LEG DESIGN FOR A SMALL WALKING ROBOT

by

Michael B. Binnard

Submitted to the Department of
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ABSTRACT

The mobility of a walking robot is determined by the kinematics and mechanical capabilities of its legs. The two walking robots built at the MIT Mobile Robotics Lab, Genghis and Attila, have been quite successful, but limited by their mechanical design. The goal of this project was to explore different options for the mechanical design of robot legs; earlier projects were efforts to build an entire robot, where the leg mechanism was only a small part of the problem. I started by identifying four problems with Attila's legs. Using biological examples and other walking robots for inspirations, I built and tested several different kinematic designs. After evaluating each mechanism, I concluded that a small walking robot should have a sprawled stance like insects, with slightly different front, middle, and back legs. I built two prototypes of a leg mechanism that could be used on such a robot.

Thesis Supervisor: Professor Rodney Brooks
Title: Associate Professor of Electrical Engineering and Computer Science

For Mom and Dad.

So, is this the best $100,000 you ever spent, or what?

Acknowledgments:

I want to thank all the people who helped with this project, and made sure I knew what I was doing: Colin, Rod, Cynthia, Anita, Dave, Chris, and Jill.

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CHAPTER 1: INTRODUCTION

1.1 Why a walking robot?

The most common reason to build a walking robot is improved maneuverability. According to the US Army, half of the Earth's surface is inaccessible to wheeled or tracked vehicles **[US Army, 1967]**. Engineers who build robots with legs like to think their creations will be able to traverse that difficult terrain.

Another reason to build walking machines is to learn something about locomotion. Comparative biologists study locomotion because it is an easily quantifiable behavior that most organisms share **[Full, unpublished]**. Most animals move, and velocities and distances are easy to measure. It makes more sense to compare energetics and strategies of locomotion than mating rituals, or feeding patterns, which are hard to quantify.

Building legged robots is a good way to test theories about walking that are observed in animals. For example, if you think you understand how a kangaroo uses elastic properties of its muscles and tendons, you can build a machine based on the same principles. If the machine works, then your kangaroo model may be sufficient.

A third reason to build a walking robot is to see what the issues and problems of locomotion really are. For example, when you notice that your walking machine doesn't work because the feet won't track a straight line, you know that animals must have found solutions to this problem, either in the mechanics of their bodies, or with coordination and control.

1.2 Legs of walking robots

Traditionally, walking robots have been large machines. Two of the more famous robots, the Ohio State Adaptive Suspension Vehicle and the General Electric Quadruped, are the size of small trucks **[Liston and Mosher, 1968]** **[Waldron, et al, 1984]**. They were designed to carry one passenger and a payload. These vehicles are self contained, but not autonomous. The GE Quadruped is manually controlled. The ASV has computer controlled motion, but a human driver provides direction and velocity control.

Smaller walking robots have been built by Hirose and Raibert **[Hirose, 1984] [Raibert, 1986]**. They both concentrated on control issues. Their robots operate in carefully designed laboratory environments, perform little or no sensing of the environment, and have external power supplies and control computers.

All of these robots have very different leg designs. The ASV and Hirose's quadrupeds were designed for maximum energy efficiency, and both use pantograph mechanisms to keep the leg gravitationally decoupled. These designs were selected after evaluating mathematical models and computer simulations of linkages **[Song et al, 1981] [Song et al, 1983] [Hirose, 1984]**.

The MIT Mobile Robotics Lab has a different approach to walking robots. Their robots, Genghis and Attila, are small (about 14 inches long) and are fully autonomous. In the laboratory, both robots use external power, but can be battery powered **[Angle, 1989] [Angle, 1991]**. Genghis and Attila are designed to operate in unconstrained environments; their behaviors are controlled by sensor data. When the control software is completed, Attila should be able to explore outdoors. Genghis and Attila are successful robots, but both are limited by the mechanical design of their legs.

1.3 What I did

Previous efforts to build a walking robot have tackled all of the issues and problems with building a complete system. For this thesis, I limited myself to one part of the problem: the mechanical design of legs. My goal was to evaluate different leg designs that could be used on a small autonomous walker like Genghis or Attila. I started by looking at Attila to see what was good and bad about his legs.

Mechanically, Attila's legs have two big innovations: a global degree of freedom that keeps them vertical when the robot is on a slope, and separate workspaces for walking and climbing.

I identified four problems with Attila's legs that I wanted to address. The first problem is that the advance motor on Attila's legs move the feet in arcs, and not straight lines. Second, the knee actuator on Attila is too slow compared to the other degrees of freedom. Third, the walking workspace for the feet is too small, and finally, all six legs are identical, even though front, middle, and back legs have different requirements.

Once I'd decided what the goals for the new legs were, I began looking at other walking machines and animals for inspirations and ideas. Examining biological systems was extremely helpful, and gave me many ideas to try. I built small models of different mechanisms and kinematic designs. Because my time was limited, most of these models were not complete working prototypes.

After trying out several different kinematic designs, I decided that a small walking robot should have a sprawled stance, similar to a cockroach. The front, middle, and back legs of a cockroach have similar degrees of freedom, but different link lengths **[Full, unpublished]** . I designed a leg mechanism for such a robot, and built two prototypes. Legs for an actual robot could use the mechanism from the second prototype.

1.4 Approach

Two basic ideas determined the methodology of this research. First, I decided that the best way to identify good leg designs was to explore as many weird and different options as possible. Second, I leaned towards an empirical approach because it's easier to see a design's real advantages and disadvantages when you have actually built it.

For Attila, because of time constraints, a kinematic design was selected early on, and only changed slightly in different prototype stages. Once the robot neared completion, the disadvantages of the leg design became apparent, but it was too late to make changes.

For this thesis, I wanted to explore the pros and cons of many different leg designs. A natural tendency in design is to fall in love with your first idea, and convince yourself that it is the best. But to get a good understanding of what works and what doesn't, it is necessary to look at many options.

I used an empirical approach to these experiments because you cannot hide issues when you really build something. Working with a model on paper, it is difficult to know which details can be ignored, and which will affect the actual performance. Questions like "Will this pinch clamp hold the shaft?" "Are axial forces on this gear important?" and "Will this motor be able to lift the leg in any configuration?" are much easier to answer with a real prototype.

1.5 Terminology

Four notes on terminology in this thesis:

1. Genghis and Attila are considered considered male entities, because that is how we talk about them in the laboratory.
2. I named the kinematic models and prototype legs I built after famous people with great legs because that makes it easier to refer to different designs.
3. Leg links are referred to with the words used by biologists: The femur is the upper link (thigh), and the tibia is the lower leg. Joints are hips, knees, and ankles.
4. During walking, each leg has two distinct phases: When the foot is on the ground, the leg is in the stance phase; when the foot is in the air, the leg is in the swing, or recovery, phase.

CHAPTER 2:
WALKING ROBOTS AT THE MIT MOBILE ROBOTICS LAB

There have been two walking robots constructed at the MIT Mobile Robotics (Mobot) Lab. The first, Genghis, was made as simple as possible **[Angle, 1989]** . The purpose of building Genghis was to prove that Brooks' subsumption language was a viable way to program mobile robots.

Genghis was remarkably successful, but was limited by his mechanical and electrical systems. His limitations inspired Attila, whose goal was to walk and climb on difficult terrain. The kinematics and sensors were designed for rough terrain locomotion.

Now, three years after Attila was started, the mechanical and electrical systems are nearly complete. He can walk on flat floors, and rough terrain software is being written. Attila's sensors, electronics, and mechanical design all have some disadvantages and drawbacks, but that is inevitable in a project of this complexity.

2.1 Genghis

Genghis is a simple robot. He was built because Brooks wanted to demonstrate that a simple control network can perform complicated tasks.

Despite his simple design, and small amount of software, Genghis can walk, turn, and climb over stacks of books. For the state of the art in walking robots, Genghis was one of the best, and by far the smallest, simplest, and least expensive.

Equally remarkable, Genghis proved to be a durable and robust robot. Genghis was built four years ago, and has worked reliably since then. Most other robots at the Mobot Lab worked for a while, but once their creator moved on to other projects, they quickly fell into disrepair.

Genghis has six legs, because that is the minimum for efficient statically stable walking. Each leg has two degrees of freedom, lift and advance, shown in Figure 2.1. Ideally, a walking robot should have three DOFs per leg in order to allow arbitrary foot placement, but to keep things simple, Genghis has only two.

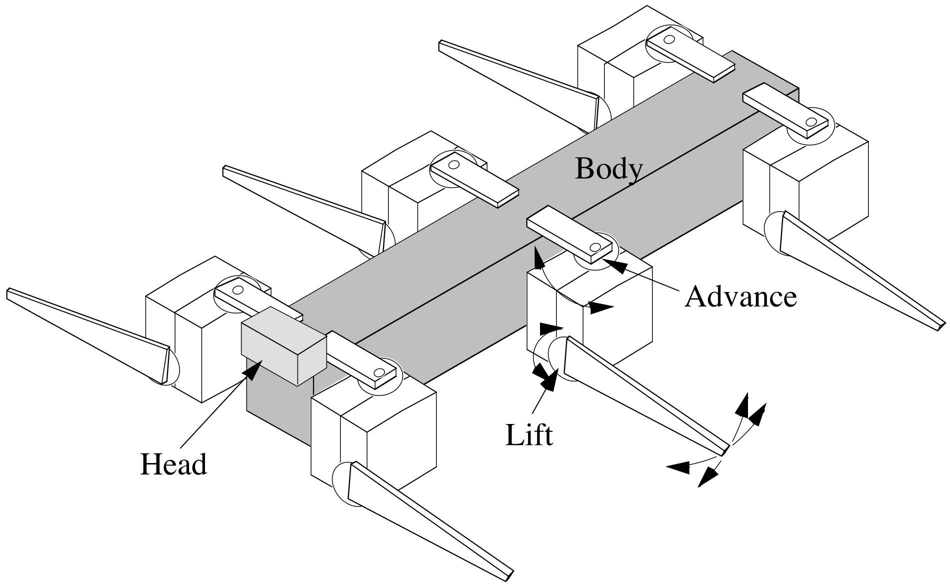


Figure 2.1: Genghis

Genghis' legs are actuated by Futaba servos, which are commonly used in radio controlled cars and planes. The advance servos are smaller, since they do not work against gravity. This assumption is only true when the robot is walking on a horizontal surface, however. When Genghis climbs a slope, the advance motors do work against gravity. (See Figure 2.2) Genghis' slope climbing abilities are limited by the advance servos. At slopes greater than about 30 degrees, the nylon gears in the servos break.

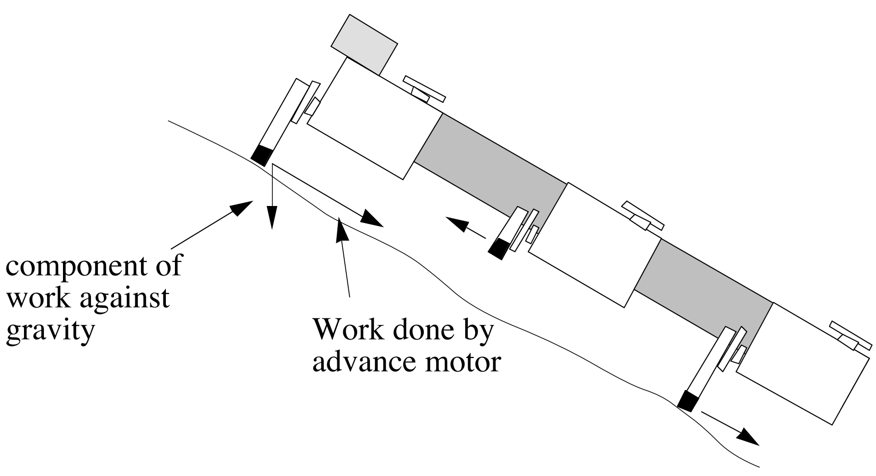


Figure 2.2: Genghis climbing a slope

2.2 Attila

Attila is an extremely complicated robot **[Angle, 1991]** . Most of the effort in the Attila project went into the sensors and integration of the whole system. Attila has about 150 sensors, and ten computers. Getting all that to work was a formidable task. Because the purpose of building Attila was to integrate a complete robot, each part of the robot could not be fully optimized. For example, a leg design had to be selected early on, or the project could not be completed in a reasonable time.

Mechanically, the biggest new idea on Attila is a global fourth DOF for the legs (described in Chapter 4) which decouples gravity from the leg loading. This DOF frees Attila from the problem which limited Genghis slope climbing.

Attila's legs were designed with the philosophy that walking and climbing are very different activities. (See Chapter 3) Attila's legs have different workspaces for walking and climbing. This distinction is important, and designing a dual-purpose leg is a good idea.

2.3 Problems with Attila that I addressed

When I looked at Attila's legs, and what they are capable of doing, I identified four major problems. The first issue is the straight line problem. In order for the robot to walk forward in a straight line, the feet must track a straight line backwards relative to the robot's body. Because the advance actuator on Attila is a gearmotor, Attila's feet move in arcs when it walks. (See Figure 2.3) The lateral components of these arcs require the feet to slip on the ground, and apply lateral forces on the robot's body. When Attila takes big steps, the lateral forces are large, and the resulting torques make the body yaw.

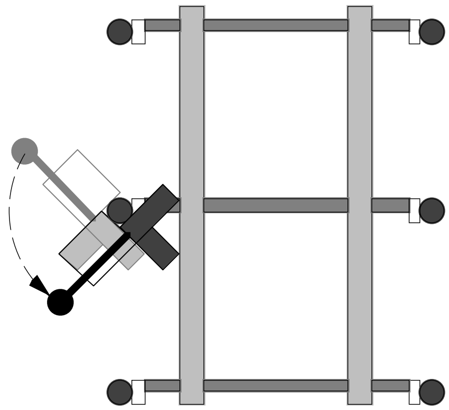


Figure 2.3: Attila's advance DOF

The second problem with Attila's legs are the "knees." In order to produce large forces for climbing, the knees on Attila are driven by a lead screw. The large reduction ratio of the screw results in a slow motion, but a large force. For walking, however, the speed of the knees limits the maximum speed of the robot.

The third disadvantage of Attila's legs is their limited walking workspace. Attila's legs were designed with two separate workspaces, one for walking and one for climbing. The walking workspace is determined by the advance and lift DOFs because the knee only makes small motions for walking.

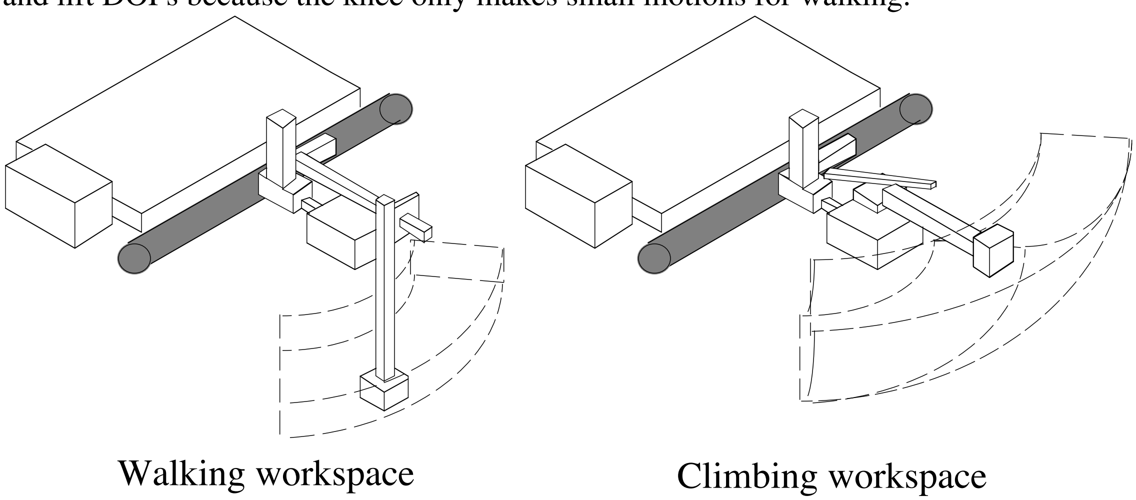


Figure 2.4: The two workspaces of Attila's legs

The lift DOF can only move approximately 30° in each direction. This makes a vertical travel of around 2 inches at the foot. The advance motion is constrained by the straight line problem; keeping the yaw torques small requires taking smaller steps. These constraints on the range of motion result in a small walking workspace for the foot.

The idea that walking and climbing are different, and that a good leg design can do both is a good one. One way to measure such a leg's performance is the size of an obstacle that requires climbing. Ideally, a walking robot should be able to adjust its gait to avoid small obstacles without breaking stride. Climbing requires stopping after each step while the robot looks for new footholds. For Attila, any obstacle bigger than 1 inch requires climbing instead of a simple walking adjustment. A robot with a larger walking workspace would be able to step over those obstacles, instead of climbing over them.

The final problem with Attila’s legs is that the front, middle, and back legs are all identical. At first, this may seem a logical decision, because it simplifies the robot. But the front, middle, and back legs play different roles in locomotion. For example, the back legs are never required to pull the robot up a step. In insects, the front legs do not propel the robot forward. A walking robot should have front, middle, and back legs that are designed with those differences in mind.

CHAPTER 3:
DESIGN CONSTRAINTS

3.1 Attila's constraints

For the design of Attila's legs, The important design constraints were: minimum size, an 8 inch vertical step height, and low moment of inertia.

For a robot of Attila's size, being able to climb up an 8 inch vertical step is a good goal. However, Angle did not pay as much attention to climbing down a step. Even though Attila can climb up a step with ease, getting down the other side is a difficult problem. The reason for this difference is because Attila's legs can reach high above their normal walking configuration, but can't reach very far down.

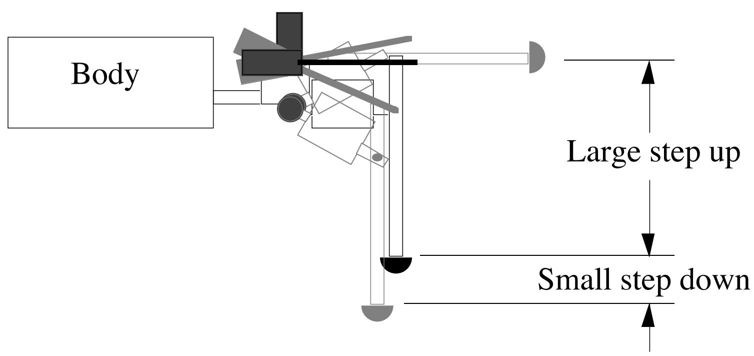


FIGURE 3.1: Attila's vertical step range

Another important constraint on Attila's leg design was a low moment of inertia. Since the kinetic energy of the legs is wasted at the end of the swing and stance phases, a low moment of inertia improves the robot's energy efficiency. A leg with a large moment of inertia would also require stronger motors to move it. Because of the moment of inertia constraint, Attila's legs were built with all three motors near the hip. One drawback of this decision is that a large volume must be left clear around the hips so the motors won't collide with the body.

