Design of an Artificial Creature

by

Colin M. Angle

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Abstract

The design of a complete robotic system is described. This robot, Attila, is meant to be a general exploring creature, able to traverse rough terrain and climb steep slopes. In order to achieve this goal, a small six legged robot was designed and built. It weighs approximately 6.5 lbs, is 14" long, and uses 23 motors to drive its legs and other systems. It uses over 150 sensors of 14 different types to provide information concerning the terrain it is traversing, its configuration, and its health. The robot is controlled by a network of eleven microprocessors. In order to control complexity on the robot, the system was broken down into six subsystems which were designed and tested independently. This structure also allows for easy future expansion and improvement.

Thesis Supervisor: Prof. Rodney Brooks

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Acknowledgements

Attila is a tribute to the MIT ARTIFICIAL INTELLIGENCE LAB. Its open and sharing atmosphere made it possible to complete this overly ambitious project. Special thanks to my thesis advisor Rod Brooks for believing enough in me to allow me to take on the building of Attila, for dedicating the substantial amount of lab resources required for the project, and for taking on the "mere" matter of programming the beast. Many thanks to Cynthia Ferrell, Olaf Bleck, Chuck Rosenberg, Mike Binnard, and Deniz Yuret for all the enthusiasm and effort they put into building many of the subsystems on the robot. Without their help, Attila would not have been possible. Thanks to Dave Barrett, Eric Vaaler, Andrew Christian, and Inaki Garabieta who patiently taught me more practical mechanical engineering knowledge than I learned in my entire undergraduate education. A warm thanks to Anita, Ian, Jerry, Boo, Roger, Maja, and the rest of the wonderful people in the AI lab who make it a place where wild ideas become reality.

I would like to sincerely thank my entire family for their continuing support of my escapades at MIT. Finally, thanks to my loving wife Jill. Without her support, advice, patience (lots of patience), this thesis would not have been possible.

Dedicated to my wife Jill.

Wow, our first kid! (twins actually)

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Chapter 1
Introduction

THE DESIGN OF AN ARTIFICIAL CREATURE

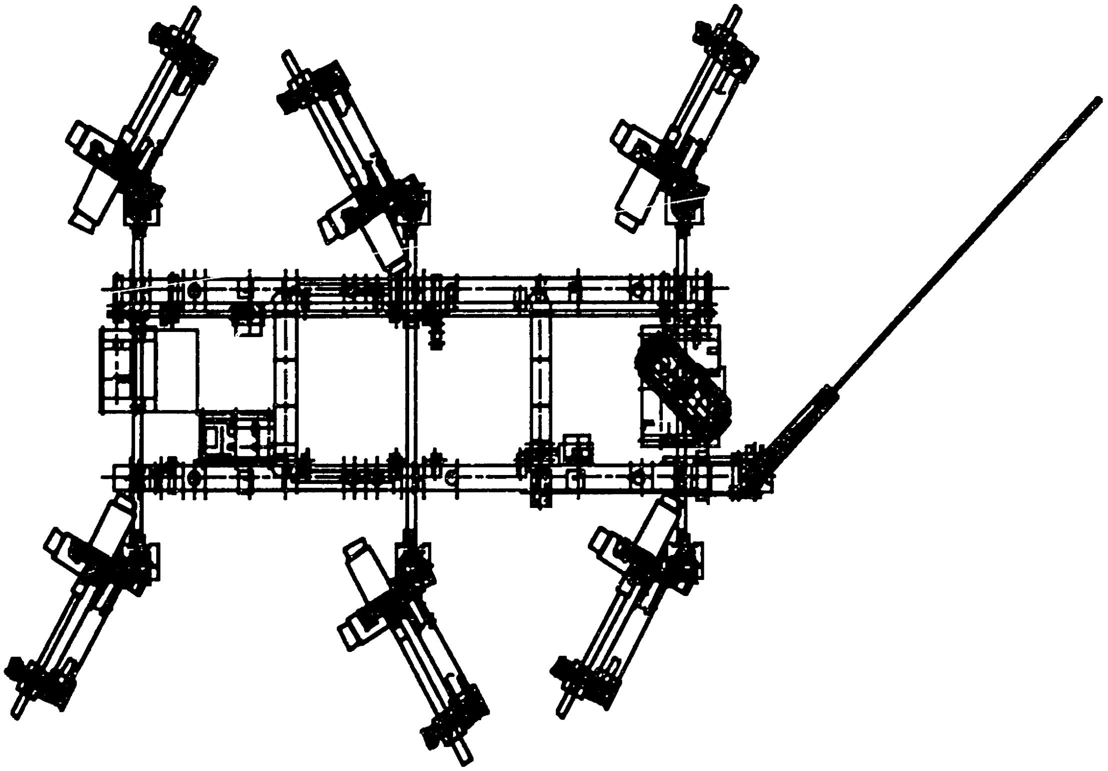


Figure 1.1 The Attila walking robot

We have all seen robots such as R2D2 or C3P0 in the movie "Star Wars." They were real creatures displaying emotion, understanding the world around them, travelling all over the galaxy exploring new worlds, and having their own adventures. Unfortunately robots such as those do not yet exist in reality. For sure, there have been many attempts to build robotic systems, but the emphasis has not been on building complete creatures, it has centered on building innovative mechanical designs, researching control problems, or investigating new sensors. I feel that the time is ripe to pull together various robotic technologies in order to create complete autonomous systems, or as I call them "artificial creatures."

A robot is a collection of actuators, sensors, and controllers which purposefully operate in some type of environment. The concept of an artificial creature is a refinement on that notion. It is a machine which "lives" in *our* environment. It has a general set of sensors which allow it to characterize the world around it in sufficient detail to determine where safe places are. It is endowed with sufficient dexterity and mobility to allow it to break out of the highly constrained environments, which have been the prison of many robots, and explore real world environments from offices and stairways to rocky mountainsides and forests.

The concept of "living" goes beyond mobility and sensory systems. In order to qualify as an artificial creature, the machine must not rely on humans for its minute to minute operation. It must be able to self-calibrate its sensors and even realize when a sensor has gone bad.

The Mobile Robotics (Mobot) Lab at M.I.T. has been working toward the construction of artificial creatures for many years. Allen, the first robot built at the lab, showed that large off-board computers were not required to control behavior-based systems [Brooks 86]. Herbert, a robot whose purpose was to collect soda cans, demonstrated how complex tasks could be accomplished by breaking the task down using many simple sensors and simple control laws [Connell 90]. Several other robots were built through which techniques to improve a robot's reliability were developed.

Genghis, the predecessor to Attila, was built to investigate the mobility advantages of a walking robot and for use as a testbed for Brooks's Subsumption Control Architecture [Brooks 89]. Genghis's legs proved to be remarkably good sensors and allowed the robot impressive mobility. However, the robot suffered from an inability to handle steep terrain, and the sensors which it carried were very limited [Angle 89].

The Attila project is an attempt to expand the sensory and mobility capabilities of Genghis and, in doing so, create a robot that could be rightfully called an artificial creature. In order to begin, we have come up with a set of goals which an artificial creature should meet. The following goals have been identified for the Attila robot. These goals are grouped into locomotion requirements, sensory requirements, and system requirements [Angle and Brooks 90].

Locomotion Capability Requirements

-The robot must be able to locomote over rough terrain. This includes both outdoor terrains such as mountain slopes and forests, and indoor terrains such as offices and hallways.

-The robot must be able to climb. It should be able to handle slopes in excess of 60 degrees and be able to make a step high enough to climb 8 inch stairs.

-The robot must be tolerant of falls. In particular, it should be able to recover from a fall onto its back.

Sensor Capability Requirements

-The robot must be able to sense its supporting terrain well enough to ensure its safety.

-The robot must be able to sense its environment well enough so that its actuators can reliably produce locomotion.

-The robot must be able to sense the environment ahead well enough to plan paths around or over obstacles.

System Requirements

-The robot must be able to be developed incrementally. Each subsystem should be able to be designed and debugged separately from the others.

-The robot must be built in such a way that new systems can be added and old systems can be replaced quickly and easily.

The remainder of this thesis is broken up into the following chapters. Each of the chapters deals with satisfying a set of the above goals.

Chapter 2 - Why a Small Walking Robot? Chapter 2 investigates the reasons for choosing Attila to be a very small legged robot as opposed to a larger robot, or a wheeled one.

Chapter 3 - Leg Kinematics. Chapter 3 explains the decisions behind the kinematic design of the legs. Design goals are established, and a design is arrived at which satisfies these goals at the desired scale. The forward kinematics of this leg are also included.

Chapter 4 - Leg Loading. Chapter 4 deals with modelling the weight of the robot and deriving the forces and rate requirements at the leg joints in an effort to choose the actuators for the robot. The strength of the leg is also calculated to ensure that it can handle the weight of the robot.

Chapter 5 - Climbing and Inclination. Chapter 5 looks at the effect of inclination on the robot's stability and leg loading. It also examines what it means to be a good climber. Two methods of improving a robot's stability during climbing are investigated. The method Attila uses, vertical leg servoing, is shown to provide superior stability as well as the ability to recover from falls to the robot's back.

Chapter 6 - Sensors on a Legged Robot. Chapter 6 describes Attila's hierarchical layering of sensors that help ensure the robot's safety. Two examples are given showing how Attila's multiple sensors can be used together to solve a task without jeopardizing the robot by allowing a higher level, less reliable sensor alone control the robot's fate.

Chapter 7 - Connectors, Modularity, and Computers. Attila is a complex robot. Chapter 7 illustrates some of the problems that this complexity causes and how modularity, local control, and a smart subsystem architecture were used to solve these problems. Chapter 7 also includes a summary of the smart subsystems on Attila.

Chapter 8 - Summary and Future Work. Chapter 8 contains a roundup of the major points contained in each chapter. It also looks at the problems of time estimation and identifies some areas of future development for Attila.

Chapter 2

Why a Small Walking Robot?

CHOOSING THE ROBOT'S SCALE

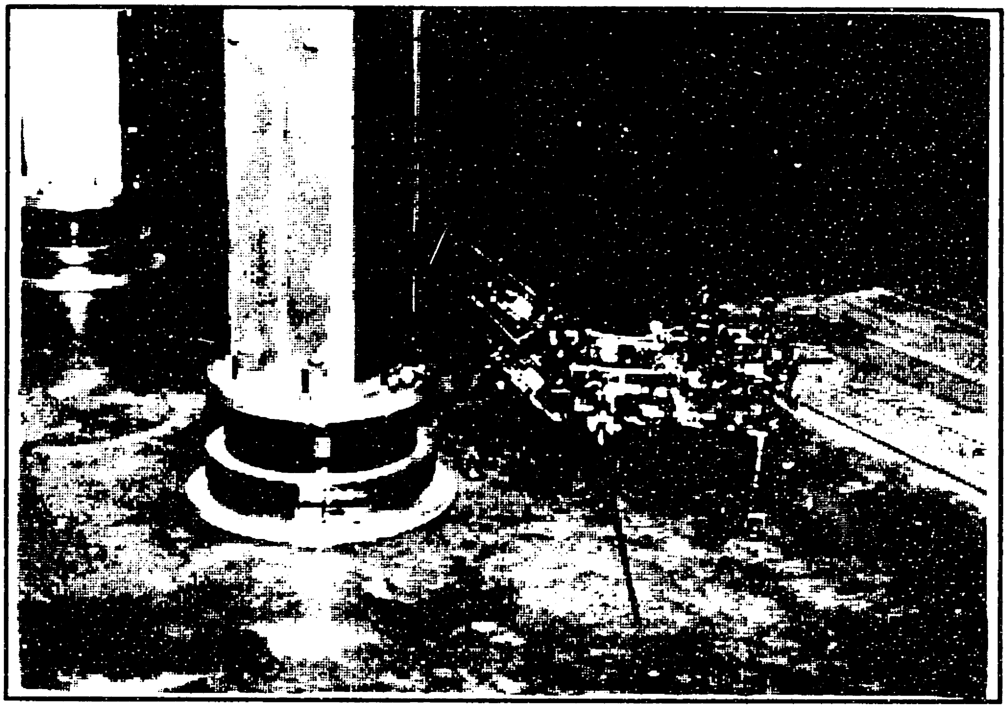


Figure 2.1 Walking robots of dramatically different scale
On the left is the foot of the Carnegie Melon Ambler hexapod walker. Attila is standing on the right.

How big should a robot be? It seems reasonable that the larger the robot is, the more "stuff" you can put on it. A larger robot should also, it would seem, have a much easier time traversing rough terrain. These two points, however, are not totally accurate.

It is hard to argue the first point directly, for it is certainly true that the bigger a robot is, the more space there is to put things. The question is, is all this space necessary given today's trend towards miniaturization? Cameras which were once 2 feet long are now 2 inches long, or smaller. The advent of micro controllers has brought powerful computational capabilities down to the miniature scale. Also, there has long existed plenty of small motors to drive a small robot. So, it is very possible to fit in a tremendous amount of computational power, sensing ability, and actuators in a tiny package. In most cases, if the designer is willing to look for small systems, it is possible to satisfy the computational and sensory requirements of a given robot at a very small scale. The robot Squirt, developed at the Mobot Lab, combined a microprocessor, an actuator, batteries, and sensors to allow it to find dark places and move toward noise, all at a size only slightly bigger than one cubic inch [Flynn et. al. 89].

Some tasks involve transporting material or forcefully altering our environment, and thus require massively sized robots to accomplish them. These robots, however, do not fall nicely in the category of artificial creatures. They are more like machines. Humans are not very adept at carrying huge loads or knocking down walls, so why should this be a requirement of an artificial creature? If it needs to perform one of these tasks, it could, perhaps, climb into a huge dump truck or crane and operate that. When that task was completed, it could get out and do something else. In this way the artificial creature could haul tons of gravel one day, and fly to the moon the next -- without having to bring its dump truck along with it!

The argument that larger robots are more mobile than smaller robots is not as true as it might seem. For a walking system, there are three classifications of terrain: terrain which can be traversed normally, terrain which must be climbed over, and impassible terrain.

Normally traversable terrain. Normally traversable terrain, represents terrain with obstacles which are smaller than the step height of the legs of the robot. It does not matter the shape of the obstacle, the robot simply can step over it. For a person, such terrain would include fields and plains.

Climbable terrain. Climbable terrain is terrain which contains obstacles too large to step over, but not so difficult to step up onto and then over. This terrain is, in essence, normally traversable terrain tilted at an incline less than the maximum inclination a system can handle. At a human scale, hills, large boulders, mountains and even many cliffs, for skilled rock climbers, fall in this category.

Impassable terrain. The third type, impassible terrain, includes obstacles which require either a step height greater that that of the walking system attempting to cross the terrain, or moving up an elevation too steep for the walker. In either case the only way past such an obstacle is to go around. For humans, sheer cliffs are impassable to all but the most elite rock climber.

This said, large systems still seem to have obvious advantages. For example, table 2.1 compares the categorization of the terrain classes for an Attila-like robot, and for a dramatically larger walker such as the CMU Ambler [Bares et al 89].

Terrain Catagory	7" tall Attila	15' tall Ambler
normally traversable	obstacles <9"	obstacles <38"
Climbable	<70% slopes	<60% slopes
Impassable	>9" obstacles >70% slopes	>38" obstacles >60% slopes

Table 2.1 Classification of terrain types for two robots of different scale

The terrain which the robots see, however is very different. Consider, for example the terrain shown below in figure 2.2.

Figure 2.2 Rough Terrain

To a 15' high, 10' wide walker, the terrain shown in figure 2.2 consists of 3' high boulders which it can step over. To a 7" high 10" wide walker, the terrain looks dramatically different. The vertical boulders are well out of reach and impassable, but there exist some boulders which can be climbed up, and from those the bigger boulders are reachable, and the robot can make it over. Another option for the small walker would be to take full advantage of its small size and walk between the large boulders, and face a terrain which includes small rocks and pebbles all less than 8" high. By choosing this route, it can traverse the terrain without even having to climb.

We have all seen tiny animals climbing up steep slopes which we could never climb up. One reason for this is that the animals are at a smaller scale. Their bodies are smaller, their legs are smaller, and their feet are smaller. Thus, when climbing, the footholds which they need to find are nothing more than cracks, or small indentations. Small robots, just like small animals can take advantage of their reduced foothold requirements. A small robot may well be able to scale a steep slope on which a larger robot couldn't find a single foothold. This is illustrated in figure 2.3.

All in all, the size of terrain obstacles in nature seems to change dramatically as you look at it from the perspective of a small scaled system. A big system's rock to step over may be a small system's mountain to climb up, or impassible object to go around. A small system's slope to walk up, or pass to walk through, may be a large system's impassable cliff, or meaningless gap between rocks.

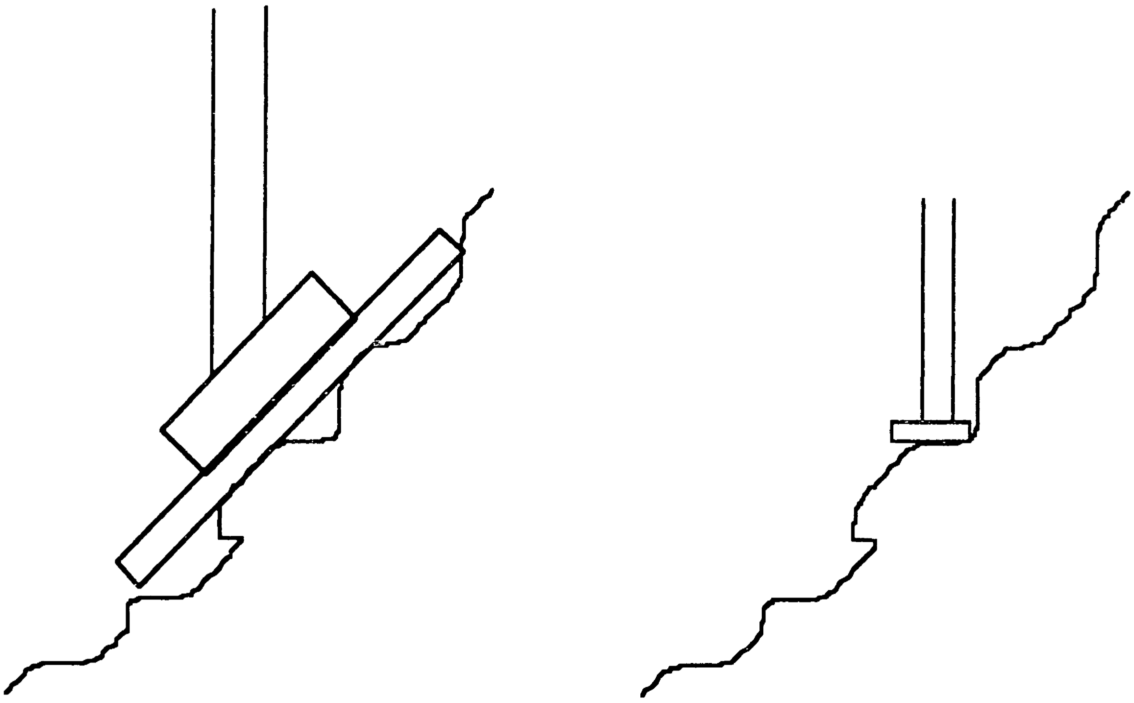


Figure 2.3 A smaller foot might have an easier time finding footholds

The point of this investigation into terrain and scale is not to prove that smaller systems have better mobility, for we certainly cannot claim to have proven anything conclusively here. The point is that given the goal of achieving great rough terrain traversing ability, building an enormous system with large a step height is not necessarily the only or best approach. Nature contains examples of this point: a cat can get to far more places than an elephant, horse, or even a dog.

