Transfer of Support in a Dynamic Walking Robot

by

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Abstract

My goal is to understand how a legged system can transfer support between the feet during a dynamic walking gait. My approach is to build a legged robot that uses a dynamic gait and to explore control algorithms that provide smooth transfer. The robot I have built has five links that move in a plane: a pelvis, two legs, and two feet. The links are connected by revolute joints which are actuated by electric motors. The robot can balance on one foot and walk with a dynamic rocking gait.

Ground speed matching has been used to improve the exchange of support. In ground speed matching the closing velocity between the foot and the ground is manipulated by appropriate ankle motions. The improvement in transfer of support included reduced peak forces and a gradual loading of the striking foot.

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You are all invited out to Salt Lake to come skiing.

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Chapter 1

Introduction

One of the defining characteristics of animal-like locomotion is not the gait, or whether it is bipedal, quadrupedal, or hexapedal, fast or slow, but how graceful it is. A truly graceful walking robot does not yet exist. I believe that a key ingredient for graceful walking is the smooth transfer of support from one leg to the other. Smooth transfer means that the leg is loaded over a period of time instead of instantaneously and that there is little much vibration during loading. This thesis describes a project to study the transfer of support between the feet during a dynamic gait en route to a smooth step and a graceful walk.

I have developed a simple experimental platform, GeekBot. In designing the GeekBot, the goal was to create a very straightforward robot that could be built quickly and easily maintained, but was still capable of rich behavior. I have built a control system that produces two distinct behaviors. The first allows the robot to actively balance on one foot while performing configuration changes. The second is a dynamic walking gait.

I developed an algorithm for smooth support transfer. The algorithm reduces the impact velocity of the striking foot. Experiments with ground speed matching indicate improved support transfer as measured by reduced striking velocity of the feet, reduced peak forces developed during ground contact, and a lower rate of force loading of the feet. The striking velocity of the free foot is halved, as are the peak forces in the vertical direction. The rate of loading of the free foot is also decreased by about a factor of two.

1.1 Background

Early work with walking concentrated on statically stable gaits. McGhee's group at Ohio State University built an insect-like hexapod that walked with a number of gaits, turned, walked sideways, and negotiated simple obstacles [12]. Gurfinkel and his co-workers in the USSR built a machine with characteristics and performance quite similar to McGhee's [15] [4] [2]. Hirose's quadruped walker smoothly transfered support among the legs in order to keep the body level [6] [5]. The primary considera-tion for robots such as these was maintaining the center-of-gravity above the polygon of support created by the feet as opposed to the loading of the individual legs.

Subsequent legged robots used dynamic gaits in an attempt to exhibit the speed and grace of natural walkers. Kato and his co-workers built a biped that walked with a *quasi-dynamic* gait [14] [10]. This machine walked using a statically stable gait except for brief dynamic periods when it destabilized itself to tip forward so that support would be transferred quickly from one foot to the other. Miura and Shimoyama [13] built a walking machine that may have been the first to balanced itself actively. Their *stilt biped* was patterned after a human walking on stilts. Marc Raibert's Leg Lab has built robots that run instead of walk. Different robots have run fast [7], controlled their step length [9], and performed aerial gymnastics [8] [16]. Dynamic legged robots, from Miura and Shimoyama's [13] *stilt biped* to Raibert's [7] dynamic runners and hoppers have been concerned mainly with stabilizing the walking or running cycle. Foot placement was used as a method to balance the robot, and the loading was unimportant. Raibert's robot's springy legs did improve foot loading, as only the unsprung mass of the foot is decelerated quickly, instead of the whole robot mass.

There has been some work that was more concerned with the loading of the feet. In order to achieve better performance with his running biped, Koechling [11] became interested in the loading of the legs during high speed running. He found that off-axis loads would destabilize his robot in pitch. To solve this problem, he implemented a form of ground speed matching to which had the effect of realigning the impact force of touchdown. Borvansky [1] implemented ground speed matching in a simulation of a running ostrich. His goal was to emulate the movements and grace of an ostrich as closely as possible. In [3], Dunn explains a kinematic solution to a smooth biped gait. Dunn creates a path of the center-of-mass whose velocities before and after an instantaneous exchange of support are aligned.

For the most part, the previous work in the literature has been concerned solely with stabilizing the walking or running cycle. No one has directly addressed what is involved in achieving a smooth transfer of support. With the GeekBot, we want to improve how the feet are loaded and how support is transferred between the legs. If this transfer can happen smoothly, the walking motion will become more efficient, as more energy is carried through each step. Also, the walking motion will happen more gracefully, which I feel is an important goal.

1.2 Thesis Contents

The remainder of this thesis describes the work I have done and what was learned. In the following chapter I describe the mechanical design of the GeekBot, the robot that was used for the experiments. In Chapter 3 I discuss the control used for each of the three gaits. In Chapter 4 I explain the ground speed matching algorithm and the improvements it made to transfer of support. Chapter 5 contains the concluding remarks.

Chapter 2

Robot Design

The primary goal when designing the GeekBot was to create the simplest possible robot that could exhibit rich enough behavior to study support transfer. This simplicity would allow the robot to be constructed as quickly as possible, leaving more time for the development of control strategies. Also, with a simple design, we hoped to minimize robot down time.

2.1 Design Philosophy

Four major decisions were made early to guide the GeekBot's design:

1. The machine will be planar.
   Walking in the plane captures enough characteristics of 3D walking to make the results useful and interesting. A planar machine simplifies both the actuation and control required since out of plane effects can be ignored.

2. The machine will have two legs and actuated ankles.
   A minimum of two legs is necessary for walking, and additional legs would only add to the robots complexity without a substantial increase in its capabilities. We need the actuated feet to allow us to control the load transfer dynamics.

3. The machine will be powered by electric motors.
   Electric motors were chosen for their controllability and the ease of using them in a revolute joint.

4. The machine will carry neither its own power supplies nor its own computing resources.
   Removing the weight of the power supplies and computing power greatly reduces the power requirements of the actuators. Again, the goal is to study smooth walking, not to develop an autonomous walker.

2.2 Structure

As shown in Figures 2-1 and 2-2, the robot consists of five links: a pelvis, two legs, and two feet. The legs are connected to the pelvis through revolute hips, and the feet are connected to the legs through revolute ankles. The axes of all of the joints are parallel, and are powered by electric motors. Unlike the kinematics of a human, that allows natural placement of the leg fore and aft of the pelvis, the GeekBot's kinematics encourage a side-to-side rocking motion. Progression is possible only in the lateral direction.

Component	Length (m)	Mass (kg)
Pelvis	0.311	0.292
Leg (L)	1.022	0.576
Foot radius (R)	0.1334	0.336
Ankle offset (h)	0.05525	
Motor		0.752
Gyro		2.040

Table 2.1: Mechanical Specifications of Geekbot Components. L, R, and h refer to kinematic parameters diagrammed in Figure 4-3.

Table 2.1 gives the dimensions of the GeekBot. I wanted the GeekBot to be tall not only to be visually appealing, but also to have a slower tipping frequency. A slow tipping frequency reduces the performance constraints of all of the joints.

2.2.1 Legs and Pelvis

The legs and pelvis are made of carbon fiber tubing, chosen for its stiffness and light weight. Aluminum lugs are bonded into the ends of the tubes and motor brackets are screwed into these lugs. The bearing of the motor output shaft support reactions between the links.

