Knee Design for a Bipedal Walking Robot Based on a Passive-Dynamic Walker

by

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in Partial Fulfillment of the Requirements for the degree of

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ABSTRACT

Passive-dynamic walkers are a class of robots that can walk down a ramp stably without actuators or control due to the mechanical dynamics of the robot. Using a passive-dynamic design as the basis for a powered robot helps to simplify the control problem and maximize energy efficiency compared to the traditional joint-angle control strategy. This thesis outlines the design of a knee for the robot known as Toddler, a passive-dynamic based powered walker built at the Massachusetts Institute of Technology. An actuator at the knee allows the robot to bend and straighten the leg, but a clutch mechanism allows the actuator to completely disengage so that the leg can swing freely. The clutch operates by using a motor to rotate a lead screw which engages or disengages a set of spur gears. Control of the knee is accomplished by utilizing the robot's sensors to determine whether or not the knee should be engaged. The engagement signal is then fed through a simple motor control circuit which controls the motor that turns the lead screw. The knee design was successfully implemented on Toddler but more work is required in order to optimize his walking. In order to study the dynamics of walking with knees, we also built a copy of McGeer's original passive walker with knees.

Thesis Supervisor: Ernesto E. Blanco

Title: Adjunct Professor of Mechanical Engineering

Acknowledgements

Above all I would like to thank Dr. Russ Tedrake for giving me the opportunity to work with him on Toddler. I have always wanted to build robots. This project has given me invaluable experience doing just that and has further strengthened my desire to do this as a living. I would also thank Prof. Sebastian Seung, who generously let us build robots in his neuroscience lab. I must also thank Prof. Ernesto Blanco for all the guidance he has provided me as my advisor. Finally, I must whole heartedly thank all my brothers at Zeta Beta Tau for making my time here at MIT a much more pleasant experience.

Chapter 1

Introduction

Achieving efficient bipedal walking is a challenging problem that roboticists are still trying to solve. The traditional approach has been to use a precise joint-angle control strategy to explicitly control every joint at all times. This strategy requires a complicated control system, usually results in an unnatural looking gait, and is energy inefficient. A relatively new strategy is to base the walking robot on a passive-dynamic walker. A passive-dynamic walker takes advantage of its own mechanical dynamics to determine its walking motion. Such a walker is capable of walking stably down a slope without any controllers or actuators; gravity supplies the energy that is lost due to friction and collisions with the ground with each step. Modifying the design to include actuators removes the dependence on gravity to re-supply the lost energy and allows the robot to walk on the flat.

1.1 Brief Background of Passive-Dynamic Walkers

The class of robots known as passive-dynamic walkers was introduced in the late 1980's by Tad McGeer [1]. McGeer took the development of airplanes as an inspiration, noting that the Wright brothers first mastered gliding before adding energy for powered flight. McGeer successfully designed both a straight-legged and a kneed version of a two-dimensional robot that was capable of walking down a range of shallow gradients in a smooth and graceful manner without actuation. The walker was constrained against falling over sideways by using two pairs of legs and walked essentially as if it were using a pair of crutches. Since McGeer, more complex passive-dynamic walkers have been made, including 3D bipedal walkers that incorporate knees and arms [2].

1.2 The MIT Toddler Project

Since passive-dynamic walkers rely on gravity to power them, actuators must be added to them before they can walk on flat surfaces. By adding a small number of actuators to a few degrees of freedom, it is possible to capitalize on energy efficiency as well as to allow the dynamics of the system to simplify the control problem. A project led by Russ Tedrake of the Seung Lab at the Massachusetts Institute of Technology successfully actuated a simple straight-legged passive-dynamic walker [3]. The robot that they developed was named Toddler, and can be seen in Figure 1. Two other powered robots based on the passive-dynamic design were built around the same time, one at Cornell University and one at Delft University of Technology in the Netherlands [4]. Toddler is unique in the sense that he uses a reinforcement learning algorithm to teach itself to walk. While most walking robots would require too many trials to successfully utilize a reinforcement learning algorithm to learn to walk, the simplified required control due to the passive dynamic design along with some clever programming by Dr. Tedrake allow for Toddler to learn to walk from a blank slate in about twenty minutes [5].

Toddler is actuated by four servos, two on each ankle. The hip joints are completely passive and the arms are simply mechanically coupled to the opposite leg. If the servos are commanded to hold rigidly at the neutral position, Toddler simulates passive-dynamic walking and can walk down a ramp without any control. Toddler walks by rocking side to side on his curved feet in order to obtain foot clearance. With each step, Toddler rocks onto one leg, lifting the opposite leg off the ground. The lifted leg is free to swing forward like a pendulum and take a step. Toddler then rocks onto this leg, allowing the other leg to swing forward and repeat the process. In the purely passive mode, Toddler requires gravity to provide the energy for the walking motion. He is capable however of using his ankle actuators to put energy back into the system instead of relying on gravity, which allows him to walk on the flat.