A small scale robot enjoys many other benefits. On the mechanical side, small robots benefit from a favorable strength-to-weight ratio, reduced dynamic effects, and lower power requirements. On the practical side, they are cheaper to build, do not need large areas to develop and test, will not hurt anyone if they malfunction, and best of all, you can carry them around in a suitcase.

The strength-to-weight ratio is the biggest win for small robots. Simply stated, the strength of a structure scales by its cross sectional area, while the weight of that structure scales by its volume. As a structure is proportionally scaled up, its weight increases much more quickly than its strength does. This means it is relatively easy to make a small structure very strong with very little mass, while large systems are often both tremendously heavy and fragile.

For example Attila could fall down every other step while walking, continuously picking itself up and continuing. If a large walker, like Ambler, ever fell, it would be catastrophic. This fact translates not only into better system robustness for Attila, but also easier control. The control system running Attila does not have to worry about an occasional step which might cause it to fall. In contrast, the control system of Ambler must guarantee that this never happens.

The low robot mass enabled by the small scale has many positive side effects. With some effort the legs can be made to have extremely low inertias. This greatly simplifies their control. The light weight of the entire robot also allows for the use of smaller, lower power motors. Large robots must make severe tradeoffs between speed and force. Despite being hundreds to thousands of pounds smaller than other walkers, Attila, with on-board batteries, can move at comparable speed to larger robots with on-board batteries, and within 1 order of magnitude of those with on-board internal combustion engines, or off-board electric power supplies [Pugh et. al. 90], [Carlton and Bartholet 87], [Hirose 84], [Bares 90], [Ozguner et. al. 84].

LEGS VS. WHEELS

Much has been said concerning the relative mobilities of wheeled and legged systems.[Waldron et. al. 84] [Hirose 84] [Hodgins 88]. Entering this debate in any quantitative way is beyond the scope of this thesis. In designing an artificial creature, however, we set forth a mobility goal. The creature is to operate in many different terrains including those made by man. The ability to climb up stairs, curbs, and steps is paramount to mobility in a man made environment. A legged robot can accomplish this task at a smaller scale than can a wheeled robot.

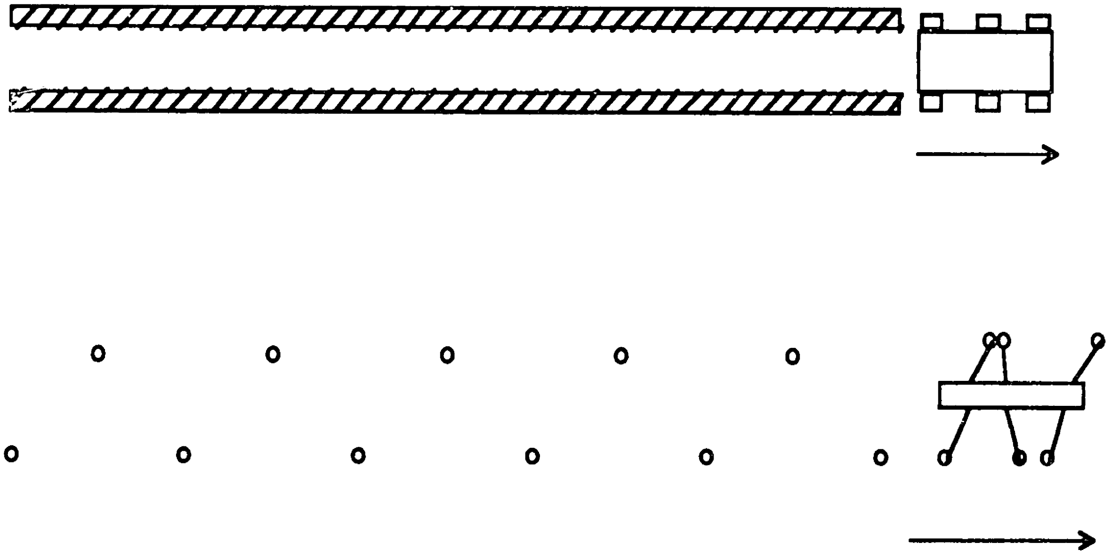


Figure 2.4 How much do you have to sense?
This figure shows the amount of terrain actually stepped on or rolled over in the course of moving forward.

There are several other advantages legged systems have over wheeled systems. The most important of which is the inherent sensing ability of the legs themselves. The ability of a leg to sweep through and step in its environment can yield huge amounts of terrain information. Even with the crudest of sensors, Attila's predecessor, Genghis [Angle 89], was able to detect obstacles and roughly sense their height and width. Any sensor which is mounted on a leg has its utility magnified because it can be moved around and aimed directly at various terrain features. Figure 2.4 shows another advantage of walking robots. A walking robot only uses discrete points of support.

In order to ensure safe motion for a robot, it is necessary to know that the terrain which the robot is moving onto will support the weight of the robot. Range sensors, while of some use, cannot provide this information reliably. What is needed is an antenna to reach out and test the exact terrain the robot is going to use for support. This is difficult for a wheeled robot since a wheeled robot rolls over a continuous path of terrain. A statically stable walking robot, however, can use its own legs as sensing antennae. Each foot can probe its new foothold before it is required to support the weight of the robot. If the desired foothold is not found, the leg can hunt around for a new foothold. Once a foothold is found, the robot can advance. If no acceptable footholds are found, the robot can retreat and try a different path.

Legs also offer great flexibility. A legged robot such as Attila could move in any direction, forward, backward, or even sideways, if it was needed. Legs can be used for many things other than locomotion, such as pushing rocks together to make a cairn, or moving an object out of its way. There are countless small tasks such as these which would allow a legged system to succeed where a wheeled system would fail.

Chapter 3
Leg Kinematics

OVERVIEW OF GOALS

There are many different ways to determine how good a leg is. This chapter will enumerate the design goals for Attila's legs, discuss the design decisions made, and show a kinematic design which attempts to meet the goals.

Attila is meant to be a small, quick, lightweight exploring robot. The following list of attributes has been identified as leg characteristics desirable to this end.

Large vertical step height. Vertical step height is the height to which the foot pad on the leg can be raised. The vertical step height determines the highest wall the robot can step over. For example, stair-climbing is a goal for the robot. Stairs are made up of many eight to ten inch walls. Thus Attila must have at least an eight inch vertical step height. While an eight inch vertical step height might be easily attainable for a six foot robot, in order for Attila, which stands approximately seven inches tall, to achieve it the step height must be made a primary design goal.

Minimized actuator loading. Achieving the desired step height cannot come at the cost of huge moment-arms which translate into big motor torque requirements. For example, in the leg arrangement shown in figure 3.1, from the Genghis walking robot [Angle 89], a large vertical step is achieved, however, in order to allow the robot to lift itself with that leg, the drive motor must have an output torque equal to the mass of the robot times the full length of the leg. The goal is to find a kinematic design which reduces the output torque required and thus allows for smaller drive motors.

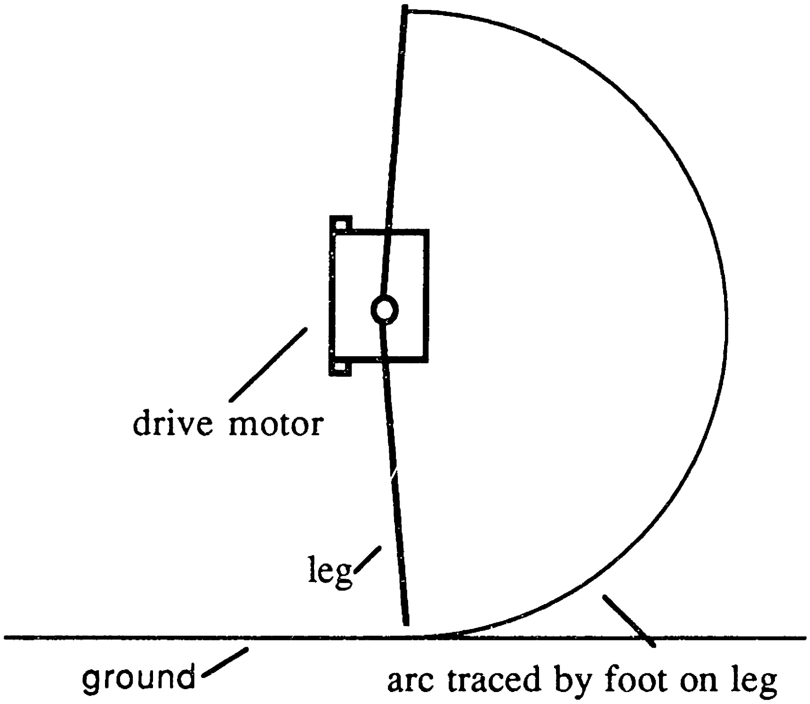


Figure 3.1 Step height of Genghis's leg
This simple leg can achieve a step height twice the length of its leg. The drive motor, however, must support the robot's mass with a moment arm equal to the length of the leg when the leg is horizontal.

Minimized dynamics. As the scale of a robot decreases, it must be able to move its legs more quickly in order to maintain the same speed as a larger robot. Thus it is necessary to minimize the inertia of the leg. A low inertia will allow simplified control and reduce the size that the leg actuators need to be in order to achieve a given velocity.

Small size. The goal is to build the smallest robot possible while meeting the other project requirements.

Three degrees of freedom. Three degrees of freedom is the minimum number to allow arbitrary foot placement on a surface. In traversing rough terrain, the robot must be able to place its foot anywhere it can find a foothold. A robot with three-degree-of-freedom legs is able to move in any direction (forward, backward, or sideways.)

Efficiency. The leg design should be such that a minimum of work is done against gravity while walking. The small scale of the robot does not allow for much extra power capacity on board.

DESIGN ISSUES

Designing a leg is like a puzzle. First you figure out what pieces you have to use and then fit them together to solve the puzzle you have defined. In designing Attila's leg, the first step was figuring out which actuators could best be used to meet the size and inertia requirements. Then the three degrees of freedom were chosen, keeping in mind both the design goals and the best set of actuators.

Actuators

The actuators found on legged robots can be broken down into two categories, linear actuators, and rotary actuators. Below is an attempt to characterize these actuators as they are used on legged robots.

Linear actuators. There are three main types of linear actuators: DC gear motor driven lead screws, hydraulic cylinders, and pneumatic cylinders. Linear actuators have two main advantages for use in legged robots. Their linear motion lends itself to simple cartesian leg designs or control strategies. Linear actuators can deliver tremendous force to a linkage with respect to its size and weight. On the down side, linear actuators do not scale well. It is not possible to find a recirculating ball nut less than a half inch in diameter, and while it is possible to find very small hydraulic and pneumatic cylinders, the servo valves required to control them are larger than DC motors which could replace the cylinder. Lead screws are also very susceptible to being gummed up and thus should be enclosed if they are to be used in a dusty environment.

Rotary actuators. The main type of rotary actuator used on robots today is the simple DC motor. DC motors can be very small in size, they are easy to control, and gearmotors (DC motors with integral gear boxes) are sealed to the environment. It is a problem, however, to find small gearmotors with high output torques.

Given that Attila needs both to be small and operate in potentially dusty environments, linear actuators should only be used when there does not exist a rotary actuator that meets the torque requirements.

Vertical axis first vs horizontal axis first

The next step in designing a leg is to choose the orientation of the first joint on the leg, the joint between the body of the robot and rest of the leg. It is this joint which is actuated to advance the robot when it walks. The joint can be oriented so that its axis of rotation is either horizontal (figure 3.2), or vertical (figure 3.3).

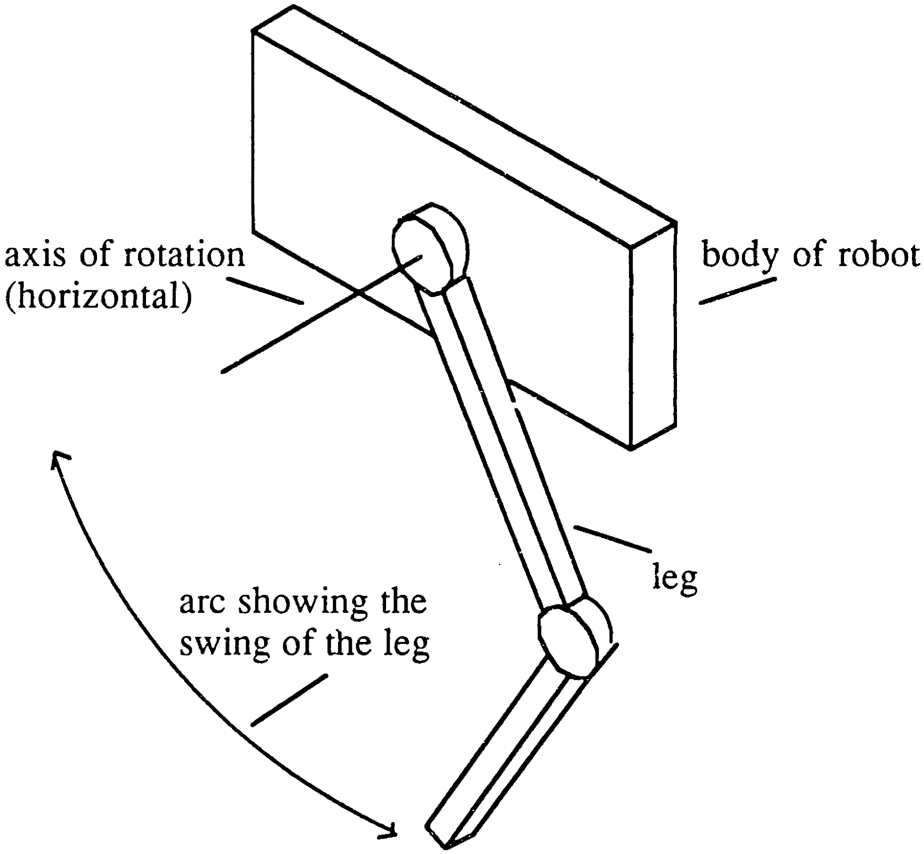


Figure 3.2 Leg with horizontal axis for the first degree of freedom

The main advantage of the horizontal axis first is that gravity can be used to aid the swinging motion of the leg as it walks. This arrangement is similar to the kinematic design of most mammals' legs. As such a legged system walks, its legs swing back and forth in an oscillatory motion. This motion is driven by gravity and, with very little additional power, walking can be achieved. [McGeer 90] These systems can also be narrower than their vertical axis first counterparts because the leg can swing along the length of the robot and not out away from the robot.

The main disadvantage of a horizontal axis first is that it is gravitationally loaded at all times. While allowing gravity to affect the prime moving degree of freedom helps reduce the energetic cost of swinging the leg during recovery, it also means that that same degree of freedom must bear the full weight of the system during stance. This forces that actuator which drives the first axis to do a great deal of mechanical work against gravity.

The first axis is the axis which moves the system forward when it walks. Thus, it determines the ultimate speed of the robot. By choosing this axis to be perpendicular to gravity, we may find some energetic benefit, but we also force that actuator to bear the weight of the system, as mentioned above. In practical terms, since both high velocity and high torque are required, the primary actuator must be much more powerful than any of the motors required to operate a vertical axis first kinematic leg design at an equal performance. It is interesting to note that of the walking robots designed to traverse rough terrain, the only two that have adopted this strategy have been powered by hydraulic actuators. These are the GE Quadruped [Mosher 69] and the Ohio State Adaptive Suspension Vehicle [Waldron et. al. 84]. This is probably due to the extreme force and velocity flexibility which hydraulic systems yield.

By choosing the first axis to be vertical, moving the robot forward can be decoupled from gravitational loading. As seen in the figure 3.3 above, the gravitational loading of the leg is supported by the bearings in the first axis. Although this decoupling means that the leg is unassisted by gravity in swinging back and forth, if the leg is made to have a low inertia about the first axis, it can still move very rapidly with a small motor.

The vertical axis first leg design is superior to the horizontal axis first design at Attila's scale. The decoupling of the swinging motion of the leg from the lifting motion of the leg allows for the use of a weaker, faster motor to drive the swing, while a slower more powerful motor can drive the lift. This is important because a motor which could both swing the leg and lift the robot, such as would be required by a horizontal axis first design, would not be able to meet the size and weight specifications for Attila.

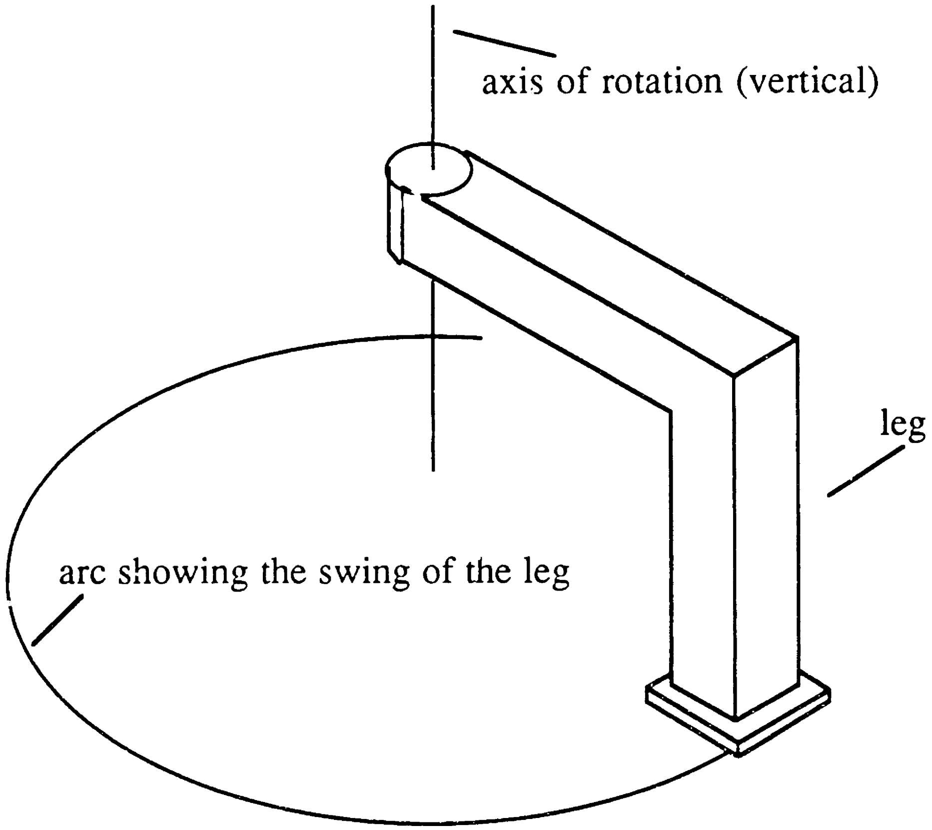
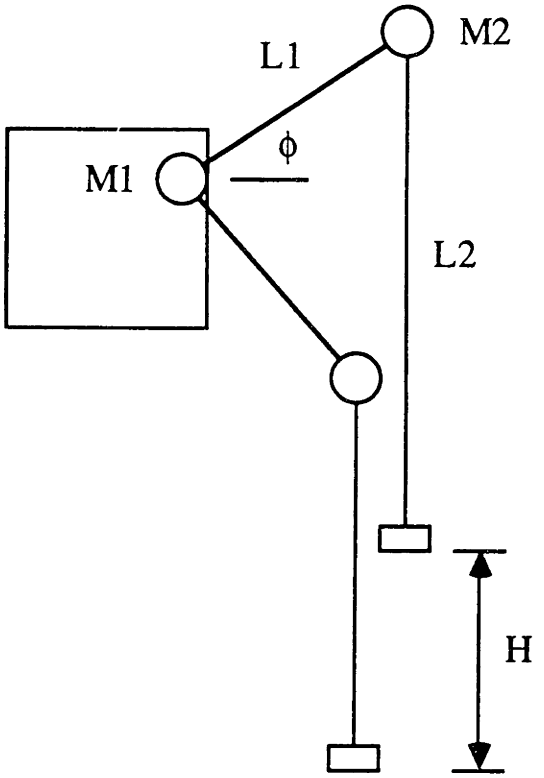


Figure 3.3 Leg with vertical axis for the first degree of freedom

Achieving large step height

As mentioned in the earlier, a goal is to allow the leg to make a very high step while minimizing the size of the motors required. From our three degree of freedom design criteria we determined that the leg must have at least two links as shown in figure 3.4. Given these two links, we examined the possible configurations to achieve the desired step height with minimum torque requirements.



