit their natural dynamics. The clutch joint is expected to increase control options for passive-dynamic systems while maintaining good efficiency relative to the precise joint-angle controlled robotic counterparts.

## 1.1 Background

Robotic movement is characterized by stiffness and rigidity, easily discernable from the smoothness of natural human motion. This stereotype is manifested in common imitations of robotic walking, "celebrity" robots, and the modern "robot dance." The choppy movement is attributed to the historical approach to robotic design and control. Every joint is independently actuated, effectively canceling out the system's natural dynamics, in order to precisely control the desired behavior at each joint in the system.

Honda's ASIMO robot, considered the most advanced humanoid robot to date, employs a complicated control system to determine the torque-control at each joint for a desired movement. ASIMO can walk, run and even climb stairs, but its gait is neither human-like in form nor in energy requirements, requiring over 10 times the energy of a human for a simple walking task [1].

A new approach to robotic design and control was developed by Tad McGeer in the late 1980s to address the problems of energy, efficiency and complicated control while creating more anthropomorphic movements [2]. Named Passive-Dynamics, this approach assumes that the uncontrolled, or "passive," system should naturally demonstrate the desired behavior. With such a system, only a small amount of actuation and control is needed to close the gap between natural and desired behavior in a varied environment. Following this model, McGeer developed several mechanical walkers that use gravity to stably walk down small slopes with no actuation and no control. Pictured in Figure 1-1, these walkers demonstrate the ability of a passive device to develop stable and anthropomorphic gaits by using gravity.

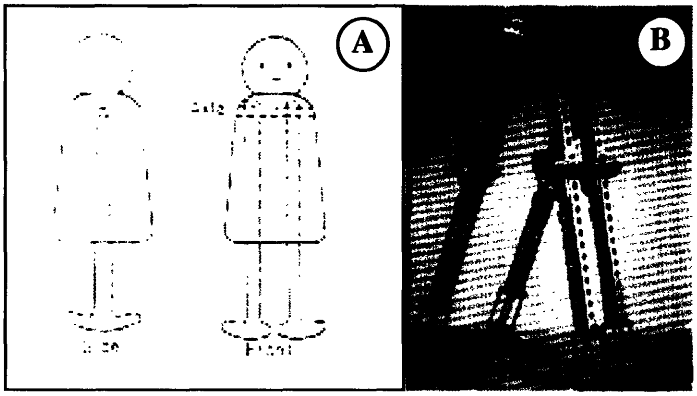

Figure 1-1: McGeer's Passive Walkers. McGeer's passive-walker toy (A) and his kneed walker (B) are simple mechanical devices capable of unpowered stable walking.

The success of these simple models stimulated research in the dynamics of walking, and in the development of high efficiency actuated robots based on the passive-dynamic model. A number of biped walkers have been developed at universities around the world to study the dynamics of legged motion and develop strategies for robotic applications. Among the most well known of these walkers is the "Toddler v5.0" robot, an under-actuated learning biped developed by Russ Tedrake at MIT [3]. Toddler v5.0 was developed from a simple walker modeled after McGeer's toy design by adding pitch and roll actuation in each ankle for flat surface walking (Figure 1-2).

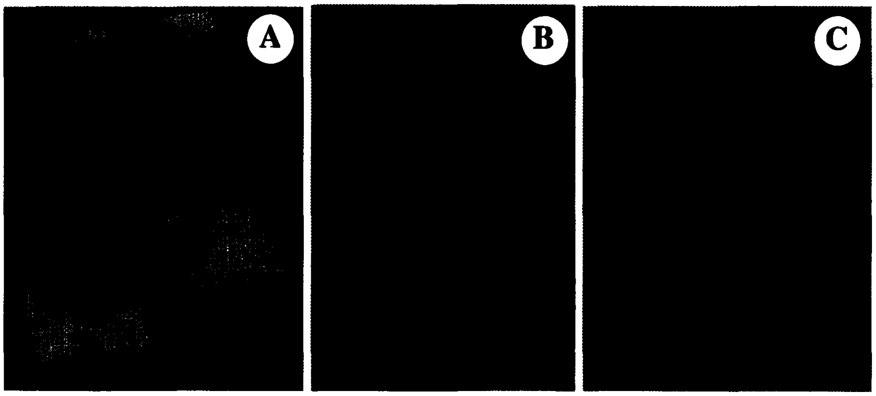

Figure 1-2: Evolution of the Toddler biped.

The simple walker in Figure 1-2A is a completely passive device that walks with a stable gait down small inclines by using gravity to replace the energy lost by friction and foot collisions with the ground [4]. Toddler v5.0 in (Figure 1-2B) is the same simple walking device with actuation added in the ankles to assist in walking on level surfaces. With its ankles locked in the normal position, the biped behaves like the simple walker; on a flat surface the ankle actuation is used to replace the energizing effect of gravity on an incline. Toddler v6.0 (Figure 1-2C) is the latest in Tedrake's line of bipeds, adding a knee joint to each leg of the Toddler model [5]. Using similar ankle actuation, a servo motor and specialized clutch at the knee provide the capability for the knee joint to operate as passive or actuated.

## 1.2 Project Overview/Summary of Work

I have been developing a new biped a similar to Toddler v5.0 to test a clutch mechanism developed for actuated bipeds to exploit their passive-dynamic design. The biped is a straight-legged walker with a single motor at the hip joint to intermittently control the leg angles and velocities for stable 3D walking on flat terrain. The robot is able to walk unpowered down an incline, and employs the motor through the specialized mechanical clutch to recreate the gait on flat surfaces.

A control system for the motor and clutch is developed to replicate the robot's natural walking gait. Several control strategies were implemented to explore the ability to replicate the robot's natural walking gait with minimal actuation. This paper describes the progress from the initial design of the clutch to the implemented control strategies.

Chapter 2 describes the motivation and development of the clutch mechanism, and the adaptation of the clutch into “Artie,” the hip actuated biped. Chapter 3 describes the mechanical design of Artie and its preliminary passive walking performance. The implementation of the electronics and control system is detailed in Chapter 4, followed by a description of the system model and natural dynamics test in chapter 5. Chapter 6 describes the control testing, and the paper closes with conclusions and an outline of future work in the final chapter.

# Chapter 2

# The Clutch

This project began with a search for a reliable clutch for the knee joint of the next generation Toddler robot. Previous designs, as will as those employed by similar bipeds, were limited in meeting the desired performance abilities. This section describes the need and requirements for a passive-dynamic clutch, and the design of the working clutch developed to meet those requirements. In the final section, I describe the development of the hip-actuated robot built to test the clutch performance for intermittently actuated passive-dynamic walking.

## 2.1 Clutch Requirements

The first requirement of the clutched passive joint is the ability to exhibit both passive and actuated behavior. This is achieved by implementing a clutch system that enables the joint switch between passive and driven modes. For the stance phase of the walking cycle, it is especially important to be able to hold the leg in the fully extended, straight-leg position. For more robust applications, one should be able to drive and hold the joint in any position and at any moment while minimizing the control complexity and energy requirements.

A variety of knee joints used on passive-dynamics robots for similar applications are shown in Figure (2-1). Each has worked successfully for its respective robot, but falls short of the desired clutch performance in at least one area.