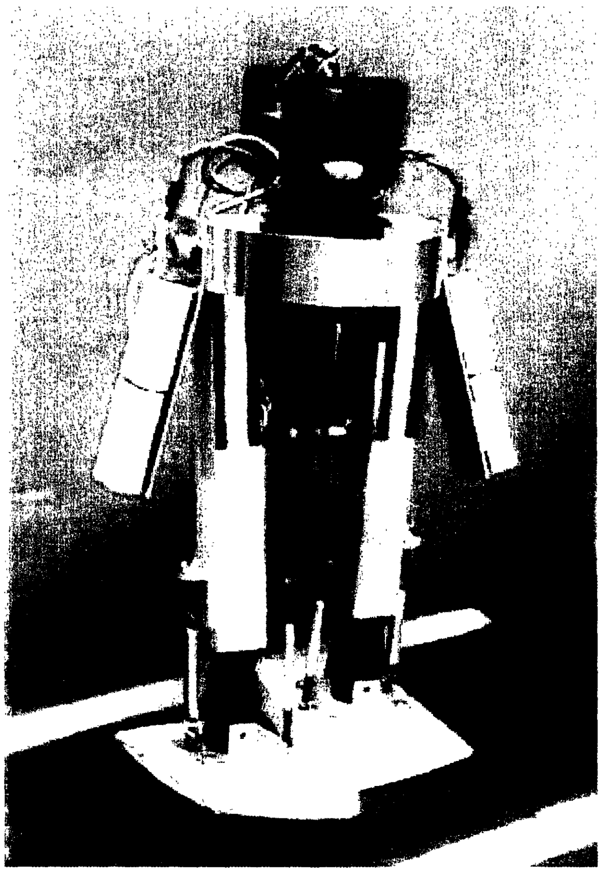

Figure 1-1: The robot known as Toddler

The goal of this thesis is to advance the Toddler robot such that it incorporates knees into its design. While adding knees complicates the dynamics of the system, there are a number of advantages that make it beneficial to do so. Walking with knees would allow for a much more familiar and anthropomorphic gait. Knees would enable the robot to obtain a much larger degree of ground clearance, which would allow it to traverse more rugged terrain. Finally, increasing the complexity of the robot would demonstrate that it is indeed possible to harness the advantages of a passive-dynamic design even while approaching the level of complexity obtained by the joint-angle controlled robots.

Chapter 2

Mechanical Knee Design

2.1 Design Requirements

When designing a knee for a walker passed on the passive-dynamic model, there are a number of requirements that must be met. The knee must be able to swing freely and with minimal energy loss. The robot must also be able to lock the knee so that the leg does not buckle when it is standing on it. Beyond just being able to lock the leg, however, we also want the robot to be able to drive the knee such that it can bend or straighten the leg. While the purely passive walkers of McGeer and others demonstrate that the dynamics of the robot will cause the swinging leg to bend and straighten on its own, the ability of the robot to manually straighten or bend the knee would allow for increased robustness as the robot would not be completely disrupted in the case that something interferes with its step.

A challenge arises with wanting the knee to be drivable while still allowing it to swing freely. If the robot utilized a joint angle control strategy, it would be a simple matter to just place a servo at the joint. Such a solution is not acceptable for a passive-dynamic based design, however, since back-driving a motor would not allow the leg to swing freely. A clutch mechanism of some sort is required so that a motor can be coupled or decoupled from the joint as required.

2.2 Knee Clutch Design

When considering what the nature of the knee-clutch mechanism should be, a number of readily available commercial solutions were first investigated. Many different manufacturers offer a variety of different types of slip clutches, spring clutches, electric brakes, and other similar products. After an extensive search, however, no suitable product was found. A common problem was scale. Most clutches and brakes commercially available are designed for physically larger systems with high torque and high RPMs. These products also typically weighed at least five or six pounds each, which is absurdly heavy for this application considering that the entire straight-legged version of the robot only weighed about six pounds. Placing that much weight in the knees would greatly affect the dynamics of the robot. Most of the products were also much too physically large. Other problems arose for individual products. Most of the mechanical clutches would be hard to engage and disengage when desired, or only operated in one direction. The electrical clutches and brakes were among the heaviest of the products and were often overly expensive. The most straightforward solution was to design our own simple clutch mechanism.

The clutch that was designed for the knee is extremely simple. The knee is powered by a Futaba S9350 servo located on the upper portion of the leg. When operating at 4.8V, the servo is capable of supplying 111 oz-in of torque, which is more than sufficient for our purposes. A 24 tooth spur gear attached to the output shaft of the servo can mesh with a 48 tooth gear rigidly attached to the lower half the leg at the connection joint. The 2:1 gear ratio allows the knee a full 90 degree range of motion given the 180 degree operating range of the servo. When the knee needs to be driven, the servo can provide torque through the meshed gears. In order for the leg to swing freely, the gears need to separate and completely disengaged from each other.