ϕ = the leg angle physically constrained to be within +/- 45 deg.

L1 = length of the first link

L2 = length of the second link

M1 = rotary actuator between leg base and L1

M2 = rotary actuator bewteen L1 and L2

H = step height

Figure 3.4 Simple two link leg with vertical second link

The leg in figure 3.4 is a first attempt to meet the design criteria. The labels used in this figure for the components of the leg will be referred to throughout this chapter. M1 is used to raise and lower the leg. M2 provides a second degree of freedom, although in this example it only servos L2 to remain vertical. A constraint is placed limiting ϕ to +/- 45 degrees. This is because as ϕ increases or decreases away from zero, the foot moves closer and closer to the first vertical axis discussed above. This results in less forward motion in each step cycle. If ϕ was allowed to go to +90 degrees or - 90 degrees, there would be no forward motion. With this angle constraint, the following equations characterize the step height and loading of this leg.

$$H, \text{step height} = L1\sqrt{2} \quad \{3.1\}$$

Therefore, in trying to achieve an 8 inch step height:

$$L1 = 8'' / \sqrt{2} = 5.6''$$

$$\text{Maximum loading} = L1 * \text{mass of robot} \quad \{3.2\}$$

This configuration seems unacceptable since a 5.6 inch crossbar is not consistent with the desired scale. Such a long crossbar also forces M1 to support an unreasonable load for a small DC gear motor. Chapter 4 will discuss the limitations of actual gear motors in more detail.

If the constraint that L2 be vertical is removed, the step height, H, is no longer solely dependant on L1 and it becomes possible to reduce the length of L1 as shown in figure 3.5.

Again ϕ is constrained to +/- 45 degrees, but by allowing the second link to swing up, the first link can be made much shorter as shown in the equation below.

$$\text{step height} = L1\sqrt{2} + L2 * (1 + \sqrt{2}/2) \quad \{3.3\}$$

If we choose L1 = 2.75", which is consistent with the robot's scale, then it is possible to meet the 8" step height goal.

$$L2 = (8'' - L1 * \sqrt{2})/(1 + \sqrt{2}/2)$$

$$L2 = 2.4''$$

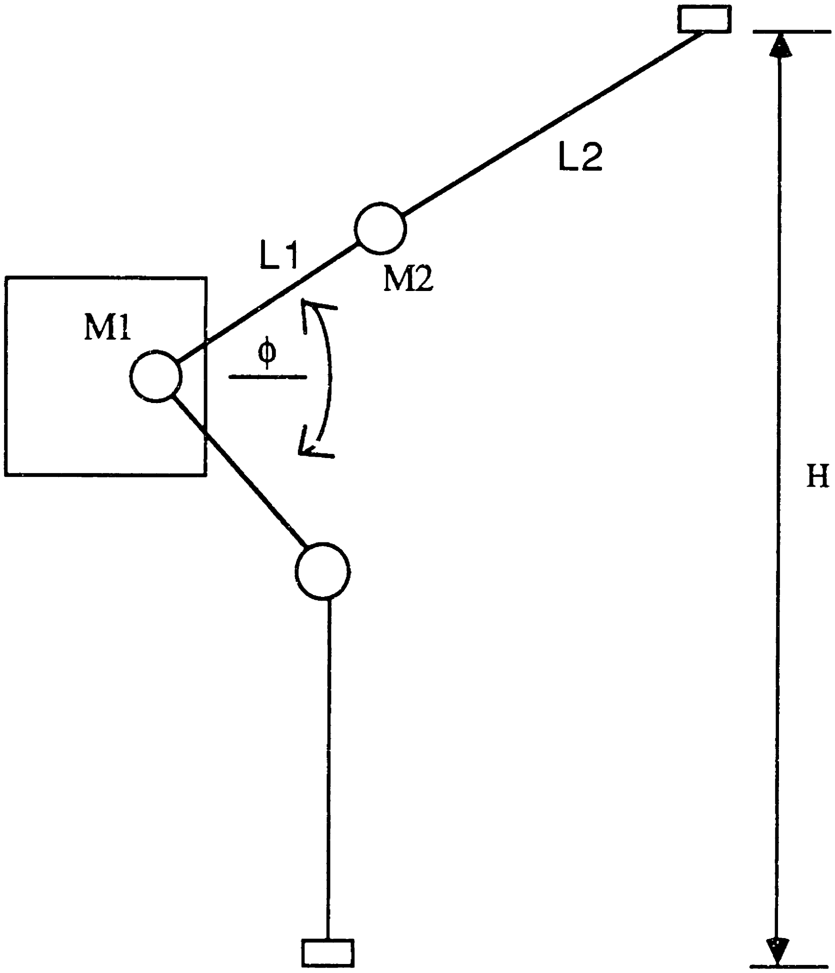


Figure 3.5 Simple two link manipulator

This seems to improve things, but we are still faced with M1 having to support the weight of the robot using a moment arm equal to L1 + L2. It is here that we noted that simple walking and climbing are two very different activities. Walking does not require the foot to be lifted very high off the ground. Humans, in fact, barely lift their feet off the ground in normal walking [McMahon 84]. Climbing, on the other hand, requires very high lifting of the leg. This distinction between walking and climbing fits closely with the distinction between stepping motions where L2 is near vertical and where L2 must be swung up to raise the foot high. The point is that it is not a useful configuration to have L1 only partially raised when L2 is not near vertical. In other words, whenever the robot is climbing (L2 is being swung out), L1 will always be raised to its maximum height. With this knowledge, M1 can be decoupled from the climbing motion by using a mechanical stop to support any load on L1. This is shown in figure 3.6.

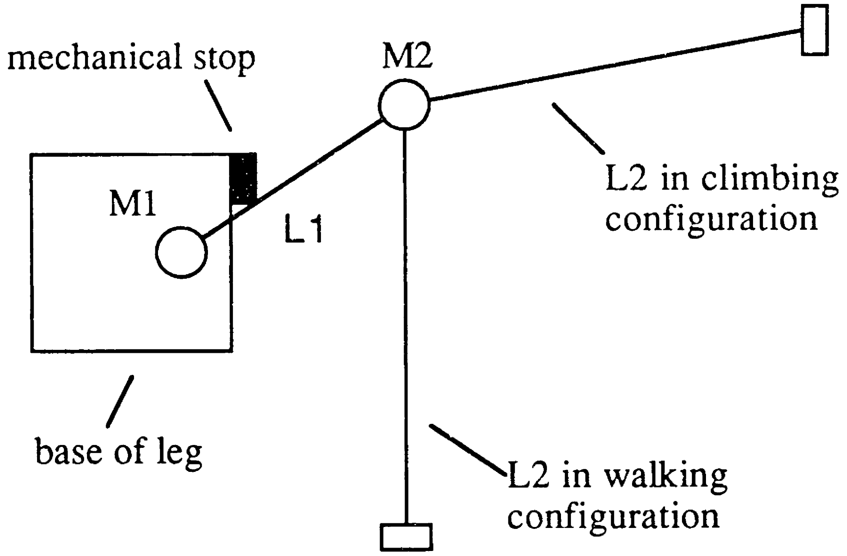


Figure 3.6 Using a mechanical stop to reduce torque loading on M1

The leg is shown here in two positions. The first, with L2 vertical, represents the top of the leg's workspace while in its walking configuration. While climbing, L1 remains against the mechanical stop which eliminates the torque loading on M1. This is because the mechanical stop will not allow M1 to rotate any higher.

At this point the problem of high torque on M1 has been solved as well as a kinematic design which allows for a large step height. The remaining problem is that M2 still sees very high torque loading while the robot is climbing. Since M2 only has to move L2 large distances when the robot is climbing, it does not have to be a high speed actuator. This is because, during climbing maneuvers, the robot must take extra care in insuring its footholds are solid and will have to spend extra time searching for each successive foothold.

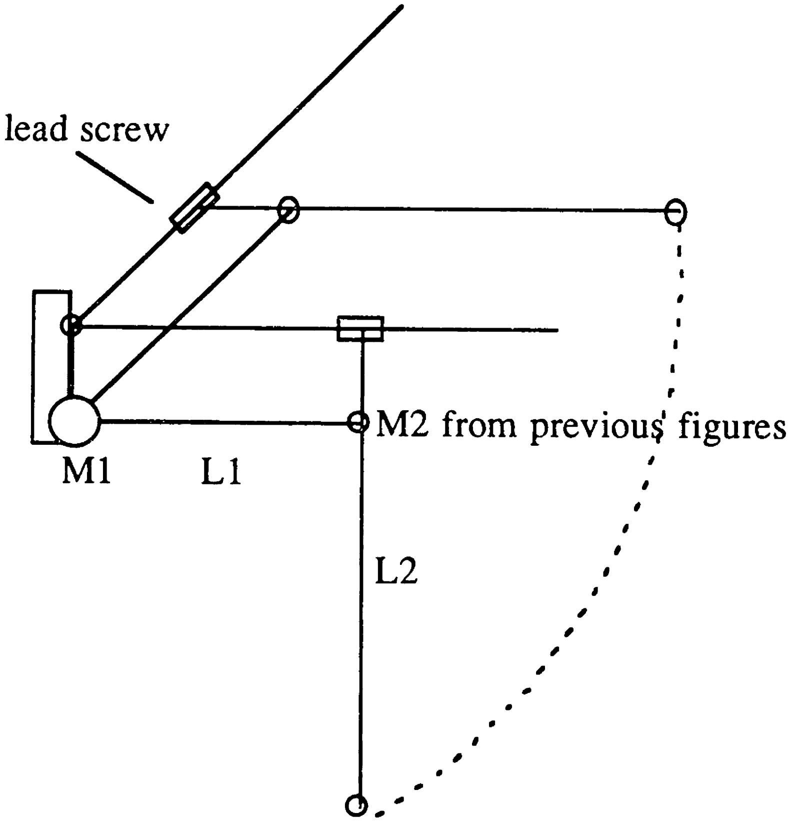


Figure 3.7 The final configuration of Attila's leg

Thus, the first approach to this torque problem would be to use a large gear motor for M2. This has two problems. First, there does not exist a DC gear motor which fits the size constraints and has a gearbox that is rated at a high enough torque for climbing. Second, if there existed such a gearbox, placing it at the joint between L1 and L2 would violate the constraint of maintaining low inertia. Thus, figure 3.7 shows a modified configuration of the leg in figure 3.6 which replaces M2 with a lead screw. A lead screw gives a very large effective gear reduction allowing the leg link to be driven very forcefully. The motor which drives the lead screw can be located near the leg's axis of rotation, thereby maintaining a low inertia for the leg.

CHOOSING LINK LENGTHS

Now that the configuration has been chosen for Attila's leg, all that remains is to choose the lengths of the members in the leg, specifically L1 and L2. The length of L1, or the leg crossbar, determines how far the robot will advance in a given step, how high the foot can be raised during normal walking, what the moment arm seen by M1 is, and how much physical space there is to mount control systems on the leg. The length of L2 determines the ground clearance of the body of the robot, the moment arm M2, the linear actuator, faces while climbing, and the amount of room there is to mount sensors on the leg.

Design issues	Making the crossbar (L1) longer	Making the crossbar (L1) shorter
step length	increases the step length (good)	decreases the step length (bad)
step height for normal walking	increases step height (good)	decreases step height (bad)
moment arm seen by M1	increases moment arm (bad)	decreases moment arm (good)
space to mount control systems	more space to mount systems (good)	less space to mount systems (bad)
bending moment under a given load	greater bending (must be big enough to measure)	less bending (must be less than ultimate yield)

Table 3.1 The pros and cons of crossbar length

Table 3.1 shows that, in general, making the crossbar longer has a positive effect on leg performance. The limiting factor is that the motor M1 must be able to handle the increased moment arm which a longer crossbar produces. Using Attila's predecessor, Genghis, as a model, the crossbar length was chosen to have half its maximum moment arm, thus allowing Attila to be twice as heavy. This choice made the length of the crossbar approximately 3 inches. This length satisfies all of the design issues above.

Design issues	Making the leg link (L2) longer	Making the leg link (L2) shorter
ground clearance	ground clearance improves (good)	ground clearance decreases (bad)
moment arm driven by linear actuator	moment arm increases (bad)	moment arm decreases (good)
space for mounting sensors	more space for sensors (good)	less space for sensors (bad)
bending moment	bending moment increases (must be big enough to measure)	bending moment decreases (must be less than ultimate yield)
step height	step height increases (good)	step height decreases (bad)

Table 3.2 The pros and cons of leg link length

The length of L2, the leg link, had fewer hard constraints on it than the crossbar. The use of the linear actuator to drive this link eliminated the worry that the moment arm would be too large for any reasonable length leg. The step height determination equation, equation 3.3, based on figure 3.5, is not easily physically realizable using the lead screw actuation scheme. The problem is that L1 and L2 cannot be made parallel as they are shown in figure 3.5. There is approximately a maximum 135 degree angle between the two. Figure 3.8 shows the physical limits of the angle on a final version of Attila's leg.

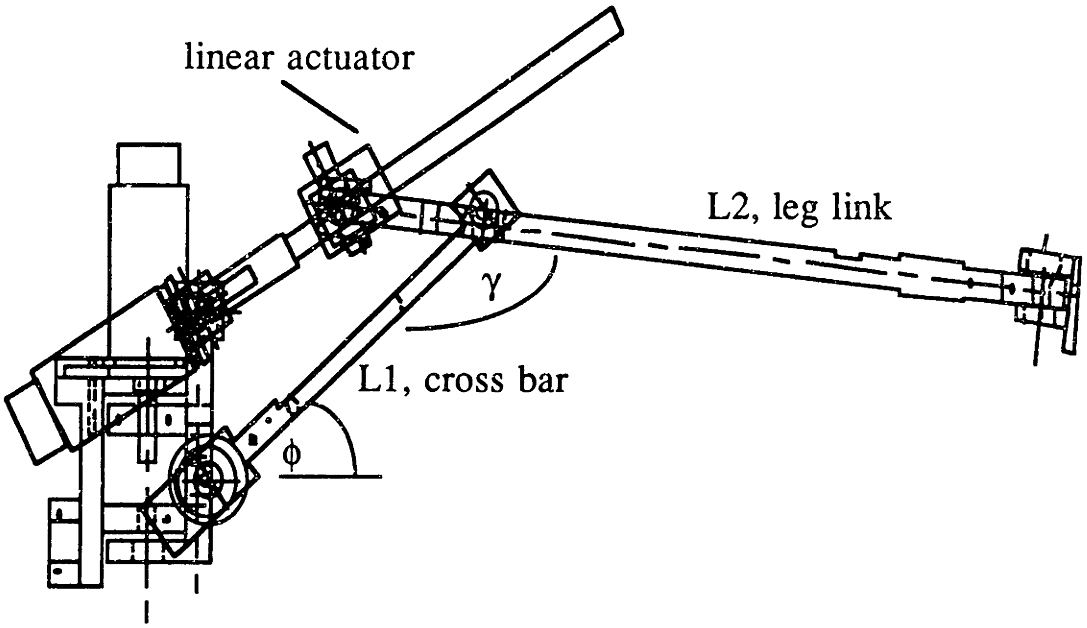


Figure 3.8 A final version of Attila's leg extended to the limits of its full step height

Based on figure 3.8, a more accurate version of the step height equation {3.3} from figure 3.5 includes this link angle limitation and is shown below.

$$H\text{, step height} = 2 * L1 \sin \phi_{max} + L2 * (1 - \sin(\phi_{max} + \gamma_{max})) \quad \{3.4\}$$

$$\phi_{max} = 45 \text{ deg}$$

$$\gamma_{max} = 135 \text{ deg}$$

$$H = 2 * L1\sqrt{2} + L2$$

$$L1 = 3''$$

$$H = 8''$$

$$L2 = 3.8''$$

Thus to achieve a step height of 8 inches, the leg link must be at least 3.8" long. Since the moment arm of the leg link was not a major problem, the leg was lengthened to allow for easy mounting of sensors. Based on these specifications, the leg shown in figure 3.9 was designed.

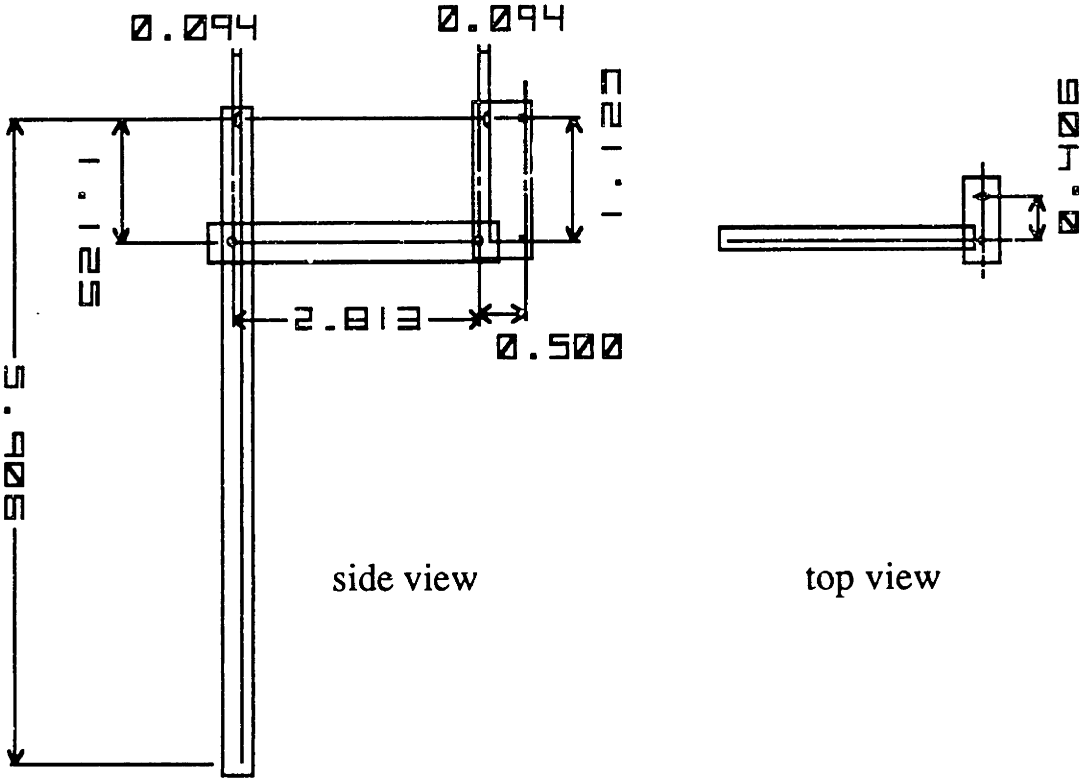


Figure 3.9 Dimensions of Attila's legs

It is now possible to work out the exact kinematic of the legs. The joint angles of the leg are reported through the use of three joint angle sensors mounted on joints of the leg. Figure 3.10 shows the location of these sensors. These sensors are named the lift sensor, the rotation sensor, and the linear sensor. The linear sensor measures the angle of the joint most greatly coupled to the linear actuator. It does not measure the extension of the lead screw. The leg can be simplified into a three link leg based on the measured three joint angles.