2.2.2 Feet

Originally, the Geekbot had flat feet which were used during static walking. During initial rocking trials, the GeekBot would inevitably end up walking on the edges of the feet. To solve this problem, we changed the feet to circular arcs, with the center of the arc above the ankle. By having curved feet, we can control which point on the foot the robot is resting on. Since the point of contact is also the center-of-pressure, curved feet allow us to control ground reaction forces based on ankle position, rather than force feedback. The feet are aluminum with rubber pads on the soles. The pads serve both to cushion landing, and to provide some traction with the ground. The feet also serve double duty to planarize the GeekBot's motion.

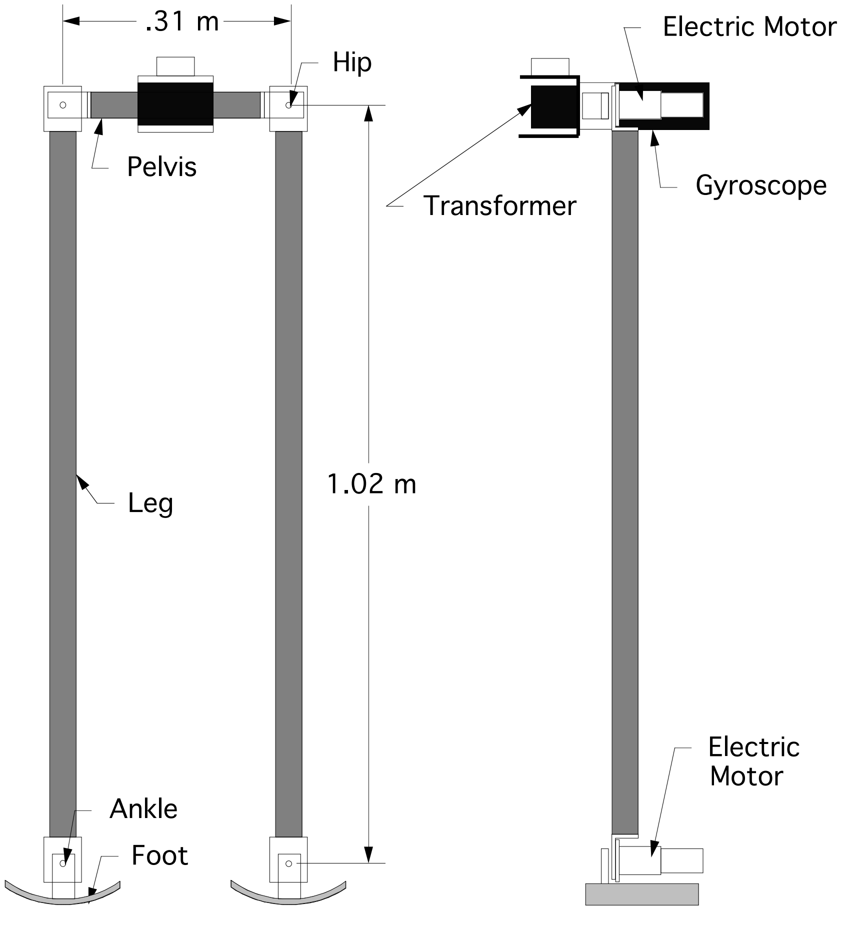

Figure 2-1: Schematic of GeekBot. The GeekBot stands approximately 1.09 meters tall and weighs about 7 kg. The four actuators are electric motors located at the joints. Potentiometers at each joint measure relative angles and a gyro attached to the pelvis measures the inertial orientation of the pelvis. Foot switches measure foot ground contact. Computers, power amplifiers for the motors, and electrical power supplies are located off board.

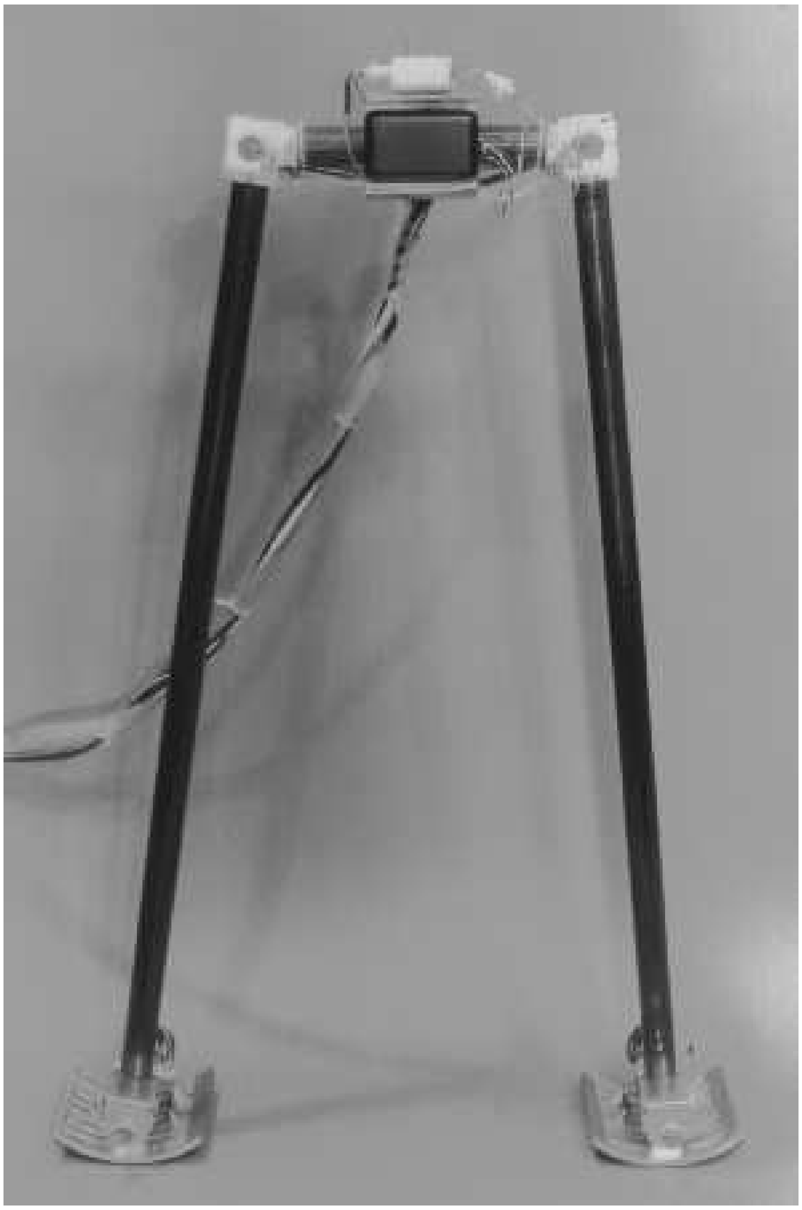

Figure 2-2: Photograph of GeekBot. The umbilical attached to the center of the pelvis contains motor power lines and instrumentation signal lines.

2.3 Actuation

We chose MicroMo Series 3557CR DC Micromotors, coupled with 159:1 38/1 series Gearheads to actuate the robot's joints. They were chosen for large motor power, high output speed and maximum output torque. Copley Controls Corporation 300 Series current amplifiers drive the motors. The current amplifiers are controlled by our standard Leg Lab interface hardware.

Motor—MicroMo 3557CR	
Power	72W
Voltage	24V
Torque constant	0.043Nm/Amp
Stall Torque	0.511Nm
No load speed	5300rpm
Weight	289g
Efficiency	0.82
Inertia	6.28×10^{-6}Kgm^2

Gearhead—MicroMo 38/1	
Reduction	159:1
Continuous maximum torque	5.3Nm
Intermittent maximum torque	7.0Nm
Efficiency	0.60
Gearbox weight	336g

Table 2.2: Characteristics of chosen motor and gearbox.