Energy efficiency is often a major constraint in the design of walking robots [**Waldron et al, 1984] [Hirose, 1984] [Full,1989]**. But robots like Attila that operate in laboratory environments are usually powered by external power supplies. When a robot is going to be externally powered, maximum energy efficiency shouldn't be a primary constraint, because it restricts design options too much.

Another reason why the legs' moment of inertia shouldn't be a primary concern is that the size of the motors is determined by the mass of the robot. Legs that are strong enough to support the robot's body will easily be strong enough to move the leg around.

3.2 My design constraints

For this investigation, the important design constraints were: linear steps, maximum workspace, minimum mechanism, and low motor weight.

The complexity of the mechanism was an important issue with several designs I considered. A few of the legs required complicated, bulky mechanisms to produce the desired motions. These were deemed unacceptable because they are heavy, and require more moving parts and size.

3.3 Size

There are several advantages to building a small walking robot. Smaller robots have better strength to weight ratios, are less expensive, and you can test them on a desktop **[Angle, 1991]** . Small walking robots are also easier to mass produce, and are better suited to planetary exploration **[Angle and Brooks, 1990]** .

There are some disadvantages to making a robot too small, however. The actuators, electronics and sensors have minimum sizes. It can be very difficult, or impossible, to fit all of the desired actuators, sensors, and electronics on a small robot.

Attila is close to being the minimum possible size for a robot of his complexity. For every subsystem of the robot, "getting things to fit" was one of the major issues. A slightly larger robot would allow more choices for actuators and kinematics, and would have more space available for extra features, like a payload compartment, or grippers on the legs.

3.4 Walking and climbing

For the design of Attila's legs, Angle decided that walking and climbing are different activities, and a good leg should be able to do both. Walking can be described as moving at a constant speed over relatively even terrain. Climbing is when the robot has to stop and search for footholds.

When a robot is walking in an unstructured environment, there are two types of obstacles it will encounter. The first are small enough that it can step over or around them without breaking stride. Larger obstacles require the robot to stop and search for footholds to climb over it. The difficulty of a terrain can be quantified by how much climbing is required.

The larger the walking workspace for a robot is, the more terrain is "easy" for it. Attila has a small walking workspace, so any terrain with variations bigger than about 1 inch requires climbing, and is "difficult". A good way to compare leg designs is what size obstacle requires climbing.

3.5 The linear step problem

For a robot to walk in a straight line, the feet should move in straight lines relative to the robot's body. Otherwise, the feet must slip on the ground. There are two approaches to generating linear steps. The first is to use a sensor to determine the non-linearity of the foot path, and use software to correct it. The second approach is to build a mechanism that generates a straight foot path mechanically.

When Attila's legs were designed, the straight-line problem was going to be solved with the first technique. Strain gages were installed to measure the lateral forces on the legs, and the knee degree of freedom would then be servoed to keep this force zero. When the robot was built, though, it became apparent that this strategy was unfeasible because the strain gages do not provide accurate enough force measurements, and the knee is too slow.

The second option is to use a mechanism that produces linear motions. Hirose's quadrupeds and the Adaptive Suspension Vehicle use pantographs with linear actuators to produce linear steps **[Hirose, 1984] [Waldron et al, 1984]** . On an Attila sized robot, however, commercially available linear actuators are too big for this technique.

I investigated several designs that produced linear or nearly linear steps without linear actuators. The Mikhail Baryshnakov (See Chapter 9) and Carl

Lewis (See Chapter 10) legs have complicated and bulky mechanisms, but the Roger Craig leg (See Chapter 11) is relatively simple.

The final two prototypes I built, the Ashley Richardson legs (See Chapter 12), do not produce linear steps. A third revision of that design could solve the linear step problem by using the linkage from the Roger Craig leg, custom built linear actuators, or more control software.

All of the degrees of freedom on the Ashley Richardson legs operate at the same speed, so the only requirement for a software solution is a reliable sensor to measure lateral forces on the body. This sensor would probably be at the hip. Data from this sensor could then be used in the servo loop to make linear steps.

CHAPTER 4:
BIOLOGY

4.1 Walking Models

Animals use two different techniques to improve energy efficiency **[Cavagna, et al 1977] [Blickhan & Full 1987]**. The first is the inverted pendulum model shown in Figure 4.1, where kinetic and gravitational potential energies are exchanged during each step. The pendulum effects are used independently for each leg, and for the body as a whole. McGeer's passive dynamic walker uses the inverted pendulum model to conserve energy **[McGeer, 1990]**.

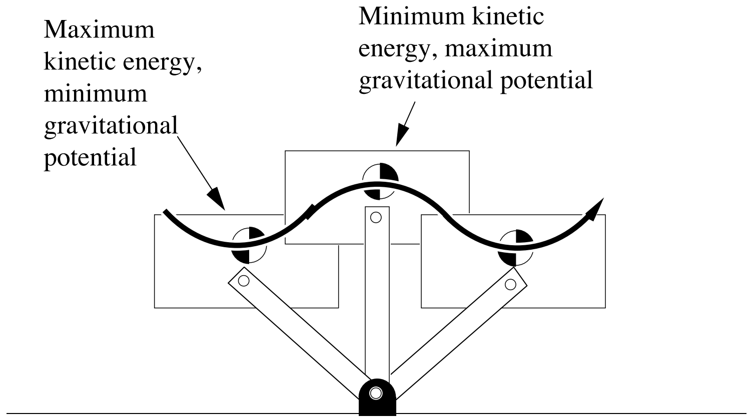


Figure 4.1: Inverted pendulum walking model

The second technique exchanges kinetic energy with elastic potential energy during each step. This technique, which can be modelled as a spring-mass system (See Figure 4.2), is used in running gaits. The elastic energy is typically stored in tendons and muscles **[Cavagna, et al 1977] [Blickhan & Full 1987]**. Raibert's hopping machines use this model for their legs **[Raibert, 1986]**.

In animals that use both models, the body and legs are oscillating systems, with a preferred frequency. As the animal changes speed, the stride length changes, while the frequency remains the same. Only when the stride length is maximized does the frequency increase **[Mochon and McMahon, 1980]**.

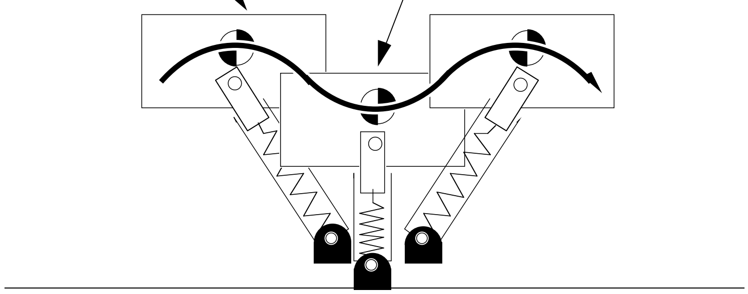


Figure 4.2: The spring-mass walking model

Many walking robots, including the Adaptive Suspension Vehicle and Hirose's quadruped, use a different model of locomotion **[Waldron, et al 1984] [Hirose 1984]** . (See Figure 4.3) The idea behind this model is to move the body horizontally at a constant speed, so the kinetic energy is constant.

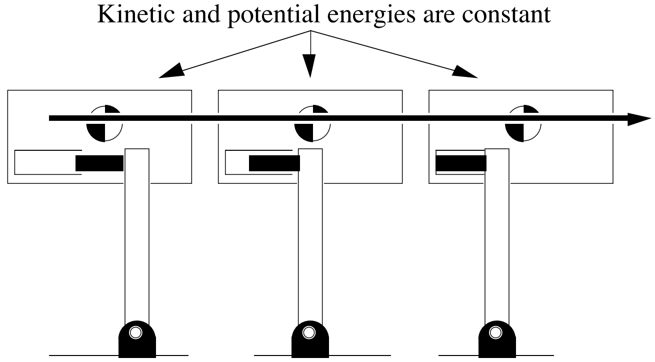


Figure 4.3: A walking model used in some walking robots

4.2 Front, middle, and back leg differences

On most all walking animals, the legs are not all identical, because the legs have different uses. For example, on a cockroach, only the back and middle legs propel the body forward. The front legs actually work to decelerate the body in each step **[Full et al, 1991]** . The legs also have links that are different lengths **[Full, unpublished]**. (See Figure 4.4)

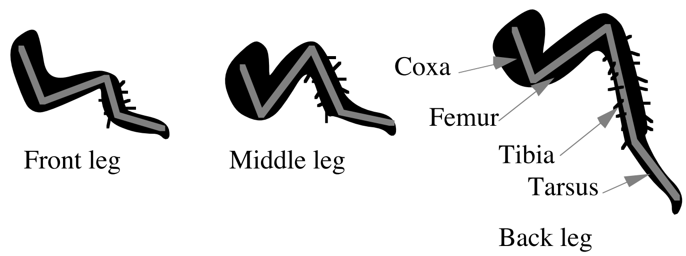


Figure 4.4: Leg lengths of a cockroach, blaberus discoidalis

The coxa-body joints on cockroach middle and back legs are hinge joints, but the front leg has at least two degrees of freedom in the coxa-body joint **[Full, unpublished]** . Presumably, the front legs require extra mobility because they have to pull the insect up a step.

CHAPTER 5:
DEGREES OF FREEDOM

Mechanically, the most important aspect of a leg is the kinematics, or degrees of freedom (DOFs) it has. One of the goals of legged machines is to be able to place the foot anywhere within its workspace. Legged walkers are able to traverse difficult terrain because they can select an appropriate foothold, and put their foot on it. Without arbitrary foot placement, a walking machine is limited in the terrain it can handle.

We live in a three dimensional world, so three degrees of freedom are required for arbitrary foot placement. Most animals have many more than three DOFs per leg, but for the sake of simplicity, most walking machines don’t bother with more than three.

5.1 Attila’s legs

Like most other walking machines, Attila’s legs have three independent DOFs, shown in Figure 5.1. They are advance, lift, and the knee. One advantage of this configuration is that longitudinal motion (from the advance DOF) and lifting are decoupled. The knee DOF is primarily used for climbing, and only makes small motions for walking.

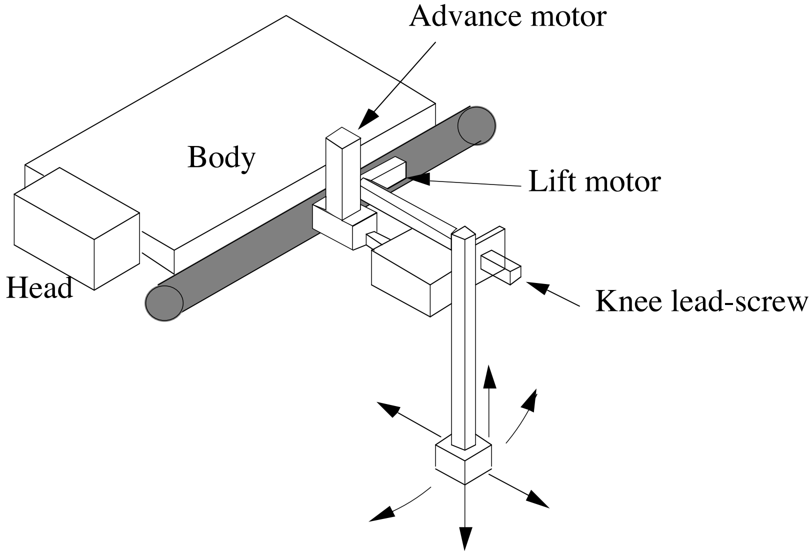


Figure 5.1: Attila's Degrees of Freedom

The main disadvantages of Attila's DOFs are the limited walking workspace, and the straight line problem. The small workspace lowers the difference between easy and difficult terrain for Attila. Because Attila's legs produce longitudinal motion with rotation of the advance DOF, walking creates lateral forces and yaw torques on the body. These forces and torques increase with increasing step size.

A significant feature of Attila is that all six legs are joined by a global fourth DOF. This DOF rotates all six legs about lateral axes in order to keep them aligned with gravity. (See Figure 5.2) This provides two advantages when the robot is climbing on a slope.

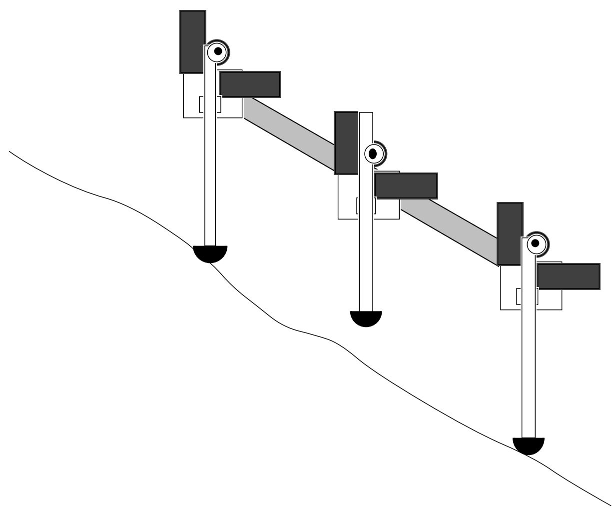


Figure 5.2: Attila's legs stay vertical when he climbs a slope

First, the legs always are always in the same orientation relative to gravity. This means the advance motor never has to do any work against gravity. Genghis' slope climbing abilities were limited by the advance motor's ability to lift the robot against gravity when climbing a hill. In actual practice, however, the global DOF is not always capable of keeping the legs vertical because it's not powerful enough. When this happens, the advance motors do have to work against gravity, but they are not strong enough to move the robot.

The second advantage of the fourth DOF is that it moves the robot's center of gravity closer to the slope, which improves stability. If the legs were always perpendicular to the body, the robot would tip over at moderate inclines. (See Figure 5.3)

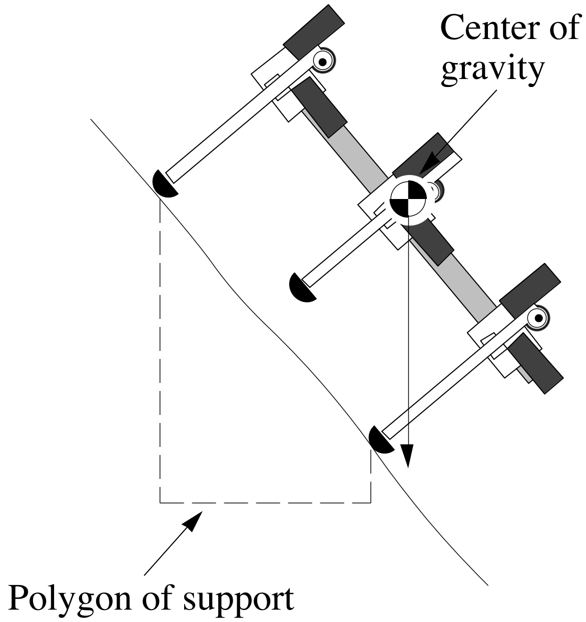


Figure 5.3: With the legs perpendicular to the body, the robot will fall off the slope

5.2 DOFs in animals

Mammals typically have legs that operate in a vertical plane, parallel to the longitudinal axis of the body. The three DOFs a robot needs for a mammalian stance are Shown in Figure 5.4. The swing DOF is what propels the robot forward, and allows the legs to act like pendulums. In mammals, the swing phase is almost totally passive; the muscles do not expend any energy **[Mochon and McMahon, 1980] [Basmajian, 1976]**. McGeer built a bipedal machine that demonstrates this idea **[McGeer, 1990]** .

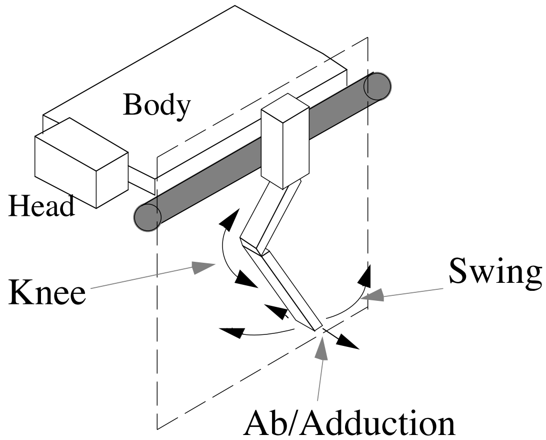


Figure 5.4: DOFs for mammalian stance

The other two DOFs, the knee and ab/adduction allow arbitrary foot placement. The knee DOF is also used to change the leg length for uneven terrain and to keep the foot from hitting the ground during the swing phase.

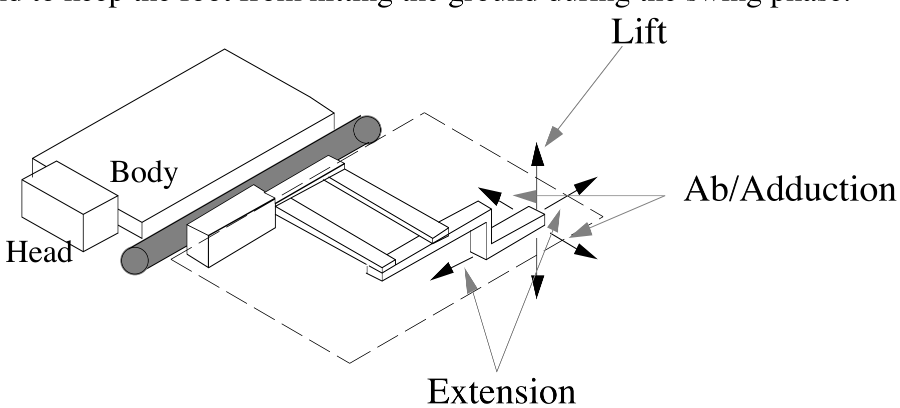


Figure 5.5: DOFs for a sprawled stance

The third stance type described in Chapter 6 is a sprawled stance, like that used by most insects and small reptiles. To build a robot with a sprawled stance, the three DOFs you would want are: extension, lift, and ab/adduction. (See Figure 5.5) The lift DOF must be strong enough to support the weight of the body, and should have enough range of motion to easily step over obstacles. The extension DOF must be strong enough to push the robot up a slope. The ab/adduction DOF only has to work against gravity when the robot is tilted to one side.