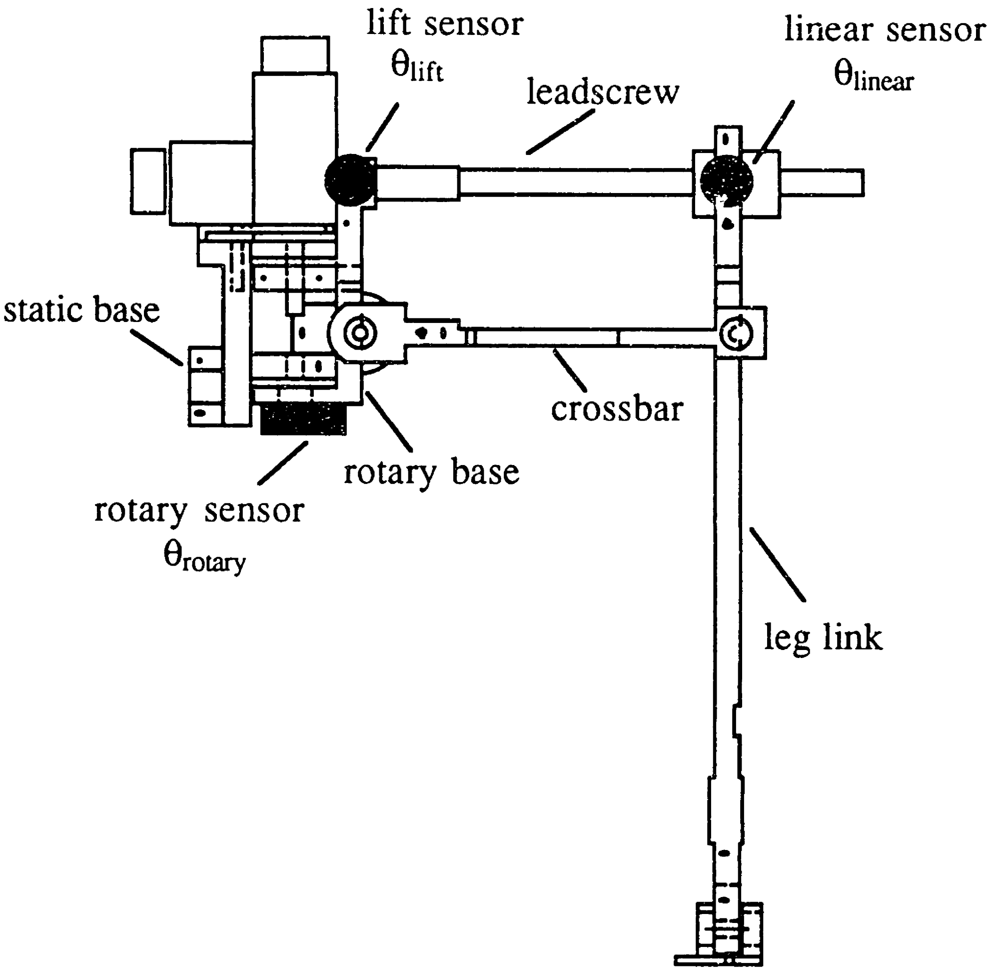


Figure 7.10 Location of joint sensors on the leg

We will represent the links of the leg using transformation matrices. The methods used in the following description are described in *Robot Manipulation* [Lozano-Perez 85]. A transformation matrix is the result of a multiplication of a rotation matrix, which, in this case, represents the rotation of a link about the base of its frame, and a translation matrix, which, in this case, represents the linear dimensions of the leg. The transformation matrices are derived below.

θ_{lift} = the angle between the rotary base and the lead screw

θ_{linear} = the angle between the lead screw and the leg link

θ_{rotary} = the angle between the rotary base and the static base

δx = linear translation in the x direction

δy = linear translation in the y direction

δz = linear translation in the z direction

Link 1. The first link is the rotary base of the leg. It is connected to the base of the leg through a rotary joint with a vertical rotational axis. Figure 7.11 shows this link and its linear dimensions.

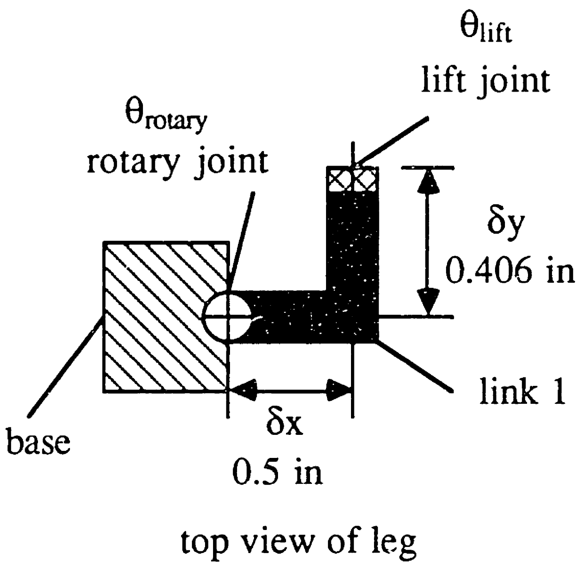


Figure 7.11 Link 1 of the leg

From figure 7.11, it is possible to form the translation matrix, A_1, for link 1.

$$A_1 = \begin{bmatrix} \cos\theta_{rotary} & -\sin\theta_{rotary} & 0 & 0.5 \\ \sin\theta_{rotary} & \cos\theta_{rotary} & 0 & 0.406 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Link 2. Link 2 represents the lead screw. There is a complication concerning this link. Despite the fact that the link changes in length, the length of this link is not measured directly. Thus, in order to form the translation matrix for this link, it is first necessary to derive the length of the link, X, based on θ_{lift} and θ_{linear}. Figure 7.12 defines the variables used in the derivation.

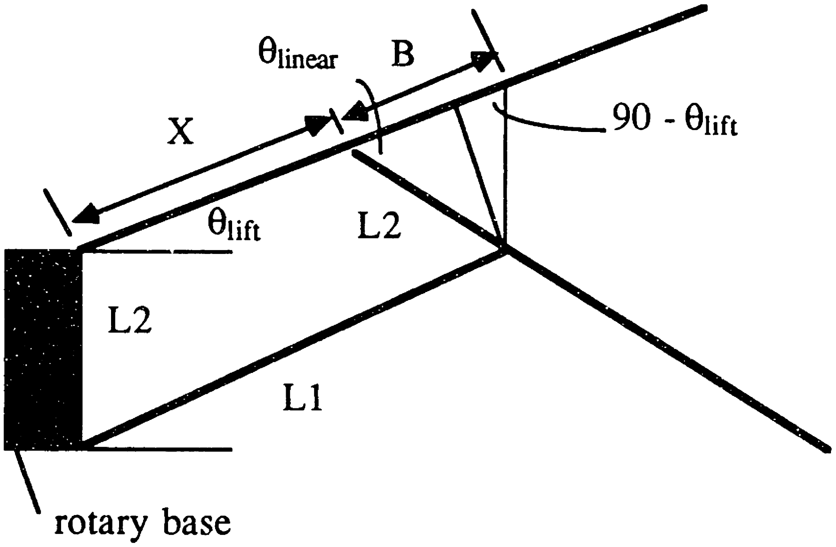


Figure 7.12 Deriving the length of the lead screw

The rotary base has the same length, L2, as the upper leg link. B is the distance from where the top of the leg link is to where it would be if the leg link was vertical. The length of the lead screw, when the leg is vertical (B = 0), is equal to the length of the crossbar. Thus, when the leg is not vertical, the length of the lead screw can be expressed as the difference between the length of the crossbar, L1, and the length of B.

$$X = L1 - B$$

All that is necessary to find X is to find the length of B. B can be broken up into 2 parts, as shown in figure 7.12, by the perpendicular dropped from the lead screw to the crossbar/leg link joint. The length of the inner part of B is equal to:

$$L2 * \cos \theta_{linear}$$

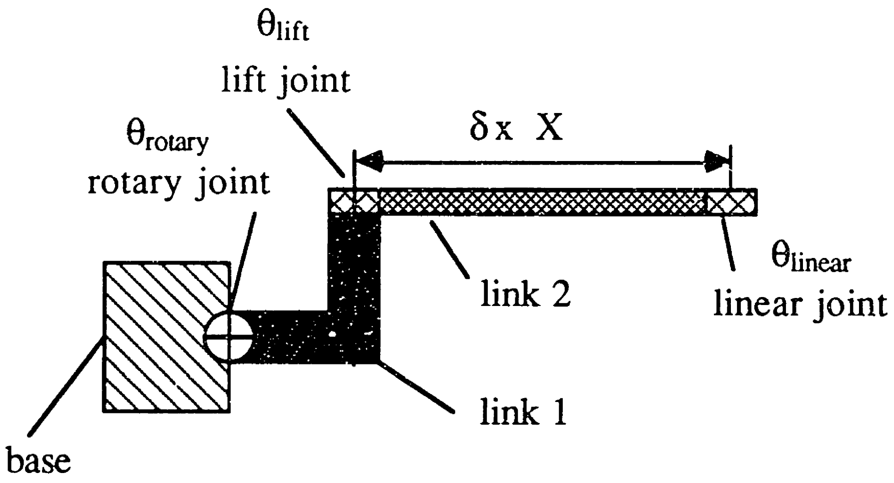
While the length of the outer part of B is equal to:

$$L2 * \sin \theta_{linear} * \tan \theta_{lift}$$

Putting this together,

$$X = L1 - L2(\cos \theta_{linear} + \sin \theta_{linear} * \tan \theta_{lift}) \quad \{3.5\}$$

Figure 7.13 shows the leg model with the addition of link 2.



top view of leg

Figure 7.13 Link 1 & 2 of the leg

$$A_2 = \begin{bmatrix} \cos\theta_{lift} & 0 & \sin\theta_{lift} & X \\ 0 & 1 & 0 & 0 \\ -\sin\theta_{lift} & 0 & \cos\theta_{lift} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$X = L1 - L2(\cos\theta_{linear} + \sin\theta_{linear} * \tan\theta_{lift})$$

$$L1 = 2.813, \quad L2 = 1.13$$

Link 3. Link 3 represents the leg link. It connects to the second link via a rotary joint with the rotational axis in the y direction. Figure 7.14 shows the three links which make up the leg.

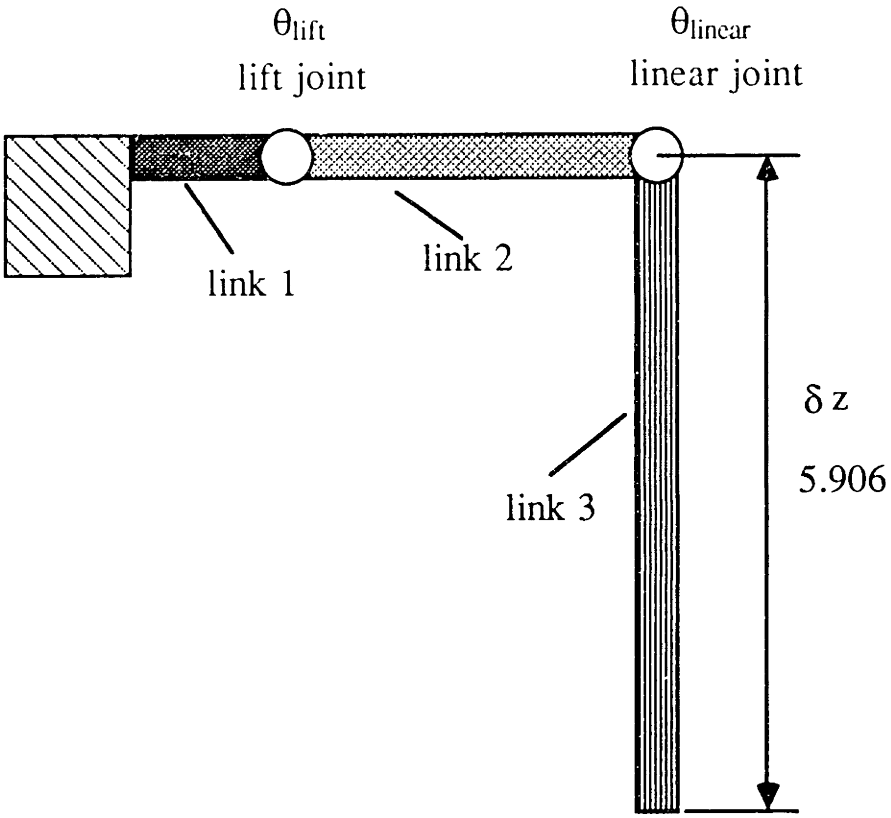


Figure 7.14 All three links on the leg model

$$A_3 = \begin{bmatrix} \cos\theta_{linear} & 0 & \sin\theta_{linear} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_{linear} & 0 & \cos\theta_{linear} & 5.906 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The forward kinematics of the robot can now be found by multiplying these 3 matrices together to form the final transformation matrix T. To find the endpoint of the leg from the matrix T, take the first three entries of the 4th column. They are, in order, the x component, the y component, and the z component.

$$T = A_1 * A_2 * A_3 \quad \{3.6\}$$

If it had been possible to measure the joint angles of the joints on the leg's crossbar instead of the joints on the lead screw, the forward kinematics would be simpler. It would not be necessary to determine the length of the lead screw from the joint angles in order to locate the position of the foot. Unfortunately, these two joints cannot easily mount joint angle sensors. In future versions of the leg it would be worthwhile to solve this problem.

SUMMARY

This chapter examines the process used to develop the kinematic design of Attila's leg. The severe size constraints limit the types of actuators which can be used to drive the leg. Despite this, a leg design which combines a large powerful step height with a fast walk is achieved. It was possible to achieve this leg design by making a distinction between walking and climbing. Two drawbacks of the leg are its somewhat complex forward kinematics, and the fact that a rotary actuator had to be used for the normal lifting of the leg. If the lifting could have been accomplished with a nonbackdrivable linear actuator, the robot would enjoy the benefit of not having to expend any power in order to stand. The next chapter will illustrate how Attila solves this second problem to some degree.

Chapter 4
Leg Loading

OVERALL GOALS

In the previous chapter we specified a set of design goals and came up with a kinematic design which attempted to meet those goals. Implicit to that whole design process were two assumptions. First, gearmotors could be found which would provide the forces and velocities required for the leg. Second, materials exist which are strong enough to allow the construction of such a design. The goal of this chapter is to validate these two assumptions.

It is first necessary to develop a robot model which will accurately predict the weight of the robot. This model, combined with the previous chapter's kinematic model of the leg will provide enough information to determine motor performance constraints and then evaluate actual motors for selection. With the actual motors selected, an exact weight can be derived from the model. This weight is then compared with the actual weight of the robot and discrepancies and their implications are analyzed. Finally, the strength of the proposed leg is checked to determine whether it will fail under the actual loads it will have to support.

ROBOT MODEL

In order to analyze the loading forces on the legs of the robot, we had to come up with a model of what the completed robot will weigh. As a starting point, Attila's predecessor, Genghis, was used. Genghis is shown in figure 4.1.

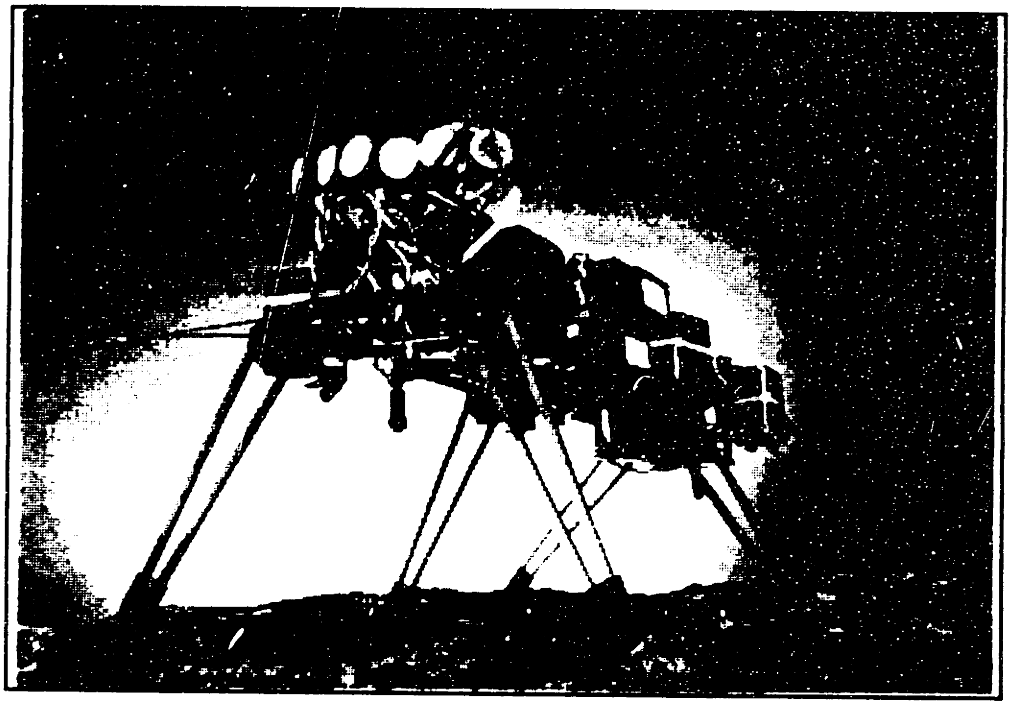


Figure 4.1 The Genghis walking robot

Genghis is a 14 inch long, six-legged walking robot. It has four computer boards, twelve motors, and a very minimal chassis. Genghis was used as a model because it was assumed that a robot of the same type and scale would have a similar weight distribution. In all, Genghis weighs forty ounces. Table 4.1 shows the mass distribution on Genghis.

Robot part	Mass	% of total weight
structure	10 oz.	25
electronics (includes sensors)	14 oz.	35
motors	12 oz.	30
batteries	4 oz.	10
Total weight	40 oz.	100

Table 4.1 The mass distribution of the Genghis walking robot

The next step was to determine what the mass distribution for an Attila walking robot would be. Attila was to be much like Genghis, and thus the mass distribution estimate would be similar to the distribution for Genghis. The main anticipated change between Genghis and Attila was the mass of the electronics. Genghis's computer boards were made by pressing metal pins into a perforated fiberglass board and then hand wiring the connections between these pins. These boards tended to be quite heavy, weighing approximately 2 1/2 ounces each, when fully populated. Attila uses printed circuit board technology and surface mount components. Thus it was hoped that the percent of the total robot mass accounted for by the electronics on Attila could be reduced by as much as 50%. This new distribution is show in Table 4.2.