2.4 Instrumentation

In keeping with the design philosophy, the instrumentation of the robot is simple and includes:

- **Potentiometers to measure relative joint angles.** Potentiometers were chosen over encoders mostly due to their simplicity and the ease with which they can be utilized and trouble shot.

- **A gyroscope to measure the inertial orientation of the pelvis.** By combining the relative joint angles with the inertial orientation from the gyro, the inertial orientation of every link can be obtained.

- **Foot switches to sense foot ground contact.** Because the feet are curved, each foot has three electrical switch mechanisms. The active regime of the individual switches overlap so that at least one switch is closed for any foot orientation if the foot is in contact with the ground. The three switches are wire OR'ed as one virtual foot switch.

- **Forceplate.** A Kistler Type 9284 piezoelectric forceplate was used to measure ground contact forces. While the force plate outputs the forces and moments about all three axes, only the vertical force measurement was used. The forceplate was connected to a PC, where data could be manipulated and sent to the lab's UNIX network. The forceplate data was not incorporated into the control algorithm. Instead, it was used as an evaluation tool.

2.5 Computation and Data Collection

Computing power for the GeekBot was provided by a four node Inmos transputer network. One node reads sensors and runs servo code to drive the current amplifiers at 500 Hz. Another node, also coupled to an I/O board, is located within a control box and reads joy stick, switch, push button, and slider information and makes this information readable to the rest of the network. Two nodes connect to a Sun 3 workstation through a VME backplane and run task level (state machine) control code and kinematic calculations at approximately 150 Hz. Connection to the Unix LAN occurs through the VME backplane.

Communication between the transputer nodes takes place over RS422 lines that are decoded to RS232 at each node. Node processing speed is determined by specifying a desired cycle time and incorporating wait states that occupy the time between required CPU time and the desired cycle time.

The user interface runs on a Sun 4 workstation. From this interface, data can be displayed, variables set, and data recorded. The recorded data can then be analyzed using other programs.

2.6 Hardware Problems

The major failure in the GeekBot's design was in the hip motors. The motors were only marginally powerful enough. The motors had difficulty achieving their desired position during balancing and during the single support phases of the static and dynamic walking gaits. A desired position could be held if the GeekBot was manually set there, or if that position was at a lower energy state. The hips could not effectively raise the legs above a certain level.

A second problem with the motors was their gearheads. The gearheads stripped as high torques were commanded. When motors with a higher gear ratio and supposed higher output torque were used, those gears ended up stripping too. In this case, because of the increased gear ratio, the effective inertia of the motor rotor was more than doubled. When the robot would strike the ground, the output stage of the gearhead would see a very large inertia looking back at the motor. These collisions wore out the gears even faster than with the lower ratio gearheads.

Figure 2-3: GeekBot test setup. The foot on the left is standing on the forceplate. Behind the robot is one of the transputer nodes, the Copley amplifiers, the electrical power supplies, and the Sun 3 workstation.

Chapter 3

Robot Control

I decided to give the GeekBot two behaviors:

- Active balancing on one foot.
- A full dynamic walking gait.

3.1 Balancing

The GeekBot is capable of actively balancing on one foot. During balancing, the robot is in single support, and the stance ankle provides all of the control torques. The hips are servoed to desired joint angles, which can be varied while balancing. The controller handles slow configuration changes caused by the hip movements.

The control algorithm was derived by approximating the dynamics of the robot in stance as an inverted pendulum. The model incorporates the stance foot and a lumped mass rotating about the stance ankle, as shown in Figure 3-1. The lumped mass corresponds to the legs, pelvis, and free foot. An LQR controller was than developed for the linearized simple dynamics.

In practice, the control algorithm constantly recalculates the location and angular velocity of the center of mass. These states, as well as the foot's orientation and rate, are then fed back through a gain matrix to calculate an ankle torque.

$$\tau_{ankle} = -\begin{bmatrix} 8000 & 8000 & 2000 & 2000 \end{bmatrix} \begin{bmatrix} \beta \\ \theta_{com} \\ \dot{\beta} \\ \dot{\theta}_{com} \end{bmatrix}$$

Though based on the simplified pendulum model, the controller is fast enough to reject the disturbance due to slow movements of the hips, and therefore the c.o.m., without having to compensate for or even monitor the full dynamics of the robot.

The movement of the center of mass while the robot is balancing and changing its configuration is shown in Figure 3-2. Note that the system is only controllable if the c.o.m. is located over the foot. It is also necessary to monitor the ankle position and the input torque to insure that the foot does not roll onto either edge.

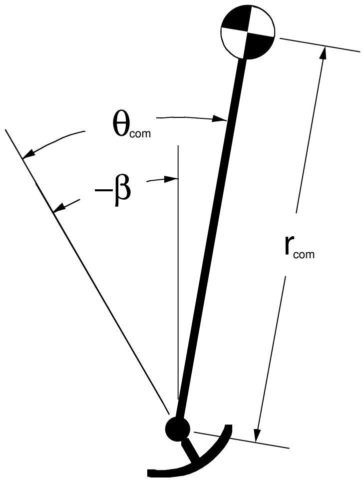

Figure 3-1: Simplified Dynamics for Balancing. For the balancing control, the Robot is modeled as a foot, which is at angle β with respect to the vertical, and a lumped mass, which is at angle θ_{com} with respect to the foot.

3.2 Dynamic Walking

During dynamic walking, the robot rocks from side to side. As it tips to the side it rocks onto one leg. The body of the GeekBot then rises as it moves towards its apex. After reversing direction it begins falling back down towards the centerline and the other foot. There is a brief double support phase after the robot touches down again, after which the robot lifts off onto single support on the other foot. The trajectory of the center of mass of the robot during dynamic walking is shown in Figure 3-3.

By increasing and then decreasing the stance width during alternate single support phases, an inchworm type of walking can be produced. Actually, it is more of a shuffle, as one foot is placed farther away, and then the other foot is brought back to the nominal stance width during the second part of the step.

A finite state machine shown in Figure 3-4 regulates the rocking motion. Control of the rocking cycle involves two basic concerns:

1. Controlling the kinetic energy during single support so that the robot does not over rotate about the roll axis, and returns to double support.

2. Adding sufficient energy during double support so that the robot will rock into another single support phase.

3.2.1 Over rotation

The first concern is addressed by comparing the robot's rotational kinetic energy to the work that gravity can do on the system as it rotates to its apex. If gravity can do enough work to slow the system down before the GeekBot reaches its apex, no active