5.3 Parallel 4-bar linkage

The parallel 4-bar linkage shown in Figure 5.6 has several characteristics that make it a good leg. It has a large range of motion, is lightweight, and can be actuated in several ways. It can be used as a pantograph, as in Hirose's robots **[Hirose, 1984]** or the Mikhail Baryshnakov leg (See Chapter 9) to produce linear motions.

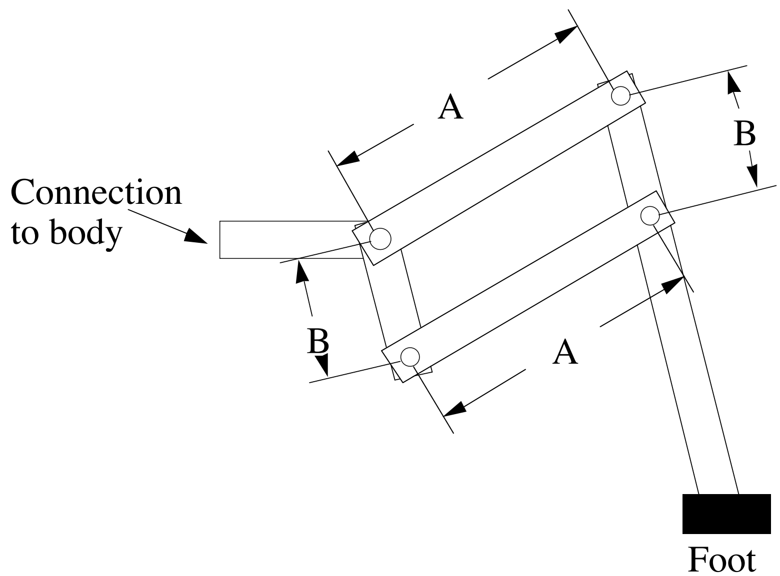


Figure 5.6: The parallel 4-bar linkage

This linkage can also be actuated by two rotary actuators, as shown in Figure 5.7. The advantage of this method is that two motors can produce three useful DOFs. Motor 1 changes angle α to produce the swing DOF. Motor 2 changes β to make the extension/contraction DOF. The third DOF, ab/adduction is achieved by using both motors simultaneously. The Ashley Richardson legs (See Chapter 12) use the 4-bar linkage in this way.

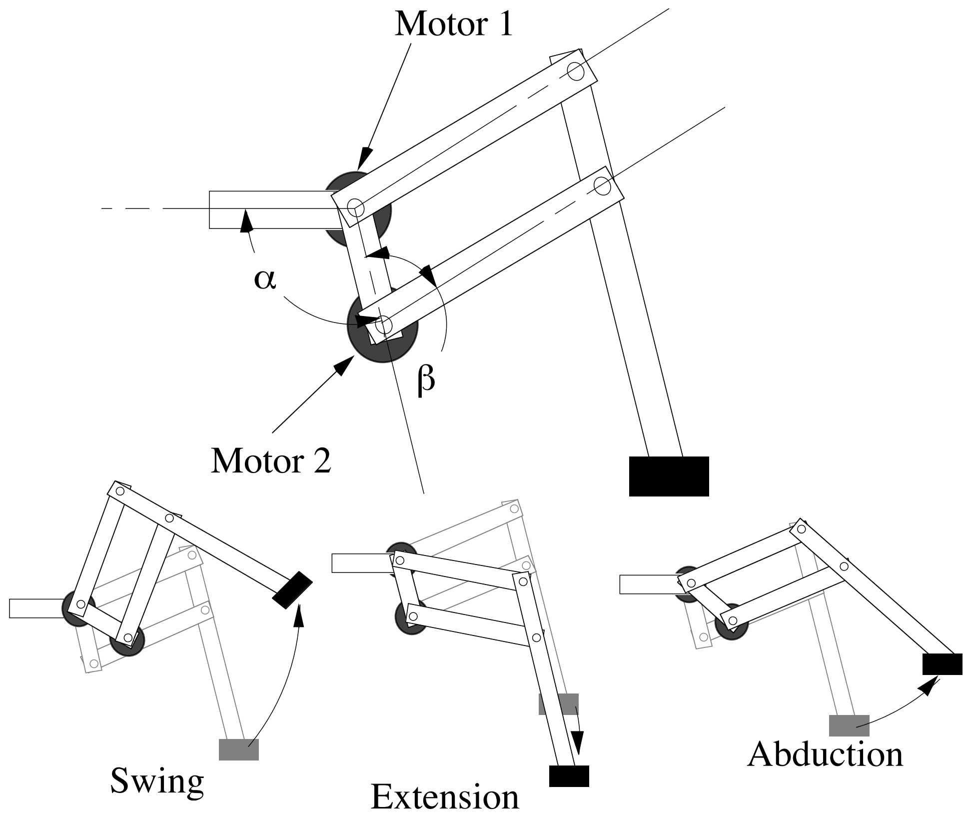


Figure 5.7: Actuating the parallel 4-bar linkage with 2 motors

CHAPTER 6:
ACTUATORS

6.1 DC Gearmotors

Genghis and Attila both use DC gearmotors to actuate their legs. Gearmotors make good actuators because they are clean, all the moving parts are sealed from the environment, and they are simple to control. Motors with sufficient power ratings are easy to find, and are small enough to fit on the robots.

The disadvantage of gearmotors, however, is that their output torque is limited by the gears. On a walking robot like Attila, the legs move at a relatively slow speed, but require a large torque. Gearmotors are better suited to high speed, low torque applications. Applications that require large torques at modest power levels are better suited to linear actuators than DC motors. There are several types of linear actuators that might be useful on small walking robots.

6.2 Gearmotors on Attila and Genghis

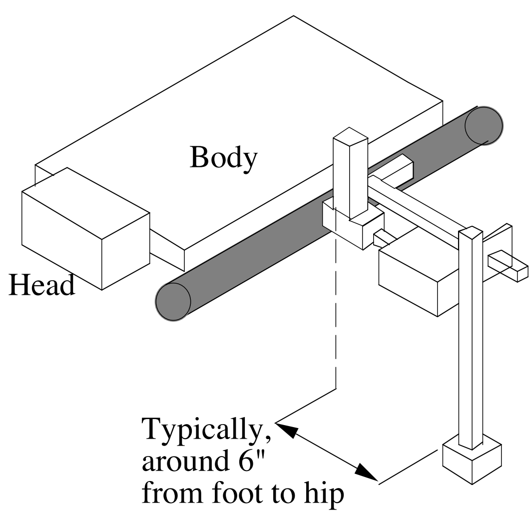


Figure 6.1: Moment arm for supporting the robot's weight

For an Attila sized robot the motors support the weight of the robot on moment arms that are around 6". (See Figure 6.1) The robot will weigh around 10 lbs when finished, and each leg should be able to support half that weight. A reasonable speed for the legs is for them to complete a motion (typically around 90˚)) in one second when fully loaded.

$$\text{Torque} = (\text{distance})\ (\text{force})$$

$$\text{Torque} = (\ 6''\ )\ (\ 1/2\ )\ (\ 10\ \text{lbs})$$

$$= 480\ \text{oz in}$$

$$\text{Power} = (\text{torque})\ (\text{angular velocity})$$

$$= (3\ \text{Nm}) \frac{\left(\frac{\pi}{2}\ \text{radians}\right)}{(1\ \text{second})}$$

$$= 4.7\ \text{watts}$$

For a 2 second motion, Power = 2.4 watts

Attila's legs use MicroMo 1319 motors with 15/8 gearboxes. These motors have a maximum power rating of 1.2 watts, which is less than optimal. A more powerful motor would be better, but since DC motors can be overdriven intermittently, the power capability of this motor is adequate.

The maximum torque for the 15/8 gearbox, however, is only 75 oz in, which is woefully inadequate. A gearbox capable of producing the 480 oz in of torque weighs around 7 oz, almost 10 times as much as the 15/8 gearbox. This is not an acceptable solution, because it would nearly double the robot's weight. Genghis' servo motors suffer from the same problem. The motors are powerful enough, but when he climbs a steep slope, the nylon gears in the servos break.

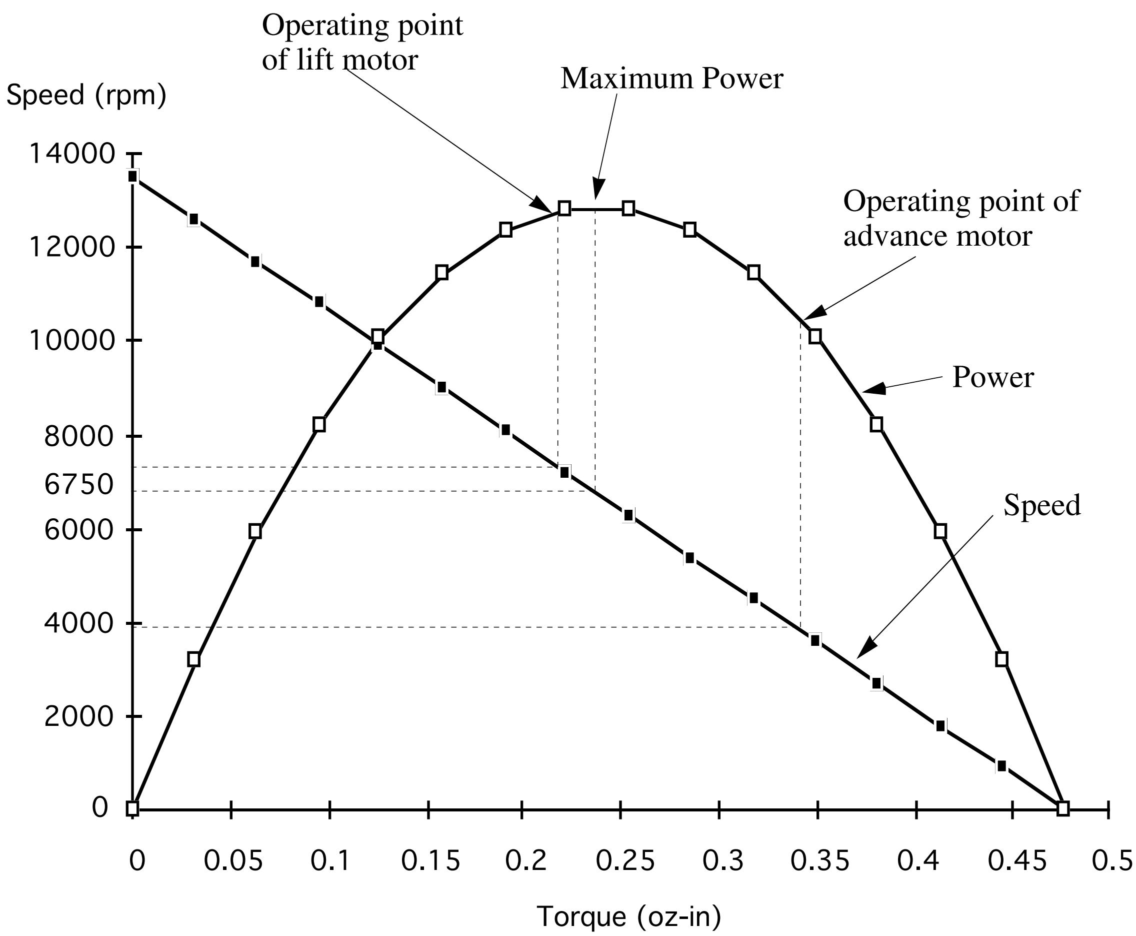


Figure 6.2: MicroMo 1319 Performance curves

Another consideration is the operating point of the motor. The 1319 motor has a no load speed of 13,500 rpm. The maximum power output will be at half that, or 6750 rpm. Assuming the same 90 degrees in one second motion as before, and a 485:1 gearbox (used on Attila's lift motors), the motor runs at a speed of:

$$\text{Speed} = \frac{\left(\frac{1}{4}\ \text{revolution}\right)}{1\ \text{second}}\ (\,485\,)\ (\,60\ \text{sec/min}\,)$$

$$= 7275\ \text{rpm}$$

This is close to the maximum output speed of 6750 rpm. For a 262:1 gearbox (used on Attila's advance motors), the motor speed would be 3930 rpm. So, the advance motors on Attila will only produce approximately 75% of the 1.2 watts they are capable of producing.

6.3 Gearmotors for my prototypes

For my leg prototypes, I used the same DC motors that Attila uses, because they were readily available, and easy to control. Since the prototype legs only had to support their own weight, the torque limitations weren't a major problem. Using the 1319 motors was the quickest, and easiest way to test the kinematics of my designs.

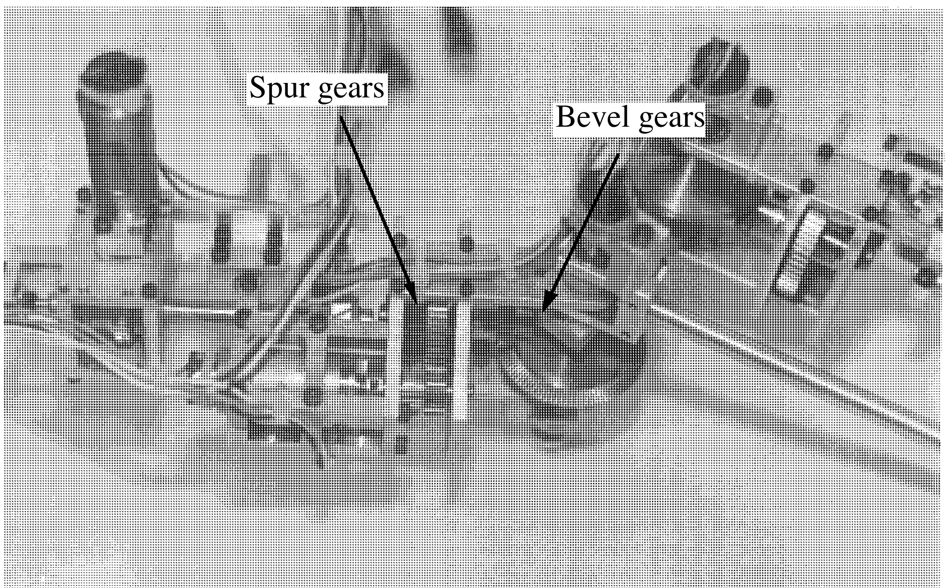


Figure 6.3: Photograph of 9:1 external gearing for my final prototype

On the final prototype, the MicroMo motors were connected to an external gearbox providing 9:1 reduction, in two stages. The first stage contains spur gears, and the second has bevel gears to keep the motor in line with the leg links. (See Figure 6.3) The stall torque of the 1319 motor is .477 oz in. The motors I used had a 141:1 reduction gearbox. The stall torque of the integral gearbox is

$$(.477 \text{ oz in})\ (141) = 67 \text{ oz in},$$
(assuming 100% efficiency)

With the 9:1 external gearing, the actual output torque is

$$(67 \text{ oz in})\ (9) = 605 \text{ oz in.}$$

Assuming 90% efficiency in the external gears, that gives

$$(605 \text{ oz in})\ (90\%) = 544 \text{ oz in.}$$

This is a reasonable torque for a real leg.

6.4 Lead screws

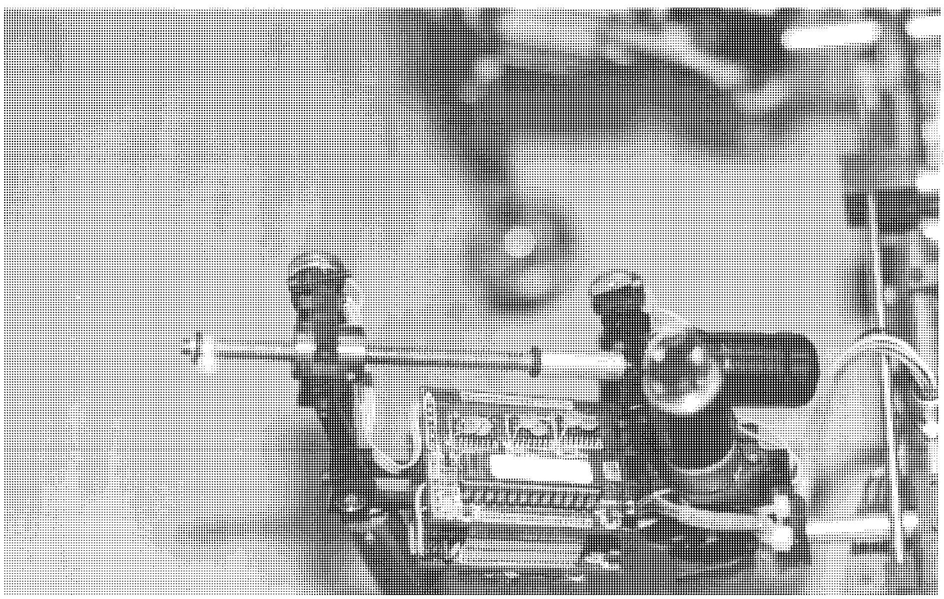
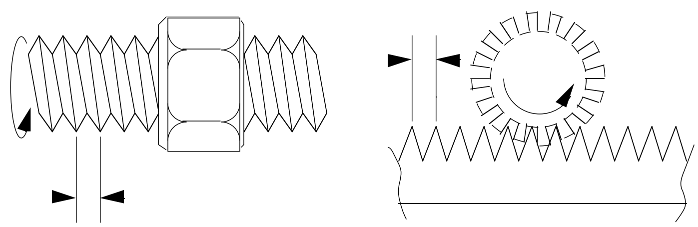


Figure 6.4: Photograph of the lead screw in Attila's knee

Lead screws can be driven by DC motors, and provide slow motions with large forces. Attila’s knee DOF is actuated by a lead screw. (See Figure 6.4) The recirculating ball nut on Attila’s knees has a high efficiency, but is somewhat bulky and expensive. This actuator has the additional advantage that it is nearly non-backdrivable. A robot with non-backdrivable actuators would require no energy to maintain a static posture. Attila’s lift motors are backdrivable, so the robot must use energy to stand.

Attila's knees had several problems, however. Compared to the other DOFs, the knee is extremely slow. This makes the control software more complicated, and limits the speed of the robot. This problem could easily be solved by using a different motor and gearbox to drive the lead screw. Attila's knees use a 1319 motor with a 76:1 gearbox. A gearbox with less reduction would make the knees faster, but would also reduce the maximum force.

A minor disadvantage of the lead screw on Attila is that the screw protrudes from the knee, and could easily get caught or broken on obstacles.



Nut moves 1 tooth for each complete revolution of the lead screw.

Rack moves 1 tooth when pinion rotates 1 tooth (1/16 revolution for a 16 tooth pinion)

Figure 6.5: Reduction ratios for lead screw and rack and pinion

6.5 Rack and Pinion

Another linear actuator that can be driven with a DC motor is a rack and pinion. A lead screw advances the nut one thread per complete revolution, while a rack and pinion moves one tooth for every tooth on the pinion (See Figure 6.5). This difference makes a rack and pinion faster, but less forceful than a lead screw.