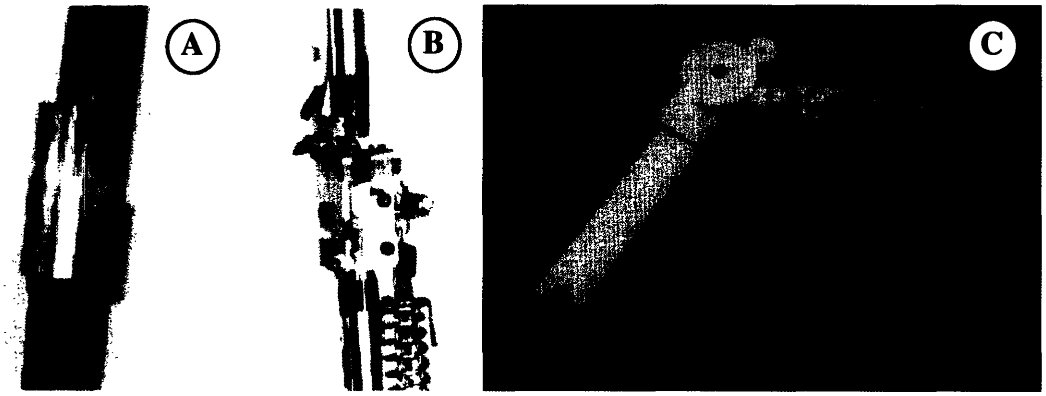

Figure 2-1: Sample Biped Knees. (A) A model of a McGeer walker used suction cups to keep the knee locked in the stance phase [5]. (B) A mechanical latch and solenoid lock and unlock the knee [6]. (C) Toddler v6.0 knee clutch disengages the knee actuator with a DC motor.

One of the earliest knee designs, McGeer's suction cup latch (Figure 2-1A) is a completely passive device. The suction cup grabs the lower leg when it swings forward and is carefully tuned to release the leg with the appropriate timing. Though it works without energy or control requirements, the suction cup strategy is limited to a single position and hold period during walking.

The knee joint designed for MIKE (Figure 2-1b) uses a passive latch to prevent hyperextension and to mechanically lock the knee in the straight-leg position for the duration of the leg's "stance" phase [6]. A triggered solenoid then releases the latch for the passive swing phase. While this joint has low power requirements, with only one solenoid trigger per step, it is also limited because it can hold only one position, and depends on the leg's momentum to engage the latch.

Figure 2-1C shows a joint developed by Andrew Baines for actuation beyond the straight-legged latching [5]. The joint uses a servo motor to drive and hold the knee at any angle through a small geartrain, and actively disengages the gears for a passive mode. The switch is made by the physical separation or rejoining of gears by using a DC motor and lead screw to control the position of the upper gear. Drawbacks with this design include collisions between the gear teeth when re-engaging the clutch, and low bandwidth.

Although this model has demonstrated successful performance, a better design could improve the control complexity and energy requirements. It is desired to keep all gears intact and to be able to change modes with a simple switch. The design also requires considerable power to maintain the knee in a straight position, driving the lower leg into the hyperextension cap. Since one leg must always be in the straight position during walking, this method amounts to significant power loss and is undesirable wear on the servo.

## 2.2 Clutch Design

The clutch solution is illustrated in the Figure 2-2. It is a differential-brake style clutch using an electromagnetic brake to engage and disengage the upper and lower legs. The solution was inspired by the differential-style design suggested by Jonathan Hurst of the Robotics Institute at Carnegie Mellon University [7].

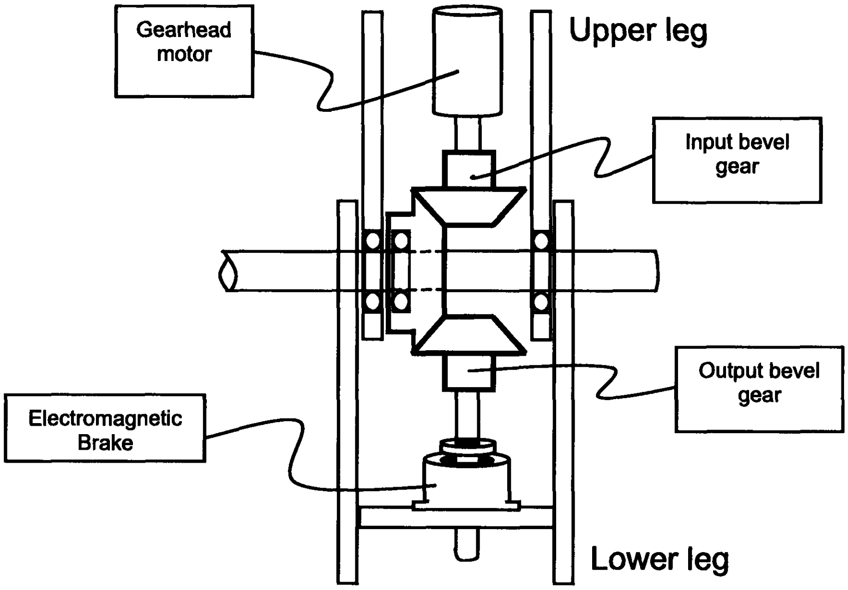

Figure 2-2: Schematic of Clutch Mechanism. The clutch uses an electromagnetic brake to couple/decouple the upper and lower legs, allowing the simple interchange between passive and driven modes at the joint.

A solid shaft connects the upper and lower legs with ball bearing at the pivots so that the lower leg swings freely about the joint axis. A bevel gear is mounted onto the joint shaft over a ball bearing so that it also can turn freely on the shaft that holds the lower leg. A motor mounted on the upper leg directly drives this gear through the "input" bevel mounted on the motor shaft. A third bevel is mounted on the lower leg, opposite the motor shaft bevel. This "output" bevel is coupled to the output shaft that connects to a brake mounted on the lower leg.

The motor is always coupled to the bevel gears, and drives the output shaft at a rate equal to the motor shaft. The passive/actuated mode is controlled by the coupling between the output shaft and the lower leg, and this coupling is determined by the state of the brake. When the brake is disengaged there is no coupling between the output shaft and lower leg, so the joint is passive and acts as it would in the absence of a brake. When driven, the output shaft spins freely in the brake housing not affecting the position of either leg. When the brake is engaged, the output shaft is locked into place and effectively becomes a rigid piece of the lower leg. When driven, the output shaft turns by rotating around the larger bevel gear, thus rotating around the joint axis.

## 2.3 Knee Clutch Prototype

Figure 2-3 shows the knee clutch prototype. A 6 Watt Maxon *A*-max DC motor with a 111:1 planetary gearhead drives the input bevel. The output shaft is connected to a 6 Watt 8.2 oz magnetic brake with a maximum hold capacity rated at 15 lb-in. The white gears on the outside of the leg are connected to a potentiometer calibrated to measure the leg joint angle.

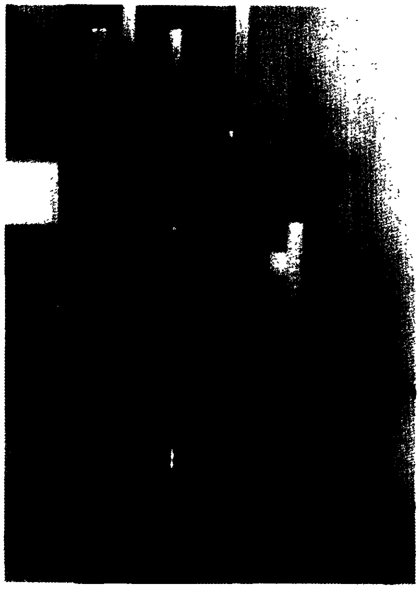

Figure 2-3: Knee Clutch Prototype.

Simple tests with the motor and brake connected to a 24 V power supply showed good performance and potential for the clutch, but highlighted weaknesses in the brake hold capacity and backlash in the bevel gears that detract from good performance.

With the upper leg mounted to the table top, and no power to the brake, the lower leg swings passively with low friction. Initial clutch tests involved engaging the brake at various points in the passive swing cycle, and at a variety of swing velocities. The brake response time was satisfactory, but it was not strong enough to catch the leg at high velocities. Also, the gearhead motor was not strong enough to passively hold the joint at angles greater than about 40-degrees from the equilibrium position.

Simple motor control tests with the brake engaged demonstrated good performance despite noticeable backlash in the bevel gears. By controlling the motor to follow sine waves at a variety of frequencies and amplitudes, the leg recreated a range of swing cycles with flattened peaks because of the gear teeth spacing. Again, the brake frequently slipped under the weight of the leg at large angles, but worked effectively in the smaller range of angles typical for a walking swing cycle.

A major source of the slipping was the weight of the leg, made larger and heavier than necessary for due to the material available and ease of manufacturing. The backlash was caused by a slight misalignment in the gear axes and the low quality of the gears, so the problem could be solved by more precise manufacturing and using a set of precision gears with no backlash between the engaged gear teeth.