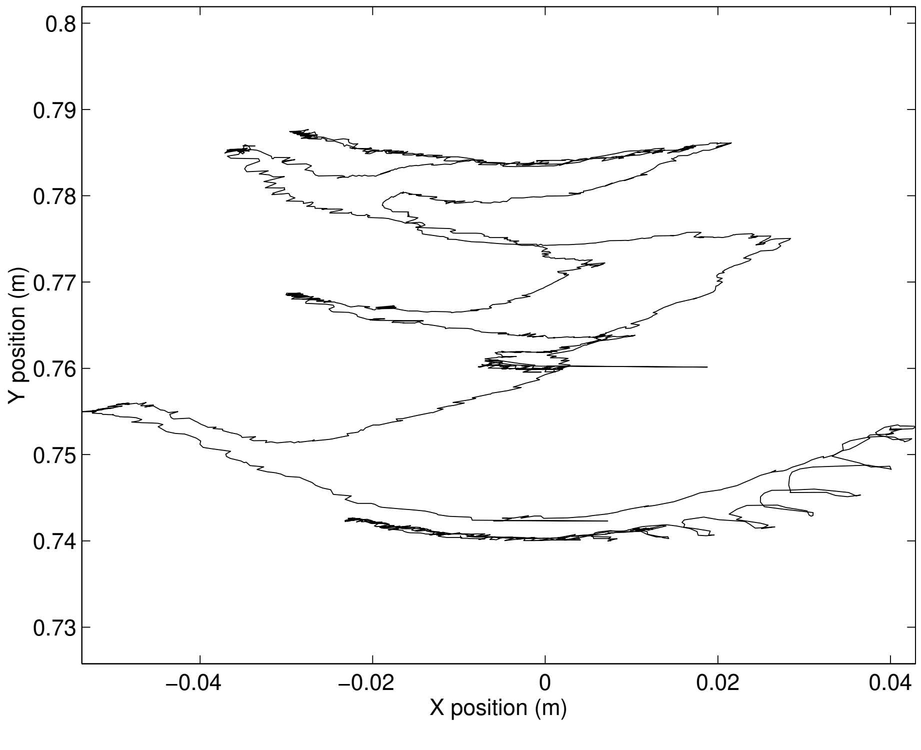

Figure 3-2: Center of Mass Trajectory During Balancing. The center of mass moves as the GeekBot moves its hips. The changes in height are caused by the configuration change. Notice that the c.o.m stays within 5 centimeters of the origin. The foot has a width of 15 cm.

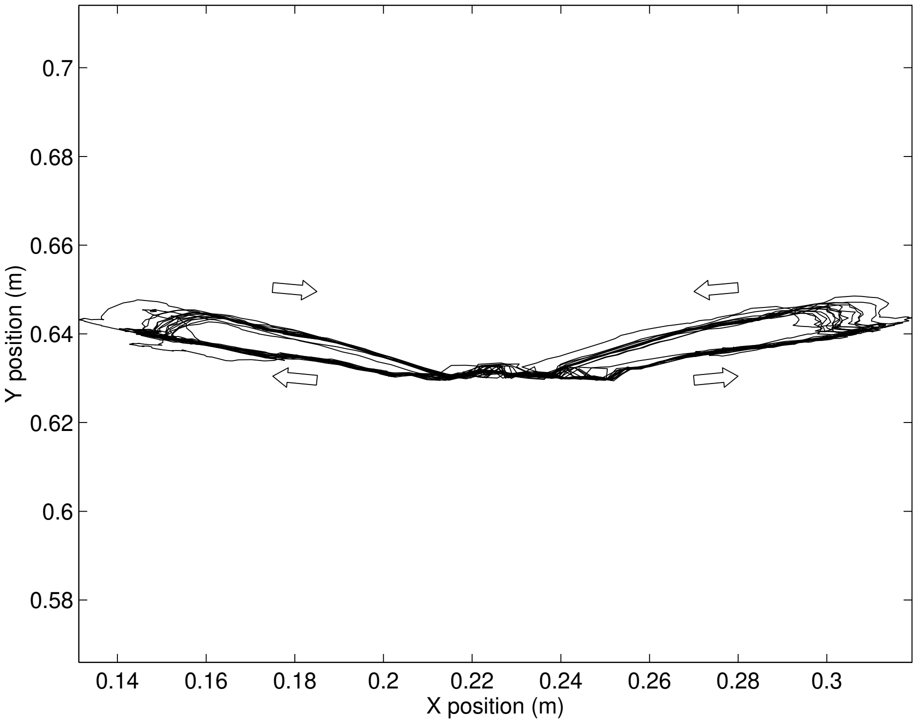

Figure 3-3: Center of Mass Trajectory. The center of mass rocks up and to the left or up and to the right during the first part of single support. At the apex, the robot reconfigures itself to move the center of mass outward. The robot then falls back to double support. The flat portion of the plot in the middle is the double support phase. This data is calculated over 15 rocking cycles.

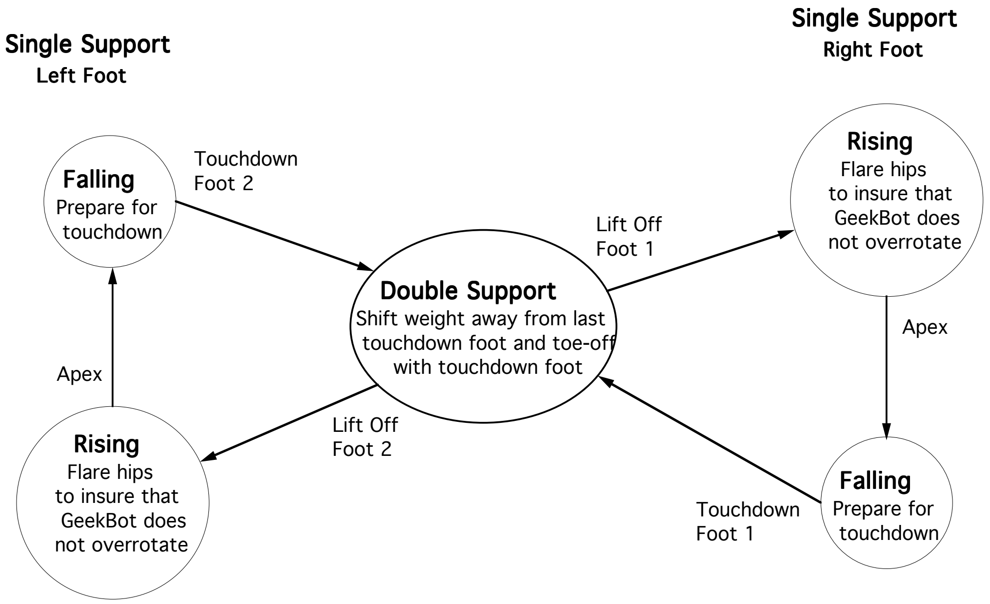

Figure 3-4: State Transition Diagram. The rocking control cycle is governed by the finite state machine described above. The action during each state is explained in the circles, and the transition condition is shown by the arrows.

control is needed. If there is too much kinetic energy, the robot's control system must dissipate the excess kinetic energy.

To develop a control law that will remove the excess kinetic energy, we modeled the robot's movement during single support as another simple inverted pendulum (Figure 3-5). When the robot spreads or flares its hips, as shown in Figure 3-6, the center-of-mass moves away from the foot, and the moment of inertia of the robot increases. If you assume that the robot can change its configuration instantaneously, then increasing the length and inertia of the pendulum will happen with conservation of angular momentum. Initially, if the pendulum has moment of inertia I_1, mass m at a radius of r_1, is at angle θ and angular velocity ω_1, and subject to gravity g, then the robot's initial kinetic energy is

$$T_1 = \frac{(I_1 + mr_1^2)\omega_1^2}{2}$$

and the work to be done by gravity, is

$$V_1 = mgr_1(1 - \sin\theta).$$

Through the configuration change, momentum is conserved, so we can determine T_2 from an angular momentum (H) balance.

$$H_1 = H_2$$

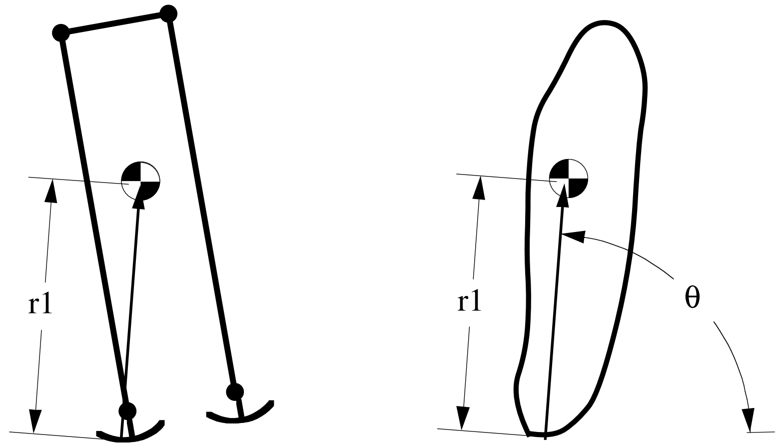

Figure 3-5: Inverted Pendulum Model of GeekBot in Single Support. The left diagram indicates the true robot configuration. The right diagram shows the robot reduced to an equivalent rigid body model.