The rack and pinion costs less than a recirculating ball nut, and all the bulk is in one place. With a lead screw, the nut and motor are at opposite ends of the screw, but with rack and pinion, the pinion and motor are together. The rack and pinion still has the protrusion problem, but in the opposite direction. The geometry of the two actuators is shown in Figure 6.6.

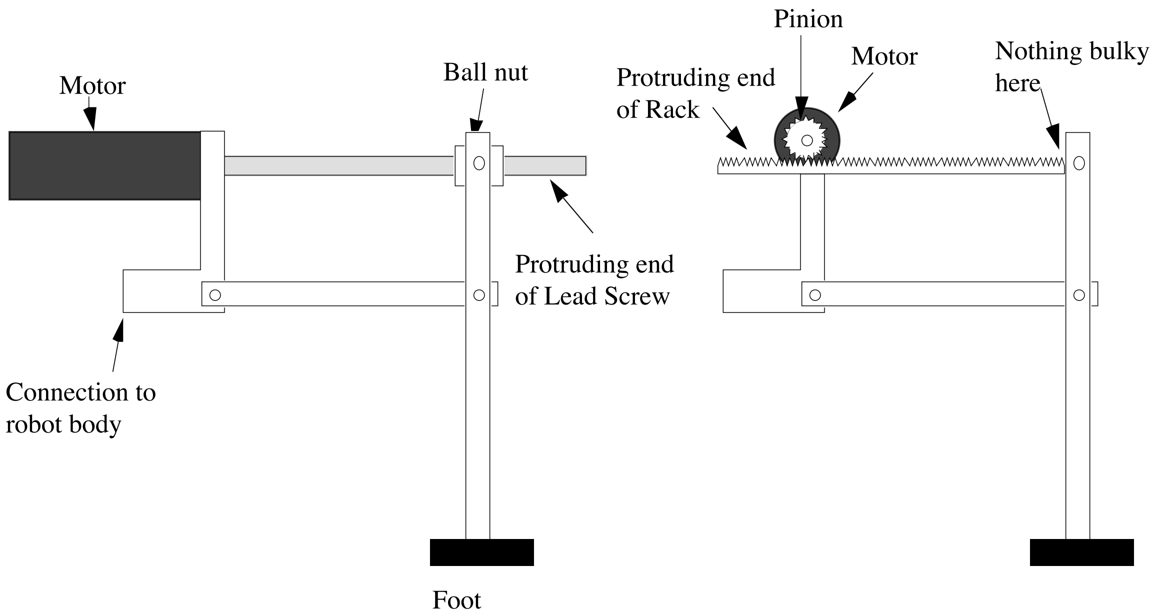


Figure 6.6: Lead Screw and Rack and Pinion Geometry

6.6 Hydraulics and Pneumatics

The third common linear actuator is a hydraulic or pneumatic cylinder. Pneumatic systems are simpler and cleaner that hydraulics, but aren't as controllable. Hydraulic cylinders can be driven at any speed, and held at any position. Pneumatics are usually bang-bang actuators; they don't allow speed control or intermediate positions. This difference makes pneumatics an unlikely choice for actuating a walking robot.

Hydraulics are used in heavy machinery because they have good power to weight ratios, easy power dissipation, high flexibility, large force capability, and simple overload protection. Hydraulics have been used in some walking robots, but typically only large ones **[McGhee, 1976] [Waldron et al, 1984]**.

Small hydraulic systems are not easily available because there is no demand for them, but would probably be good actuators for a small walking robot. A small hydraulic system has the same advantages as a large one. The biggest disadvantages of hydraulic actuators are that they're messy and expensive.

A typical hydraulic system has a positive displacement pump pressurizing a fluid accumulator. A pressure relief valve determines the maximum pressure, and protects the pump from burning out when there is no fluid flow.

Cylinders are connected to the reservoir by valves, which can be mechanically or electrically controlled. A schematic of a possible hydraulic system for a walking robot is shown in Figure 6.7. In this system, the electrically controlled valves have three states. Normally, the fluid lines connected to the cylinder are terminated at the valve, which holds the cylinder at a fixed position. An electric signal can connect the cylinder to high and low pressures to move it in either direction. This means the cylinder can be moved in either direction with a single valve, and will hold a static position with no electrical signal.

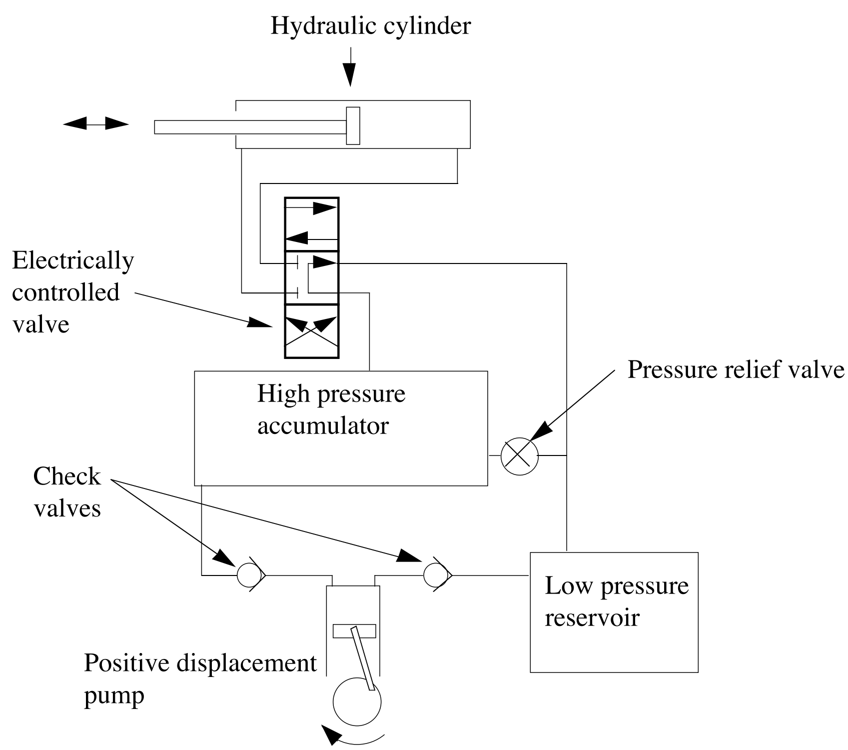


Figure 6.7: Schematic of a hydraulic actuation system

Using hydraulics to actuate a robot would allow larger forces, and more design flexibility. It would also move more weight to the body from the legs. The pump would be driven by an electric motor for laboratory applications, but when the robot goes outside, it could be powered by a small gasoline engine. Gasoline is a much more efficient way to store energy than batteries, so the robot could run for a longer time. Switching between an electric motor or a gas engine would not require any modification to the hydraulic system.

It may be possible to find cylinders that are the right size, but valves probably have to be custom built. Because this system would require little flow, it should be possible to build small valves that mount directly on a printed circuit board.

CHAPTER 7:
STANCE

There are many ways to classify walkers: number of legs, static or dynamic stability, energetics, gaits, or stance.

There are three basic stance types, shown in Figure 7.1. The first is used by most mammals. The legs operate in a vertical plane, parallel to the longitudinal axis of the body. This configuration improves energy efficiency by allowing the legs to swing like pendulums. Energetics are also improved by providing an energy-free standing mode. Mammals can lock their knees, supporting their weight with the skeleton, and not with muscles.

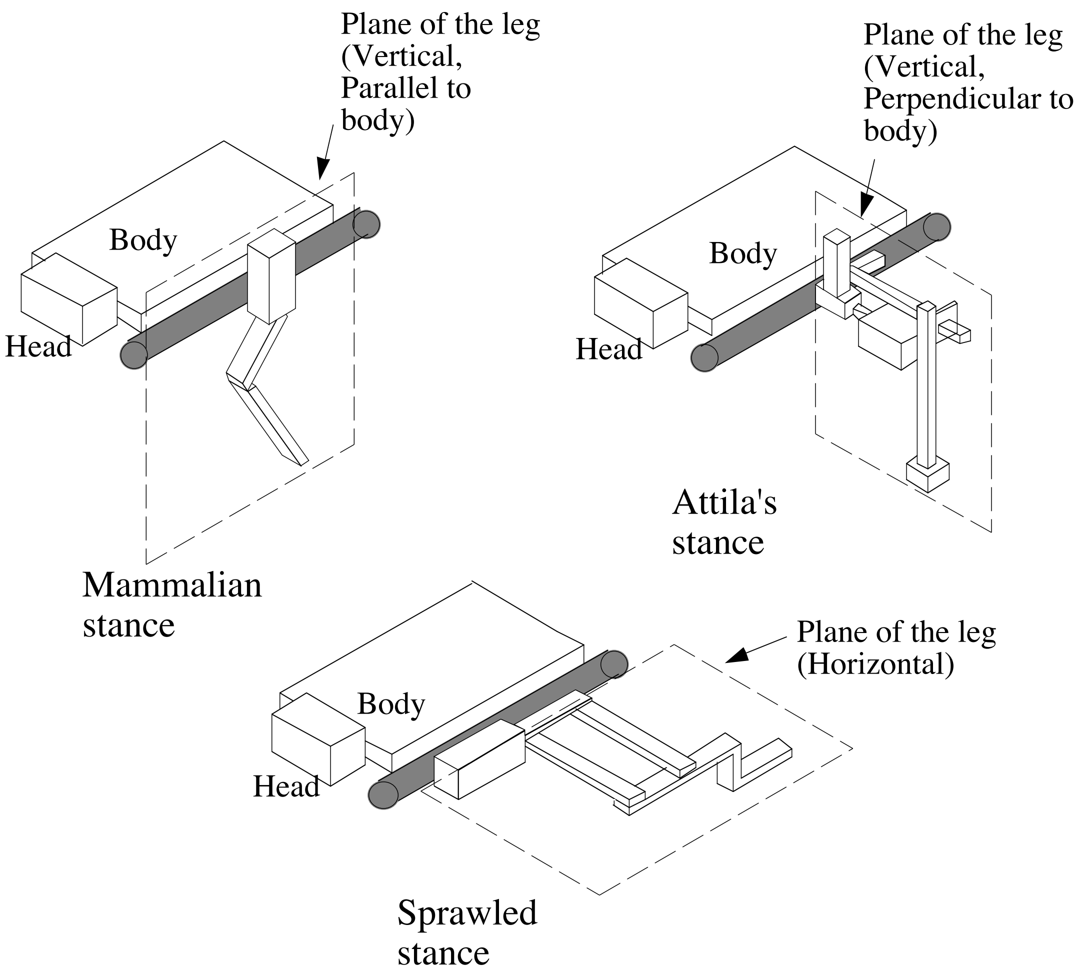


Figure 7.1: Three stance types

Some robots have been built with this stance type, including the Ohio State Adaptive Suspension Vehicle **[Waldron et al, 1984]**. A mammalian stance was selected for the ASV because of the energetic advantages, and also because it presents a narrower track and less frontal area than a sprawled stance.

The second type of stance is found in many walking robots, and some reptiles, where the legs primarily operate in a vertical plane perpendicular to the longitudinal axis. This is the stance that was chosen for Attila and Hirose's quadruped **[Angle 1991] [Hirose 1984]**. Its primary advantage is that it decouples the advance and lift degrees of freedom, so only one DOF has to support the robot's weight. A disadvantage of this stance is that the kinetic energy of the legs is lost at the end of the swing phase. Attila also has no energy-free stance; the lift DOF must always expend energy to stand. Making the lift DOF non-backdrivable would solve this problem.

These first two stance types have been compared several times, and have both been used in walking robots **[Waldron et al, 1984]**. The reasons for selecting one or the other stance type are usually energy efficiency and keeping the DOFs decoupled.

The third option is the sprawled stance used by many insects and small reptiles. Since most animals are insects, this is the most common stance type in the animal kingdom **[Full, unpublished]**. It is relatively rare in walking robots, however. Here the legs primarily operate in a horizontal plane. This provides a low and wide stance, which improves stability. Genghis uses this type of stance **[Angle, 1989]**.

In animals and robots that use the first two stance types, the body typically maintains a constant orientation to gravity. When a human climbs a mountain, his body usually remains as vertical as possible. Hirose’s quadruped always keeps its body horizontal. Attila compromises; his body follows the slope of the hill, and the global DOF keeps the legs vertical. Maintaining a constant orientation to gravity is an advantage because the leg design can be optimized to support the body weight in a known direction.

Sprawled animals, however, pay little attention to gravity. Their bodies tilt and tip to follow undulations in the terrain. Because of their large strength to weight ratio, the forces generated by their legs are large compared to gravitational forces, and they can support their weight in any orientation. Also, they have excellent traction; many insects and lizards have positive footing on glass. A robot built with a sprawled stance, sufficient strength to weight, and good feet could traverse varied terrain without keeping its body aligned with gravity.

When Attila climbs a slope, he must change his steps as the slope changes. (See Figure 7.2) A sprawled robot, on the other hand, would climb a slope using exactly the same motions as he would on flat terrain. (See Figure 7.3) The advance DOFs must work against gravity, but with a high strength to weight ratio, this is not a problem.

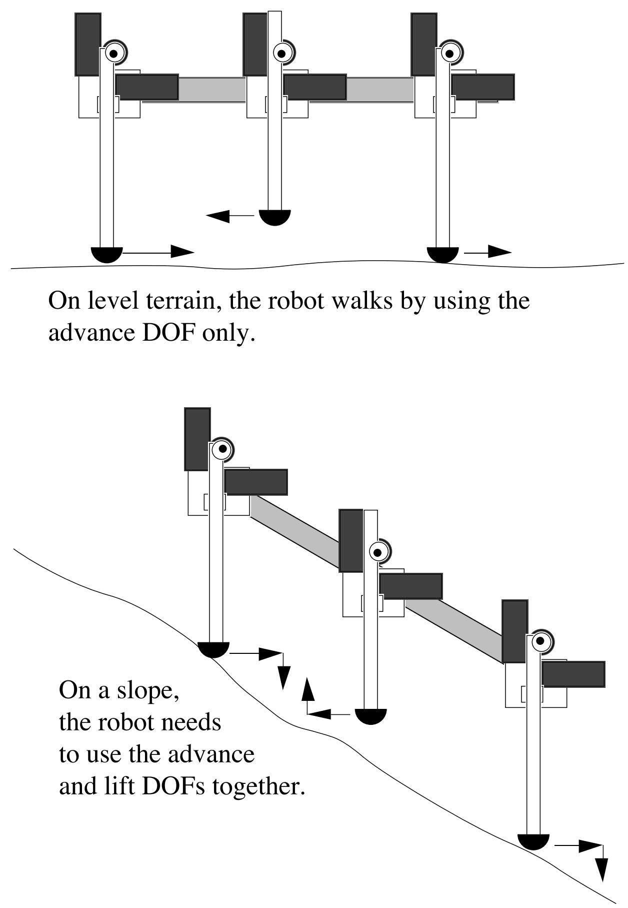


Figure 7.2: Attila walking on level ground and a slope

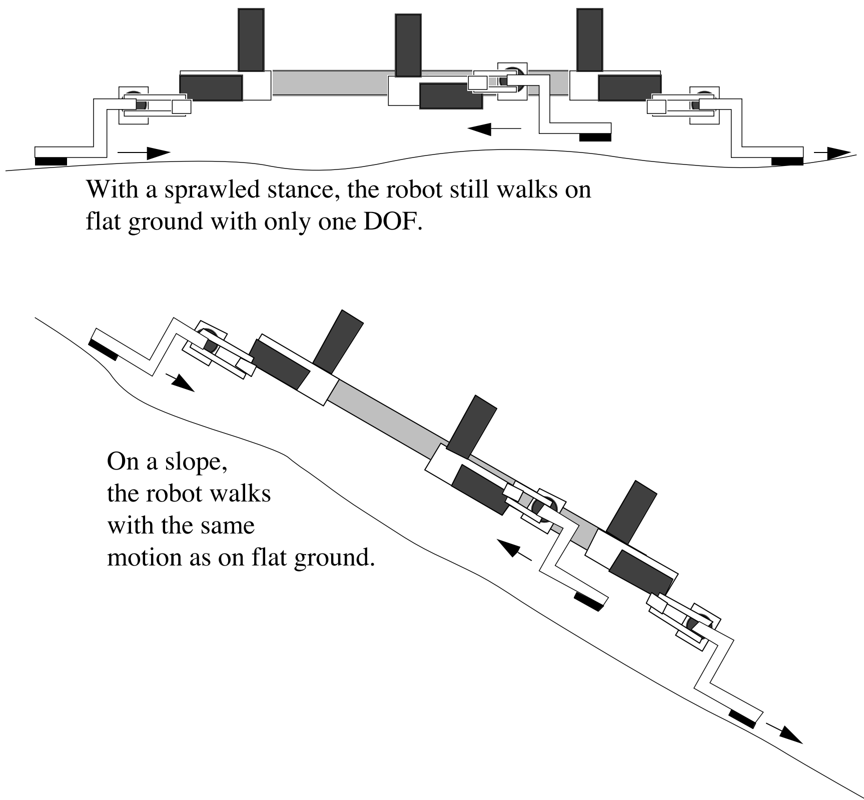


Figure 7.3: A robot with a sprawled stance walking on flat ground and a slope

A sprawled stance requires less control software to navigate over varied terrain. One goal of designing a robot's mechanical and electrical system is to minimize the software requirements. A body and legs that can operate at an arbitrary orientation to gravity do exactly that.

The requirements for such a robot are a stable stance, strong legs, and good feet. In order to provide static stability at arbitrary orientations, the stance must be low and wide. A high strength to weight ratio requires proper actuator selection and kinematic design. Most walking robots do not have the strength to weight ratio needed to walk at arbitrary orientations to gravity. They keep their legs oriented to gravity to make more efficient use of the power they have.

The final requirement for a sprawled walker is feet that can easily maintain traction on a wide variety of surfaces. The quality of a foot can be described by what is required for a foothold. Feet that need a horizontal surface for footholds are not very good; feet that will stick to any surface are better for rough terrain locomotion.

CHAPTER 8:
THE ARNOLD SCHWARZENEGGER LEG

The first leg I built was the Arnold Schwarzenegger leg. (See Figure 8.1) The goal of this design was to have only one motor that worked during the stance phase. A robot leg has two different loads: the body and itself. During the stance phase, the leg must support the body's weight and propel it forward, but during the swing phase, the leg works only on its own mass.