These solutions were implemented in the next prototype as well as an improved feedback system. The knee clutch has only a potentiometer to measure the angle between the upper and lower leg. A better feedback system will use encoders on the motor and the leg to give position and velocity feedback.

The next prototype, described in the following section, is a modification of the knee clutch design into a hip clutch to control the angle and velocity between the two legs of a simple walker.

## 2.4 Development of Hip Clutch

With the preliminary knee clutch tests demonstrating good potential for the device as a passive/actuated joint, the project direction changed to focus on the performance of the clutch as the lone actuator for a simple walker. The design was modified into the hip joint of a biped, coupling its legs through the clutch to allow angle and velocity control intermittently during passive-dynamic behavior. The adapted clutch is shown in Figure 2-4.

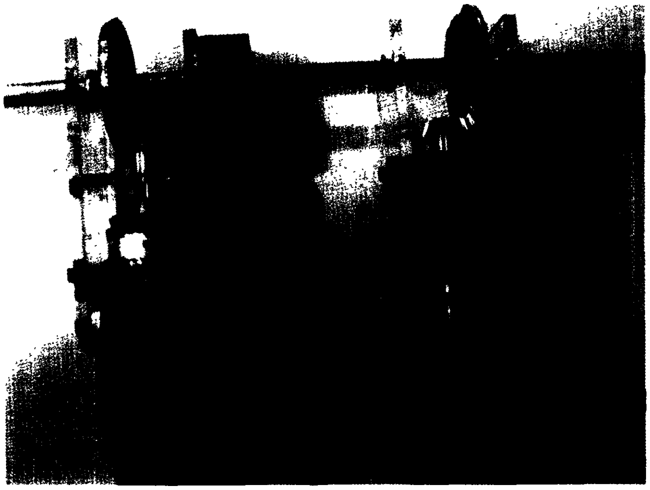

Figure 2-4: Hip Clutch Mechanism. The clutch is adapted to a hip joint to mimic the simple walker with the ability to control the torque and angle between the legs.

Formerly split between the upper and lower part of one leg, the motor and brake are now split between two legs. The legs are coupled using two pairs of bevel gears. The smaller bevel on the motor leg is attached to the shaft of the 6 Watt 1.9 oz Maxon *A*-max DC motor with an 84:1 2.4 oz planetary gearhead. The smaller bevel on the brake leg is mounted on the output shaft that sits connects to the 5 Watt 3.2 oz brake. The larger bevel gear of each pair is mounted on the hip shaft with a set screw so that the torque is translated between gears across the shaft. Both the brake and motor were scaled down due to the decreased weight of the legs and 4:1 bevel gear reduction, resulting in a reduced torque requirement for both parts.

Chapter 3 describes the implementation of the hip joint into a passive walker and details the major components of the biped's body.

# Chapter 3

# Artie – Mechanical Design

Like Toddler, Artie is modeled after the simple walker of [4]. The robot is mechanically designed to passively develop a stable walking gait on small inclines by using gravity to power its downhill strides. Like the simple walker, the biped walks by "stable falling," catching itself with the front leg and then pivoting over that leg for the next step. The pivot leg, called the "stance" leg, is effectively stuck to the ground without slipping, and the single point of contact between the foot and the ground becomes the pivot point for the entire robot body. Once the body's center of mass has passed the pivot point, the robot begins to "fall" again, but the opposite leg, in the "swing" phase, swings forward to catch itself. Upon contact with the ground, this leg becomes the new stance leg, releasing the former stance leg to swing forward for the next catch. These walkers are capable of maintaining a stable gait on incline because the energy lost from the swing leg's collision with the ground is replaced by gravitational potential energy from the next leg as it is released to enter the swing stage.

This section describes the assembly of Artie as a passive walker, followed by a few words on the biped's early inclined walking performance.

## 3.1 Mechanical Components

Artie is the combination of the simple passive walker and the modified hip clutch mechanism described in the previous chapter. Unpowered, the biped is a larger version of the passive walker. Implementing the clutch system provides a means of putting energy into the system by adding torque between the legs. Figure 3-1 describes the biped body. Figure 3-2 shows the robots computers housed in the body that that will passively hang on the hip shaft between the legs for untethered walking.

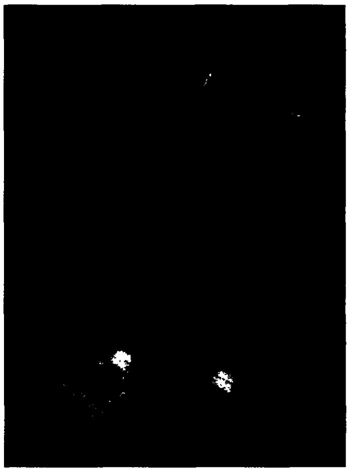

Figure 3-1: Hip-Actuated Biped, "Artie."

Artie has two legs connected by steel shaft that acts as both the hip and shoulder joint. Both the legs are attached to the joint shaft on ball bearings, so they swing freely about the shaft axis. The lower part of each leg is aluminum extrusion; the upper part of each leg is widened to fit the bevel gears, and is made with laser-cut acrylic for manufacturing convenience.

The legs are controlled by a single motor, which connects through the clutch that allows rapid interchange between fully passive and actuated modes, as described in the previous chapter. When engaged, the leg angle is fully actuated and can be directly controlled by the motor. With the clutch disengaged, there is no coupling between the motor and leg, and the robot is fully passive.

Two encoders give position and velocity feedback for the angle between the legs. One encoder is connected to the motor shaft, measuring the rotation of the motor shaft. The second encoder is attached to the outside of the brake leg and reads the angle between the leg and the joint shaft.

The curved feet provide foot clearance and lateral stability without affecting the forward dynamics of the system. Clearance must be made in order to provide room for the swing leg to swing forward without scuffing the ground. Most bipeds, including humans, employ knees for foot clearance. However, a second joint in the leg significantly changes the system natural dynamics.

Lateral stability is provided by the reaction force of the ground in contact with the curved feet. Because the legs have only one degree of freedom in motion – that is, rotation about the hip axis – they cannot compensate for any side-to-side perturbations. The feet provide stability by creating a stable lateral rocking. Further details on the development of the curved feet can be found in [3].

Figure 3-2: Computer Housing.

The robot's head and body contain the computer and a majority of the electronics devices. The head and body are rigidly connected and hang on the shaft by Delrin® bearings so it hangs passively on the joint axis. The weight of the computer relative to the head keeps the body oriented vertically, and prevents the body from swinging with large amplitudes during walking.

Overall, the biped measures about 22 inches tall and 12 inches wide, weighing about 3.75 pounds without the computer and other electronics. The computer body weighs approximately 1.1 pounds.

## 3.2 Passive Walking Performance

Artie's first steps were slightly irregular in step size and direction, but not unstable. Although the biped did not develop the desired stable walking gait beyond the first several steps, it seemed dynamically inclined toward the expected behavior if such parameters as weight and leg inertias were properly tuned.

Several obvious problems included slipping at the point of contact between its feet and the ground, as well as a mismatch in the leg inertias with the curvatures of the feet. The feet used on Artie were designed for the body of Toddler v5.0, but complications with the CNC mill prevented manufacturing the appropriate feet for Artie. The feet generally work because Artie is similar in shape and size to the Toddler biped.

Aside from choosing a surface with more friction, the slipping can be improved by adding some weight to the robot. This will be achieved when the control system and batteries are places on board the robot for untethered walking.

Satisfied with walking of the passive system, the rest of this project focuses on implementing and testing the electronics and clutch control system.

# Chapter 4

# Electronics

The electronics are necessary to implement the clutch actuators and feedback sensors by providing power, control and an interface to evaluate the system performance.

Figure 4-1 shows the general configuration for system control.