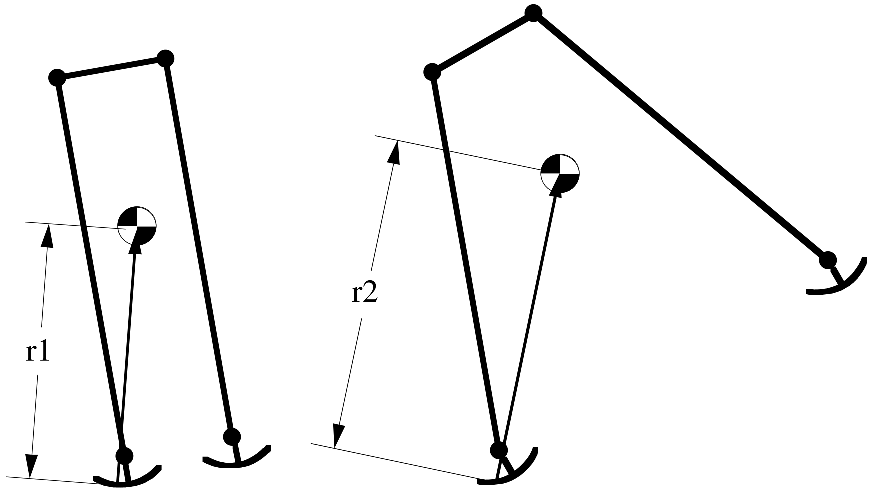

Figure 3-6: GeekBot with Flared Hips. The figure on the left indicates the GeekBot configuration prior to flaring. The right-hand side depicts the GeekBot in "spread-eagle" configuration, with the hips flared

$$(I_1 + mr_1^2)\omega_1 = (I_2 + mr_2^2)\omega_2$$
$$T_2 = \frac{(I_2 + mr_2^2)\omega_2^2}{2}$$
$$T_2 = \frac{(I_1 + mr_1^2)^2\omega_1^2}{2(I_2 + mr_2^2)}.$$

The potential energy difference for the new configuration is now

$$V_2 = mgr_2(1 - \sin\theta).$$

For a positive flare, $r_2 > r_1$ and $I_2 > I_1$. This gives two results. First, $T_2 < T_1$, the kinetic energy decreases. Second, $V_2 > V_1$, the potential energy difference increases.

From this result a control strategy was developed. During the rising portion of single support, the control system calculates its kinetic energy and the potential energy difference. If there is more potential energy than kinetic energy, nothing is done. If there is more kinetic energy than the amount of work gravity can perform on the system, the robot flares the hips proportionally to the amount of excess energy, making the kinetic energy less than the available work.

This control strategy was implemented successfully on the robot, but not with out several modifications. First, when the robot flares its hips, it moves in such a way as to cause the center of mass to move in a straight line along the original angle θ. As added protection to stop an over-rotation, a small value is added to the calculated kinetic energy. This addition makes the robot flare its hips a minimum amount during each single support state. Lastly, the configuration change is not instantaneous as assumed earlier and momentum is not conserved. The configuration change actually adds a little energy to the system as it accelerates the hips, and then removes some as it decelerates the hips. In spite of theses limitations, the control strategy works adequately to stabilize the rocking cycle for normal rocking most of the time. It was necessary to watch the GeekBot for the time when there was too much energy to dissipate, and the control system did not have enough time to act.

3.2.2 Double Support

From single support, the robot moves to double support. The control algorithm shifts the robot's hips towards the striking foot, and kicks or toes-off with the previous stance foot. Both of these actions add energy by getting the machine kinematically moving in the right direction for the next single support phase. The hip is driven to an arbitrarily chosen 90° angle. The toe-off is done by driving the ankle with an experimentally determined feedforward torque.

Ideally, with an efficient transfer of support, most of the energy will be carried through the double support phase, into the following single support phase. The current idea about solving this problem is based on Dunn's concept presented in [3]. The idea is to lengthen the stance leg while shortening the striking leg. If these actions are done correctly, the velocity of the center of mass before and after exchange-of-support is unchanged. As a first cut at this type of transition, the robot currently performs a "toe-down," where the striking foot is collapsing as freely as the ankle motor can be backdriven. The incorporation of toe-down had a noticeable benefit in the transfer of energy through double support. The toe-down effectively shortens the strike leg, which agrees with Dunn's method. It may also result in a form of ground speed matching.

Chapter 4

Smooth Transfer of Support

A smooth transfer of support is a desirable trait in a legged system. By reducing the impulsive loads of ground contact, the chance of damaging the leg structure is diminished. During rough terrain locomotion, a gradually loaded foot has a better chance of recovery if the foothold fails. Lastly, one can make an argument that with a smooth transfer of support, energy transfer through the double support phase will be more efficient: extraneous forces that do not directly contribute to locomotion will be minimized.

One way to make transfer of support smooth is to reduce the speed at which the foot approaches the ground, much as an aircraft adjust the rate of descent during landing. We call the process of reducing relative velocity before contact "ground speed matching." Many animals ground speed match when running, as they pull their legs back to them before their feet touch the ground. During smooth transfer experiments, the GeekBot's hips were mechanically locked to 90°. As the robot falls to the ground from a single support phase, both ankles are servoed so that the velocity between the foot and the ground is zero at touchdown.

Experiments with ground speed matching indicate improved support transfer as measured by the striking velocity of the feet, the peak forces developed during ground contact, and the rate of force loading of the feet. The striking velocity of the free foot is halved, as are the peak forces in the vertical direction. The rate of loading of the free foot is also decreased by about a factor of two.

4.1 Benchmarks

A force profile recorded when the GeekBot falls from single support as a rigid body, is shown in Figure 4-1. This is a worst case scenario, with no hips, and ankles servoed to a fixed joint position. The vertical force rises almost instantaneously to the full robot weight, and there is significant ringing due to the internal dynamics of the robot. The peak force seen by the forceplate is approximately two body weights.

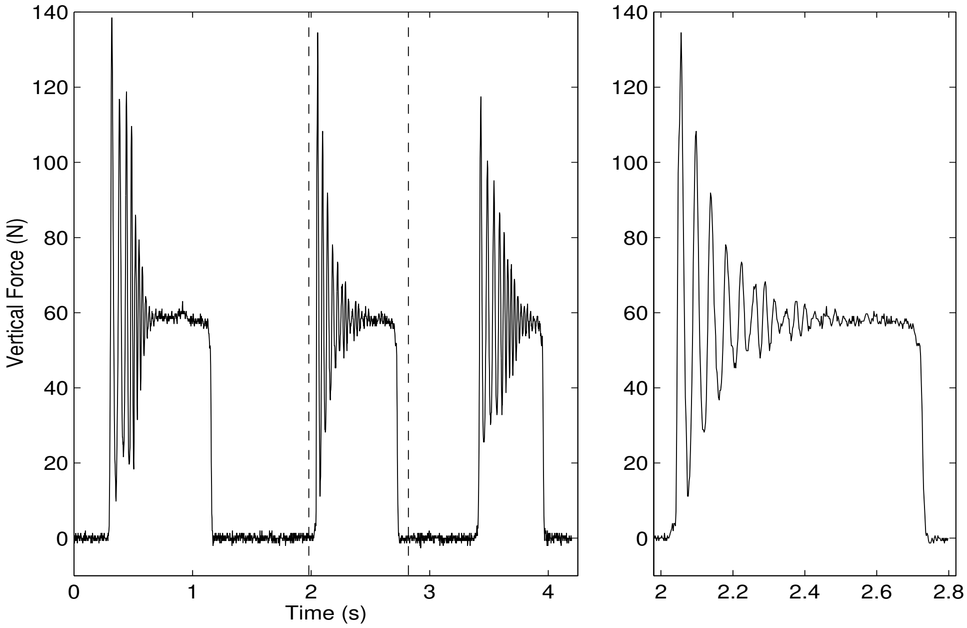

Figure 4-1: Force data with no control action. The plot on the left shows three consecutive left footfalls. The plot on the right is a close up of the area between the dashed lines.