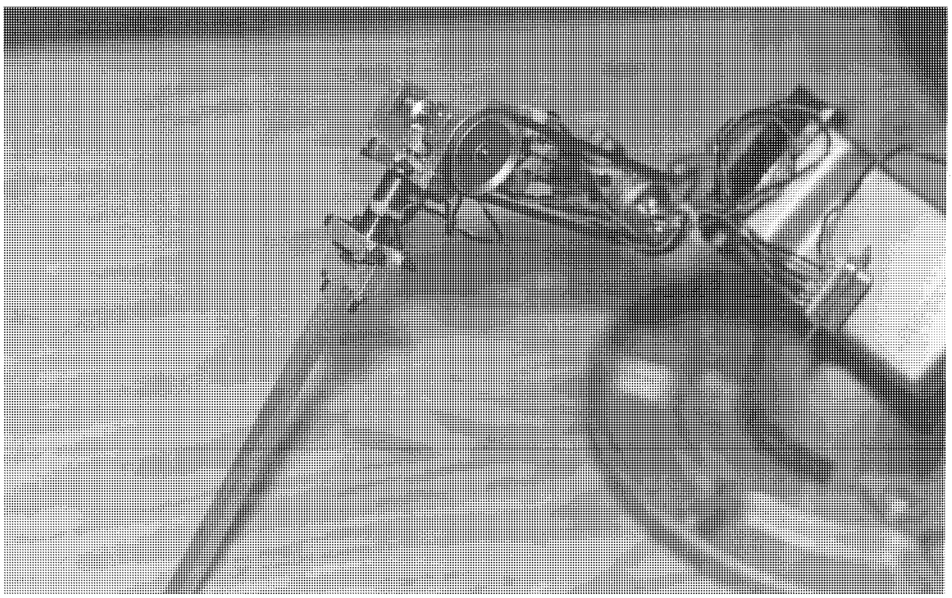


Figure 8.1: Photograph of the Arnold Schwarzenegger leg

On Attila's legs, the torque requirements of all three motors are determined by his total mass: the lift motor supports the robot's weight, the knee pulls him up large steps, and the advance motor accelerates him forward. All three of these motors are stronger than necessary for moving the leg during the swing phase.

A leg design that combines propulsion with support in one DOF would require only one large motor. Other DOFs to control foot placement would only operate during the swing phase, so they could use smaller motors. In addition, a leg that uses only one DOF during the stance phase will have better energy efficiency **[Song et al, 1981]**.

The Arnold Schwarzenegger leg accomplishes this by using a rubber belt to link the hip and knee joints. This coupling creates an extension/contraction DOF, which is actuated by the large motor. The smaller motor is locked with a brake during the stance phase, so it doesn't have to support any of the body weight. During the swing phase, the brake is released, and the small motor can change the knee angle independently.

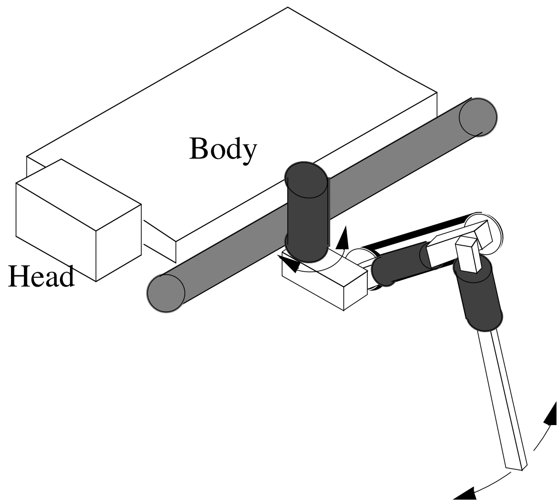


Figure 8.2: third DOF for the Schwarzenegger leg

The third DOF for this leg would be a rotational swing at the hip, shown in Figure 8.2, but this was not included on the prototype. To walk, the third DOF would rotate the leg so that it points backwards. Then, the extend DOF will push the robot forward.

The knee mechanism is shown in Figure 8.3. The pulley and bevel gear are both fixed to the shaft, but the leg links freely rotate on it. When the knee motor is locked, the bevel gears cannot rotate relative to each other, so the tibia rotates with the pulley. When the leg is in the air, the extend motor holds the pulley and bevel gear in place. The knee motor can then rotate the tibia around the knee shaft.

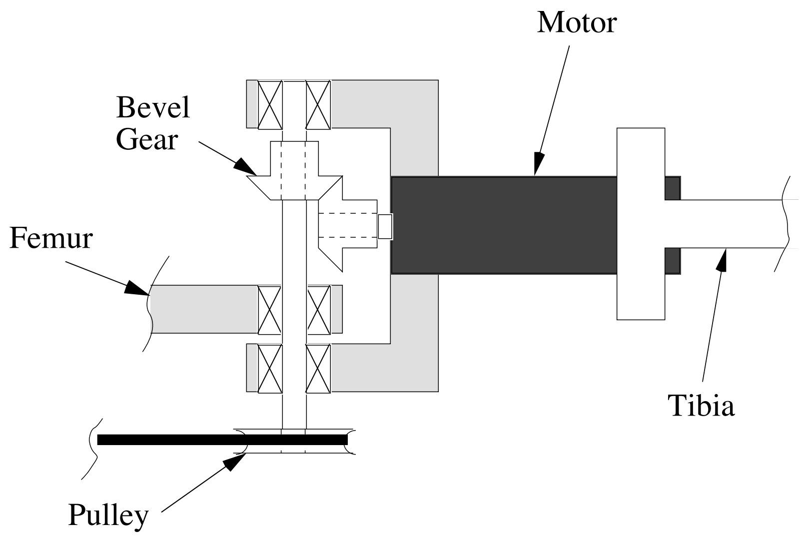


Figure 8.3: The knee mechanism

The brake on this prototype was implemented with a spring loaded pawl that held the bevel gear teeth in place. A small motor pulled against the spring and disengaged the pawl to release the brake. Figure 8.4 shows the brake mechanism.

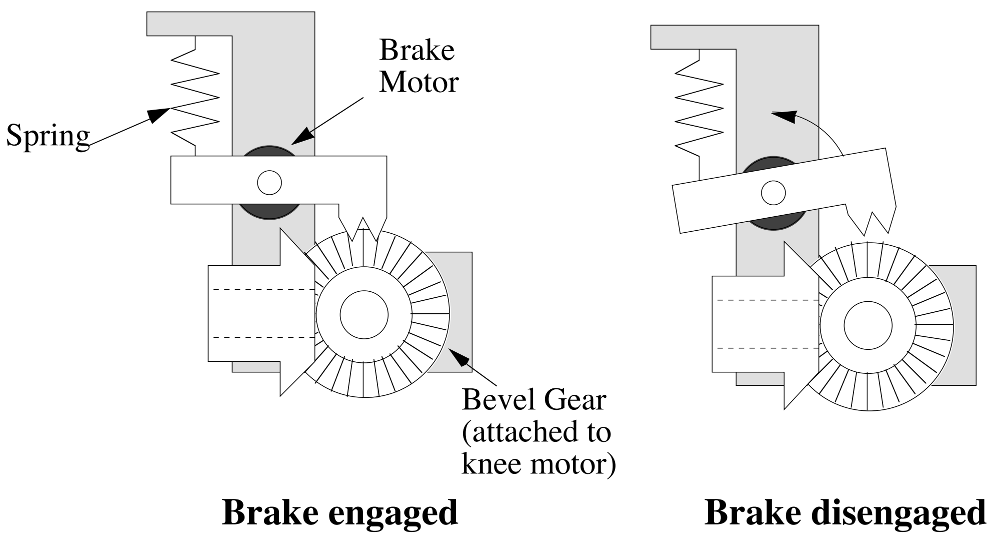


Figure 8.4: The brake mechanism

Another advantage of this design is that the bevel gears allow the motors to be in line with the leg links, instead of protruding to the side. (See Figure 8.5) This makes the legs less bulky, and reduces the problems of interference with other legs and the body. Attila's legs had to be mounted an inch from the body to keep the motors from colliding with the body. In this prototype, the motors were actually used structurally as links. This saves weight because the leg requires less structure.

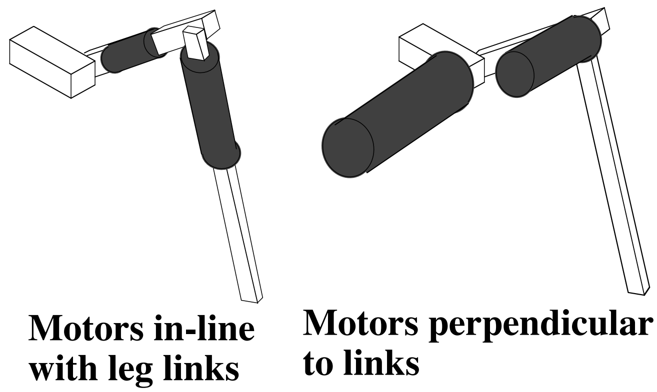


Figure 8.5: Two ways to mount motors

A disadvantage of this design is that the motors move their own mass. The same kinematics could be achieved with the motors inboard of their respective joints. (See Figure 8.6) This change would reduce the leg's moment of inertia, and the torque requirements of the motors.

This leg did succeed in its goal of making only one DOF dependent on the robot's mass. However, the DOFs it has: extension and knee, are not the right ones for walking. The Schwarzenegger leg cannot easily control body height. To raise the body, the robot would have to lift the leg, adjust the knee, and then put the foot down again.

A bigger problem is the transition from stance to recovery phases. The knee DOF can only operate when the leg is not supporting any weight, but it is required to lift the foot off the ground. To walk, the robot would have to transfer its weight to the new set of legs, and then lift the feet for the recovery phase.

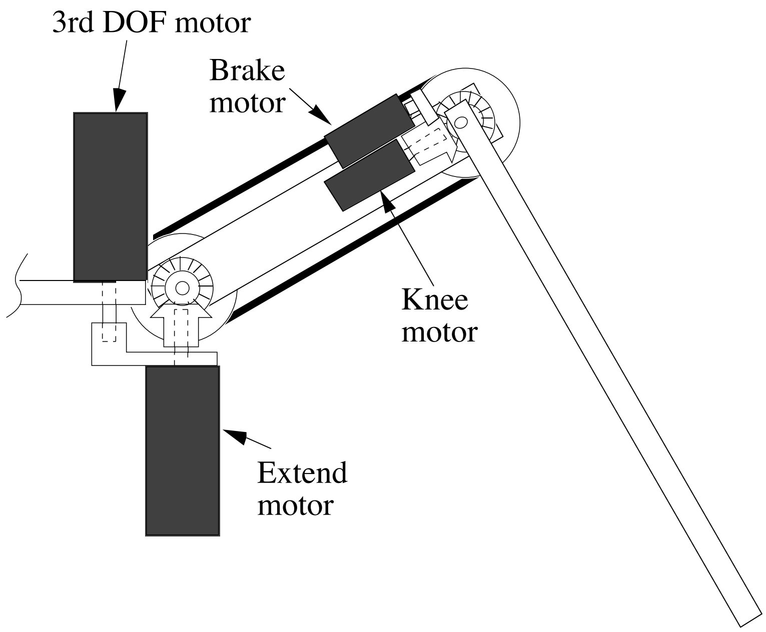


Figure 8.6: A better design for the Arnold Schwarzenegger leg

CHAPTER 9:
THE MIKHAIL BARYSHNAKOV LEG

The second leg design I looked at is the Mikhail Baryshnakov leg. (See Figure 9.1) The goal of this design was to create a mechanism that produced a linear step with one DOF. The Barshnakov leg uses a pantograph mechanism to produce a linear step. The same principle is used by Hirose in his PANTOMEC legs **[Hirose 84]**.

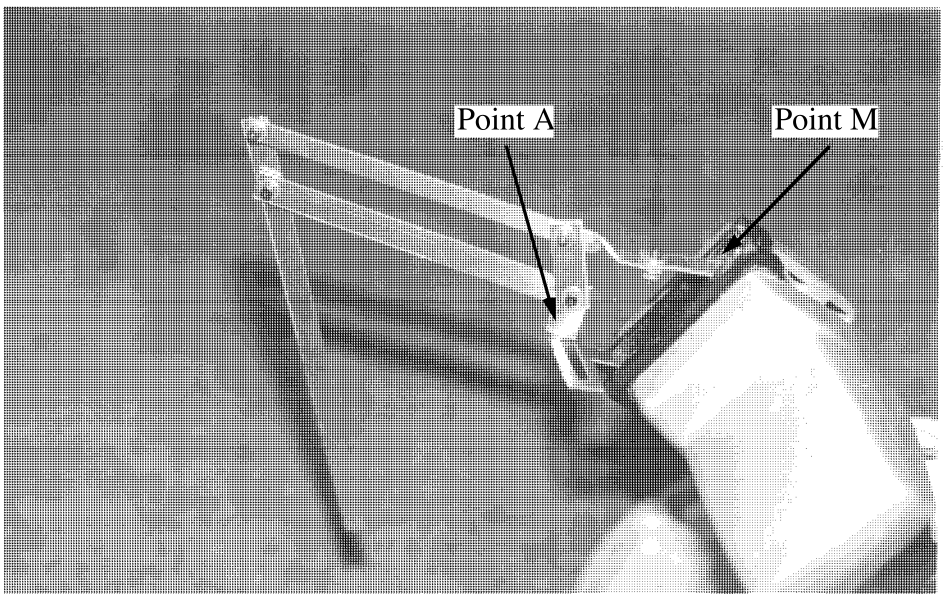


Figure 9.1: Photograph of the Mikhail Baryshnakov prototype

The linear advance DOF would be actuated by a motor at Point M. Point A on the pantograph is constrained to follow the linear slot. This straight line motion is duplicated at the foot. To create a knee DOF, the slot is moved closer to or further from the body. A third DOF lifts the foot by rotating the entire mechanism around a longitudinal axis.

These three DOFs: lift, knee, and linear advance, are better suited to walking than the rotation, extension, and knee of the Schwarzenegger leg. Another advantage is that they are similar to the DOFs of Attila's legs, which would allow using some of the existing Attila software.

The prototype of this leg was built out of sheet metal, without motors. This model allowed evaluation of the kinematic design without requiring much machining time.

The Baryshnakov prototype succeeded in producing a linear foot motion. A complete leg with motors, however, would require a much more complicated mechanism. Hirose's PANTOMEC legs use a linear actuator at point A, but because of Attila's smaller size, there is not enough room for a lead screw or rack and pinion. A Baryshnakov leg would require some form of slider at point A, which would probably be rather inefficient.

Another problem with this leg is that even though the foot is moving in a straight line, it still rotates relative to the body (See Figure 9.2). One solution to this problem is to use another parallel 4-bar linkage to keep the foot parallel to the body. I built a wooden prototype of this mechanism. (See Figure 9.3) This model eliminated the foot rotation problem, but at the expense of more complexity.

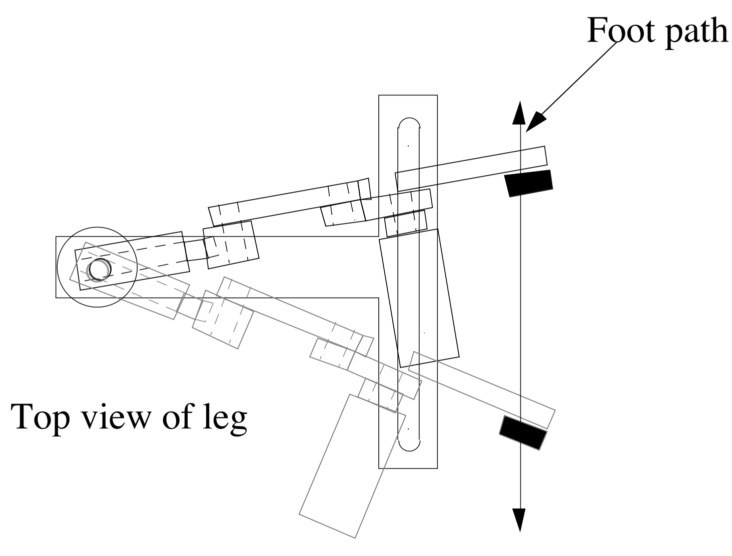


Figure 9.2: Foot still rotates during the linear step

Implementing the knee DOF would require even more mechanism and bulk. The knee DOF would have to be strong enough to be non-backdrivable during the stance phase.

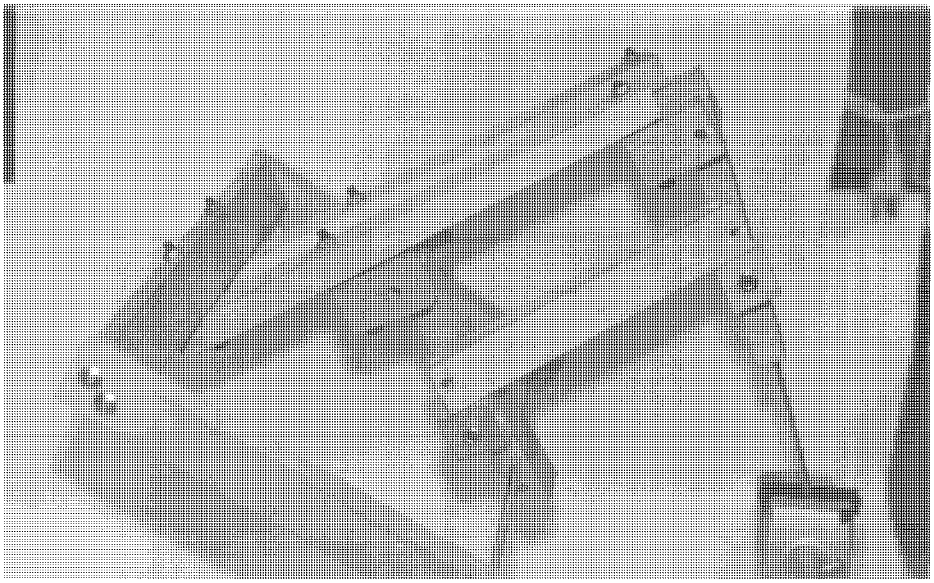


Figure 9.3: Photograph of the wooden leg

This leg does produce linear steps, but has an extremely complex mechanism. This would probably result in a heavy, inefficient, and bulky leg, which is not what you want on a walking robot. I concluded that there must be a simpler alternative, especially since a walking robot does not require a mathematically perfect straight line. The other straight-line mechanisms I looked at were designed to produce nearly linear motions.