Gear separation is accomplished by placing the servo on a linear bearing. The bearing used in this design is the mini-rail series from the Pacific Bearing company. The top and sides of the extruded aluminum stock which composes the upper portion of the leg are cut away in a 1.3 inch channel in which the servo can translate. The servo itself is approximately 0.8 inches thick, leaving about half an inch worth of travel. The servo only needs to travel the small distance required to clear the gears from each other, so a gap of this size is more than sufficient. A piece of 4-40 threaded rod is used as a lead screw to engage and disengage the gears. The lead screw is turned by a Maxon A-max ironless core DC electric motor. The advantage of this design is that while it is easy to rotate the rod to produce a linear motion and move the servo, it is not possible to force a linear motion and rotate the rod. This means that no energy is required to hold the servo in place. A solid model of the basic knee design can be seen in Figure 2-1. The model represents an intermediate step in the design process. It does not include the motor used to turn the lead screw, nor does it show the servo mount that was later designed to secure the servo, but it succeeds in showing the basic strategy of the knee design.

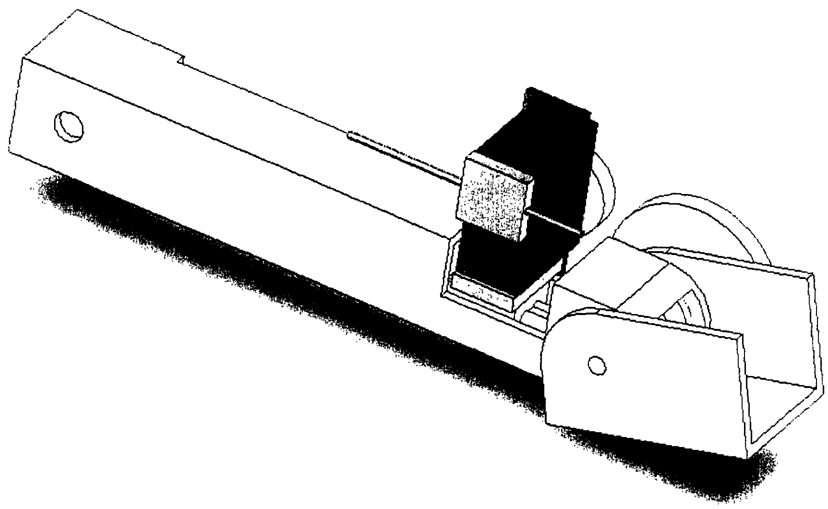

Figure 2-1: Solid model of the knee assembly.

A servo mount was designed in order to ensure that the servo is properly secured on the mini-rail. A small aluminum plate is attached to the slider of the mini-rail. Two screw holes on the front of the plate allow the servo to sit on top of the plate and be attached by two front screws. This attachment in itself is enough to allow the servo to translate on the rail, but when the clutch is engaged the servo tends to lean away from the engaged gears. In order to supply more support, the servo is also attached to another small aluminum plate located on top of the servo. This aluminum plate is in turn connected to the original bottom plate by a stiff sheet of aluminum sheet metal running down the side of the servo. In this manner the servo is encased in a rigid aluminum box which supplies more than adequate support. A small section of the side piece of sheet metal extends beyond the back of the servo. It is on that extended piece that the threaded rod runs through to actuate the servo along the mini-rail.

This concludes the mechanical design of the knee. Figure 2-2 shows a photograph of the assembled knee and leg. The third gear visible in the picture is connected to a potentiometer used to measure the angle of the knee. Measuring the angle is necessary in order to successfully implement and control the knee, a topic discussed in further detail in the next chapter.