Robot part	**Mass**	**% of total weight**
structure	??	25
electronics (includes sensors)	??	18
motors	??	43
batteries	??	14
Total weight	??	100

Table 4.2 Estimated mass distribution of Attila based on the distribution of Genghis

From table 4.2, we could estimate the mass of the entire robot based on the mass of the motors. There are three motors on each leg: one to control the rotation of the leg, one to raise and lower the leg, and one to drive the linear actuator. These motors are shown in figure 4.2. We can express the mass of the entire robot based on these motors in equation 4.1.

$$\text{Estimated mass} = \frac{1}{\text{\% of mass due to motors}} * (\text{mass of rotary motor} + \text{mass of linear motor} + \text{mass of lift motor}) * \text{number of legs} \qquad \{4.1\}$$

Estimated mass = 13.8 * (the sum of the masses of the motors)

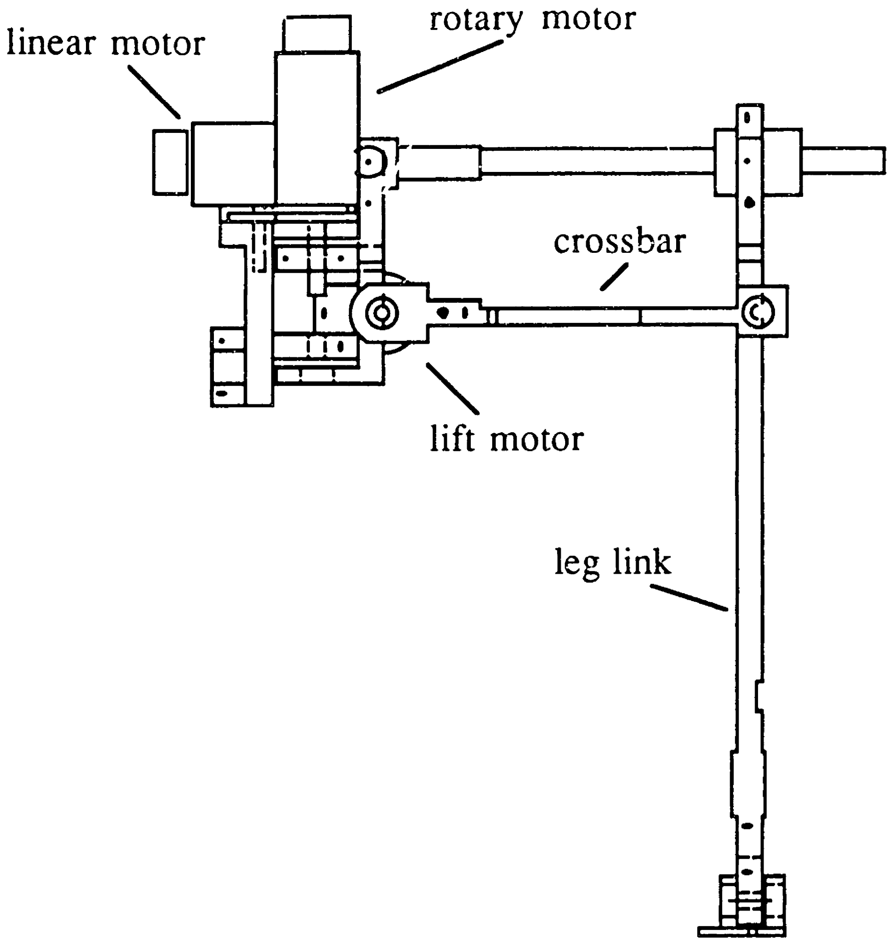


Figure 4.2 The motors on an Attila leg

MOTOR SELECTION

The next step is to derive the equations which relate forces on the leg to loads on the motors. Figure 4.2 shows the positions of the motors and labels both the leg link and the crossbar all of which will be referenced in these equations.

Rotary motor. The rotary motor's job is to move the robot forward. In doing so, the motor does not have to support any of the robot's mass due to the vertically aligned axis of rotation for this degree of freedom. This motor must only accelerate and decelerate the mass of the robot. With the leg link vertical, as it is normally during walking, the rotary motor is connected to the foot through a moment arm equal in length to the crossbar.

Following is a list of the assumptions used to derive the force equations for the rotary motor:

- The goal for the top speed of the robot is 24 in/sec.
- The robot would like to accelerate to its top speed in 20 seconds.
- The crossbar length is 3 in.
- 3 legs are on the ground at all times.

$$\text{Desired acceleration} = \frac{\text{top speed}}{\text{time to accelerate to top speed}} \quad \{4.2\}$$

$$\text{Desired acceleration} = 1.2 \text{ in/sec}^2$$

$$\text{Torque required} = \frac{\text{crossbar length} * \text{desired acceleration} * \text{robot mass}}{\text{number of legs on the ground}}$$

{4.3}

$$\text{Torque required} = \frac{3 \text{ in} * 1.2 \text{ in/sec}^2}{3 \text{ legs}} * \text{robot mass} = 1.2 * \text{robot mass}$$

Following is a list of the assumptions used to derive the speed equations for the rotary motor:

-The goal velocity is 24 in/sec.

-The linear speed of the robot is equal to the magnitude of the velocity vector of the foot.

$$\text{Revolutions per second} = \frac{\text{desired velocity}}{2 * \pi * \text{crossbar length}} = 1.3 \text{ rev/sec} \qquad \{4.4\}$$

Lift Motor. The lift motor drives the crossbar up and down. This action raises and lowers the leg during normal walking. In order for the robot to walk in an alternating tripod gait with an added safety factor, it should be able to support 1/2 the mass of the robot. This degree of freedom can be reasonably slow since the leg does not have to be lifted very high off the ground while walking unless there is an obstacle in the way.

Following is a list of the assumptions used to derive the force and speed equations for the lift motor:

- The crossbar length equals 3 in.
- The leg link is vertical.
- It should take less than 1/2 sec. to fully raise the leg.
- Raising the leg requires a rotation of the lift motor of 90 deg.
- Each leg should support 1/2 the mass of the robot.

$$\text{Required torque} = \frac{\text{robot weight} * \text{crossbar length}}{2} = 1.5 * \text{robot weight} \qquad \{4.5\}$$

$$\text{Revolutions per second} = \frac{\text{revolutions required}}{\text{lift time}} = 0.5 \text{ rev/sec} \qquad \{4.6\}$$

Linear motor. The linear motor drives the lead screw which moves the leg link. The highest loads on the linear motor occur when the leg is making a high step such as the one shown in figure 4.3. In this configuration, the linear motor must drive the foot down with a force greater than the weight of the robot. This is so that if the robot is able to get one leg over the lip of a ledge, it can haul up the rest of the robot. This degree of freedom does not have to act very quickly because it only makes large moves while climbing.

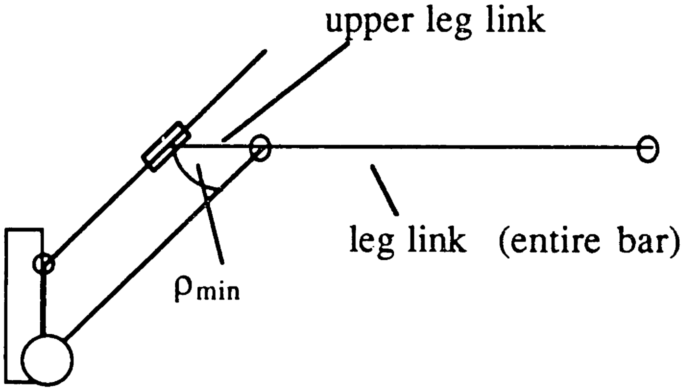


Figure 4.3 Attila's leg in maximum step height configuration
This figure shows Attila's leg while making a maximum height step. The leg link represents the entire link from foot to ball nut on the lead screw. The upper leg link is the part of the leg link from the crossbar joint to the ball nut. ρ_{min} is the angle between the crossbar and the upper leg link in the maximum step height configuration.

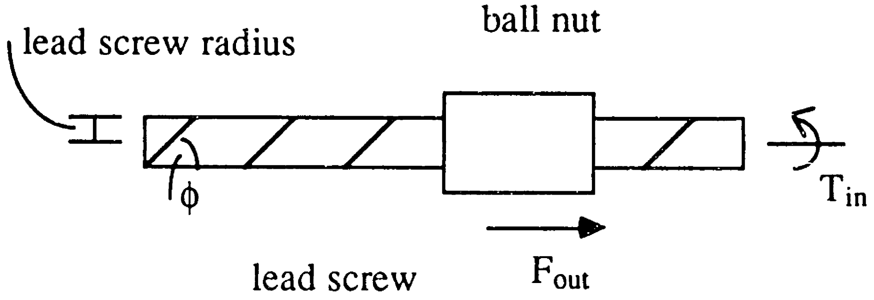


Figure 4.4 A detailed look at the lead screw assembly
This figure shows the ball nut riding on the lead screw. T_{in} is the torque delivered to the lead screw by the gearmotor. F_{out} is the linear force the ball screw can exert on the leg link to which it is attached. ϕ is the pitch angle of the lead screw.

Following is a list of the assumptions used to derive the force and speed equations for the linear motor:

- The pitch angle, ϕ, defined in figure 4.4, of the lead screw is 18 degrees or the ball nut advances 0.0625 inches per revolution of the lead screw.
- The minimum angle, ρ_{min}, defined in figure 4.3, between the crossbar and the upper leg link is 35 degrees.
- The linear actuator is 80% efficient.
- The length of the upper leg link, defined in figure 4.3, is 1.125 inches.
- The length of the leg link, defined in figure 4.3, is 6 inches.
- The linear motor should be able to drive the leg down in 10 seconds.
- Driving the leg down requires the ball nut to move 1.75 inches.

$$F_{out} = \frac{T_{in} * \text{lead screw efficiency}}{\text{lead screw radius} * \sin\phi} = T_{in} * 27.7 \text{ in}^{-1} \qquad \{4.7\}$$

$$\text{Downward force} = \frac{\text{upper leg link length}}{\text{leg link length}} * \sin\rho_{min} * F_{out} = 0.09 * F_{out}$$

$$\{4.8\}$$

$$T_{in} = 0.385 * \text{downward force} = 0.385 * \text{weight of the robot} \qquad \{4.9\}$$

$$\text{Revolutions per second} = \frac{\text{required distance travelled}}{\text{distance travelled per rotation} * \text{time allotted}}$$

$$\text{Revolutions per second} = 2.8 \text{ rev/sec} \quad \{4.10\}$$

Finally, we are at the stage where the criterion to judge the three leg motors has been derived. We have developed equations which relate the weight of the robot to the required torque of the various motors, and an equation which relates the weight of the motors to the robot weight. The only assumption which must be made concerns the relative weights of the three motors.

Motor	Required torque	Required velocity
rotary motor	1.2 * robot weight	1.3 rev/sec
lift motor	1.5 * robot weight	0.5 rev/sec
linear motor	0.345 * robot weight	2.8 rev/sec

Table 4.3 Motor torque and velocity summary

In equation 4.1, derived earlier and shown again below, the weights of all three motors appear. Therefore, all the motors must be selected in order use the equation. It is possible to simplify this expression, however. A rough method of comparing the relative power demands on a motor can be found by multiplying the motor's required velocity by its required stall torque. Using the values shown in table 4.3, we find that the product of torque and velocity are very close. Thus, a gearmotor just able to satisfy the lift motor torque requirements, will also just meet the rotary, or linear gear motor requirements with a different gear ratio. Based on this fact, it is not likely that the weights of the three motors will differ appreciably, and, for the sake of equation 4.1, it is reasonable to assume all the motor weights are equal.

$$\text{Estimated mass} = 13.8 * (\text{the sum of the masses of the motors}) \quad \{4.1\}$$

By applying the assumption that motor weights are equal we arrive at equation 4.11.

$$\text{Estimated robot mass} = 41.4 * \text{weight of one of the motors} \quad \{4.11\}$$

By combining equation 4.11 with equation 4.5, shown again below, we have completed the derivation which relates the lift motor's weight with its output torque requirement.

$$\text{Required torque} = \frac{\text{robot weight} * \text{crossbar length}}{2} = 1.5 * \text{robot weight} \quad \{4.5\}$$

$$\text{Lift motor's required torque} = 62.1 * \text{the mass of the lift motor.} \quad \{4.12\}$$

The most difficult set of criterion to meet was the criterion for the lift motor. This is because as higher and higher torques are required, the gear ratio of the motor must be increased. The higher the gear ratio, the less efficient the gearmotor is, the less actual torque output gain you receive for a given reduction in output speed. The challenge faced trying to find appropriate motors to drive Attila's legs is illustrated in figure 4.5. On the chart is a line representing the solution to equation 4.12. The data displayed on the chart represents the five best motor/gearhead combinations found after an exhaustive search of hundreds of motors from over 20 motor manufacturers. The characteristics of these five motors are summarized in table 4.4.

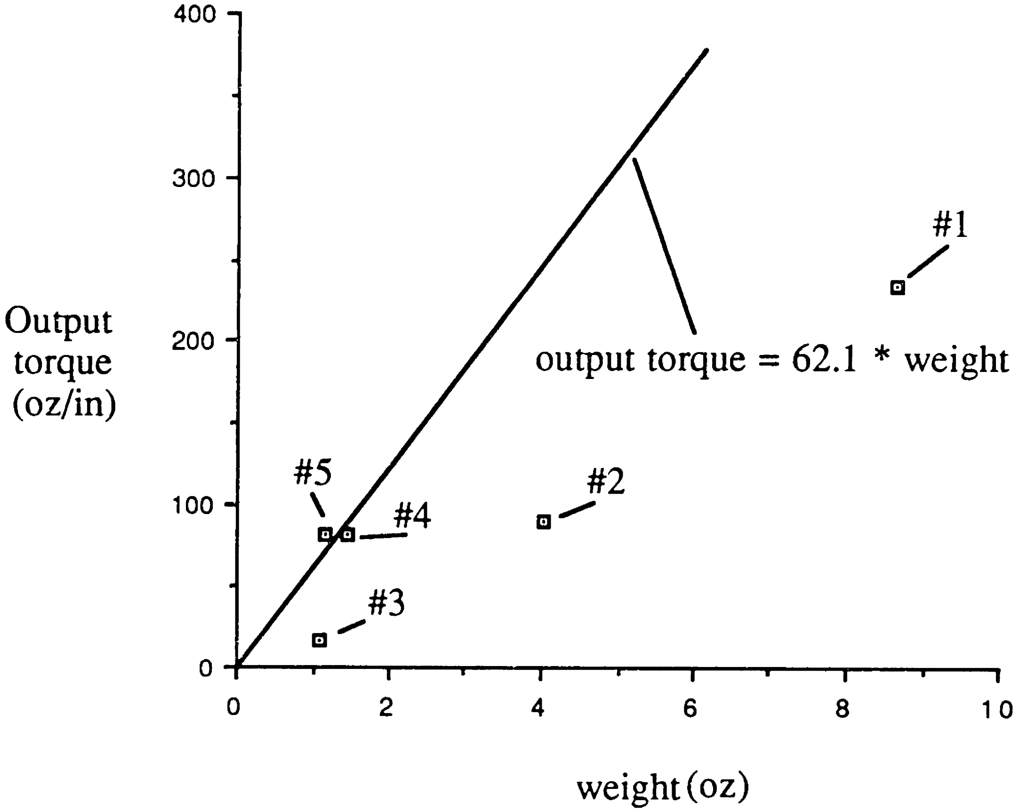


Figure 4.5 Motor Comparison
The output torque used on the graph is the minimum of the stall torque of the motor and the maximum rated torque for the gearhead.

#	Manufacturer and part #	Stall torque	No load speed	Max rated torque for gearhead	Weight
1	Maxon 2326.933 w/ 2926 gearhead	228 oz-in	1.2 rev/sec	420 oz-in	8.5 oz
2	Maxon 2322.933 w/ 2922 gearhead	319 oz-in	1.2 rev/sec	84 oz-in	3.9 oz
3	Maxon mini-motor	31 oz-in	1.6 rev/sec	10 oz-in	0.95 oz
4	Micro Mo 1331 w/ 15/8 gearhead	106 oz-in	1.3 rev/sec	75 oz-in	1.3 oz
5	Micro Mo 1319 w/ 15/8 gearhead	89 oz-in	0.88 rev/sec	75 oz-in	1 oz

Table 4.4 Characteristics of selected motors

In order for a motor to satisfy the equation derived above, it must lie to the left of the equation line in figure 4.5. Only motor 5 satisfies this requirement. It is interesting to note that the main challenge in looking for drive motors was to find a gearbox rated at a high enough output torque. For example, motors #2 and #4 would also have satisfied the leg loading requirements if the torque was not limited by the gearbox. Table 4.5 summarizes the performance of the motors finally selected for the rotary, lift, and linear actuators.

Actuator	Gear ratio	Stall torque	No load speed	Weight
linear	76:1	26 oz-in	3 rev/sec	1 oz
rotary	141:1	48 oz-in	1.1 rev/sec	1 oz
lift	262:1	89 oz-in	.88 rev/sec	1 oz

Table 4.5 Summary of leg actuators using the Micro Mo 1319 motor with the 15/8 heavy-duty spur gearbox

COMPLETING THE ROBOT MODEL

It is now possible to go back and fill in the unknown values in table 4.2. This exercise was to give an idea of what the weight budgets for electronics and structure would be.

Robot part	Mass	% of total weight
structure	10.5 oz	25
electronics (includes sensors)	7.5 oz	18
motors	18 oz	43
batteries	6 oz	14
Total weight	42 oz	100

Table 4.6 Completed initial weight estimate for Attila

Unfortunately, this weight estimate turned out to be flawed. The assumption that Genghis would be a good model for Attila neglected to take into consideration that Attila would be a dramatically more complex robot. The design goals for Attila are much more ambitious than those of Genghis. In order to achieve these goals, Attila possesses many more sensors and computers. In order to integrate all the additional electronics onto the robot, the mechanical structure must be more elaborate. Therefore, the structure and electronics possess a higher percentage of the total weight of the robot than on Genghis. Table 4.7 shows these higher percentages. The values in table 4.7 were found by weighing the systems on the actual robot.

Robot part	**Mass**	**% of total weight**
structure	45.2 oz	43.5
electronics (includes sensors)	23 oz	22
motors	20.8 oz	20
batteries	15 oz	14.5
Total weight	104 oz	100

Table 4.7 Actual weight breakdown of Attila

There are two consequences of this discrepancy between the estimated weight breakdown and the actual weight breakdown of Attila. The first is that there is a lesson to be learned. Scale alone does a poor job of predicting weight breakdown. Other factors, such as system complexity, are equally important in considering a model. The second consequence is that, since the motors were chosen based on the estimated weight, the performance of the robot will be reduced. Therefore it was necessary to make some modifications to bring the performance back up.

INCREASING LEG PERFORMANCE

The increased robot weight affects each of the three leg motors differently. In general, the goals set out for the robot's performance had a large safety margin included into them, so some of the increased weight was absorbed into this margin. Other ways of increasing the leg performance included increasing gearbox size and thereby trading-off some of the robot's speed for a greater force, and, in the case of the lift motor, a spring could be added to work in parallel with the lift motor.