CHAPTER 10:
THE CARL LEWIS LEG

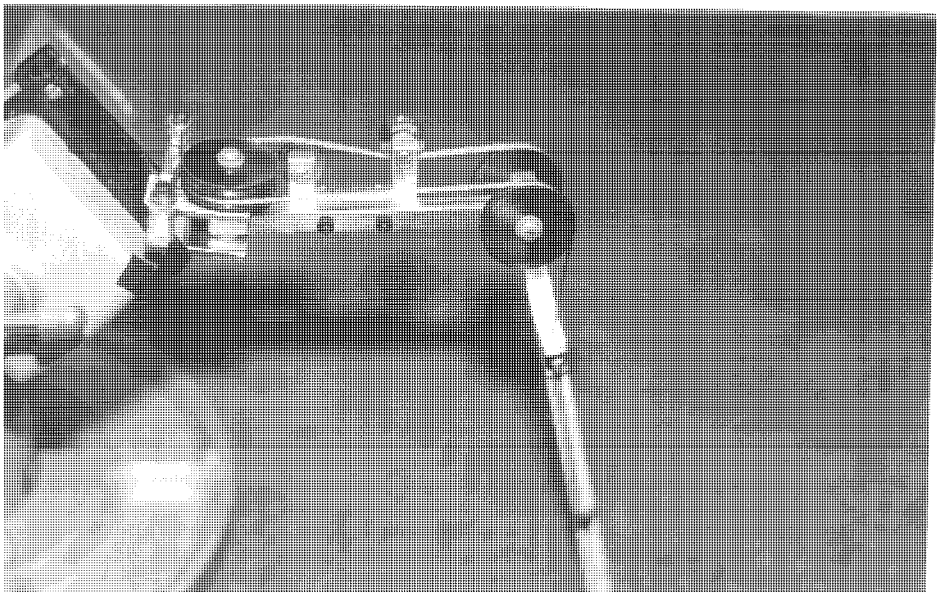


Figure 10.1: Photograph of the Carl Lewis leg

The goal of the Carl Lewis leg (See Figure 10.1) was to couple the advance and knee DOFs to produce a near straight-line foot path. Steel cables were used to produce the coupling. When the advance DOF moves away from center, a cable wraps around a pulley and pulls the knee straighter. (See Figure 10.2) One cable straightens the knee when the leg is forward, and another cable does it when the leg is behind its center position. Springs are used to keep tension on the slack cable.

The Carl Lewis leg did succeed in coupling the advance and knee DOFs. The resulting foot path is shown in Figure 10.3. The path is not exactly a straight line, but a walking robot does not require a perfectly linear step. Except for the singularity in the center of the step, this foot path would be sufficiently straight.

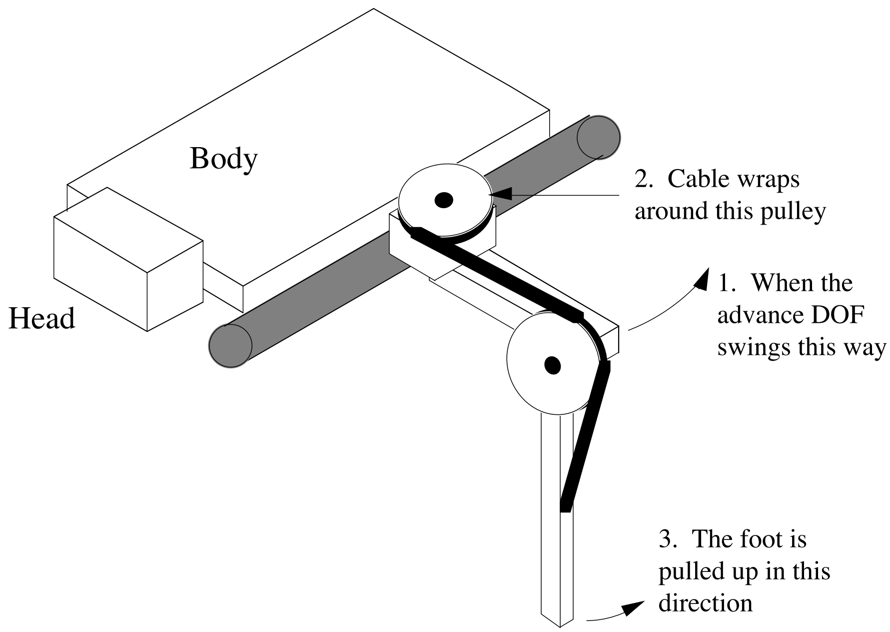


Figure 10.2: Advance and knee coupling (only one cable is shown)

The singularity in the middle occurs when the coupling switches from one cable to the other. By wrapping the cables around cams instead of circular pulleys, the exact foot path could be straightened, and the singularity could be removed.

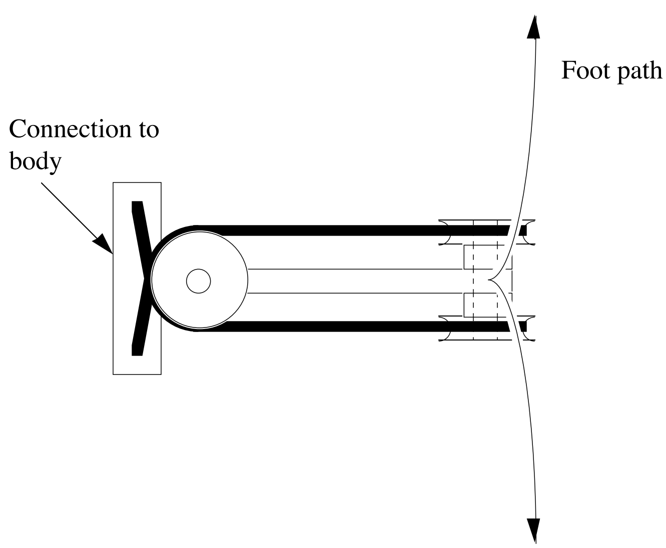


Figure 10.3: The Carl Lewis leg foot path (top view)

A bigger problem is that the springs are always pulling the knee straight. (See Figure 10.4) The cable mechanism only works when there is something working against those springs, pulling the foot down. This problem could be solved by using a stiff spring to pull the foot down, and light springs on the cables. The cable springs do not have to produce a large force; they just keep some tension on the cables so they stay on the pulleys.

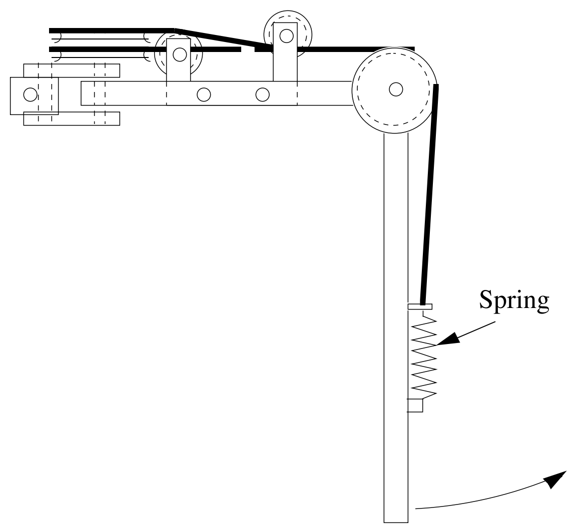


Figure 10.4: Springs pull the foot up

A better solution, though, would be a leg with only one cable. If the front legs never move behind the center position, and the back legs never move forward of it, only one cable is needed on each leg. The middle legs could point either way. Experiments on Attila have shown that having the front legs point forward and the back legs point backwards improves stability, so this solution would be logical **[Ferrell, unpublished]** .

CHAPTER 11:
THE ROGER CRAIG LEG

The Roger Craig leg was another attempt to produce a straight line foot path without a complicated mechanism. (See Figure 11.1) I used a graphical technique to generate a 4-bar linkage to produce nearly straight-line motions. This is a much simpler mechanism than the Mikhail Baryshnakov or Carl Lewis legs, and the linearity of the step is excellent.

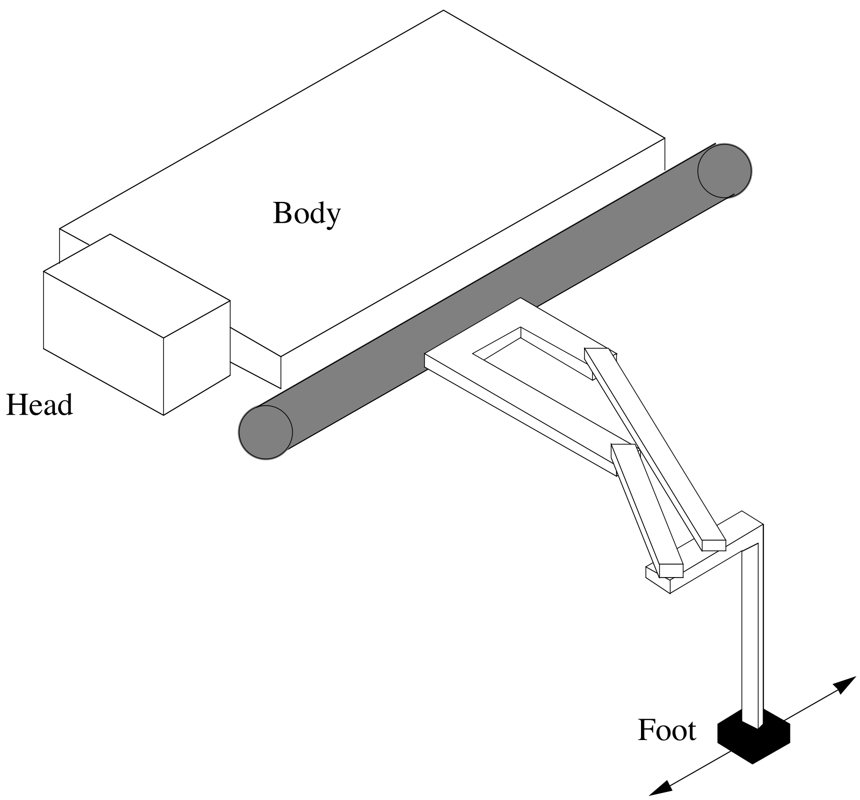


Figure 11.1: The Roger Craig leg

Figure 11.2 shows a top view of the Roger Craig linkage in three positions and the foot path it generates.

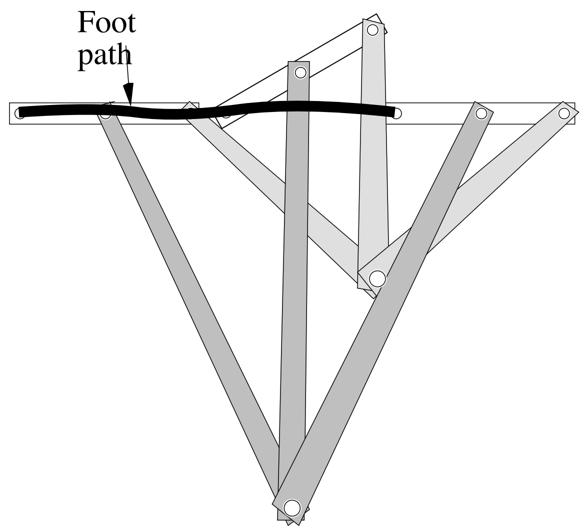


Figure 11.2: Foot path of the Roger Craig leg

The generation of the linkage is shown in Figure 11.3. The three positions A, B, and C of Link 1 are arbitrary. I tried a few different combinations; this one produced the best link lengths. Point P is where the foot would be, and points X and Y are the connections to the other links. The dashed lines connect the three different positions of points X and Y. The solid lines are the perpendicular bisectors of the dashed lines. The two points where they intersect are the other ends of the links.

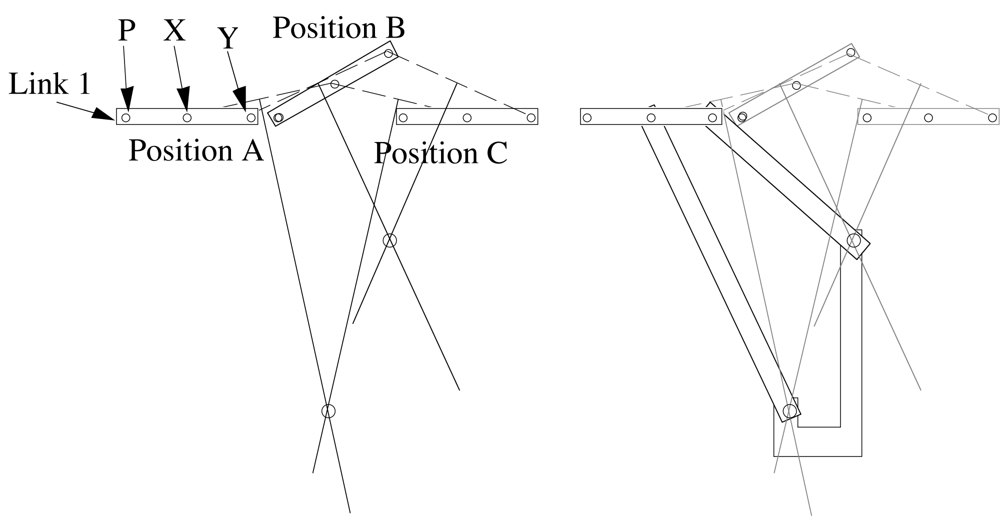


Figure 11.3: Generating the 4-bar linkage

The major drawback of this leg is that the foot will only move in a straight line if it is located directly under point P. Because Link 1 rotates during the step, if the foot was anywhere else, it would no longer trace a straight path. A lift DOF can be built that works by rotating the entire mechanism about a longitudinal axis.

To make this a viable leg design, a third DOF needs to be added. One solution to this is shown in Figure 11.4. In this design, two parallel 4-bar linkages have been added. The parallelograms assure that Link 2 always maintains the same orientation. The original 4-bar linkage constrains the center of Link 2 to move in a straight line. With these combined, Link 2 moves in a straight line without rotating. A foot connected to Link 2 would do the same.

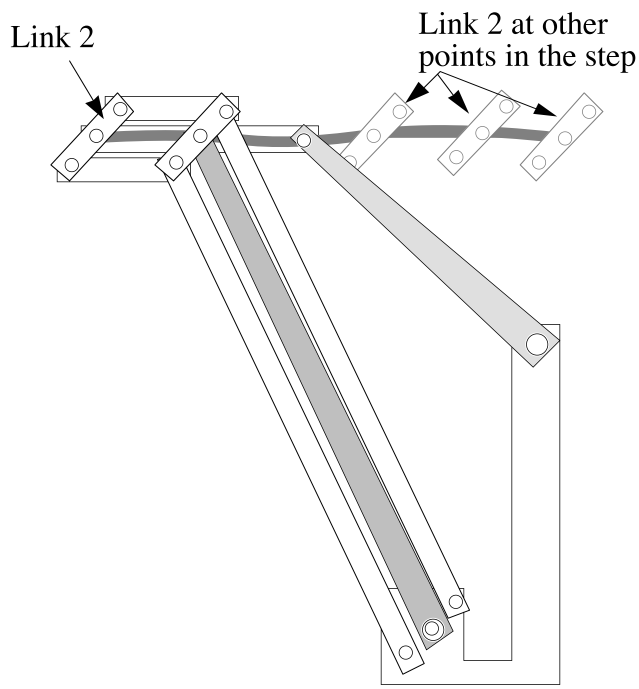


Figure 11.4: A linkage that allows 3 DOFs

This leg does not have the foot rotation problem like the Carl Lewis or Mikhail Baryshnakov legs. It is still a relatively simple and lightweight mechanism, and produces very straight steps. Of the straight line mechanisms I explored, the Roger Craig leg is the best way to get linear steps from a DC motor.

CHAPTER 12:
THE ASHLEY RICHARDSON LEGS

The goal for the Ashley Richardson leg was to build a working prototype of a sprawled-stance leg, modelled after cockroach legs. This leg uses some of the ideas from earlier kinematic models: it propels the robot by an extension motion, it has a parallel 4-bar linkage, and it uses bevel gears to keep the motors in-line with the leg links.

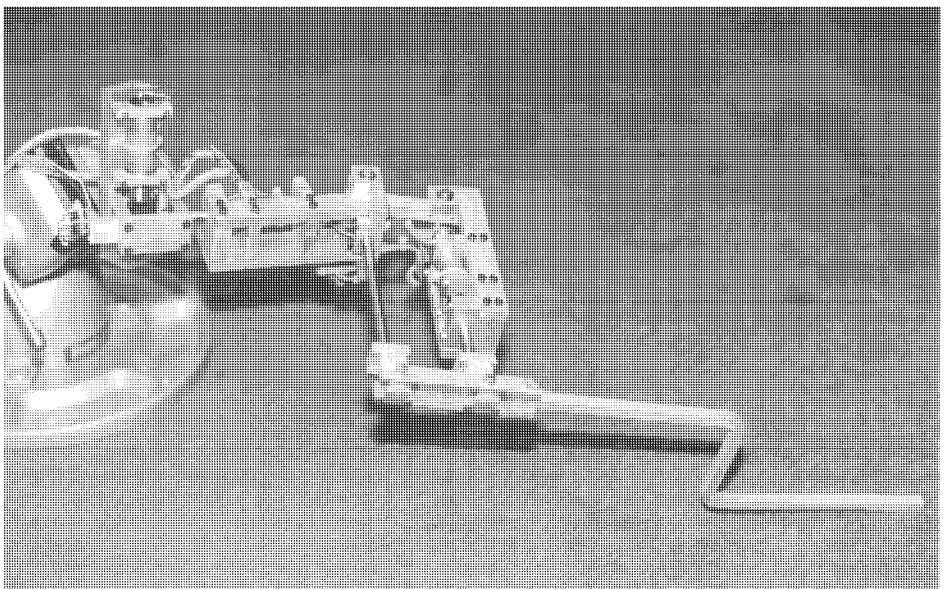


Figure 12.1: Photograph of the first Ashley Richardson prototype

I built two versions of this leg. The first (See Figure 12.1) was built to test the kinematics, and get an accurate idea of the motor requirements for making a useful leg. I used the same MircoMo motors that are on Attila's legs, because they were already in the laboratory. Since the prototype leg would only have to move its own mass, and would never support any load, I did not worry about whether or not those motors are powerful enough for a real leg.

The second prototype is closer to what would be used on a walking robot. (See Figure 12.2) The structure was made as lightweight as possible, and external gearing was added to the motors to provide more force. With one more design revision, these legs could be used on Attila or a new robot.