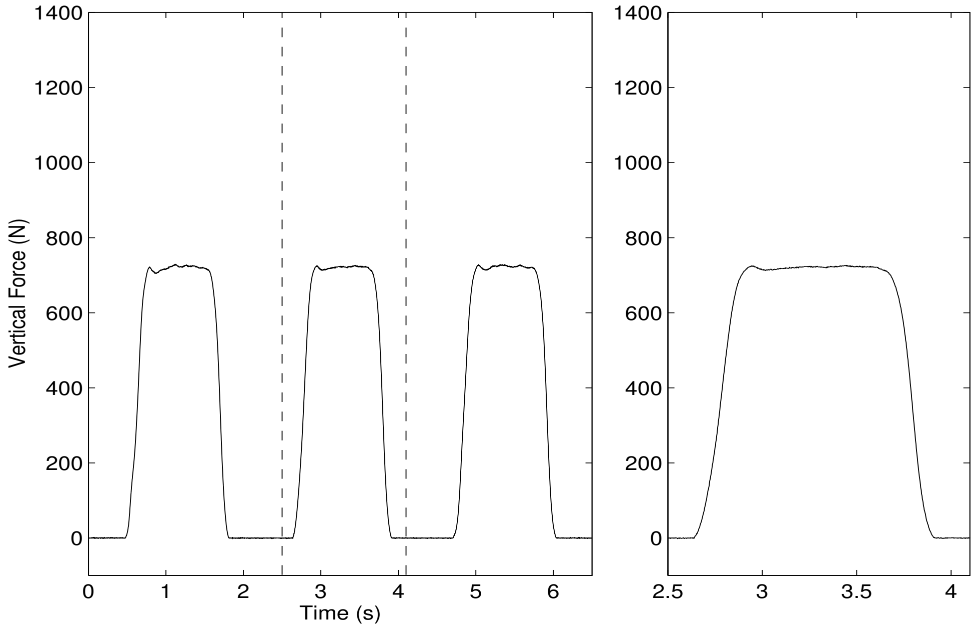

Figure 4-2: Force data from a human subject. The plot on the left shows three consecutive left footfalls. The plot on the right is a close up of the area between the dashed lines.

In contrast, when a human performs a rocking motion similar to that of the GeekBot, a markedly different force profile results, as shown in Figure 4-2. This is a best case scenario, with a fully actuated and controlled system. There is no ringing after touchdown, and the peak force is just a little over one body-weight. Also, notice that the force ramps up continuously to the full body-weight, instead of the step change witnessed by the rigid GeekBot. The human is better than the rigid GeekBot with regard to all three of the metrics discussed above.

4.2 Method

The idea behind my ground speed matching algorithm is to use a degree of freedom at the end of a linkage to remove the closing velocity between the linkage and the surface. Ideally, with a small or nonexistent touchdown velocity, the impulsive contact forces will be reduced. I am primarily concerned with reducing the vertical forces that occur during touchdown and so the primary goal in designing my ground speed matching algorithm was to reduce the vertical velocity. Due to the kinematics of the feet, it was also necessary and possible to incorporate horizontal ground speed matching.

As the Geekbot falls from its apex into double support, the stance foot is fixed inertially so that the robot is in effect rotating freely about the stance ankle. The free foot is also servoed to a fixed inertial position. It is in fact positioned so that the foot will strike the ground on its edge, instead of tangent to the curved surface. At some point during the GeekBot's descent, the extension of the free foot's arc is in contact with the ground. This can be seen by the dashed circle in Figure 4-3.

I am interested in performing ground speed matching in the vertical direction. To match the velocity of the foot to the ground, I need to solve for a position and velocity trajectory for the free ankle. As I am concerned about the vertical position and velocity, the height of the free ankle can be found by:

$$y_2 = y_1 + fy, \tag{4.1}$$

where

$$y_1 = R - (R - h)\cos\beta \tag{4.2}$$

and

$$y_2 = R + (R - h)\cos\zeta. \tag{4.3}$$

Substituting 4.2 and 4.3 into 4.1 yields

$$R + (R - h)\cos\zeta = R - (R - h)\cos\beta + fy,$$

which can be solved for ζ

$$\zeta = \cos^{-1}\left(\frac{fy}{R - h} - \cos\beta\right). \tag{4.4}$$

Similarly,

$$\dot{y_2} = \dot{y_1} + \dot{fy}, \tag{4.5}$$

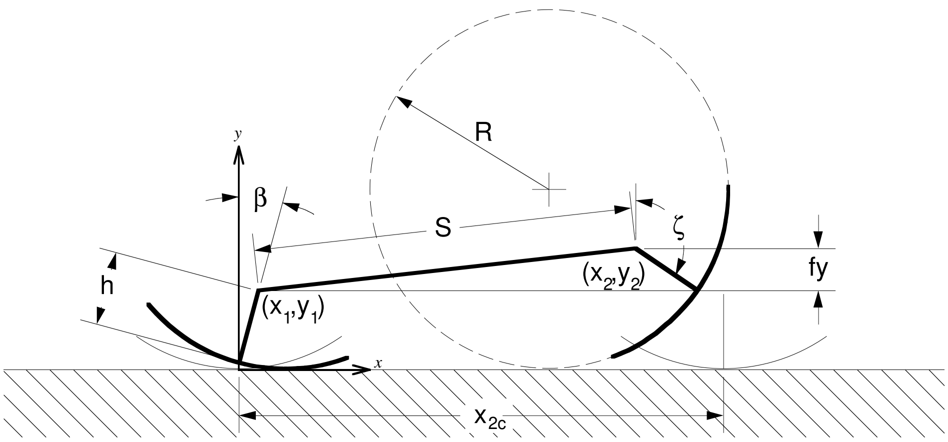

Figure 4-3: Feet Closure Kinematics. The legs and pelvis of the GeekBot are not shown for clarity. The left foot is the stance foot and the right foot is the free foot. The origin of the coordinate system is located on the ground at the center of the stance foot when it is upright. X_{2c} is the horizontal position of the center of the free foot if the foot rolls without slipping from its touchdown position and orientation to $\zeta = \pi$.

where

$$\dot{y_1} = (R - h) \sin \beta \dot{\beta} \tag{4.6}$$

and

$$\dot{y_2} = -(R - h) \sin \zeta \dot{\zeta}. \tag{4.7}$$

Substituting 4.6 and 4.7 into 4.5 yields

$$-(R - h) \sin \zeta \dot{\zeta} = (R - h) \sin \beta \dot{\beta} + \dot{fy}$$

which can be solved for $\dot{\zeta}$

$$\dot{\zeta} = -\frac{\frac{\dot{fy}}{R-h} + \sin \beta \dot{\beta}}{\sin \zeta}. \tag{4.8}$$

The free ankle's desired position and velocity can now be found from Equations 4.4 and 4.8 if β, $\dot{\beta}$, fy, and $\dot{fy}$ are known. If the trajectory for ζ and $\dot{\zeta}$ described above can be followed, the closing velocity of the foot's ground point in the vertical direction is zero.