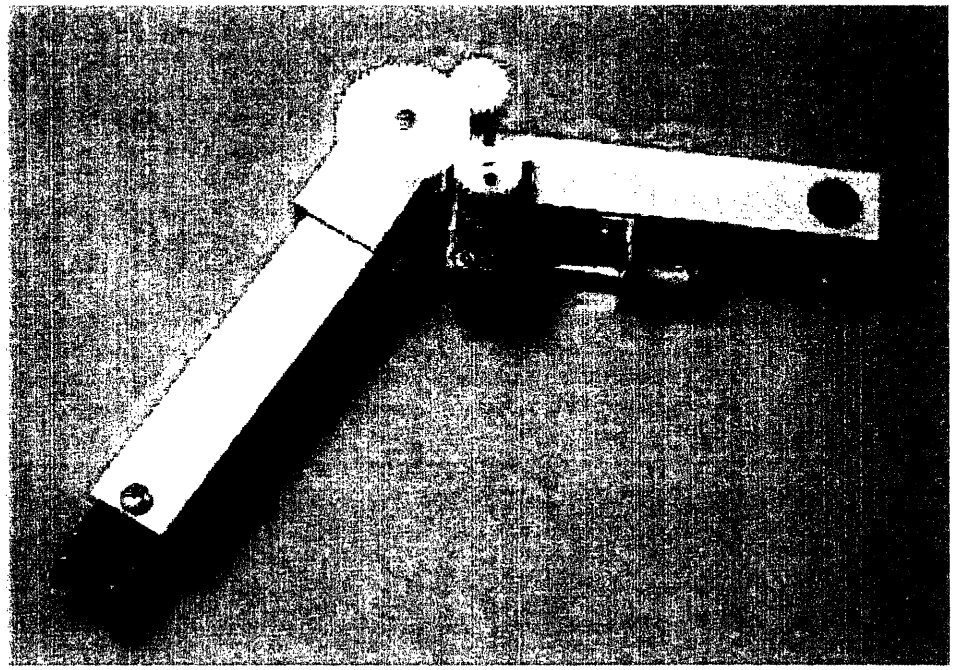

Figure 2-2: The assembled knee

Chapter 3

Knee Implementation

With the mechanical design of the knee completed, the next step is to incorporate the mechanism into the robot. A solid model of what the robot would look like with the knees implemented (the computer in the body has been removed for clarity) can be seen in Figure 3-1. There are however a number of challenges that arise with the implementation of the knees. Some sort of motor control circuit is required since the computer cannot source enough current to drive the motor which turns the lead screw on the knee clutch. Also, since the robot needs to know when to engage the clutch there needs to be some level of interaction between the knee and the robot's sensors.

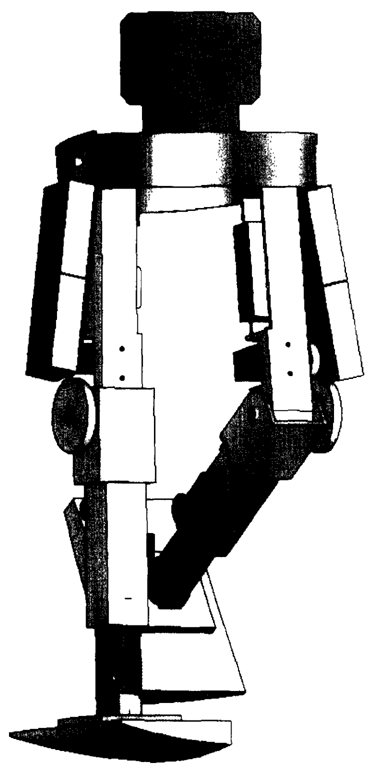

Figure 3-1: Solid Model of kneed version of Toddler

Section 3.2 Motor Control Circuit

In order to drive the motor that turns the lead screw, a motor controller circuit needed to be designed. The computer can not source enough current for the motor, so in the very least an H-bridge is necessary to source the motor directly from the battery. It was also decided to add some logic to the circuit such that the computer would not be necessary to control the knee mechanism. With the previous version of Toddler, it was easy to demonstrate the robot's passive-dynamic abilities by having it walk down the ramp without the computer turned on. In order to retain this ability, the logic controlling the knee mechanism is placed on the motor controller circuit. A diagram of the motor control circuit can be seen in Figure 3-2.

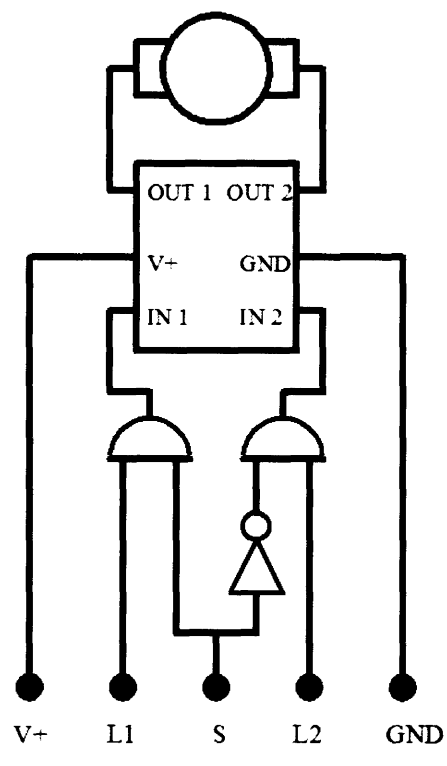

Figure 3-2: Diagram of Motor Controller

Along with power and ground, the motor control circuit needs three inputs, labeled L1, L2, and S on the diagram. The inputs L1 and L2 correspond to the signals from two limit switches that are on either end of the track which the servo moves along. These signals are high when the switch is open and low when the switch is closed. A low signal from L1 means that the servo is fully engaged, and a low signal from L2 means that the servo is fully disengaged. The signal S corresponds to whether or not the servo should be engaged. The original idea was to have S come from some sort of foot contact sensor which would return high when the robot was standing on the foot. In the current configuration, however, S is connected to an output of the robot's onboard computer. The motor controller circuit thus allows for the potential of Toddler operating without the computer, but in the current setup he does not take advantage of it. This is a result of how Toddler currently determines which foot it is standing on, a topic that will be discussed in section 3-3.