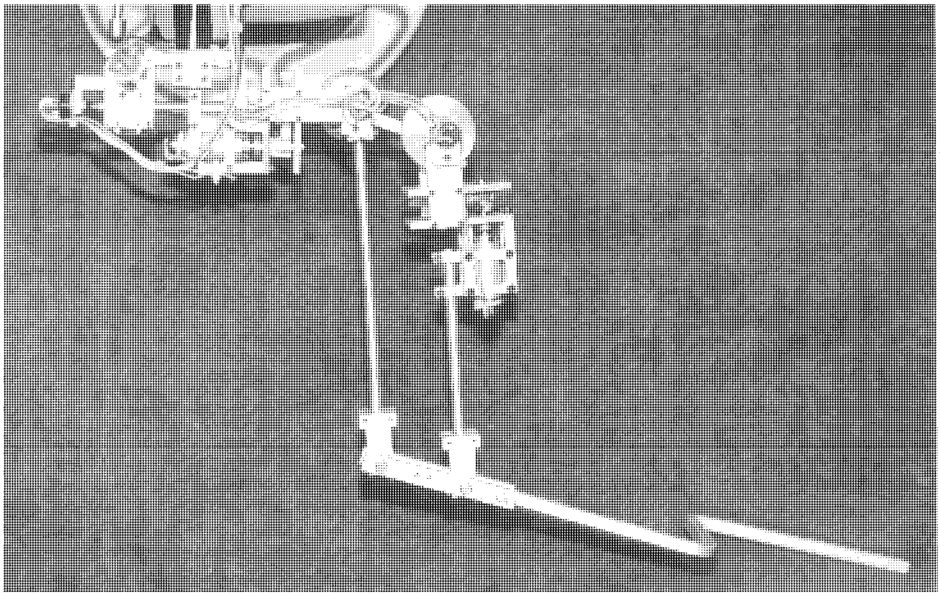


Figure 12.2: Photograph of the second Ashley Richardson prototype

Most of the effort on these two prototypes was concentrated on designing the actuation mechanism. Unfortunately, time did not permit testing of designs for the tibia and feet. The kinematics were evaluated with the simple tibia shown in the photographs. Before legs for a real robot are built, prototypes of different tibias and feet should be tested.

12.1 Kinematics

The kinematics of the first prototype are shown in Figure 12.3. Motors 1 and 2 actuate the 4-bar linkage as described in Chapter 5. Two potentiometers are used to measure angles α and β. Motor 1 controls α, and produces the swing motion. Motor 2 controls β, which extends and contracts the leg. Ab/adduction requires moving both Motors 1 and 2 simultaneously. Motor 3 rotates the leg about the axis shown in Figure 12.3, which provides the third orthogonal DOF. For walking, this is how the foot is lifted for the recovery phase.

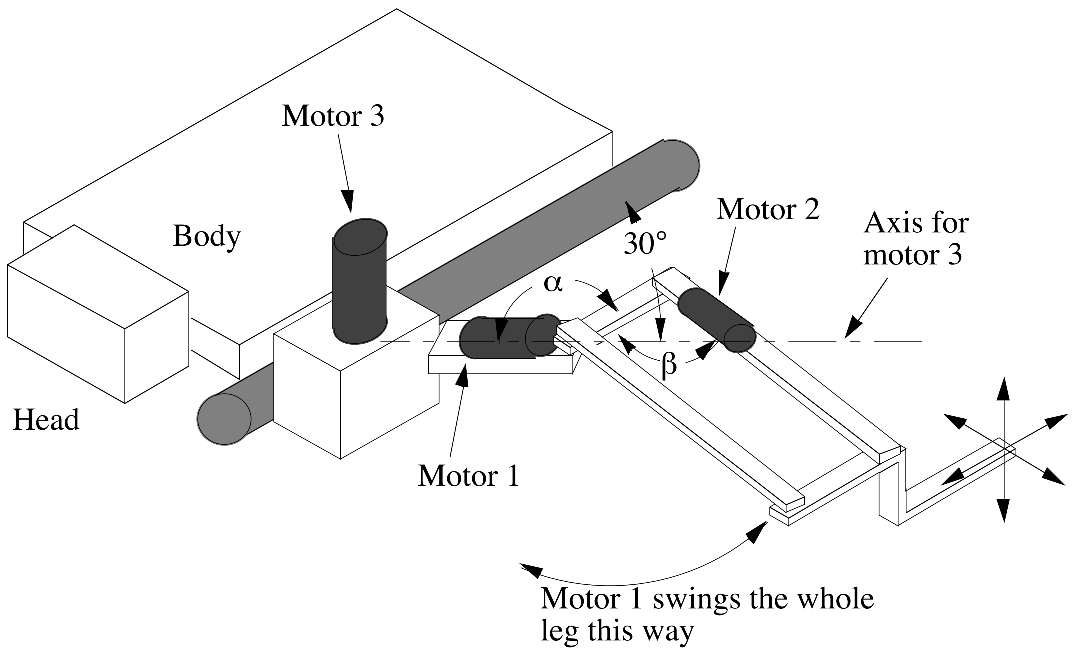


Figure 12.3: Kinematics of the first prototype

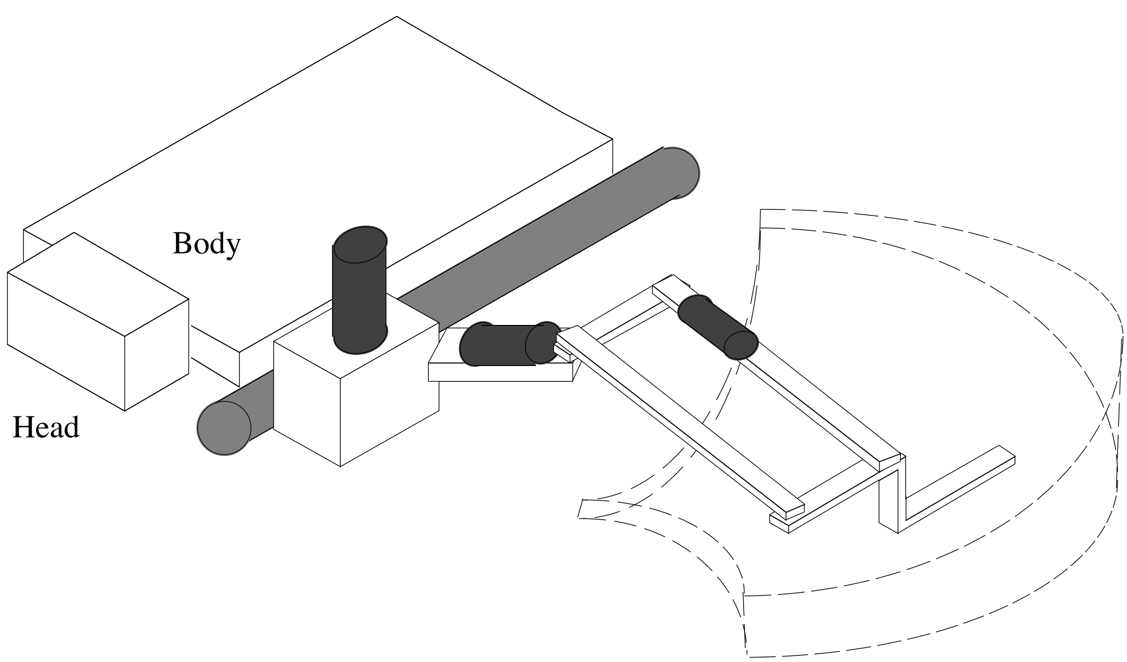


Figure 12.4: The Ashley Richardson leg's walking workspace

One advantage of this leg design is that it has separate workspaces for walking and climbing, like Attila. For walking, the leg operates in a horizontal plane, giving the robot a sprawled stance. In this mode, the foot can be placed anywhere in a relatively large area, but the vertical step size is limited to 4 or 5 inches. This workspace is shown in Figure 12.4.

For climbing situations, a fourth DOF, like the one on Attila, can rotate the leg to a vertical configuration, shown in Figure 12.5. In this configuration, the extension, swing, and ab/adduction DOFs give the foot a wide and tall workspace. The extension DOF is used to lift the robot against gravity, and Motor 3 is used to move the robot forward. In climbing mode, the kinematics of the leg are similar to Attila's, but have a much larger workspace, especially vertically.

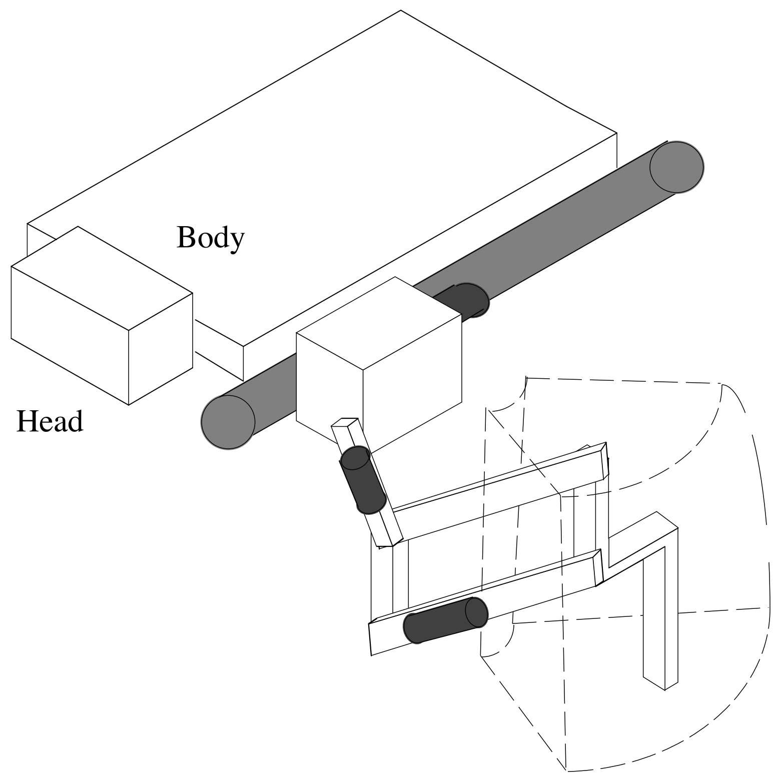


Figure 12.5: The Ashley Richardson leg's climbing workspace

Another advantage of the two modes of this leg is that they can use different feet. A walking foot can be attached to one side of the tibia, and a different climbing foot goes at the end. (See Figure 12.6) Since walking and climbing are very different activities, they should use different feet. Chapter 13 has more details on foot design.

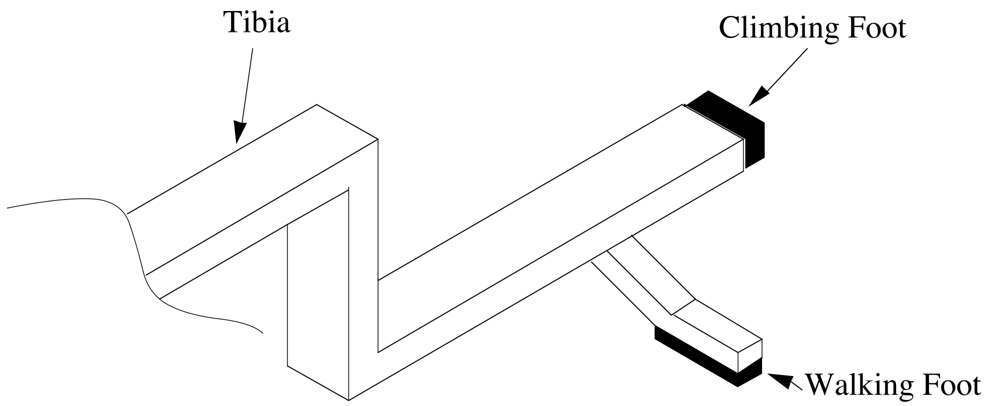


Figure 12.6: Two different feet on the tibia

The strength of Motors 1 and 2 is determined by the climbing mode, because they support the body weight. This means that they can also push the robot up a slope in the walking mode. This leg does not need a fourth DOF to maintain a constant orientation to gravity; it satisfies the strength requirement for the sprawled-stance robot described in Chapter 7.

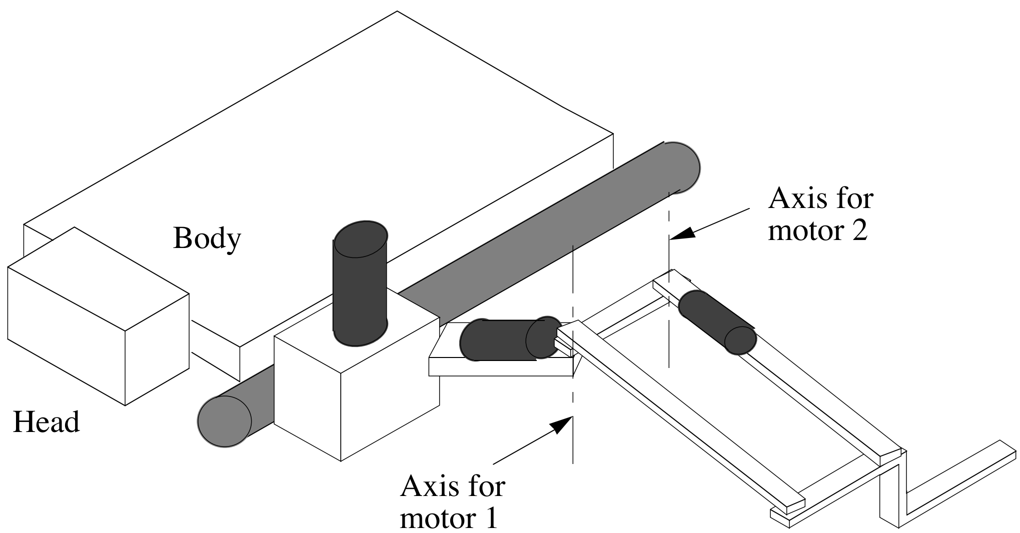


Figure 12.7: Axes of rotation for Motors 1 and 2

In the walking mode, only Motor 3 has to support the weight of the robot. Motors 1 and 2 rotate the leg about nearly vertical axes, so they do little work against gravity. (See Figure 12.7) The weight of the robot is supported by the structure of the leg instead. This will improve the energy efficiency of the robot in walking mode.

12.2 The First Prototype

The first prototype used MicroMo 1319 motors, with external 3:1 reduction in bevel gears. Because I wanted to keep the machining simple, the leg was bulkier and heavier than necessary. These two facts made the leg underpowered for use on a real robot, but sufficient for testing the kinematics and moving its own mass.

The 30˚ angle between the Motor 3 axis and the longitudinal axis of the robot (See Figure 12.8) turned out to be a bad idea. The reason this angle was in the design is that insect legs operate on axes that point towards the center of the body **[Full et al, 1991]**. However, with this leg design, when the foot is behind this axis, Motor 3 must rotate the opposite way to lift the foot. This motion would lower the knee. Ideally, the entire leg should lift at the same time. Having the knee move down when the foot goes up would complicate the control software, and make collisions more likely.

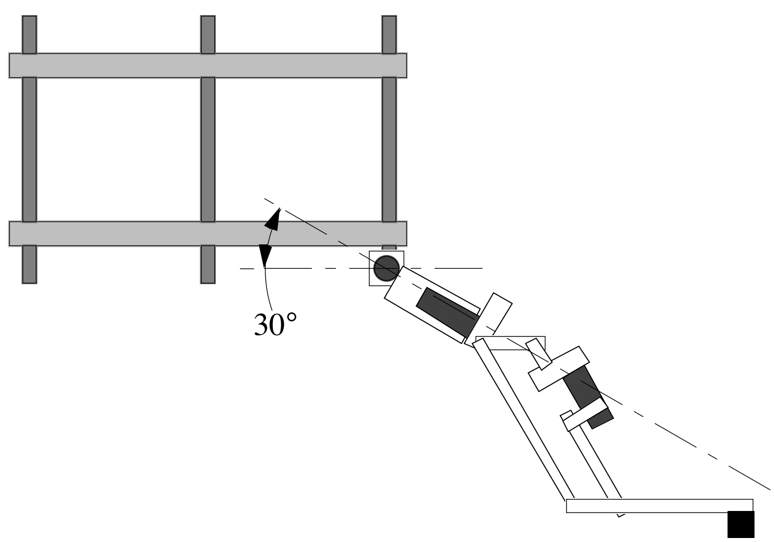


Figure 12.8: The 30 degree angle

Another problem with this prototype was set screws. All of the gears and motors were connected to the shafts with set screws, which often slipped and were easily stripped during assembly.

12.3 The Second Prototype

The second prototype was designed to be a more realistic model of an actual leg. Following the calculations in Chapter 6, I used MicroMo 1319 motors with 141:1 gearheads, and 9:1 external gearing for motors 1 and 2. Motor 3 was also a 1319 motor with a 141:1 gearhead, but it with a worm gear to provide an additional 30:1 reduction. This leg was also designed to be as lightweight as possible.

The strength to weight ratio of the leg is reasonable for a walking robot, but a larger one would be better. Most of the leg's weight is the motors and gears, so significant gains in strength to weight ratio probably require using different actuators.

A design for a version of this leg with linear actuators is shown in Figure 12.9. This design has the added advantage that the 4-bar linkage is used as a pantograph, and the foot would move in straight lines.

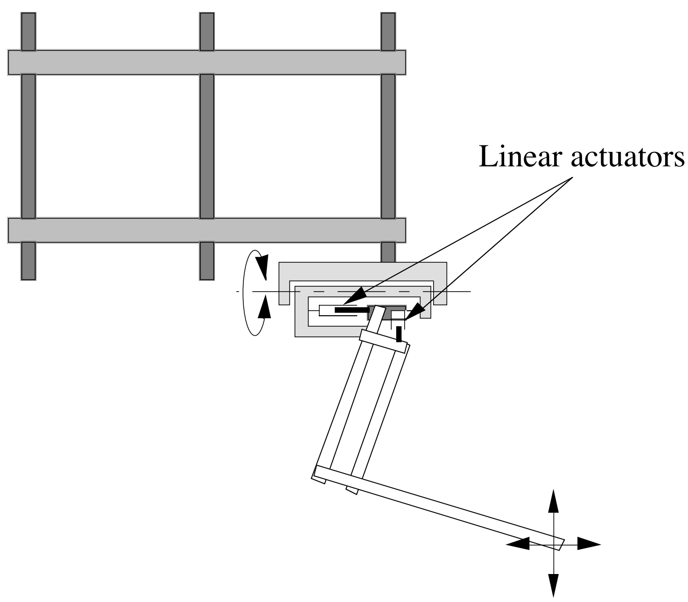


Figure 12.9: The Ashley Richardson leg with linear actuators

Another improvement in the second prototype was that the femur and tibia have hollow links. This saves some weight, and allows wires to be routed inside the leg, which will keep it neat, and also provide better protection. The second prototype used pinch clamps on the motor shafts, which worked much better than set screws. The gears were still connected to the shafts with set screws, but screws with larger heads worked acceptably.