In addition to ground speed matching in the vertical direction, there are other factors to be considered. During double support, as the free foot rotates and rolls along the ground, the ankle to ankle spacing increases if the stance foot remains at the original inertial orientation. This action excites the GeekBot's rigid hips and legs, which in return induce a resonant vibration once the GeekBot goes into the next single support phase. To prevent this excitation, the stance ankle should follow a trajectory that keeps the ankle to ankle distance constant while the GeekBot is in double support.

This trajectory can be found by solving the kinematic closure equation, based on Pythagoream's theorem. From Figure 4-3:

$$S^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2, \tag{4.9}$$

where y_1 and y_2 are defined above by Equations 4.2 and 4.3,

$$x_1 = R\beta - (R - h)\sin\beta, \tag{4.10}$$

and

$$x_2 = x_{2c} + R(\zeta - \pi) + (R - h)\sin\zeta. \tag{4.11}$$

If β, ζ, and S are known at touchdown Equation 4.9 can then be solved for x_{2c}. X_{2c} and S can then be substituted back into Equation 4.9 which can be solved for β as a function of ζ. This position and its derivative can then be used as a trajectory for a PD servo.

If you extend this trajectory beyond double support to incorporate the period when the extended free foot is in contact with the ground, an interesting and useful side-effect is found. By maintaining a constant stance width based on the free ankles movement since virtual touchdown, the stance foot is essentially pushing the free foot forward so that the free rolls on its extended surface, instead of simply falling. This rolling contact matches both the vertical and horizontal speeds at the true touchdown.

During single support, the stance foot is servoed to $\beta = 0$. Likewise, the free foot's desired position is .8 off of vertical, so $\zeta = 2.342$. During the transfer of support experiments, the hips were locked at 90°, yielding $S = .311$. By substituting these and the proper values from Table 2.1 into the equations above, $x_{2c} = .3608$.

As described above, you can now substitute x_{2c} and S into Equation 4.9 to derive the following relationship between β and ζ:

$$\begin{aligned}
.096721 \quad = \quad & .01562 - .009118(\sin\beta + \sin\zeta) + 0.1556(\beta - \zeta) \\
& +.0178(\beta^2 + \zeta^2) - .02085(\beta\sin\beta - \zeta\sin\beta \\
& +\beta\sin\zeta - \zeta\sin\zeta) - .03559\beta\zeta \\
& +.1221(\sin\beta\sin\zeta + \cos\beta\cos\zeta).
\end{aligned}$$

We do not have an analytical solution to this equation. I numerically solved it for several different values of β and then fit a cubic polynomial to the data. The cubic fits the numeric solution very well, as shown in Figure 4-4, and takes the form

$$\zeta = .1544\beta^3 + .2060\beta^2 + .7365\beta + 2.3417)$$

This cubic is easily invertible to

$$\beta = .156\zeta^3 - 1.6743\zeta^2 + 6.638\beta - 8.3663),$$

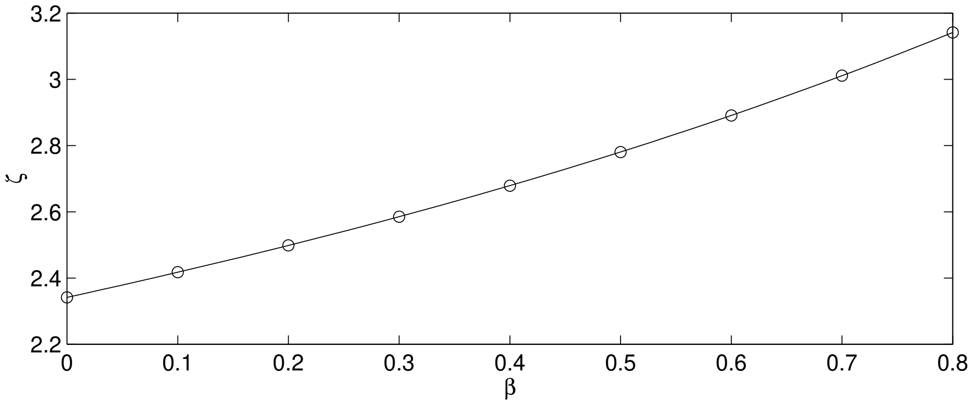

Figure 4-4: Cubic estimation of constant stance rolling kinematics. The circles are the numerically solved data points and the solid line is the cubic approximation.

and differentiable to obtain the rate trajectories

$$\dot{\zeta} = (.463\beta^2 + .412\beta + .7365)\dot{\beta},$$

and

$$\dot{\beta} = (.468\zeta^2 - 3.3487\zeta + 6.638)\dot{\zeta}.$$

4.3 Implementation

The rolling ground contact algorithm has been successfully implemented on the GeekBot. Armed with the position and velocity trajectories derived above, ground speed matching can be implemented with PD servos. As shown by Figure 4-5, the velocity before touchdown is noticeably reduced.

Ground speed matching improves the transfer of support. Figure 4-6 shows the force profile that occurs with ground speed matching. There are three things of interest in the figure. First is that the peak forces stay below 80N, as opposed to 140N without ground speed matching. Second, the free foot is loaded slowly, as opposed to the abrupt transfer that occurs with a rigid body. Though there is still a significant amount of ringing when the Geekbot touches down, the forces are oscillating about a ramp, instead of a step. Lastly, during the last two thirds of the step cycle the force profile vibrates at 6hz. This frequency corresponds to the natural frequency of the GeekBot's body. While the stance width of the robot was not held constant during the rolling action, it was minimized.

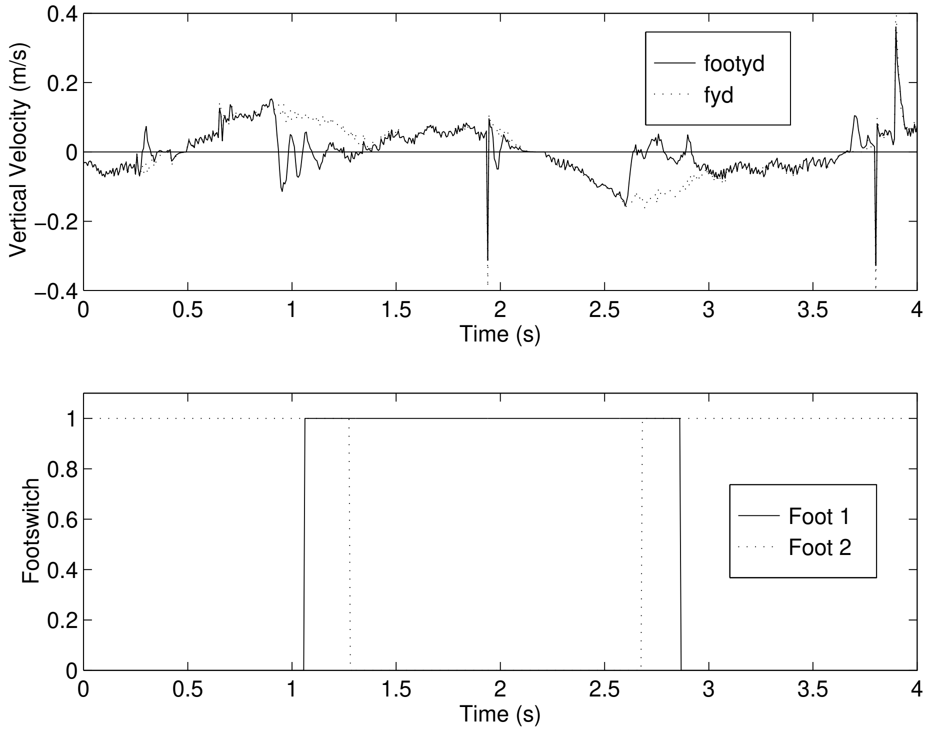

Figure 4-5: Foot contact and velocities. The top graph indicates the ankle velocities. Footyd is the closing velocity of the bottom of the feet. Fyd is the vertical velocity of the free ankle, $\dot{fy}$. The bottom graph displays a value of unity when a footswitch is activated. During the single support phases, the feet are locked inertially, so the ankle and foot velocity as equivalent. However, before every foot touchdown, the foot closing velocity (—footyd—) is reduced by the ground speed matching algorithm.