Rotary motor. The rotary motor is the only motor which does not have to support the robot's weight. Therefore, the increase in the robot's weight does not greatly affect this degree of freedom. It will only serve to decrease the forward acceleration of the robot. It was possible to use equations 4.3 and 4.4, derived earlier and shown again below, to determine the acceleration and velocity.

$$\text{Acceleration} = \frac{\text{torque required} * \text{\# of legs on the ground}}{\text{crossbar length} * \text{robot mass}} \qquad \{4.3\}$$

$$\text{Acceleration} = 0.46 \text{ in/sec}^2$$

$$\text{Velocity} = \text{revolutions per second} * 2 * \pi * \text{crossbar length} \qquad \{4.4\}$$

$$\text{Velocity} = 31 \text{ in/sec}$$

The goals were for the robot to have an acceleration of 1.2 in/sec^2 and an velocity of 24 in/sec. So, in fact, the robot's velocity has exceeded the goal. Therefore, by gearing down the rotary motor, it was possible to make a trade-off of extra velocity performance to gain better acceleration. By using the next size gearbox, we changed the performances as shown below. These are acceptable performances for the rotary motor.

$$\text{Acceleration} = 0.86 \text{ in/sec}^2$$

$$\text{Velocity} = 16.7 \text{ in/sec}$$

It is important to note that these calculations assume that the robot will walk with only three legs on the ground at a time. This is because, if the robot is using an alternating tripod gait to walk, only three legs will be on the ground at any one time. The alternating tripod gait is used primarily when a hexapod is moving so fast that there is not time to recover one leg at a time. If Attila is not walking at full speed, it is able to use a wave gait. Using a wave gait, one leg at a time is recovered, leaving five legs on the ground. While walking using a wave gait, Attila possesses a hefty acceleration of 1.4 in/sec^2.

Linear motor. The goal of the linear motor is to drive the leg link down at a force equal to the weight of the robot. Therefore an increase in the weight of the robot directly affects this actuator. Below, the actual force delivered by the chosen linear actuator is calculated.

$$\text{Downward force} = 2.6 * T_{in} \quad \{4.9\}$$

$$\text{Downward force} = 67.5 \text{ oz}$$

$$\text{Time to lower leg} = \frac{\text{required distance traveled}}{\text{distance traveled per rotation} * \text{revolutions per second}} \quad \{4.10\}$$

$$\text{Time to lower leg} = 9.1 \text{ sec}$$

In this case, it not was possible to simply gear down the motor since, even before the robot was found to be much heavier, the time constraint was just satisfied. Recall that the constraint on the time to push down the leg was 10 seconds. Thus, the robot must either climb over high ledges using a two-legged lift, or it must overdrive its motors.

DC motors can safely be overdriven as long as it is not frequent. The robot making a one-legged grasp at a ledge to pull itself up should not be a frequent event. Attila's motor drivers are configured to overdrive the motors by up to 50%. Thus, it is possible for Attila to pull its entire mass up with 1 leg in the event that it becomes necessary.

It is much more likely, however, that Attila will pull itself onto ledges using two legs. This method is preferred because the robot is held more stable. A second advantage of using two legs is that should one leg loose its foothold, the other leg is there to do the job.

Lift motor. The increase in weight of the robot causes more serious problems to the lift motor. Again, we will used equations 4.5 an 4.6, derived earlier and shown again below, to derive the actual force and velocity provided by the lift motor.

$$\text{Output force} = \frac{\text{motor torque}}{\text{crossbar length}} \quad \{4.5\}$$

$$\text{Output force} = 25 \text{ oz}$$

$$\text{Time to lift the leg} = \frac{\text{revolutions required}}{\text{revolutions per second}} \quad \{4.6\}$$

Time to lift leg = 0.26 sec

Just as in the case of the rotary motor, the lift motor moves quicker than necessary to meet the original goal. In this case the goal was 1/2 second and the leg can be raised in nearly half that time. So, it seemed that doubling the gear ratio would double the output force from the gearmotor while keeping the leg lift time within the goal. The problem, however, was that the motor was already operating at the gearhead's maximum rated output torque. Doubling the gear ratio would approximately double the stall torque, but the gearbox would break trying to apply this torque.

In order to assist the lift motor in supporting the weight of the robot, a torsional spring has been added in parallel. This spring provides an additional 10 oz. of downward force when the leg crossbar is parallel to the ground. Thus, each leg can support a maximum of 35 oz. With three legs on the ground, enough force can be generated to lift the robot. The leg loading is dramatically better when the robot uses a wave gait to walk. In this case, five legs are on the ground at any one time and thus can support up to 175 oz.

One of the advantages in choosing the vertical-axis-first kinematic design, described in chapter 3, was that it might be possible to put a leg down, lock it in place, and leave it there until it had to be lifted in its next swing phase. In this way, no power, other than the power to the "brake" has to be exerted in order for the robot to stand. Unfortunately, such a brake has not yet been located. Therefore, the lift motors must exert force whenever the robot is standing up.

Since we have exceeded the velocity specification on the lift motor, it makes sense, from an energetic standpoint, to double the gear ratio. Despite the fact that doubling the gear ratio does not help to deliver more torque, it does halve the power required to deliver the same torque. The springs also help reduce the power required to stand, as long as more legs are on the ground than are in the air. For example, while walking with a wave gait, the springs are lifting 50 oz. of the robot while the leg recovering is having to lift its leg up with 10 extra ounces of force because of the spring. Thus there is a net gain of 40 oz. of force.

SIMPLE STRAIN CALCULATIONS

Once the force on the structural members of the leg was known, it was possible to determine if the dimensions of the cross section of the legs would be able to support the loads. The leg dimensions used in these calculations are from the preliminary leg design.

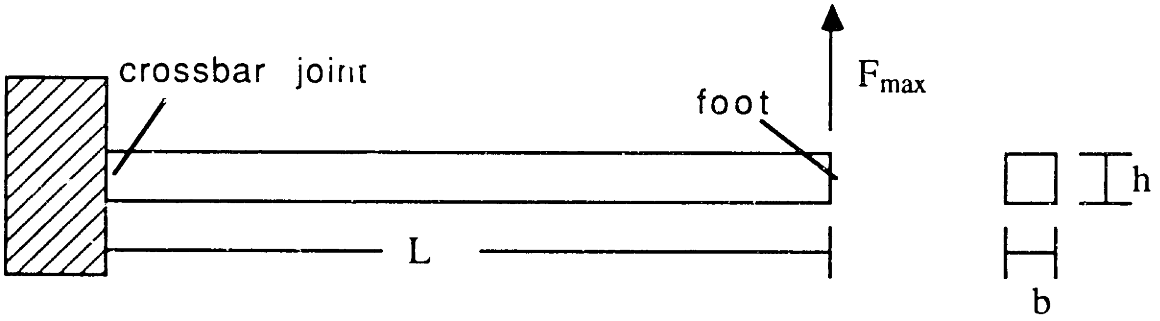


Figure 4.7 Simplified model of leg link bending

Variables used:

L = length of the leg link from foot to the crossbar joint

F_{max} = maximum force that can be applied to the foot

M_b = bending moment

σ_{yp} = yield stress of the leg material

I = moment of inertia of leg about the base

h = height of leg

b = width of leg

For the leg link on Attila; L = 4.9", b = 0.188", h = 0.188". σ_{yp} = 70,000 psi for 7075 T6 aluminum. From this it is possible to solve for the force which will cause the leg to yield.

$$I = \frac{b * h^3}{12} \text{, for a rectangular bar} \quad \{4.13\}$$

$$M_b = \frac{2 * \sigma_{yp} * I}{h} \quad \{4.14\}$$

$$M_b = F_{max} * L \quad \{4.15\}$$

Substituting 4.13 and 4.15 into 4.14 then solving for F_{max} yields equation 4.16.

$$F_{max} = \frac{\sigma_{yp} * b * h^2}{6 * L} \quad \{4.16\}$$

$$F_{max} = 248 \text{ oz}$$

This value, in practical terms, means that it is possible for one leg to carry the entire weight of the robot with a safety margin of over 2. That is to say, the leg can withstand twice the anticipated maximum load and not fail.

SUMMARY

In this chapter, the forces and velocities which affect Attila's legs were analyzed. The problem of coming up with accurate models of the robot's mass turned out to be very difficult. The straightforward method of basing the model on an existing similar system was flawed. It would have been better to put off modelling the weight until more of the robot was designed since Attila turned out to be such a dramatically different robot than Genghis. Putting off the modelling process, however, would have delayed the selection of motors, and the final design of the legs, etc. So, perhaps the robot would never of gotten to the point where a good model could be made. Luckily, it was possible to minimize the effect on performance created by the underestimate of the robot's weight. The strength of the legs was also tested to make sure that they would support the weight of the robot.

Chapter 5
Climbing And Inclination

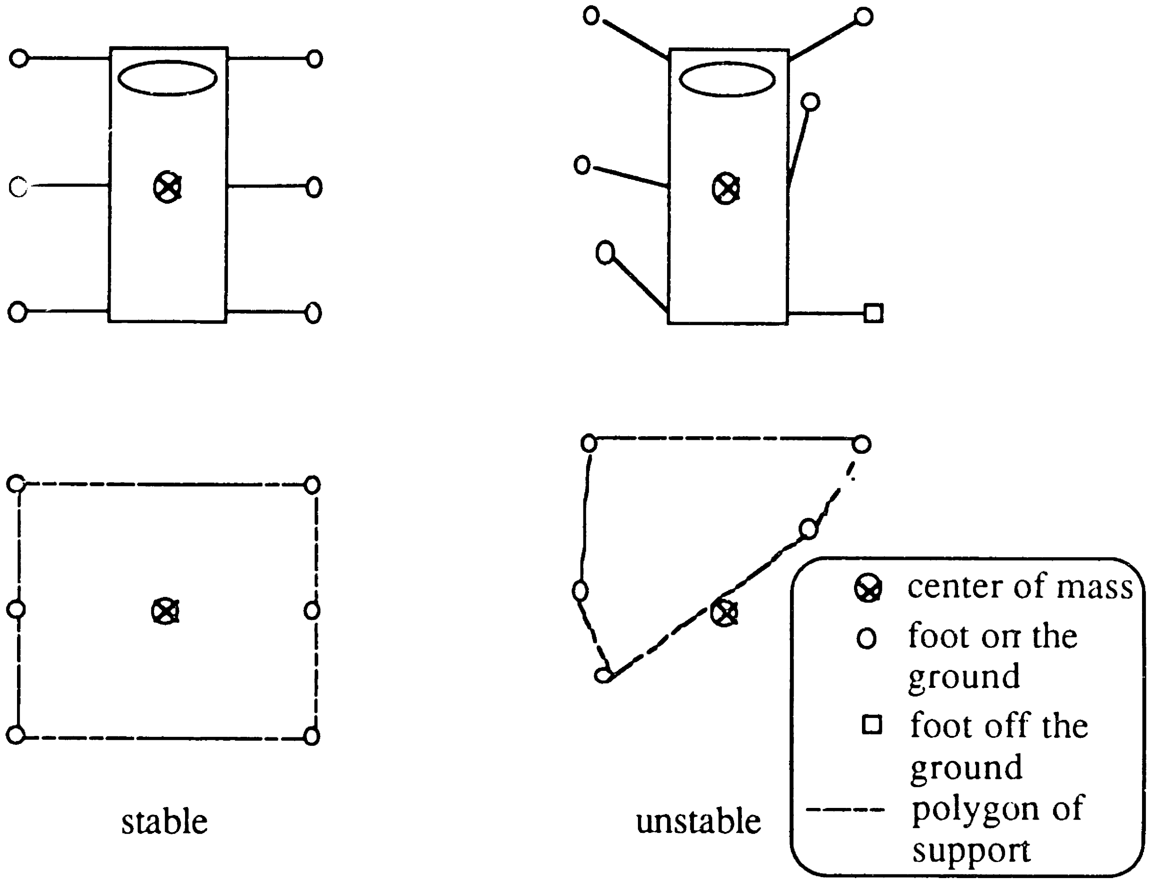
THE EFFECTS OF INCLINATION

The ability to make a high step is not enough to endow a robot with good climbing ability. A walking robot must also deal with surface slope. Inclination has two effects on a walking robot. First, there is an inclination beyond which the robot will fall off the surface being climbed unless it has some way of grasping the surface and holding on. Second, as a robot's inclination changes, so does the gravitational loading of the robot. Thus, unless the legs are designed to allow for these changes, the performance will suffer.

The rest of this chapter will illustrate these problems, show various means of dealing with them, and then explore Attila's unique solution to these problems.

STABILITY

In order to understand the effect inclination has on stability, it is necessary to first give a brief overview of a legged robot's stability. A legged robot is stably standing when its center of mass falls within the polygon formed by the feet which are currently on the ground. This polygon changes shape while the robot walks because different feet are on the ground at different times. Figure 5.1 illustrates the polygon-of-support stability requirement, while figure 5.2 shows how the support polygon changes while the robot walks using various gaits.



stable

unstable

Figure 5.1 Polygon of support formed by robot feet on the ground
The robot on the left is statically stable since its center of mass falls within the polygon of support formed by its feet. The robot on the right, however, has lifted its back foot at a time when the center of mass falls outside the polygon of support formed by the remaining legs.

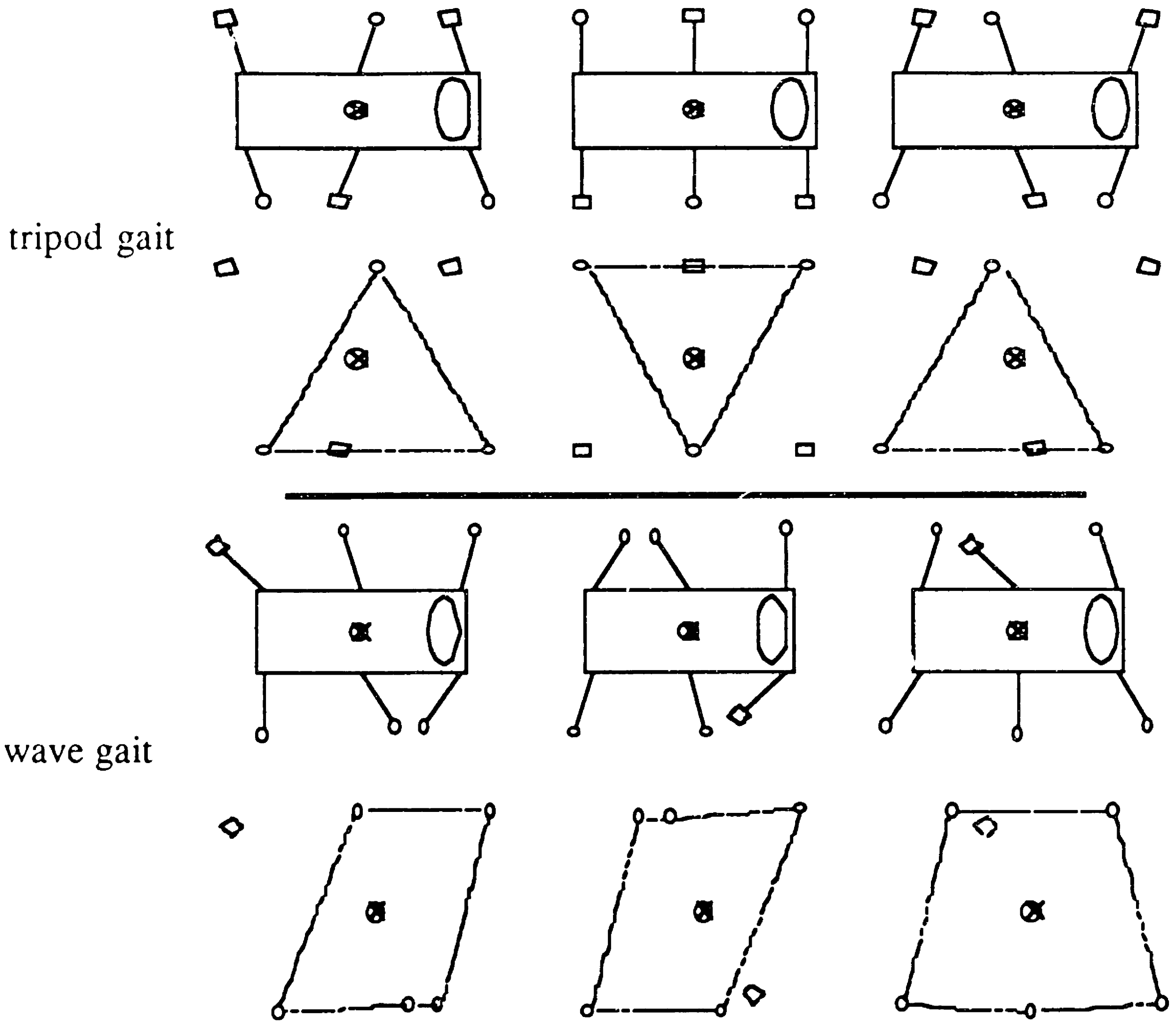


Figure 5.2 Support polygon changes for tripod and wave gaits
As the robot walks, the support polygon changes, but the center of mass is always kept within the support polygon.

Inclination causes the center of mass of the robot to move relative to the feet. This effect will continue as inclination increases until the center of mass has moved outside of the polygon of support and the robot topples off the slope. Figure 5.3 illustrates this effect.

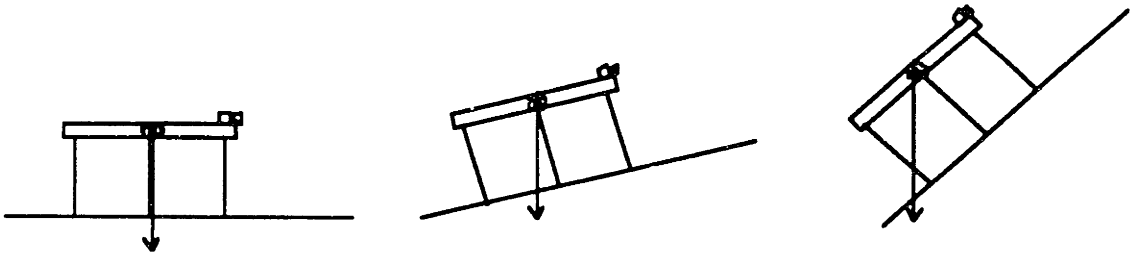


Figure 5.3 Increasing inclination reduces stability
As the inclination increases, the center of mass is, in effect, being rotated back relative to the polygon of support. The robot on the right is about to topple over because its center of mass is outside the polygon of support.

The distance the center of mass is rotated back depends greatly on the length of the robot's legs. The longer the robot's legs are, the more the center of mass is shifted relative to the robot's feet. Thus, while long legs enable the robot to have a large step height, long legs decrease the robot's ability to climb up steep inclines. This trade-off is illustrated in figure 5.4.