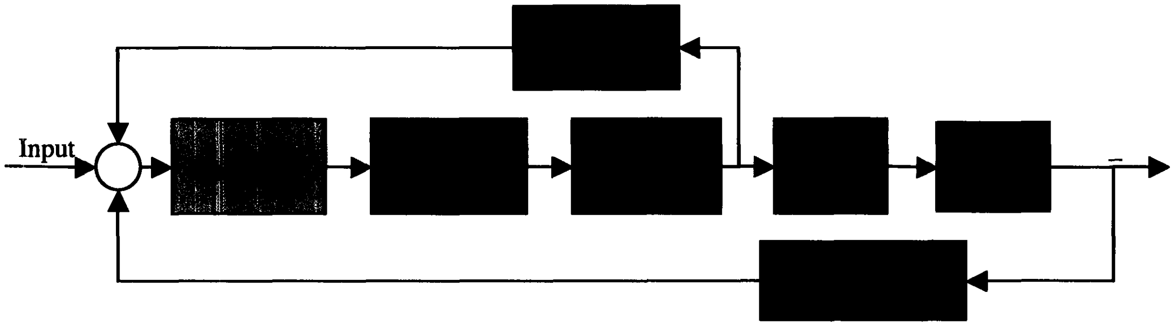

Figure 4-1: System Block Diagram

The boxes colored in blue represent the system components of the system; their configuration is described in Section 4.1. The system controller, represented by the orange box, is developed using Simulink and executed through the computer's CPU using Real Time Workshop. The Simulink implementation is described on section 4.2.

## 4.1 System Electronics

This section describes the electronics connections for power and control of the mechanical elements. Figure 4-2 gives an overview of the primary electrical components and connections.

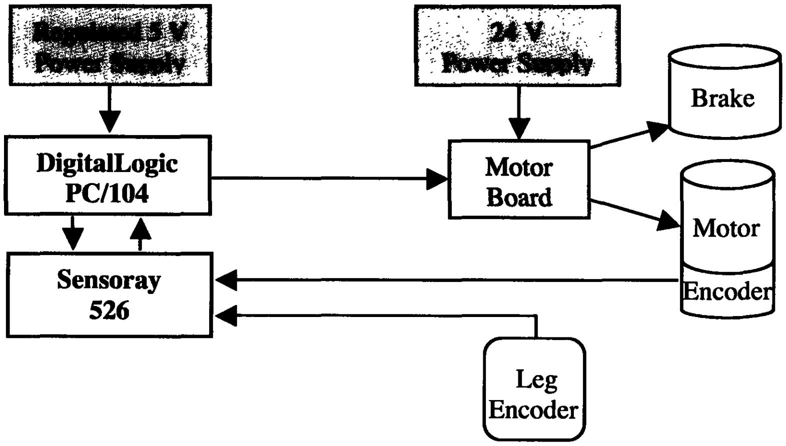

Figure 4-2: Principal Electronics Diagram.

The DigitalLogic PC/104 is the primary CPU through which the robot is controlled. Control programs and data are transmitted between the desktop computer and the PC/104 through an Ethernet connection.

The Sensoray 526 is stacked with the PC/104 and acts as an interface between the main CPU and the encoders because it provides differential quadrature encoder inputs. Both encoders are powered and send data through this connection.

The motor encoder is a Maxon digital tachometer with a resolution of 101152 counts per revolution of the output shaft. The leg encoder is a US Digital optical encoder with a resolution of 1440 for a full rotation of the leg; i.e. a resolution of 0.25 degrees in the leg angle. Connected through the Sensoray 526, the encoders provide feedback on the angular position and velocity of the motor and legs.

A regulated 5 V power supply supports the PC/104 and Sensory circuit boards, and both encoders. The voltage is regulated from a larder supply to ensure a steady 5 V during operation. Fluctuations in the supply voltage cause noise and interruptions in the processing unit.

The motor and brake are controlled by a motor controller board which sources power from a 24 V supply separate from the CPUs. The separate power supply is necessary to reduce the noise and fluctuations in the computer lines caused by large current to the mechanical elements. The motor controller system is described in detail in section 4.1.1.

### 4.1.1 Actuator Electronics

A motor controller is placed between the CPU, which will send a serial output to control the motor and brake, and the 24 V power supply required for the motor and brake. The motor controller is needed to supply the higher current drawn by the motor and brake. The PC/104 CPU and peripheral circuit board would be seriously damaged by the actuators which can draw over 1 Amp of current.

We use the Pololu Dual Serial Motor Controller because it can control two actuators independently at 24 V, converts a serial signal to PWM, and is small and lightweight.

Figure 4-3 shows a schematic of the motor/brake control system.

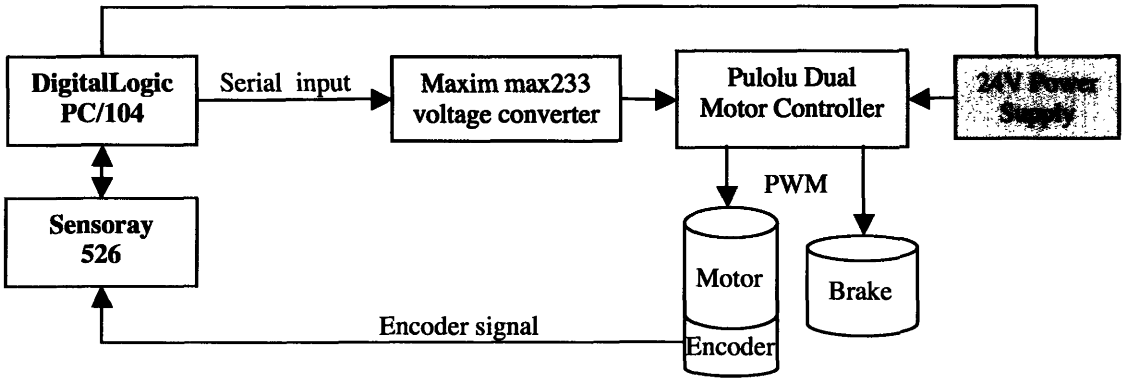

Figure 4-3: Actuator Control System.

The Pololu board takes a signal from the PC/104 and amplifies it for the motor and/or brake using the 24 V source. The serial input for the motor board microcontroller uses logic levels between 0 and +5 V, so we use a Maxim Max233 to convert the serial RS-232 voltage levels sent from the CPU serial output into the lower voltage TTL levels.

The information in the serial line includes a command for the motor speed and direction and an independent command for the brake. The Pololu microcontroller converts the serial input at these levels into the appropriate PWM signal to control the speed of the motor, and uses a dual h-bridge integrated circuit to control the motor direction.

## 4.2 Simulink Implementation

The control system is modeled and implemented using Simulink and Real Time Workshop. The Simulink model, including the motor and encoder subsystems, was created by Katie Byl. The general setup is described in Figure 4-4.

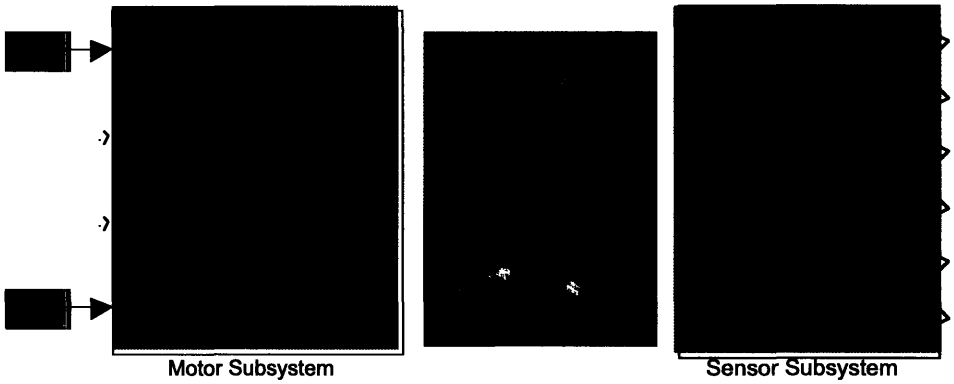

Figure 4-4: Simulink System Model.