The H-bridge used in the motor control circuit is the MC33186 Automotive H-Bridge Driver from Motorola. The H-bridge needs two input signals, labeled IN1 and IN2 on the diagram. If IN1 is high and IN2 is low, the H-bridge will return the output signals OUT1 as high and OUT2 as low, causing the motor to drive forward. If the input signals are reversed, the output signals and the motor will also reverse. If both the input signals are the same then the motor will free wheel.

The logic on the control circuit is relatively simple. The signals L1, L2, and S run through the appropriate logic gates in order to make the motor behave as desired. The L1 signal corresponds to the front limit switch. A high value would indicate that the switch is open and the servo is not engaged. The L1 signal is connected to an AND logic gate along with the S signal. The output of the logic gate is the input IN1 for the H-bridge. If both L1 and S are high, then the knee needs to be engaged but has not yet done so. Therefore the motor needs to drive forward. The S signal also runs through a NOT gate, which in turns is an input for another AND gate along with L2 signal from the rear limit switch. The output of the second AND gate is the H-bridge input IN2. If both L2 and not-S are high, then the knee needs to be disengaged but the servo is not yet fully retracted. The motor would therefore need to drive in reverse. If the knee needs to be engaged but already is, or if it needs to be disengaged but already is, then both IN1 and IN2 are low and the motor does not move.

Section 3.3 Generating the S Signal

The motor control circuit requires an input that has been referred to as the S signal. When the knee clutch needs to be engaged the S signal should be high, and when the clutch needs to be disengaged the S signal should be low. The original design for generating such a signal was to construct a foot contact sensor, as seen in Figure 3-3. The sensor was to be implemented by placing a hinge at the ankle. A small spring would hold the ankle plate away from the foot unless the weight of the robot forced them together by trying to stand on the leg. This would cause two small metal plates, one on the foot and one on ankle plate, to come together and act as a contact switch to generate the S signal. The advantage of this design is that the signal could be sent directly to the motor control circuit without every having to pass through the robot's onboard computer, enabling the robot to simulate passive walking by leaving the computer and its control program turned off.

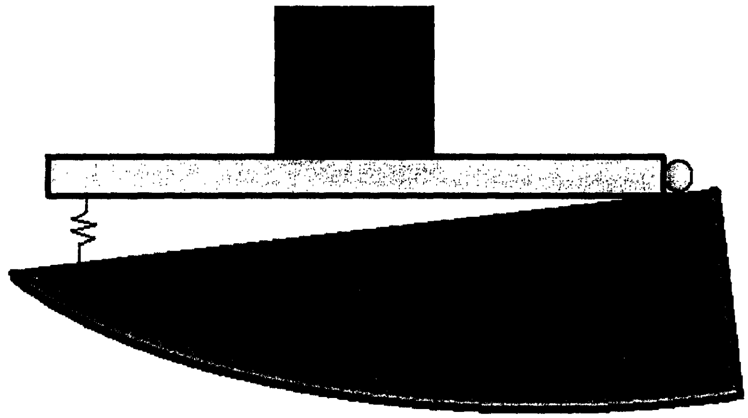

Figure 3-3: A simple diagram of the foot contact sensor

Implementing the foot contact sensor, however, revealed several problems. The spring requires energy to be compressed. This energy would be robbed from the rocking motion of the robot, adversely affecting the dynamics of the step. Prior to the contact switch, the two feet together were on the same single curve with a section missing in the space between the feet. This design allowed for a smooth rolling transition between the two feet and minimized the energy loss due to foot collisions with the ground. The contact switch, however, interfered with the rolling transition by pushing the foot of the lifted leg out of the curve of the stance foot, thereby increasing energy loss at transition. Another adverse effect is that the contact switched added new equilibrium positions for the robot. With the ankles rigidly attached to the feet, the only stable standing position is vertical. Any deviation leaning to a side would result in a corrective gravitational moment that would return the robot to the vertical position. The springs of the contact sensor, however, serve to cancel out the restoring moment and leave the robot listing to one side.

In light of the negative affects associated with the foot contact switch, another method wass required to determine which foot the robot is standing on in order to generate the S signal. The solution that was eventually adopted was to utilize the gyro and tilt sensors already in place on the robot. The robot needs these sensors to act as a feedback mechanism for its reinforcement learning algorithm. Since they are already onboard, they might as well be used to determine which leg the robot should be standing on. If the tilt sensor says the robot is leaning to one side, the leg on the opposite side can swing freely. The leg on the side in which the robot is leaning, or both legs if the robot is vertical, needs to be locked.