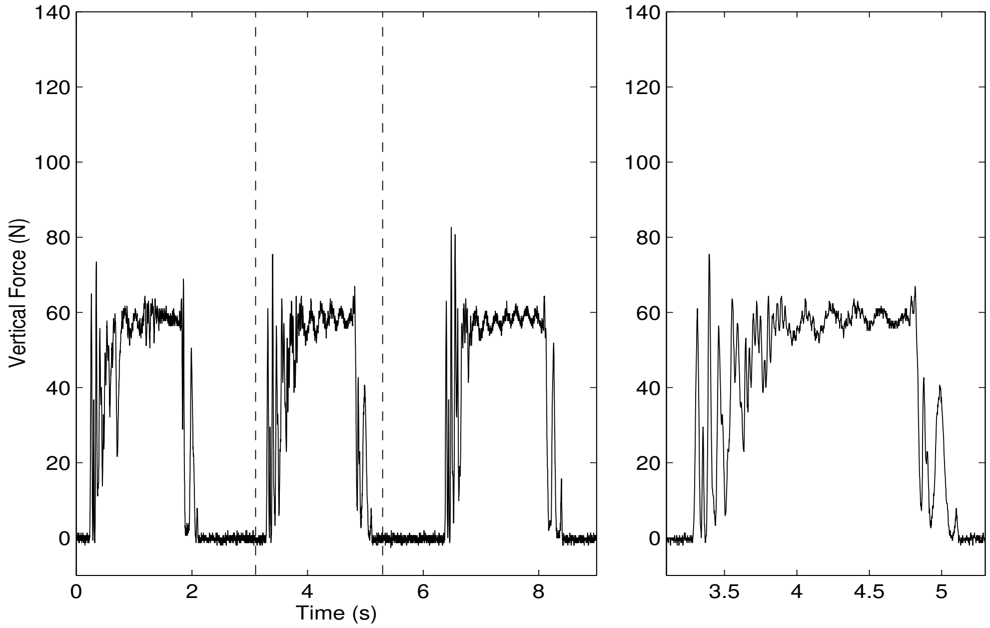

Figure 4-6: Force data with ground speed matching. The plot on the left shows three consecutive left footfalls. The plot on the right is a close up of the area between the dashed lines. The force axis scale is the same as in Figure 4-1

Chapter 5

Concluding Remarks

Graceful motion is one of the defining characteristics of animal-like locomotion. I believe that a key component of graceful movement is a smooth transfer of support. A smooth transfer of support makes locomotion easier structurally, energetically, and could help in rough terrain locomotion, when footholds may not withstand the impulsive loads of an immediate transfer of support.

I have built a simple experimental robot, GeekBot, to study the problems involved in achieving a smooth transfer of support. The GeekBot consists of a pelvis, two legs, and two feet. All of the joints are actuated by electric motors and are measured by potentiometers. A gyroscope measures the inertial orientation of the pelvis.

Control systems for several different gaits have been developed to control the GeekBot. Active balancing was achieved by modeling the GeekBot as an inverted pendulum and applying classic control techniques to the simplified dynamics. Dynamic walking was controlled by monitoring the energy of the GeekBot, and removing and adding energy in different parts of the step cycle. The dynamic walking control provided a platform on which to study smooth transfer of support.

Smooth transfer of support has been achieved by implementing a ground speed matching algorithm. In preparation of touchdown, the free ankle tries to eliminate the closing velocity between the foot and the ground. Experiments with ground speed matching indicate improved support transfer as measured by the striking velocity of the feet, the peak forces developed during ground contact, and the rate of force loading of the feet. The striking velocity of the free foot is halved, as are the peak forces in the vertical direction. The rate of loading of the free foot is also decreased by about a factor of two.

Bibliography

[1] Lance Borvansky. Simulating the running motion of an ostrich. Master's thesis, Massachusetts Institute of Technology, January 1992.

[2] E. A. Devjanin, V. S. Gurfinkel, E. V. Gurfinkel, V. A. Kartashev, A. V. Lensky, A. Yu. Shneider, and L. G. Shtilman. The six-legged walking robot capable of terrain adaptation. *Mechanisms and Machine Theory*, 18:257–260, 1983.

[3] Eric R. Dunn and Robert D. Howe. Towards smooth bipedal walking. *IEEE Journal of Robotics and Automation*, 1994.

[4] V. S. Gurfinkel, E. V. Gurfinkel, A. Yu. Shneider, E.A. Devjanin, A. V. Lensky, and L. G. Shitilman. Walking robot with supervisory control. *Mechanisms and Machine Theory*, 16:31–36, 1981.

[5] S. Hirose. A study of design and control of a quadruped walking vehicle. *International J. Robotics Research*, 3:113–133, 1984.

[6] S. Hirose and Y. Umetani. The basic motion regulation system for a quadruped walking vehicle. *ASME Conference on Mechanisms*, 1980.

[7] J. Hodgins, J. Koechling, and M. H. Raibert. Running experiments with a planar biped. In *Third International Symposium on Robotics Research*, 1986.

[8] Jessica K. Hodgins and Marc H. Raibert. Biped gymnastics. *International Journal of Robotics Research*, September 1989.

[9] Jessica K. Hodgins and Marc H. Raibert. Adjusting step length for rough terrain locomotion. *IEEE Transactions on Robotics and Automation*, 7(3), June 1991.

[10] T. Kato, A. Takanishi, H. Jishikawa, and I. Kato. The realization of the quasi-dynamic walking by the biped walking machine. In A. Morecki, G. Bianchi, and K. Kedzior, editors, *Fourth Symposium on Theory and Practice of Robots and Manipulators*, pages 341–351, Warsaw, 1983. Polish Scientific Publishers.

[11] Jeffrey C. Koechling. *The Limits of Running Speed: Experiments with a Legged Robot.* PhD thesis, Carnegie Mellon University, July 1989.

[12] Robert B. McGhee. Vehicular legged locomotion. *Advances in Automation and Robotics*, 1983.

[13] H. Miura and I. Shimoyama. Dynamic walk of a biped. *International J. Robotics Research*, 3:60–74, 1984.

[14] K. Ogo, A. Ganse, and I. Kato. Dynamic walking of biped walking machine aiming at completion of steady walking. In A. Morecki, G. Bianchi, and K. Kedzior, editors, *Third Symposium on Theory and Practice of Robots and Manipulators*, Amsterdam, 1980. Elsevier Scientific Publishing Co.

[15] D. E. Okhotsimski, V. S. Gurfinkel, E. A. Devyanin, and A. K. Platonov. Integrated walking robot development. *Conference on Cybernetic Models of the Human Neuromuscular System*, 1977.

[16] Robert R. Playter and Marc H. Raibert. Control of a biped somersault in 3d. In *IFToMM-jc International Symposium on Theory of Machines and Mechanisms*, September 1992.