The model allows user inputs to the motor and brake which are fed through the Motor Subsystem into the actual components on the biped, so that the system “plant” is the actual system. Six output signals are recorded by the Sensor Subsystem. Both subsystems are described in detail in the following sections.

### 4.2.1 Motor Subsystem

The motor subsystem is pictured in Figure 4-5. The subsystem calls for four inputs to create the serial signal to be send from the robot’s CPU to the motor controller.

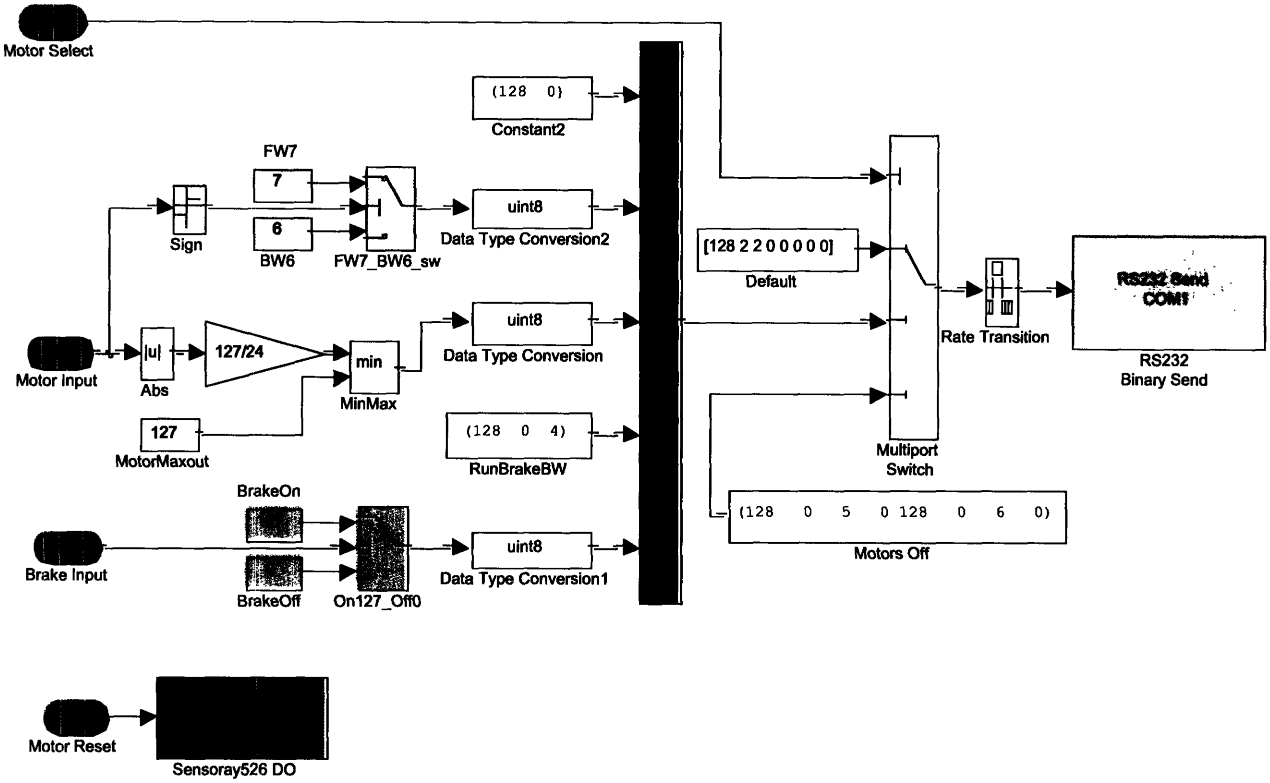

Figure 4-5: Simulink Motor Subsystem.

The first input, labeled “Motor Select”, is always given a value of 2, specifying 2 actuators to be controlled. The last input, labeled “Motor Reset” is always run with a value of 1 to keep the system running without a reset.

The motor and brake are controlled through the second and third inputs, labeled “Motor Input” and “Brake Input,” respectively. The motor input takes a voltage command between 0 and 24 V; the brake input takes a between 0 and 1 to control the motor either on or off. The block diagrams convert the inputs into the serial signal output from the CPU serial port. Details of the translation are not discussed in this paper.

Details of the serial signal required by the Pololu motor controller are described in the product manual [8].

## 4.2.2 Encoder Subsystem

The encoder subsystem is pictured in Figure 4-6. The robot encoders are connected to the Sensory 526 encoder inputs. The encoder subsystem reads and translates the encoder inputs into 6 different signals including the position and velocity of the motor and swing leg.

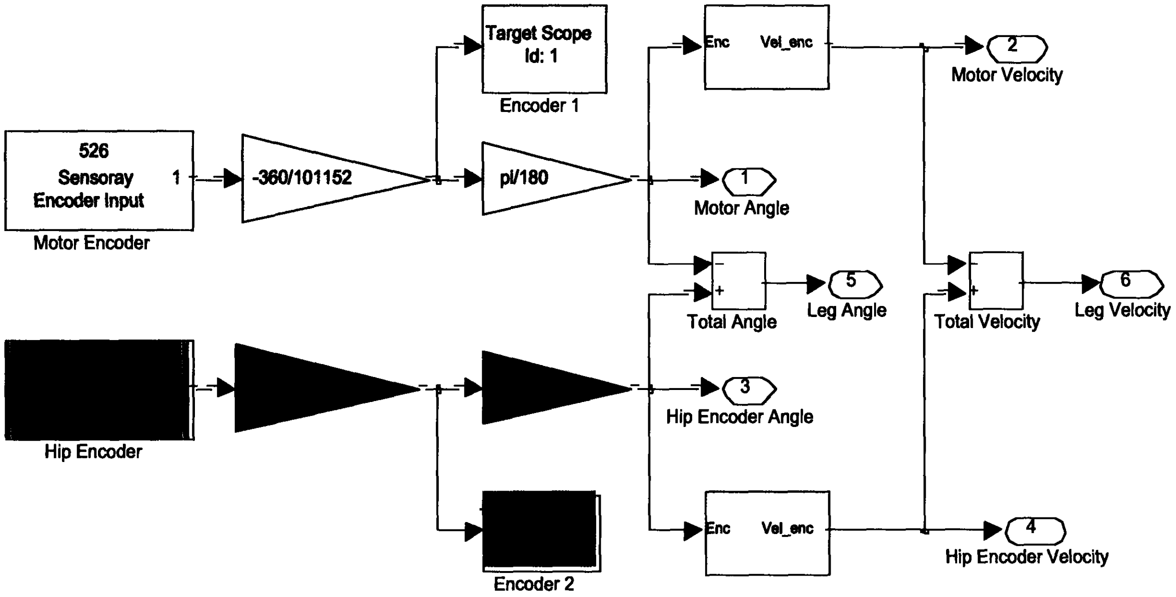

Figure 4-6: Simulink Encoder Subsystem.

# Chapter 5

# Control Test Model

The motor clutch system was created to provide intermittent actuation to a passive joint for improved control and performance in a non-ideal environment. The actuation is implemented to replace the actuating effect of gravity for passive walkers on an incline by pumping energy into the system to recreate the gait achieved by the stable passive walker. The clutch is evaluated by its ability to recreate the natural cycle of the swing leg with intermittent control. This chapter describes the system model and natural dynamics in preparation for the control testing in Chapter 6.

## 5.1 System Model

The clutch is tested by mounting the motor leg to a test bench and using the clutch system to control the swing leg position and velocity. In this configuration, the leg is modeled as a simple pendulum (Figure 5-1).