There are some advantages and disadvantages to using the tilt sensors to determine the S signal. In terms of advantages, using the tilt sensor does not adversely affect the dynamics of the robot as the contact switch did. The sensors are on board already, so no new equipment is required. Using the tilt sensors to generate the S signal would also allow the robot to anticipate needing to have its knees locked instead of just reacting to the need. With a strategy that utilizes a contact switch, the robot does not know that it needs to lock the knee until it is already trying to stand on it. Using the tilt sensors allows the robot to lock the knee a few degrees before contact so that the knee is already locked at the time of transition. Even the angular speed can be taken into account so that the robot can lock its knee early in the case that it needs to catch itself if it gets pushed to one side more quickly than normal. There are, however, a number of disadvantages as well. The onboard computer would be needed to read the tilt sensors and generate the S signal. The robot would therefore be unable to simulate passive walking with the computer turned off. The sensors are also relatively noisy, and any filter used to smooth the signal would introduce a phase lag. Despite these disadvantages, the advantages of the tilt sensor solution warrant that this method be implemented.

Section 3.4 Controlling the Knee Servo

Now that the clutch mechanism will engage and disengage as required, the servo that drives the knee needs to be programmed to behave properly. For now the only thing the servo needs to do is make sure that the leg is straight when the robot stands on it. The bending and swinging of the leg is to occur while the clutch is disengaged. It is likely however that in the future the ability for the robot to actively bend its leg will be added.

The angle of the leg is measured by 10 kilo-ohm potentiometer. When the knee engages, the servo drives the knee until the potentiometer reads that the leg is straight. Due to the dynamics of the robot the leg should already be straight, or at least close to it, when the knee engages, so the servo should not have to drive the knee far. The servo then holds the leg in place until it is time for the knee to disengage. A slight problem can arise due to hysteresis in the gears in that the leg may be able to wobble slightly even if the servo is held rigid. In order to prevent this, a possible solution is to have the servo try to drive the knee a little past straight such that it is pinned up against the mechanical stop of the leg. Such a solution solves the hysteresis problem, but also causes the servo to constantly draw power and can cause it to get very hot if used for a prolonged period of time. Another possible solution is to change the foot design of the robot such that the ground reaction force serves to keep the knee straight. This idea is explored in further detail in Chapter 4.

Another issue with the servo is that the servo itself only has a 180 degree operating range. After the gear reduction this translates to a full 90 degree range of motion for the knee, but only if the knee and the servo are properly aligned. If when the knee engages the servo is near one of its operating limits, it may not be able to provide a full range of motion for the knee. Care must therefore be taken in order to ensure the robot can maintain a full range of motion.

Given that currently the robot only needs to straighten its leg, an easy solution is to just servo back to the other end of its operating range whenever the knee is disengaged so that it will have plenty of room to straighten the leg once it is engaged. Also, since the leg will ideally already be at least close to straight when the knee engages, the servo should not need to use much of its operating range in order to straighten the leg. As it stands this solution will work fine, but it will prove to be inadequate in the future should we wish that the robot be able to bend as well as straighten its leg.

The other method to ensure that the knee will be operating in the range of the servo is to make the servo follow the knee when the knee is disengaged. When the knee bends, the servo moves with it based on the potentiometer readings so that it will always re-engage is the same relative position. The downside to this solution is that if for some reason the knee bends fast enough the servo might not be able to keep up. The servo itself can travel 60 degrees in 0.15 seconds. With the gear ratio the knee must take at least 0.3 seconds to travel those 60 degrees if the servo is to hope to keep up with it. There is another delaying factor in that the signal from the potentiometer is noisy and thus run through a filter, which introduces a phase lag. A tradeoff exists between the noise of the potentiometer and the phase lag of the filter. The less that the signal is filtered the faster the servo can respond, but with little filtration the noise causes the servo to constantly twitch even when the leg is held still. More filtration calms the signal and the servo's behavior but increases the likelihood that the servo will be unable to keep up with the knee. Of course the servo lagging slightly behind the knee is only a problem if the knee engages in the middle of a quick movement, which under normal operating conditions should not occur. Even if the knee does engage in such a manner, it is still more likely than not that the servo will have plenty of operating room to manipulate the knee since ideally only small movements will be required anyway.

Section 3.5 Putting It All Together

With the knees fully designed and built and all the details of implementation determined, all that remains is to build and assemble the actual robot. Beyond all the designs relating to the knee already outlined in this paper, the rest of the design follows that of the original straight-legged version. This includes the design for the feet, ankle actuation, the arms, computer casing, and the sensor placement in the upper legs. Some other small changes exist between the two versions, such as an improved power circuit in the kneed version which allows the robot to easily switch between AC and battery power, but for the most part the design remained unchanged. Figure 3-4 shows a picture of the fully assembled kneed version of the robot.