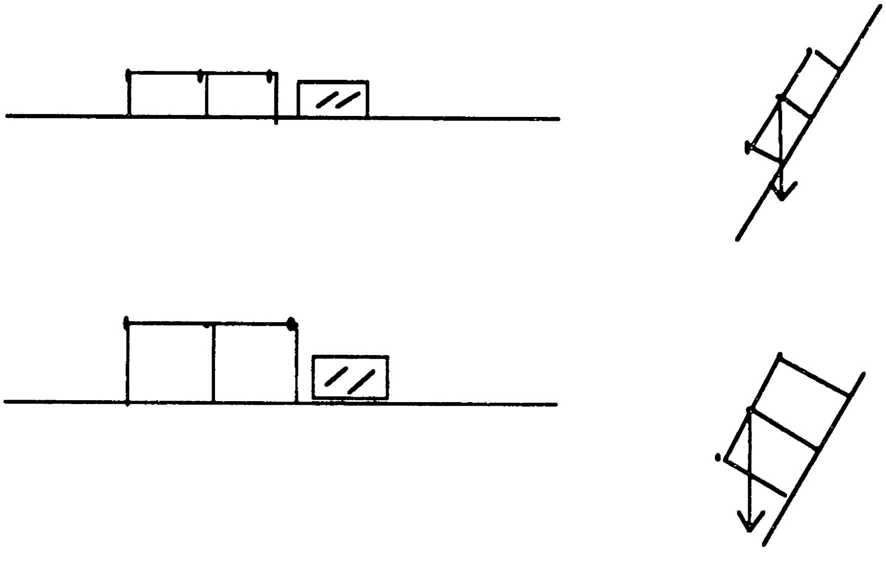
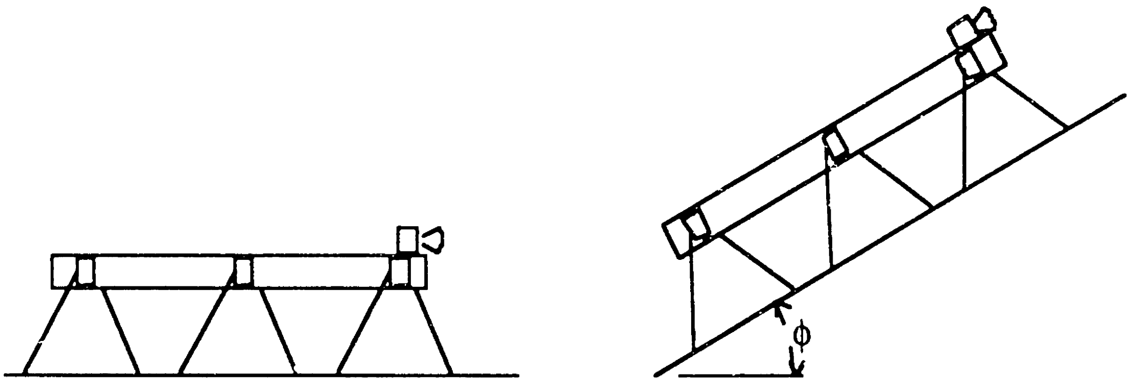


Figure 5.4 The trade-off between step height and stability
The top robot has short legs and, thus, has a small step height but is able to climb steeper inclines. The lower robot's long legs give it a larger step height but reduces stability while climbing.

INCLINATION'S EFFECT ON LEG LOADING

The inclination of a robot also affects the gravitational loading of the legs. To illustrate this effect, we look at Genghis. Genghis has simple vertical-axis-first, two-degree-of-freedom legs. When walking on flat ground, Genghis's lift motors support its weight while the robot's rotary motors only have to accelerate the robot forward. As Genghis climbs up an incline, however, this gravitational decoupling is lost. The rotary motor must support more and more of the robot's mass. This loading change is shown in figure 5.5.



Gravitational loading on lift motors α Robot weight

Gravitational loading on rotary motors = 0

Gravitational loading on lift motors α Robot weight $\cos\phi$

Gravitational loading on rotary motors α Robot weight $\sin\phi$

Figure 5.5 The gravitational loading of Genghis's motors
Genghis's rotary motor, while decoupled from gravity on a horizontal surface, becomes loaded when it climbs uphill.

HORIZONTAL BODY SERVOING

A common solution to both the loading problem and the shifting of the robot's center of mass is to adjust the relative lengths of the robot's legs so the body of the robot is kept horizontal. This is a convenient solution because it does not necessarily introduce any additional complexity into the system. Since the body of the robot is held horizontal, the center of mass does not rotate relative to the feet and remains within the polygon of support. Figure 5.6 shows how the stability is improved.

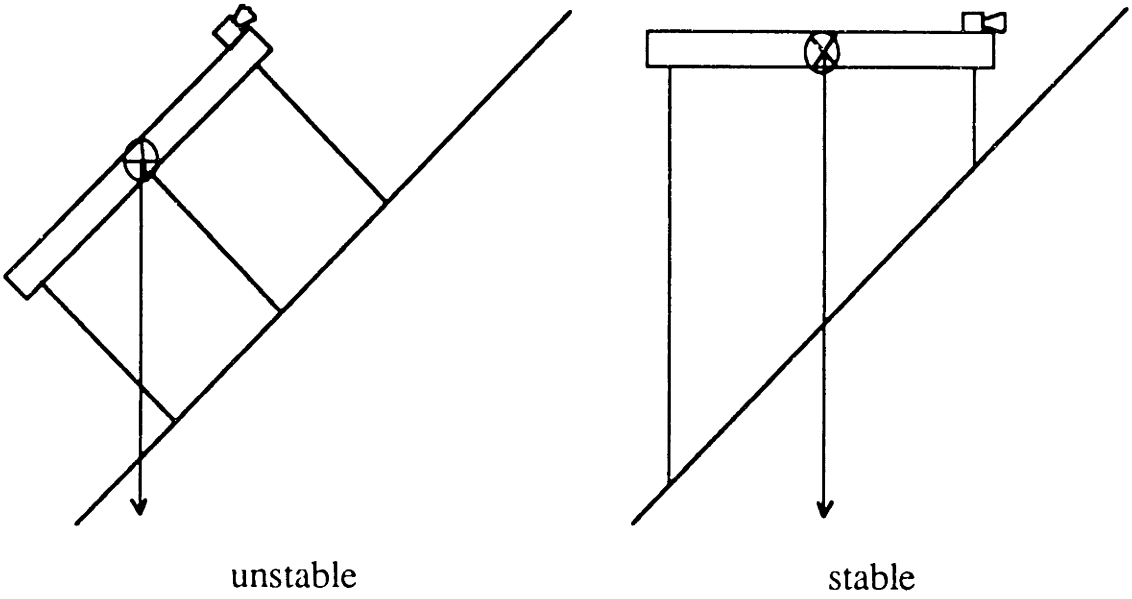


Figure 5.6 Horizontal body servoing stabilizes the robot
Lengthening the rear legs to keep the body horizontal prevents the center of mass from rotating back and destabilizing the robot.

However, the inclination such a robot can climb is limited by the step height of the legs and the spacing between them. As illustrated in figure 5.7, this limit can be derived.

d = the distance between the front most leg and the rearmost leg

H = the maximum step height of the robot

ϕ = angle of the slope

$$\phi_{max} = \tan^{-1}\left(\frac{H}{d}\right) \quad \{5.1\}$$

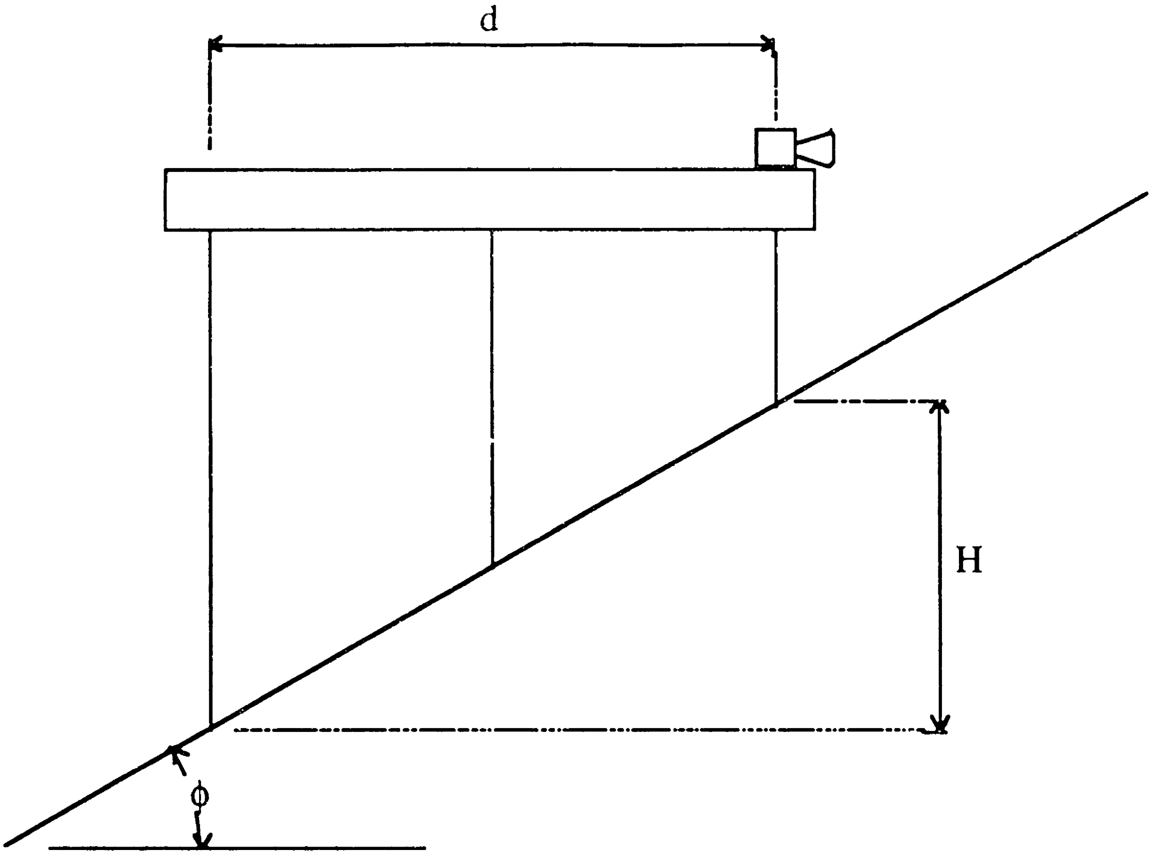
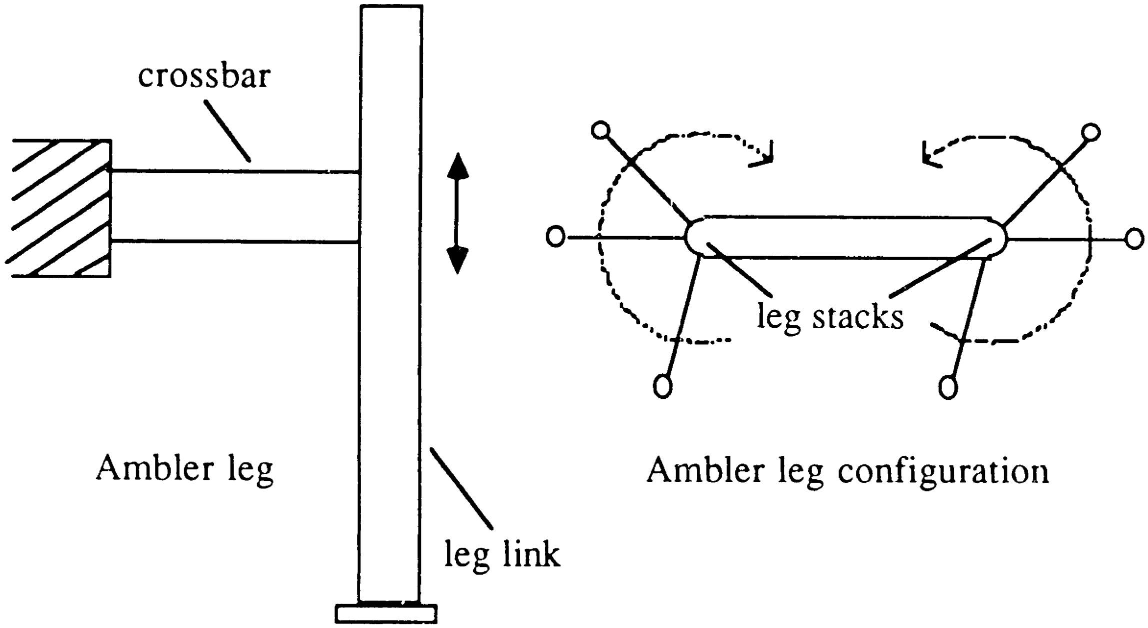


Figure 5.7 The limitation of horizontal body servoing
The maximum inclination, ϕ, that a robot using horizontal body servoing can climb is determined by the robot's maximum step height, H, and the leg spacing, d.

In order for a robot to use the horizontal body servoing method of dealing with inclination effectively, it must have characteristics which maximize the value of ϕ in equation 5.1. First it must have a very large step height within its normal walking workspace. It is not enough to achieve a large step height. It should be achieved in such a way that using the entire extent of that step height does not dramatically slow down the speed of the robot. This is because when walking up an incline, the leg may move through any or all of its entire step height with every step it makes. Attila, for example, would not do this well. Though it only takes

1/2 of a second for Attila to raise its leg the first four inches, it takes another ten seconds to raise it the remaining five.

In order to achieve the large, fast step height required with a kinematic leg design similar to Attila's, the leg must have a very large crossbar. This long crossbar, in turn, requires a powerful actuator to support it since the driving actuator must now support the robot through an extended moment arm. There are several robots which are designed this way: the Titan III [Hirose et. al. 84], the PV II [Hirose 84], and the OSU Hexapod [McGhee and Iswandhi 79]. The CMU Ambler has a slightly different configuration to allow it a very large step height. The crossbar is fixed horizontally and the leg link is driven up and down with a linear actuator [Bares 90]. This leg configuration is shown in figure 5.8.



Ambler leg

Ambler leg configuration

Figure 5.8 The Ambler leg configuration
The picture on the left shows the configuration of one Ambler leg. The crossbar remains fixed horizontally and the leg link moves up and down to control the height of the foot. The picture on the right shows Ambler's two leg stacks. Each stack consists of three legs, each of which can rotate around and through the body.

Another characteristic that a robot using the horizontal body servoing method must have is that the spacing between the legs should be as short as possible. Again, this characteristic is derived from equation 5.1. Typically, short spacing results in a short, wide body for the walkers. The Ambler is perhaps the best example of this. Its legs are stacked on two columns side by side. Thus, the spacing between the legs can actually go to zero. This configuration is also shown in figure 5.8.

VERTICAL LEG SERVOING

Figure 5.9 Attila servoing legs vertical during climbing

Attila takes a different approach to dealing with the inclination problem. Instead of servoing the body horizontal, it servos the legs so they are always vertical. All the legs are ganged together and are rotated so that the first axis of each leg is always aligned vertically. This approach is shown in figure 5.10.

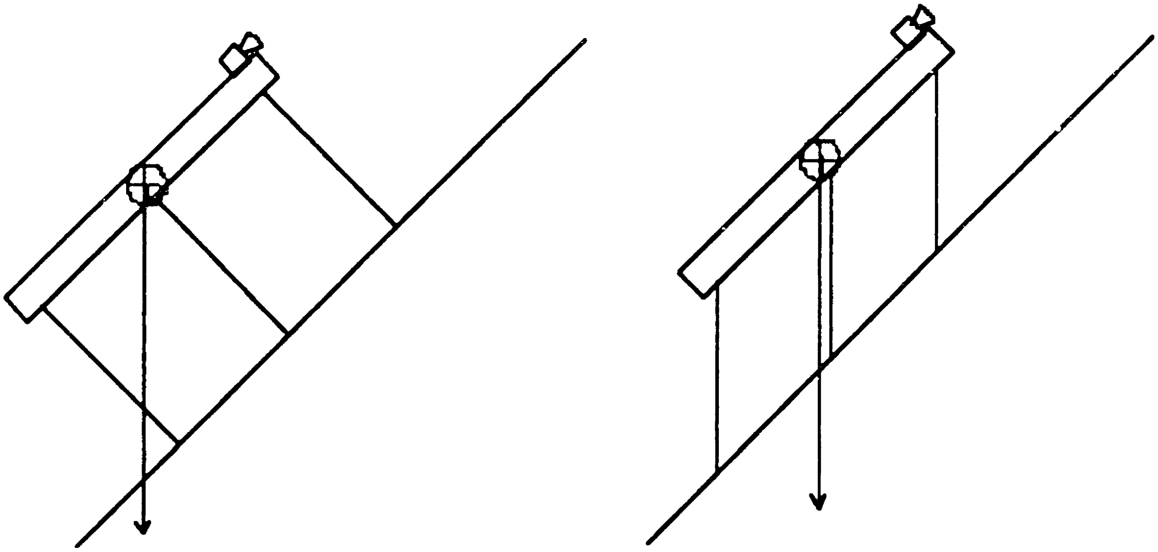


Figure 5.10 Vertical leg servoing stabilizes robot
Vertical leg servoing rotates the legs back underneath the center of mass of the robot.

Servoing the legs vertically not only solves both the problems that horizontal body servoing solves, but provides additional benefits as well. Instead of keeping the body from rotating and thereby freezing the center of mass of the robot, vertical leg servoing allows the body to rotate due to inclination but then rotates the legs back under the center of mass. The loading on the legs also does not change with inclination because the inclination of the legs doesn't change.

Unlike horizontal body servoing, the maximum inclination which a robot using vertical leg servoing can climb is not limited by the step height of the robot or the leg spacing. As Attila climbs up steeper and steeper slopes, a side effect of rotating the legs to maintain their vertical alignment is that the center of mass is brought closer and closer to the slope being climbed. This effect continues until one of two things happen. First, due to the fact that the body of the robot has thickness, it is impossible for the center of mass to be brought all the way to the surface being climbed. Thus the robot cannot climb up arbitrary slopes, although the limit for Attila is greater than 70 degrees.

The more likely limiting factor for Attila is the finding of footholds. Since Attila's feet cannot, at this point, grab onto the surface being climbed, it must rely on the normal frictional force between the robot's feet and the surface for support. As the inclination gets large, this frictional force alone will not support the robot. It is difficult to estimate this incline because it depends on the coefficient of friction and other factors of the surface being climbed which can vary widely. Once this inclination has been reached, if the robot is to continue up steeper slopes, its feet must be able to find appropriate footholds. Footholds are local portions of the surface being climbed where the slope is shallow enough to allow for stable footing. This requirement is shown in figure 5.11.

Each leg has several sensors on it to help it find appropriate footholds, but success is ultimately determined by the geometry of the incline. Attila must also rely on sensors to tell it that its feet are slipping on the surface and therefore needs to hunt for better footholds. It should be noted that this problem of finding footholds is not unique to Attila. Any system which desires to climb slopes greater than ϕ_{max} must search for footholds.

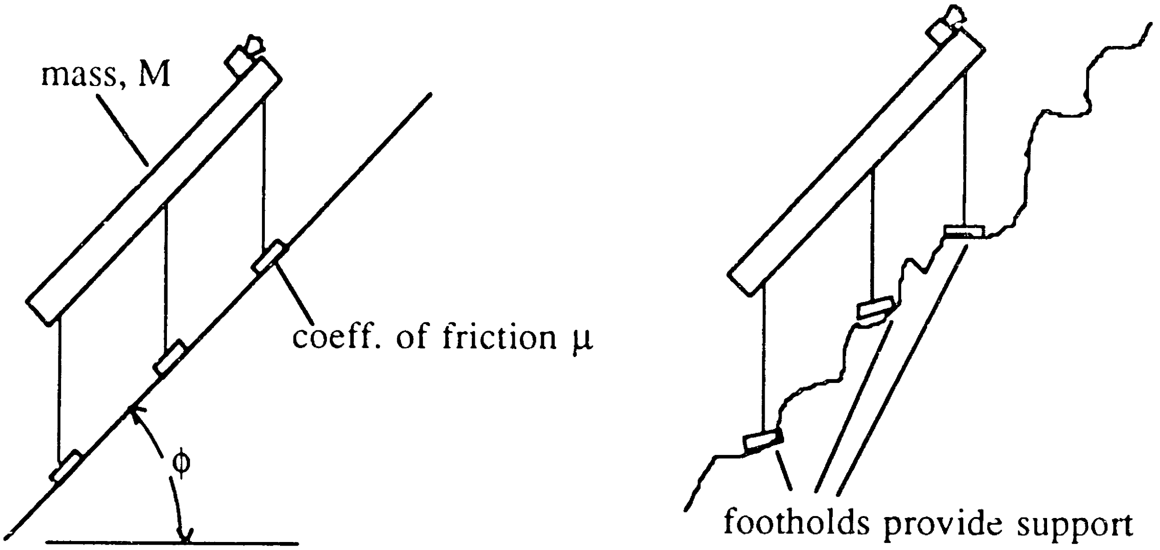


Figure 5.11 Limits to climbing inclination
The figure on the left shows a simple model of the constraint on normally climbable inclination. The maximum angle of inclination, $\phi_{max} = \tan^{-1}\mu$. For climbing slopes greater than ϕ_{max}, the robot must find footholds as shown in the figure on the right. A foothold is a place where the local slope is less than ϕ_{max}.