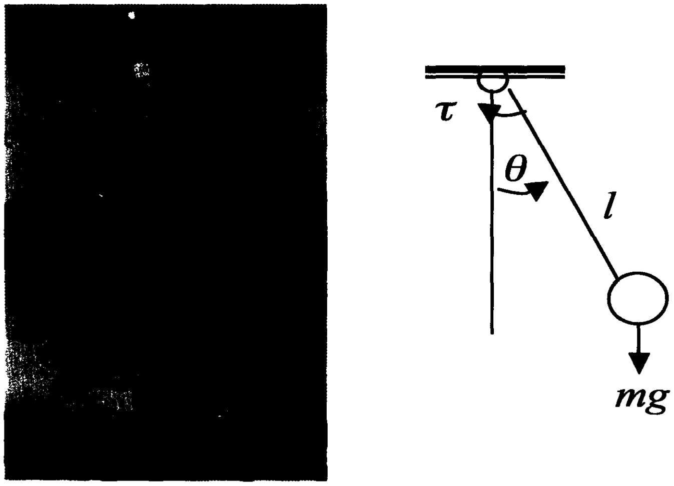

Figure 5-1: System Model.

The system equation of motion, linearized around the stable equilibrium position, is:

$$J\ddot{\theta} + b\dot{\theta} + mgl\theta = \tau$$

A quick weight and position measurement gives a moment of inertia of 0.048 kg-m$^2$ for the swing leg about the joint axis. The total mass of the leg is 0.731 kg, giving a modeled pendulum length of about 0.026m. The damping coefficient is estimated from the envelope of the free-swing oscillations to be about 0.050 kg-m$^2$/s. Based on these measured parameters, we expect the system to have a natural frequency of about 6.2 rad/sec. Measurements from the experimental trials gave a natural frequency of 5.6 rad/sec, a satisfactory match to confirm feasibility of the system model.

For all further analysis we will use the experimentally measured natural frequency and damping.

### 5.1.1 Measuring Natural Dynamics

Examination of the system natural dynamics is necessary to determine the parameter values of the system plant. The damping and natural frequency of the passive system were measured by tracking the angle of the swing leg in response to an impulse. Figure 5-2 shows some of the data from these tests.

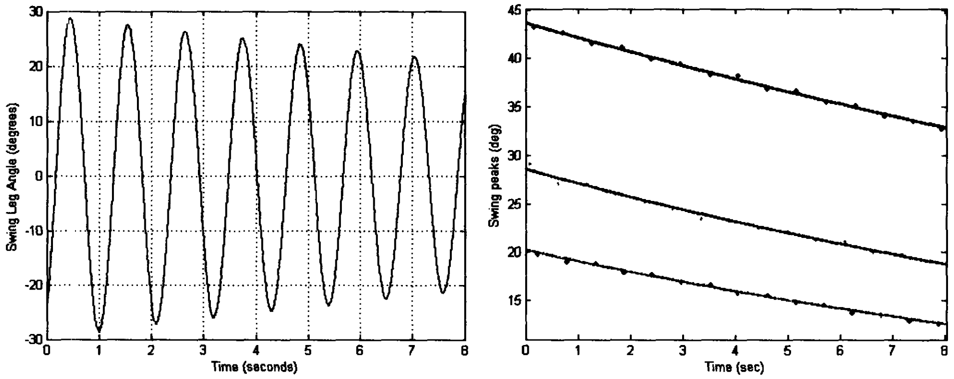

Figure 5-2: Plant Parameter Measurements. (A) Sample impulse response of passive system; (B) Comparison of decay envelope for three trials.

The natural frequency was found by measuring the oscillation frequency of the passive system; it is measured to be 5.65 rad/sec.

The damping was estimated by fitting an exponential curve to the decay envelope of the oscillation amplitudes. The fit for three trials (Figure 5-2B) gives a damping value of about 0.05.

# Chapter 6

# Control Tests

The goal of actuated control in the passive-dynamic based systems is to compensate for the energy losses from friction and collisions events, by adding the necessary energy to maintain the stable walking cycle achieved by the passive system on an incline. Thus, the desired trajectory of the swing leg for the control tests will be a sinusoid at the system's natural frequency, with an amplitude related to the desired walking speed. For the following tests, we use the natural frequency of 5.6 rad/sec and swing amplitude of 0.6 radians, or about 20 degrees. This chapter describes the different control strategies investigated and the resulting system performance for each.

## 6.1 Fully Engaged Position Control

The first control tests keep the clutch fully engaged to imitate an actuated joint with no clutch. Proportional control is used with position feedback to match the output leg trajectory to the desired sinusoid. The response for a gain value of 10 is shown in Figure 6-1.

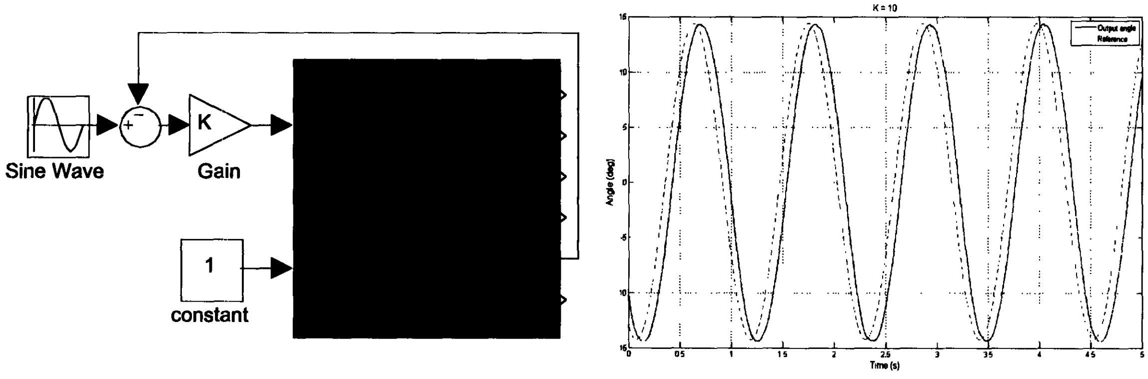

Figure 6-1: Fully Engaged Position Control.

The system response could be improved by implementing a better feedback control scheme. However, perfect control with a fully actuated system is not the goal. This response will suffice as a representative for fully-actuated control in the power consumption comparison with the clutch control models.

## 6.2 Negative Damping

Damping in mechanical systems generally comes from friction and/or a system damper, and works to decrease the system motion by dissipating its kinetic energy. As seen in the tests of Section 5.1.1, the passive system is positively damped so that the amplitude decreases with each cycle until the system finally settles in its static equilibrium position.

Alternatively, negative damping works to increase the amplitude of oscillation by adding energy to the system instead of dissipating it. If enough energy is added to just offset the positive frictional damping inherent in the system, the system will behave as if it had no damping, and maintain a steady swing cycle with constant amplitude.

Negative damping is achieved by feeding the system velocity back into the plant, changing the forward transfer function to:

$$\frac{1}{Js^2 + (b-k)s + mgl}$$

When $k = b$, the damping term goes to zero, effectively pushing the system poles to the $j$_-axis and creating a marginally stable system.

The negative damping strategy was tested by keeping the clutch fully engaged and controlling the motor with the feedback from the velocity, multiplied by a gain $K$. The control diagram and a sample response are shown in Figure 6-2.

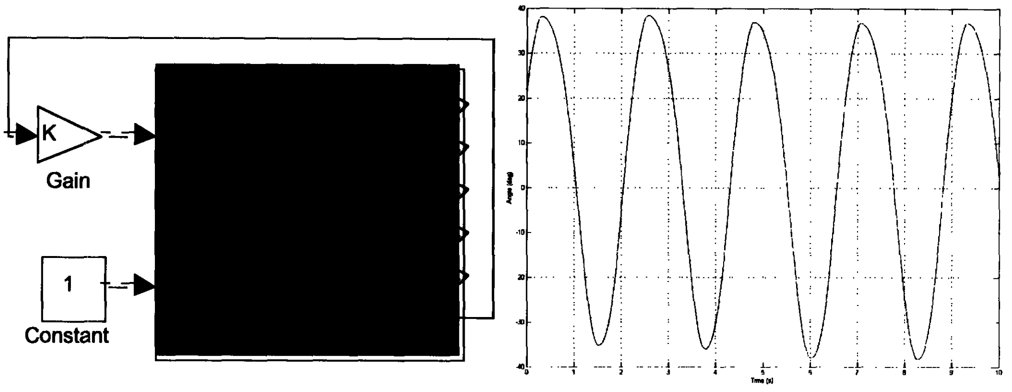

Figure 6-2: Negative Damping.