12.4 Front, middle, and back leg differences

The Ashley Richardson legs were designed to be prototypes of a mechanism that could be used on a new robot, like the one shown in Figure 15.1. An identical or similar mechanism could be used for front, middle, and back legs of a walking robot. The different legs should have different link lengths, because they need different workspaces. For a first attempt, the logical choice would be to mimic the link lengths of an insect, like the cockroach legs in Figure 4.4.

Another difference between the legs should be the direction they point. The back legs should point backwards, because they need to push back in order to accelerate the robot. The front legs should point forward because they are used for deceleration. The middle legs could point either way, but backwards is the better choice because the robot will walk forwards most of the time.

Finally, the front leg needs to reach above the robot's head to pull it up a step. This can be accomplished by adding an extra DOF to the front legs, or with a mechanism on the robot's body. Some possible solutions are presented in Chapter 15.

CHAPTER 13:
FEET

13.1 Traction

There is one goal for feet: they should stay where you put them. When a robot is walking or climbing, its major concern is finding footholds. For a foot with unlimited traction, everything is a foothold, and the robot can walk or climb easily. Insects and small lizards have feet that stick to vertical surfaces and glass. They do not have to pay much attention to finding footholds, because their feet will stay wherever they are placed.

I investigated three options for traction elements. The simplest is a flat bottomed, metal foot. As expected, this is not a good way to get traction, either on smooth floors or rocks. The flat bottom is good, however, for walking on soft dirt or sand, where a large foot contact area is required.

The second option I looked at was spikes, like cleats. This works well on rocks and gravel, but is not very good on smooth floors or tables. It is also likely that a foot with cleats on it would suffer as the spikes wore out and became dull.

The third foot had a flat, rubber bottom. Surprisingly, the rubber had nearly the same traction on rocks as spikes. It is much better suited for floors and tables, and will not be dulled with use. For a general purpose robot, where the goal is mobility on a wide variety of surfaces, flat rubber-soled feet are the best choice.

13.2 Sensors

The sensors on a foot should make it easy to find footholds. Attila's ankles have infrared proximity sensors to help find footholds and avoid obstacles. (See Figure 13.1) The original foot design also had a sensor that pointed down to sense what was under the foot.

Another goal for feet sensors is to confirm ground contact. To walk or climb reliably, the robot must know when its feet are supporting its weight. Attila's feet have a Hall effect sensor (See Figure 13.1) that detect when the foot touches something. Attila's feet have two independent parts, connected by springs, and the sensor indicates when they move relative to each other. A drawback of this sensor, however, is that it does not indicate the direction of contact. Attila knows when his foot touches something, but does not know if it hit an obstacle, or is on the ground.

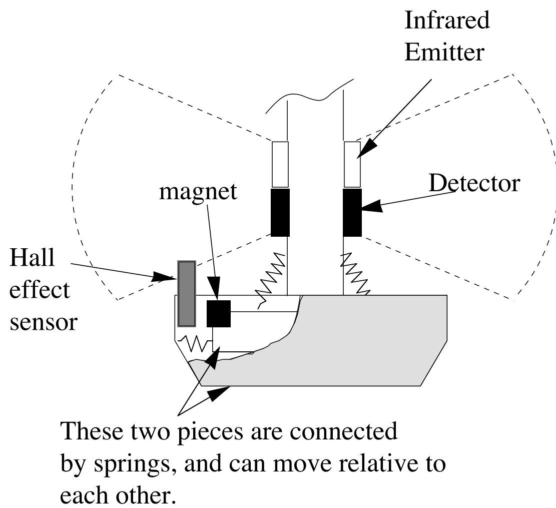


Figure 13.1: Attila's foot

An ideal ground contact sensor would distinguish between a collision with an obstacle, and when the foot is on the ground. It should also indicate when the entire foot is supported. Another problem with the sensor on Attila's feet is that when half of the foot is on the ground, the sensor indicates ground contact, but the foot cannot support any weight. (See Figure 13.2)

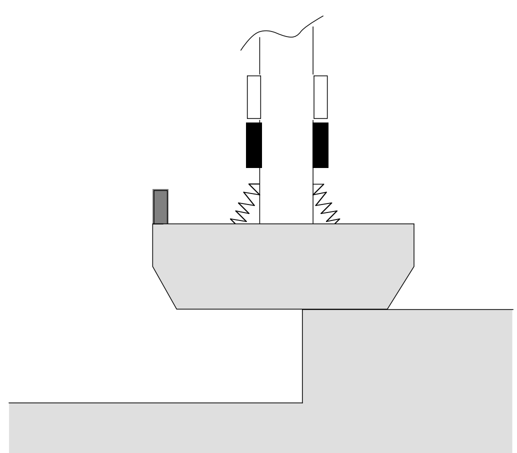


Figure 13.2: Partial ground contact

Attila also uses strain gages to detect ground contact. These sensors have problems with drift and repeatability. A more reliable ground contact sensor, inspired by the tarsus on insect legs, is shown in Figure 13.3. A potentiometer measures the position of the tarsus. A torsional spring pushes it down to position A when the foot is in the air. When the robot puts weight on the foot, the tarsus rotates to position B. The advantages of this sensor are that potentiometers are reliable sensors, and the change when the foot touches the ground is large. Two microswitches could be used to detect complete ground contact.

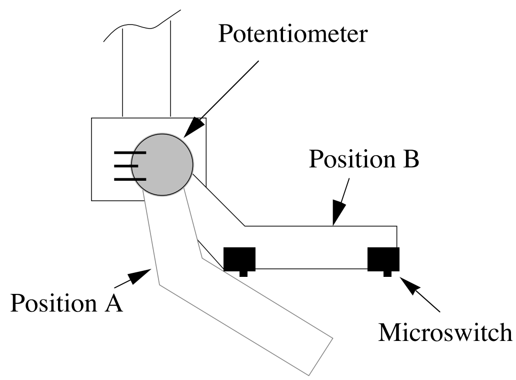


Figure 13.3: A better ground contact sensor

13.3 Reliability

It is inevitable that feet will collide with and get stuck on obstacles. More than other parts of the robot, the feet need to be durable and robust. Foot sensors need to be protected from collisions, and moving parts should be enclosed.

Reliability is a big problem with Attila's feet. The springs and wires are exposed, and easily get caught on obstacles and broken. The sharp corners also get stuck, which damages the feet.

CHAPTER 14: CONTROLLERS

14.1 Attila

Besides the kinematics and actuator selection, another facet of leg design in the computer and electronics that control it. On both Genghis and Attila the motors are driven with pulse width modulation (PWM). The drive signals are generated by a microprocessor, and then passed through an H-Bridge driver.

For Attila's legs, Signetics 8751 processors were selected because they have an on-chip communication network, the I^2C bus. The servo loop for Attila uses proportional control, with some velocity and integral effects, but not true PID control. The servo loop allows some velocity control as well as position control. Force control was not implemented because it was too complicated for the 8751 processors, and the strain gages do not provide reliable enough data.

The motor drivers on Attila's legs are Motorola MPC1710As. These chips were selected because they are small, low power, and have a brake mode. The maximum current output is 1 Amp continuous, but the motors are capable of drawing 3 Amps. Because of this difference, the maximum torque of the motors is limited by the driver chips, not by the mechanics of the leg. A motor driver with a greater current capacity would make the robot stronger, without changing anything mechanical.

Besides motor control, the leg processors are responsible for gathering sensor data and relaying it to the master processor on the body. Attila has fifteen sensors on each leg: 3 potentiometers, 3 velocities, 3 strains, 3 peak strains, 2 infrared proximity sensors, and one ground contact sensor.

The software to control the motors, gather sensor data, and communicate with the master processor is all the 8751 can handle. All of the robot's behavior is programmed in the master processor, which simulates a separate processor for each leg. Because the I^2C bus has turned out to have insufficient bandwidth, the 8751 should not be used on future robots.

14.2 My Controller

For my experiments, I used a Motorola 6811 microcontroller. This chip is well suited to robotics applications because it has on-chip analog to digital conversion, and several programmable timers. The 8751 on Attila's legs requires an external A/D converter, and only has one timer, which makes the PWM code more complex.

On my controller, the servo loop and PWM generation software is totally interrupt driven, and runs in the background. I used straight proportional control to demonstrate the kinematic capabilities of the Ashley Richardson legs. (See Chapter 12) The PWM and servo code is simple, so plenty of processor power is available for higher-level software.

The motor drivers I used were LM293B H-bridges. They also did not supply enough current to the motors.

14.3 Suggestions for Future Work

The idea of having a microprocessor on each leg is a good one. For future walking robot projects, 6811s would appear to be the processor of choice, because they have multiple timers, on-chip A/D conversion, and can support external memory. New versions of the 6811 have PWM generation in hardware, which would simplify the motor control software further. These chips would allow the leg processors to do some high-level control in addition to servo code.

For example, each leg could be independently responsible for finding its own footholds and avoiding obstacles. This would free the master processor to make high-level decisions like “Should I go around this rock, or climb over it?” Distributed intelligence would require more communication between the legs, so a communications network with more bandwidth would be required.

Another option for reducing demands on the leg processors would be to design circuitry to do the servo loop and PWM generation in hardware. This is a less attractive alternative because it would require more electronic components and larger circuit boards.

CHAPTER 15:
CONCLUSIONS AND FUTURE WORK

15.1 Leg design for future robots

The results of this project indicate that the next small walking robot should be built with a sprawled stance and different front, middle, and back legs, like the robot shown in Figure 15.1. The sprawled stance makes walking on slopes easier, and different leg designs allow optimizing each leg for how it is used.

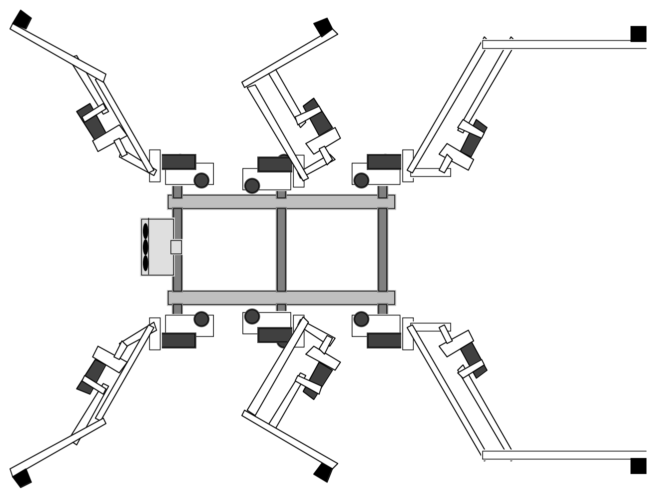


Figure 15.1: A robot with a sprawled stance

A fourth degree of freedom, like the one on Attila, can give the legs a different climbing mode for traversing difficult terrain. The fourth DOF for the front two legs should be independent of the back four. This would simulate the extra DOF of the front legs in cockroaches. An alternative would be having a hinged body that bends between the front and middle legs. These two options are shown in Figure 15.2. If space and weight permit, making the fourth DOF independent for each leg would give the robot more flexibility, but would complicate the control software.

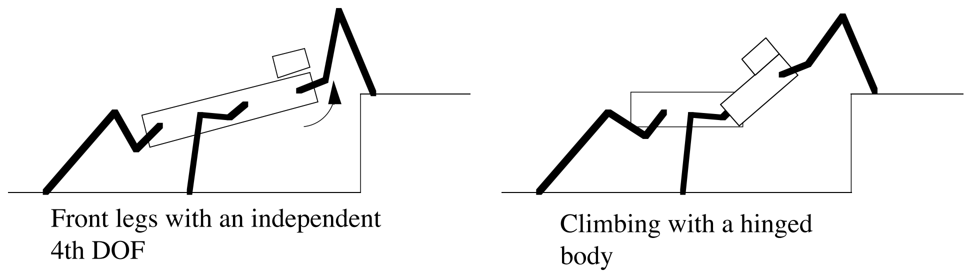


Figure 15.2: Two options for better front leg mobility

With legs similar to the Ashley Richardson legs, there are two ways to solve the linear step problem. Using linear actuators, like small hydraulics, would produce linear steps, because the 4-bar linkage would act as a pantograph. (See Figure 12.9) The second solution would be a sensor at the hip to measure lateral forces on the body, and control software to minimize these forces.

15.2 Other changes for future robots

Both of the walking robots at the MIT Mobile Robotics Lab have been built out of aluminum, and actuated with DC gearmotors. Because walking robots require low speed, high force actuators, gearmotors might not be the best choice. It might be possible to improve performance by using small hydraulics, or other linear actuators. The biggest challenge for building a hydraulic actuation system is that small, low-power valves would have to be custom made.

Using a different structural material could also save weight. Fiber reinforced plastics, like fiberglass or carbon fiber composites, have a much higher strength to weight ratio than aluminum. They also can be made into any shape without expensive machining. One possible way to make leg links out of a composite would be to carve foam molds for the links, cover them with a composite, and then use a solvent to burn out the foam. The result would be a thin walled, hollow link of any arbitrary shape. (See Figure 15.3) Sensors, like strain gages, and wires could be encased inside the composite, which would protect the electronics, and allow more versatile sensor mounting.

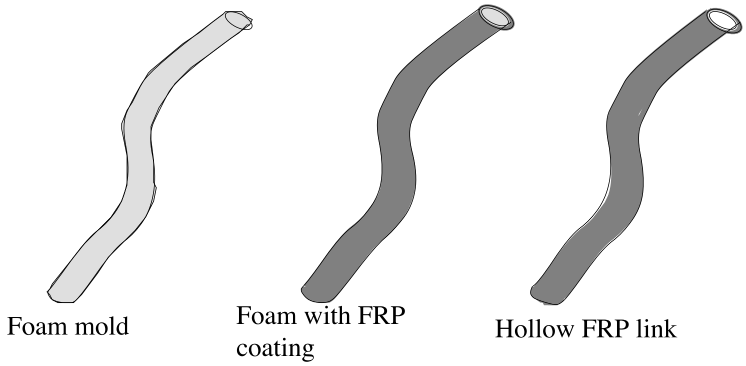


Figure 15.3: Making Fiber Reinforced Plastic (FRP) leg links

Two of the most important aspects of robot design are sensors and the integration of the entire system. These two issues were the focus of the Attila project, which included several important advancements. Many of Attila's sensors are redundant, so in case a sensor fails, he can use another instead. Attila also uses this redundancy to verify sensor data. Attila's control software is distributed over ten separate microprocessors, which all communicate on a local-area network. These ideas should definitely be included on future walking robots. Microprocessor and sensor technology is always improving, so more options will exist for future robots.

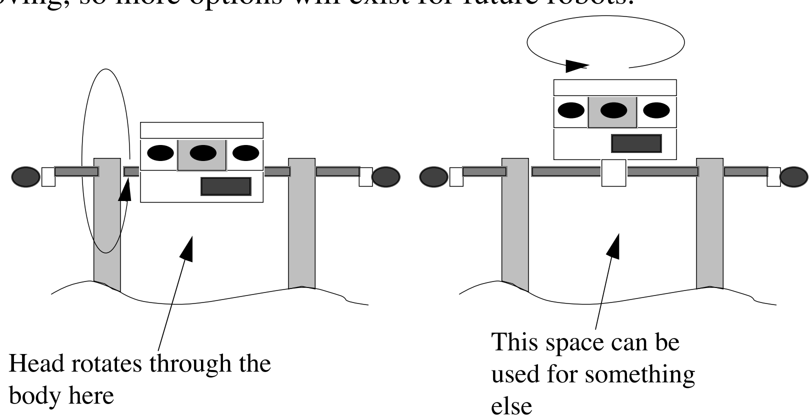
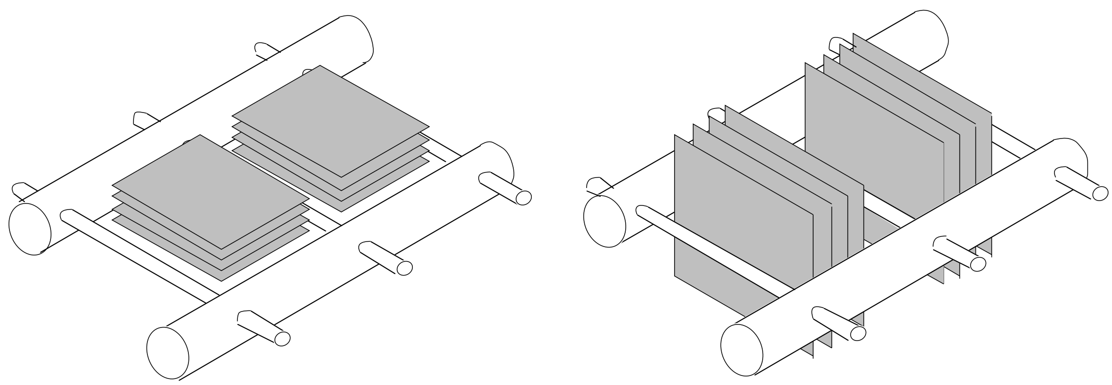


Figure 15.4: A better way to mount the robot's head

One advantage of Attila's body is that it is completely invertible. When the robot falls on his back, he can rotate the legs around 180 degrees with the fourth DOF, and walk away upside-down. The head and inertial guidance system rotate with the legs. This design could be improved by mounting the head in front of the robot, so it does not have to rotate through the body. (See Figure 15.4)

Another minor improvement that could be made over Attila's body is to mount the circuit boards vertically. The circuit boards on Attila's body lie flat, and stack on top of each other, which makes debugging and removing them difficult. The robot would be easier to test and repair if the boards mounted vertically, next to each other. (See Figure 15.5)



On Attila, the PC Boards are stacked on top of each other

If the PC Boards were vertical, testing and removing them would be easier

Figure 15.5: A better way to mount circuit boards

15.3 Conclusion

Small walking robots are a relatively new invention, and current efforts are still at the beginning of the learning curve. The approach at the MIT Mobile Robotics Lab has been to build robots that can navigate over unstructured, difficult terrain. The first walking robot, Genghis, succeeded in demonstrating the validity of Brooks' subsumption control.

The second generation robot, Attila, was designed to traverse more difficult terrain than Genghis, and have vastly improved sensing abilities. Significant advancements were made in sensor and system integration, as well as some important mechanical improvements.

Like many robots, however, Attila was limited by his mechanical systems and reliability problems. The goal of my thesis was to look at one facet of the robot's mechanical design in detail, the legs. I concluded that legs with high strength to weight ratio, good traction, and a sprawled stance would improve mobility and simplify control software. The Ashley Richardson legs are prototypes of a mechanism that could be used, with different link lengths, for front, middle, and back legs, on a sprawled-stance walking robot.

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