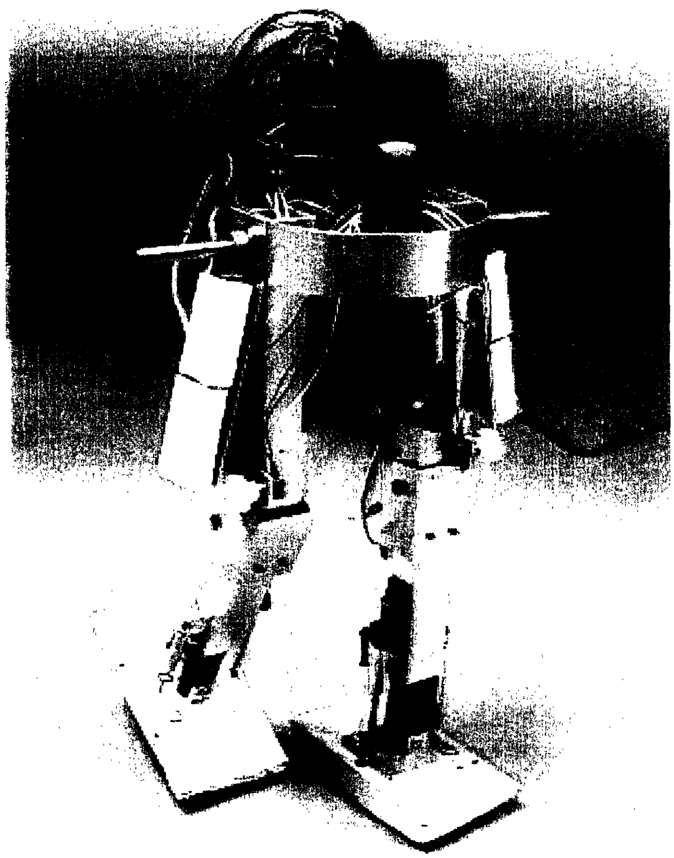

Figure 3-4: The kneed version of the Toddler

Chapter 4

Further Knee Considerations

With the knees successfully implemented on Toddler, the next step was to see which other parts of the robot should be altered in order to facilitate walking with knees. Very little of the basic design of the robot was changed from the straight-legged version to the kneed version. There are however fundamental differences between walking with knees and walking without them. For example, the kneed version does not need to rock back and forth as much in order to obtain ground clearance for the foot. The kneed version also has a definite front and back where the straight-legged version does not since the knees can only bend in one direction. It stands to reason from these and other differences that other parts of the robot might need to change in order to optimize walking with knees.

4.1 Investigating the McGeer Walker

In order to study the effect of walking with knees, we constructed a simple purely passive-dynamic kneed walker much like the one that McGeer made. The walker, which can be seen if Figure 4-1, has two sets of legs, an inner set and an outer set. The legs of each set move with each other, thereby approximating bipedalism but constraining the robot from falling over sideways. The lower portion of each leg is connected to the upper portion through a pin joint. A suction cup extends from the lower leg and engages the upper leg when the knee is straightened. When the leg first straightens, the suction cup needs to engage and lock the knee so that the walker can stand on it. The suction cup must then leak such that it disengages by the time the leg needs to bend and swing again. The leak rate of the suction cups was made adjustable be drilling and tapping a hole through the center axis of the suction cup and inserting a screw. If the screw is inserted deeply in the hole the air must pass through a number of the tight fitting threads and cannot escape as easily. A more shallow insertion allows more air to escape. Thus the leak rate of the suction cup can be adjusted by turning the screw.