The pictured trajectory is for a gain of 0.75, and shows a response that does not seem to grow or decay, but neither is it completely constant. A gain over 1.0 made the system highly unstable, pushing the swing leg beyond 90-degrees. A gain under 0.70 resulted in the system damping its swing within a few seconds.

It should also be noted that the system needed a considerable push to start moving; it was not able to start swinging itself with a small start velocity. The cause of this "sticky" behavior at low speeds is not immediately obvious, but may be nonlinear friction or backlash in the gears, sensing errors or feedback delays.

## 6.3 Clutch Pulsing/Intermittent Engagement

The strategy for engaging the clutch during motion is to command the brake on and off using a pulse generator at a frequency matching the swing cycle. The input pulse is defined by a period, amplitude, duty cycle and phase delay. Because we want the clutch engagement to synch with the leg swing, the pulse period is always matched with the period of the leg's natural cycle. The amplitude describes the voltage to the brake, and for this set of tests is kept at full voltage in the "on" state. The duty cycle and phase is defined by a period, amplitude, duty cycle and phase delay. Because we want the clutch engagement to synch with the leg swing, the pulse period is always matched with the period of the leg's natural cycle. The amplitude describes the voltage to the brake, and for this set of tests is kept at full voltage in the "on" state. The duty cycle and phase delay are varied for several motor control options to best recreate the desired leg trajectory.

### 6.3.1 Open Loop

The open loop test employs the clutch without feedback to add energy to the natural swing by engaging the actuation for a finite period once during each leg swing cycle. The motor is set at a constant velocity so that the input during each cycle should be identical. Figure 6-3 shows a block diagram of the control strategy and a sample position trajectory response.

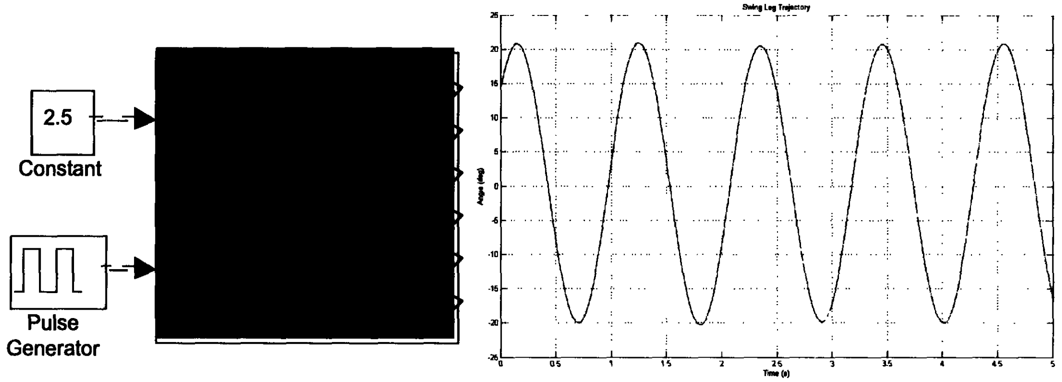

Figure 6-3: Open loop Clutch Pulsing.

The position curve has a smooth and stable pattern, but has a small overshoot for the positive angle upswing, where energy was pumped into the swing through the clutch engagement. Reducing the speed of the motor, and the engaged duty cycle to decrease the input energy fixes the overshoot problem on the upswing side, only to cause an undershoot at the negative angle. The damping in the system is large enough that each swing peak is significantly reduced in amplitude from the previous peak.

The velocity profile (Figure 6-4) highlights further problems with this strategy.

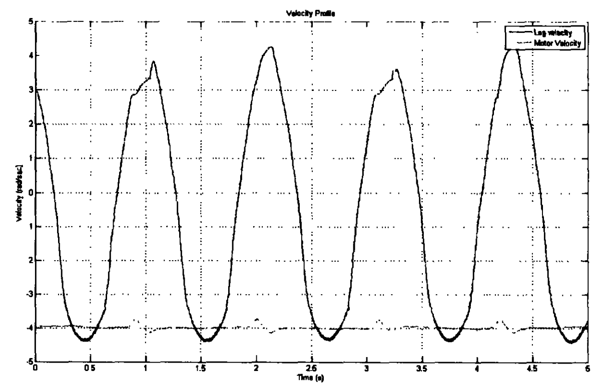

Figure 6-4: Velocity Profile

The periodic jumps on the motor velocity profile are actually shorts drops in velocity, and are mirrored by short stalls in the leg velocity. These halts are due to a short collision that occurs when the clutch is engaged, coupling the motor and swing leg at different speeds as well as adding the inertial load of the leg to the motor.

**Velocity Matching**

To avoid the energy losses in the clutch engagement collisions, the actuator should be moving at the same speed as the swing leg as the clutch is engaged. A simple way to do this is to control the motor directly from the leg velocity feedback. Figure 6-5 shows the control diagram and a sample system response.

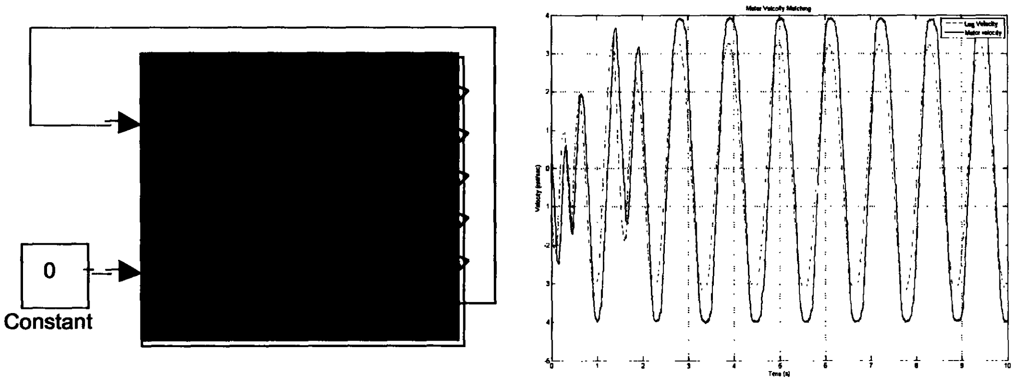

Figure 6-5: Velocity Matching.

The leg is manually moved in random sequence to show the response of the motor matching to quick changes in the velocity. After a couple seconds, the leg is left to swing “freely” because the clutch is note engaged. Note that the translated inertia of the motor moving in synch with the swing leg is enough to keep the leg at a constant amplitude oscillation. Although it is not mechanically engaged to the swing leg, the friction in the clutch system is enough to contribute kinetic energy to the swinging leg. Notice that this is essentially negative damping control without the brake engaged, where the system friction is working against the motor, but in favor of the swing leg since it is not coupled to the motor.

### Half Period Pulsing

To address the problem of lop-sided overshoot in the position trajectory for open loop clutch pulsing, we engage the clutch on both sides of the swing by setting the pulse generator to twice the frequency of the system. Sample results are shown in Figure 6-6.

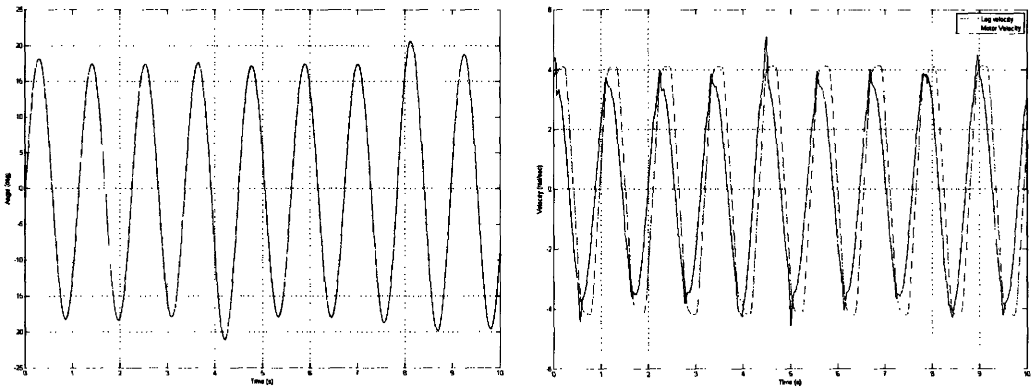

Figure 6-6: Half-Period Clutch Pulsing with Velocity Matching.

## 6.4 Clutch Pulsing with Negative Damping

The final test combines the negative damping with the pulsed engagement. The block diagram for this control is shown in Figure 6-7.

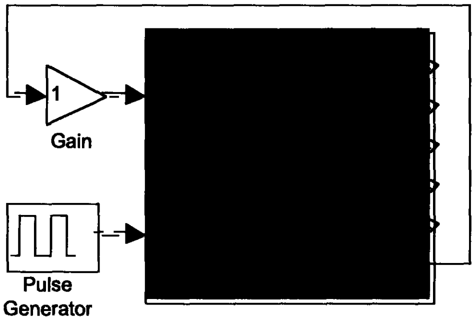

Figure 6-7: Clutch Pulsing with Negative Damping.

The response trajectories in Figure 6-8 show an improvement from the fully-engaged negative damping, but the problem persists of short stalls just after engagement.

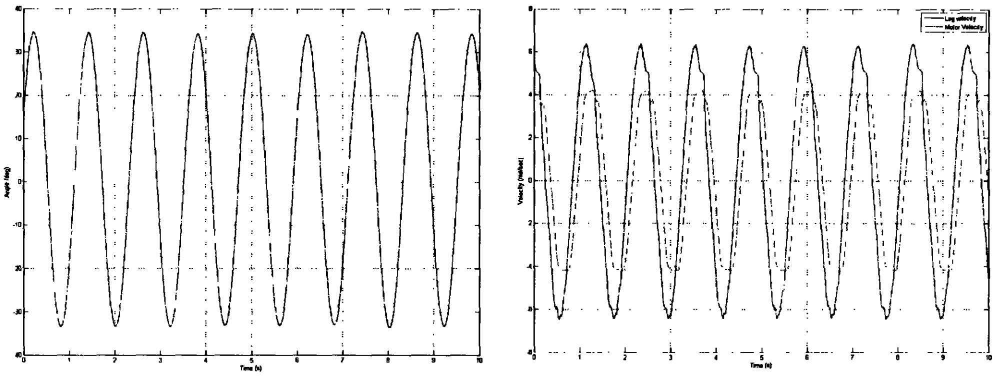

Figure 6-8: Clutch Pulsing with Negative Damping.

## 6.5 General Comments

The results from the control tests in the previous sections suggest potential for a good system response to minimally-actuated control, but also highlight some limitations in the system performance as well as some dynamics that surface with pulsed actuation, which need to be addressed in future control models.

The most obvious response issue is a mechanical problem that can be easily solved. Grinding between the teeth of bevel gear pairs, and skipping teeth was a common problem in the response tests, especially those for movement with rapid velocity changes and large angle displacements. The bevel gears wanted to push themselves apart, as expected, and the plastic housing was not strong enough to oppose that force and keep the gears fully meshed. The problem was solved for the sample trials by manually holding the plastic gear box rigid, so should also be fixed by replacing the current plastic box with a more rigid structure.

We also had problems with reliable actuation on the brake for small duty cycles (under 15%) for the pulse-generated brake commands. It is unlikely a strength issue, because the brake had no problem holding through many cycles of the fully actuated control tests. A 10% duty cycle for a 1.1 second period commands the brake to turn off about 0.11 seconds after it has engaged. The response time for the brake is rated at 27 msec, suggesting the brake could switch states four times in that period.

Other major issues include the apparent "stickyness" in the system at low speeds when commanding velocity feedback, and the effects of the load when the motor is engaged. These issues are further discussed in the sections on future work for control and mechanics in Chapter 7.

# Chapter 7

# Conclusions

This project represents the preliminary work on a clutch prototype that may prove to be a significant tool for actuation on robots based on the passive-dynamic model. The series of simple control tests suggest that a well-tuned clutch application can be used to create and maintain a smooth and natural-looking swing cycle for a biped's leg. A few more tests are needed to find out if this application is more efficient than a fully-actuated joint, and future improvements can be made on the test biped for better performance. The future work is outlined in the rest of this chapter.

## 7.1 Future Work

The project's next steps should start with examining the power consumption of the control tests explored in Chapter 6. The clutch mechanism is only valuable if it provides an improvement in the actuation efficiency compared to its fully-actuated counterparts. If the clutch proves to be significantly more efficient, the work should be continued to develop the control scheme for optimal performance and efficiency, as well as further development of the test biped to demonstrate the clutch performance as the single actuator on a minimally-actuated simple walker.

### 7.1.1 Power Consumption

A major milestone in the development of this clutch is to find out if it can be implemented with good performance while consuming less power compared to traditional actuated joints. This test can be done simply by measuring the current drawn by the motor and brake during the swing cycle with the implemented control strategy. The current can be measured by placing a known resistor in the wires to the motor and brake, and recording the voltage drop across the resistor. As long as the resistance is small enough so that the maximum expected voltage drop is small compared to the supply voltage, the added resistance to the circuit should not significantly affect the current drawn by either actuator. The resistor should be large enough, however, to have good resolution in the current sensing. Then, the power consumed is the product of the square of the current drawn and the resistor rating.

### 7.1.2 Control

The control tests are a good start in evaluating different strategies, and the performance results gave a lot of good information about what needs to be addressed in developing the appropriate control. Two items that stood out were matching the frequency of the natural swing for periodic engagement and overcoming the

To use the pulse generator for intermittent actuation, it is critical to match the actuation pulse period with the natural period of the passive system. The clutch pulsing with negative damping control strategy worked remarkably well, with a smooth swing cycle and unobtrusive clutch engagements, while in synch with the natural swing. However, a slight difference in the periods will eventually add up after a number of cycles and put the clutch engagements out of phase causing irregular swing amplitudes.

I would like to further explore engaging the clutch based on position and velocity feedback of the leg, to regulate when and whether the clutch needs to be engaged.

As efficiency is a large concern, it seems to be ideal for the motor to be off for most of the period that it is not engaged, as opposed to constantly matching the velocity feedback from the leg. This brings further complications on the control because the motor will have to be ramped up to speed just before engagement, but may prove worthwhile in the cost of efficiency.

A last issue that needs to be addressed is the effect of the added inertial load on the motor when the clutch is engaged. The answer may be to just give the velocity matching a faster response time, or it may work better to "anticipate" the load increase and push a faster velocity for the moment just after engagement. We would not want to simulate the leg load on the unengaged motor continuously, however, because that would require power similar to if the actuator was fully engaged.

### 7.1.3 Mechanics

Several improvements can be made immediately, and the biped needs to be completed to be able to carry all the necessary electronics and power supplies for untethered walking tests.

The head needs to be completed to hold the voltage regulator, motor board, on/off switch and other small electronics. Swinging arms need to be added to provide a place for the batteries. The addition of arms should also make the biped more anthropomorphic and help to reduce yaw during walking. Like Toddler, the arms should be attached to the hip joint by ball bearing and coupled to the swing of the opposite leg, so as not to add any additional degrees of freedom to the system.

There are a few structural issues that need to be addressed. The acrylic part of each leg needs to be strengthened, especially in the area that boxes the bevel gears. Acrylic was chosen for manufacturing convenience and supports were added to improve rigidity, but the piece is too flexible under the reaction forces between the bevel teeth that push the gears apart. To keep the weight down, it may be sufficient to rebuild with a thicker acrylic and extend the upper leg above the bevel gears so that a support cap can be added to "close" the box and better resist the twisting flexibility of the open-ended piece.

For a future robot, I also suggest choosing a joint shaft with a diameter larger than the 5/16" shaft used on Artie. Over 10-12 inches in length, the smaller shaft bends noticeably; this motion turns translates to small vibrations during the swing cycle and tends to increase the damping in the system. A larger shaft will have a larger bending inertia and better resist this trend.

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