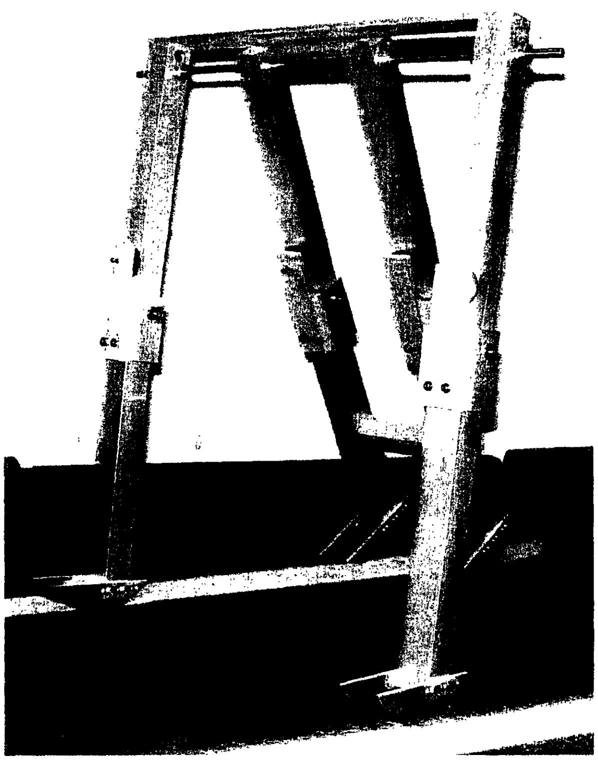

Figure 4-1: Picture of walker based on McGeer's design

A great deal was learned about kneed walking from studying this robot. As McGeer points out in his paper on passive walking with knees, if the vector of the ground reaction force passes behind the knee then the knee will want to buckle, but if it passes in front of the knee then the knee will want to stay locked [6]. It is therefore advantageous to move the foot out in front of the robot. The foot design carried over from the straight-legged version of Toddler leaves the foot centered on the leg, with half of the foot extending in front and half extending behind. The first part of the foot that makes contact with the ground when Toddler takes a step is the portion behind the knee. The knee therefore wants to buckle and energy is required for the servo to actively keep the leg straight. Should Toddler's foot be moved out in front of him, the reaction force would be used to his advantage instead of fought against. The disadvantage to the design is that there would be more energy lost to impact for each heel strike since the transition from one leg to another will be harder and more dissipative. The energy saved however from not needing to actively hold the knee locked should more than make up for it. Also, with the feet extending further out in front of him it is easier for Toddler to stub his toe. It is therefore important that his feet not be too large and that he achieves a proper amount of foot clearance.

Another insight gained by studying this walker is how the knee bends. This walker is entirely dependent upon knee flexion in order to obtain ground clearance. Unlike Toddler, it cannot lean to one side in order to help lift up the opposing leg. As the robot rolls forward on the stance leg and begins to transfer its weight to the other leg, the ground reaction force on the original stance leg causes the knee to break and leaves the leg free to swing forward as the swing leg. Working with the replica of the McGeer walker, a common problem was that the swing leg often did not bend enough in order to avoid stubbing its toe. This problem did not appear to stem from overly large feet as the legs were almost straight when the passed through the bottom of their swing arc. Instead the problem was that the leg was not bending enough.

In order to get the leg to bend more during the swing phase of the step, we took a closer look at the dynamics of the leg swing. The leg basically acts as a two-link pendulum secured at the top. A Matlab simulation of a two-link pendulum allowed for a quick and easy method of testing how deflection could be achieved. The only parameter that can be easily altered on the robot is the mass distribution, since parameters like link length are already determined by the size of the robot. The simulation gave quick insight that in order to maximize how much knee bends, more weight must be place on the upper leg than on the lower leg. When more mass is on the lower leg, the weight of the lower leg pulls the upper leg to swing with the lower and very little deflection results. This is an extremely useful insight since Toddler's lower leg has a significant amount of mass due to the foot and the two ankle actuators. In order to optimize Toddler for walking with knees, additional weight should be added to his upper portion so that he can achieve better knee flexion and foot clearance.

Chapter 5

Conclusions and Future Work

The kneed version of Toddler can walk, at least down a ramp, if not as well as we would like him to. The knees can properly engage and disengage based on the angle in which the robot is leaning. There still is however some work required on this version of the robot. Implementing the needed changes outlined in Chapter 4 will hopefully improve how the robot walks. Also, he has currently only ever walked down a ramp. More effort is still required in order to get him to work with Dr. Tedrake's learning control algorithm so that he can walk around on the flat. Overall, the progress of the kneed version of Toddler has been encouraging and serves to highly motivate the continued efforts to improve the robot.

5.1 Future Considerations

The design process for Toddler has always been an iterative one. At each iteration small improvements were made to increase the complexity and capability of the robot. Toddler started as a simple passive-dynamic walker that could only walk down a ramp. Ankle actuators were added so that he could walk on the flat. Arms were added to help balance yaw so that he could walk straighter. This thesis outlined the addition of knees, which actually corresponds to the sixth version of the robot known as Toddler. Toddler's future holds many more iterations as the robot can be made increasingly more complex. For example, all of the versions of Toddler thus far have had completely passive pin joints at the hip. It would be beneficial, however, to place another clutch mechanism and actuator at the hip so that the robot would be able to actively step over objects, climb up stairs, or walk uphill. Adding actuation to the arms instead of leaving them mechanically coupled to the legs may enable the robot to compensate better for yaw and walk straighter. Adding the ability for the robot to pivot around its stance leg, either at the hip or at the ankle, could help the robot turn and steer. No matter how complex the robot gets, there will always be room for future iterations and improvements.

5.2 Closing Remarks

Both the joint-angle control strategy and the passive-dynamic based strategy for powered walking have intrinsic advantages and disadvantages. Joint-angle control allows for extremely robust movement, but brings with it complicated control and energy inefficiency. Passive-dynamics allows for simplified control and energy efficiency, but the movement is limited by the dynamics of the robot. The design of this knee tries to bridge the gap between these two strategies, taking advantage of the passive-dynamics when the clutch is disengaged while still allowing for joint-angle control while the clutch is engaged. It is perhaps the combination of passive-dynamics and joint-angle control that will prove to be the ideal strategy for developing walking robots.

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