A robot which is climbing very steep slopes risks falling. No matter how careful the robot is, a foothold could give way, a falling rock might knock it off, or a foot may just slip off its hold. If a system is not robust enough to handle even a small fall, then, regardless of its potential ability to climb, the robot is doomed to a conservative existence. Attila's small scale helps give it reasonable protection against falls, as discussed in chapter 2. But what if the robot falls on its back?

Attila takes the idea of vertical leg servoing to the extreme. The legs can rotate a full 360 degrees around the body. This allows it to rotate its legs back under it and stand up again after a fall to its back. This ability is shown in figure 5.13. In order to avoid the use of slip rings, the legs can only rotate a single complete revolution. This is sufficient since, if the robot falls over twice, it can rotate its legs underneath it from the other direction the second time.

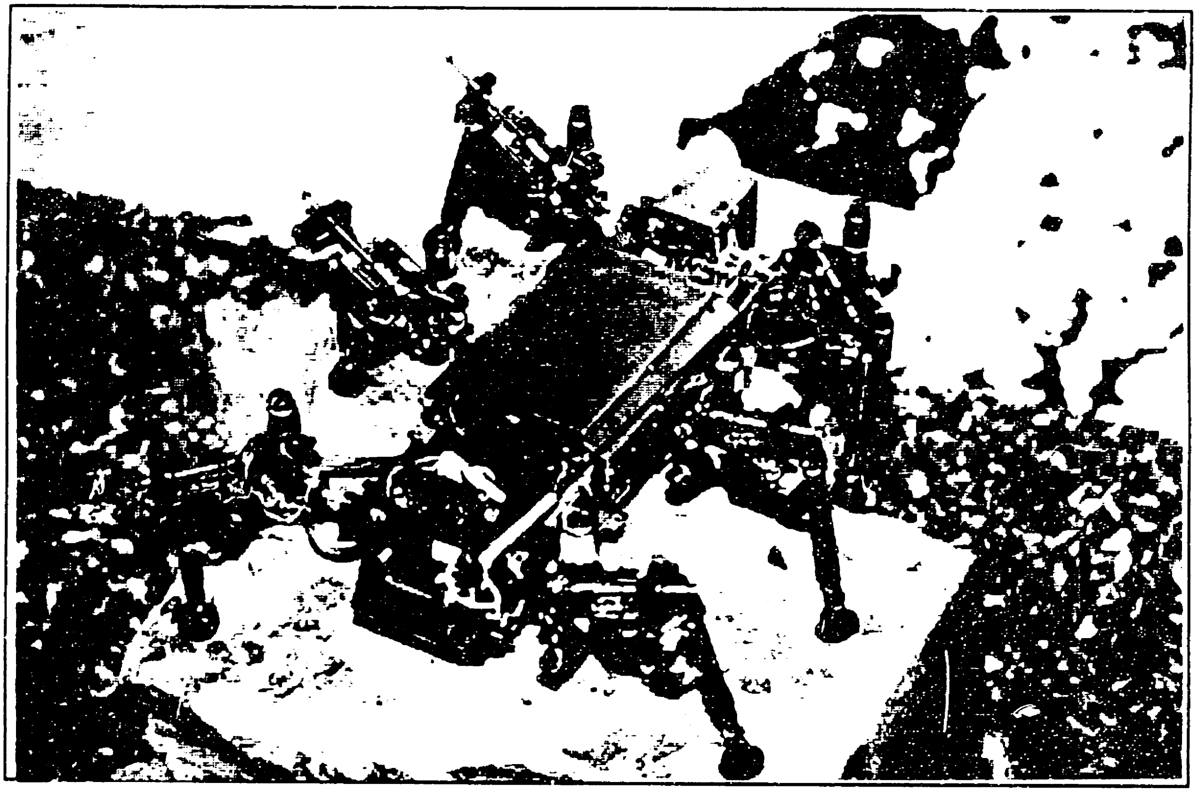


Figure 5.12 Attila upside-down

ATTILA'S BODY ROLL

Inclination's effect on the robot's roll angle causes the same type of problems that inclination's effect on the pitch angle causes. Attila uses the horizontal body servoing method in order to solve these problems. It should be noted that, due to the fact that Attila solves the roll problem differently than it does the pitch problem, Attila can climb up a steeper slope than it can climb across. Of course, if the robot needed to move across a steep slope, it could face up the slope and walk sideways.

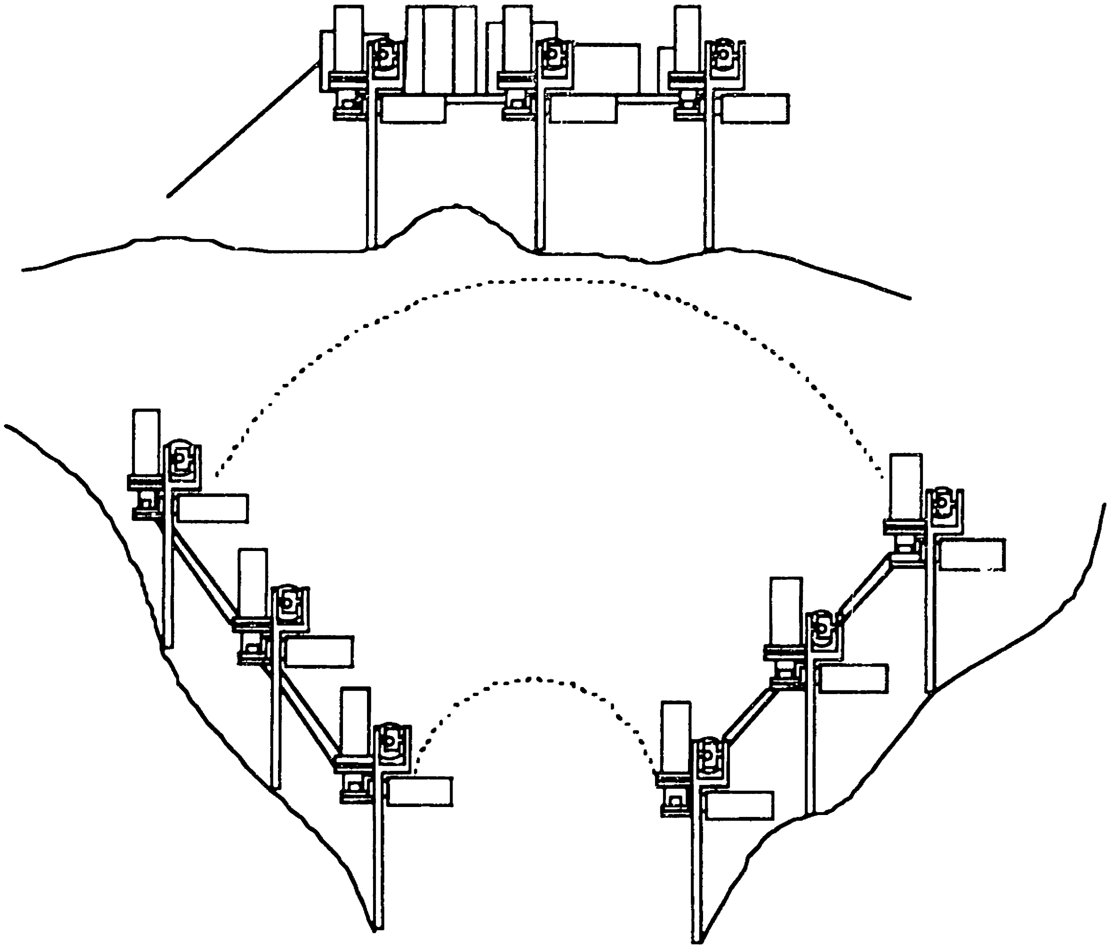


Figure 5.13 Attila's invertability

CHAPTER SUMMARY

In this chapter, the effects of a robot's inclination on stability and leg loading were examined. Two possible solutions to the problems these effects pose were described. Horizontal body servoing seems simple and straightforward, but in order to use the method effectively, the entire design of the robot is constrained. At Attila's scale, and with its desired performance, horizontal body servoing is not practical.

A second method of solving the problems was utilized--verticle leg servoing. Vertical leg servoing has the advantage that it does not require long powerful legs or constrain the length of the body in order to achieve excellent climbing ability. Attila takes the idea of vertical leg servoing to its limit and allows the robot to keep its feet under it even if it falls on its back.

Chapter 6
Sensors on a Legged Robot

OVERVIEW

In order for Attila to succeed as an artificial creature, it must be able to survive in a general environment. In order to do this, its sensory system must be able to sense enough about the surrounding terrain to keep it out of trouble.

This chapter proposes a hierarchical sensory architecture. The hierarchy is arranged with the sensors required to ensure the robot's safety on the bottom level, and sensors which serve only to increase performance of the robot at higher levels. The purpose of doing this is to establish sensory base requirements which, if satisfied with reliable sensory systems, will safeguard the robot's life. Thus it is necessary to determine what set of sensors can adequately protect the robot from harm.

It is a common misconception that the most fundamental sensor to a human's survival is vision. While it is true that vision is perhaps a human's richest and most versatile sensor, it is not the most fundamental. Without tactile sensing, a person couldn't last very long. He wouldn't notice he had cut himself until he saw the blood. He couldn't tell he had tripped on an unseen curb until he saw the world moving upwards quickly as he fell. He could have absentmindedly placed his hand on the stove and cooked it until it was well done, without noticing! Yet blind people get around quite well, and are able to keep from seriously hurting themselves.

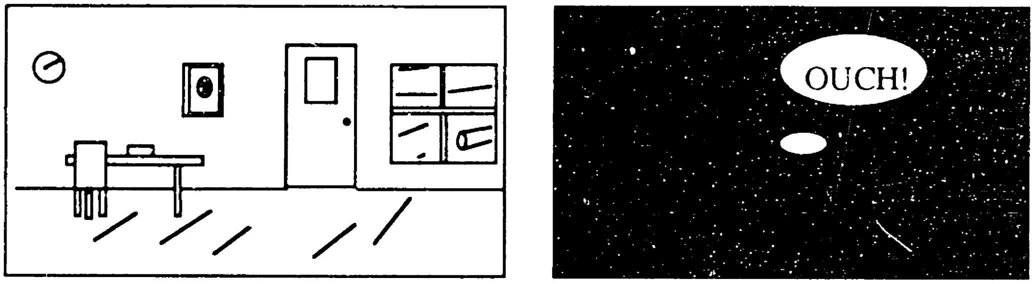


Figure 6.2 Vision vs Tactile Sensing

The point of this exercise is to get an idea of what the fundamental purpose of sensors is and how to go about designing a sensory system for a robot. As we saw above, the most important sensory system does not necessarily provide the largest quantity of information about an environment, but it provides the most relevant. The most important purpose of a sensory system for a creature, be it a human, a tiger, or a robot, is to provide that creature with the ability to realize when something is physically acting on it for this is the most direct and immediate source of harm a creature is subjected to. When designing a sensory system for an artificial creature, tactile sensing should be at the heart of the system's fundamental layer. Vision can dramatically improve the performance of the creature, but a creature should be vary wary of trusting vision over a tactile sensor with its "life."

HOW MUCH DO YOU HAVE TO SENSE?

In designing a sensory system, it is important to determine the minimum amount of sensing that is required to get by, and build up from there. The amount a robot has to sense depends on the complexity of the environment it must operate in. For example, some industrial robots' environments are so constrained that simply executing a preprogrammed set of joint motions will suffice. An artificial creature's environment is that of the "real world". A close look at Attila's domain allows for a constraint on the general environment of the "real world." Attila's world is a statically safe one. That is to say, no moving object will harm Attila. We will also assume that the robot walks with a speed such that if it were to collide with something, it would be left unharmed.

The second assumption is true for Attila. It walks at a slow enough speed that a head-on collision will do no structural damage. Since the motors can be stalled and even backdriven with no damage to them, they are safe as well. The assumption of a statically safe world is not reasonable in environments teaming with hostile life, but since Attila's overall goal is to explore remote and desolate areas, the only moving object likely to hit Attila would be a falling rock which might not even damage the robot. So, the assumption is valid since Attila's "real world" is a statically safe world with a high degree of probability.

If the statically safe world assumption was not valid for Attila, then a more complex set of sensors would have to be at the bottom of the sensory hierarchy. For example, if Attila had to avoid getting hit by moving cars, some sort of range finder, or moving car recognition system would be required at the fundamental sensor level.

The motion of a statically stable walking robot operating in a static world can be broken down into a series of discrete footsteps. Each step can be broken down into three parts, the swing of the foot to its new position, the placement of the foot, and the shifting of some of the weight of the robot onto that foot as the robot moves forward. Since the robot is statically stable, the robot can stop its motion at any time, and not fall down. Also because the world is static, the robot will never be in danger if it is currently not in danger and it does not move.

Therefore, in order to guarantee the safety of the robot, all that must be done is to ensure that shifting weight onto a newly placed foot does not cause the robot to fall, and to ensure that the robot senses collisions when advancing its body and when swinging the leg forward during recovery. In order to satisfy this condition, the robot must be aware of its physical configuration and the forces acting on it directly. A detailed breakdown of this knowledge is provided below.

The foothold can support the load. Each leg must be able to test load its foothold to make sure it can support its share of the robot's weight. In general, the leg must make this test before it is required to support its share of the weight. However, it is possible for the robot to use a gait in which any one leg fails, the remaining feet on the ground adequately support the robot. When using such a gait, the leg must verify that it's foothold can support its appropriate load before the next leg to take a step is loaded, not before the current leg is loaded.

The legs are vertical. The robot must know that the legs are servoed vertically. Otherwise, the center of mass of the robot may be in an unexpected region of the polygon of support, and moving the center of mass may cause the robot to go unstable and fall.

The body roll is known. In order to calculate the position of the center of mass of the robot with respect to the polygon of support, the body roll angle needs to be known. Depending on the robot's orientation, inclination can affect the roll angle just as it affects the robot's pitch angle. For maximum robot stability, this angle should be kept approximately equal to zero.

Leg collisions are detected during leg swing. In order for the robot to advance, the leg must swing forward from its old position to a new one. It is necessary that any collision of the leg while it swings forward be sensed so that the robot can attempt to step over whatever is in the way, or retreat and walk around the obstacle.

Body collisions during advance. When the robot's body is being moved forward, just as when a leg is being moved forward, it is necessary to detect a collision of the body with an obstacle so that the robot can respond appropriately.

Position of all the joints known. In order to servo any of the robot's DC motors to a position, a position sensor must be present. Knowledge of all the joint positions is also necessary to maintain the robot's balance.

Robot's power level known. While knowledge of the power level of the robot will not save the robot in any direct manner, the robot must know when it should start searching for more power.

SENSOR STRATIFICATION

Now that the minimum requirements for Attila's sensors have been established, it is possible to start meeting these requirements by adding actual sensors onto the robot. Below is a listing of the sensors used to satisfy the sensor requirements enumerated above.

Strain Gauges. Attila 's legs have strain gauges mounted on them to measure the force the external world is exerting on them. By measuring the forward force on each leg, the robot is able to detect collisions during the swing of the leg. If all the legs on the ground notice a sharp increase in forward force when they attempt to move the robot forward, then something must be in the way of the body of the robot. The legs are also able to measure the downward force they are supporting. This allows a leg to determine if it is actually supporting its portion of the robot's weight.

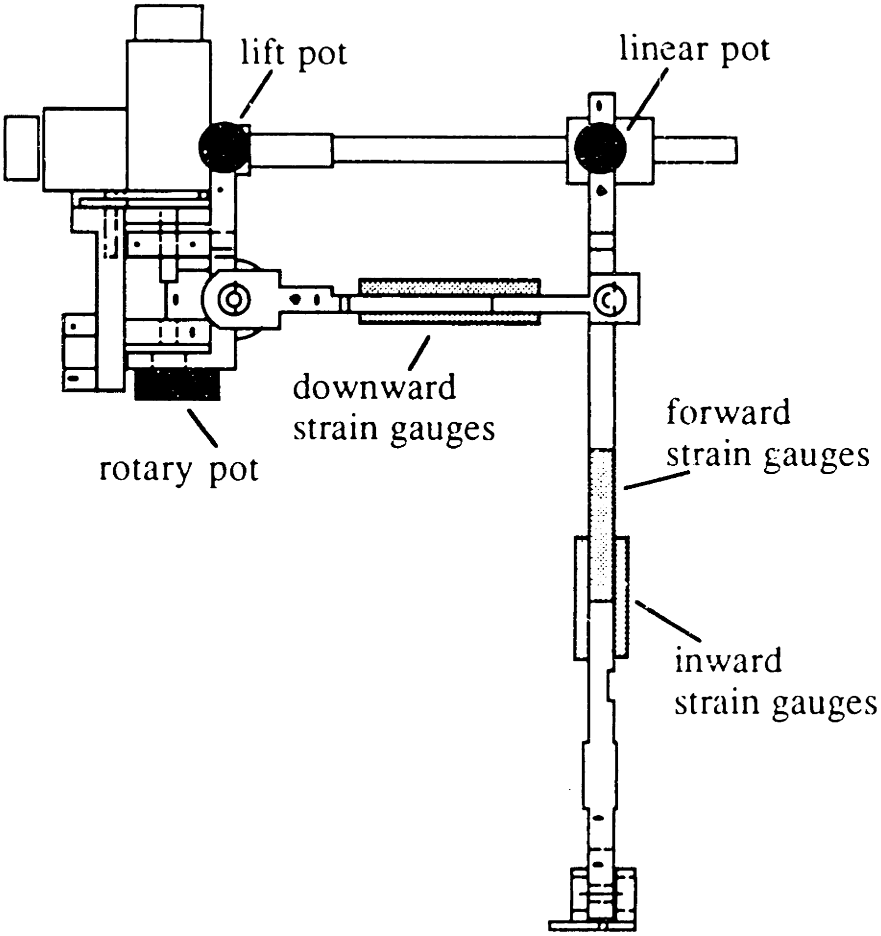


Figure 6.3 Position of strain gauges and potentiometers on Attila's legs
Note that when Attila's leg is in its normal standing configuration, as it is in this picture, the strain gauges are all orthogonal to each other, and thus are decoupled.

The gauges on each leg are mounted in 3 sets of four. Each set measures one of the 3 directions of force on the leg. The gauges are used in groups of four in order to maximize the strain signal coming out of them, and to minimize the effect of temperature on the reading of the strain gauges. The locations of the gauges are shown in figure 6.3. The force axes measured by the strain gauges are decoupled when the robot is in its normal stance, but lifting and rotating the leg causes some coupling between the gauges. In normal walking, this coupling is minimal and can be ignored. When the robot is making motions nearer to the limits of its workspace, such as making a very high step, the strain gauges can become very coupled and the values the sensors produce must be interpreted based on the known leg configuration to determine the actual forces. The strain gauges are manufactured by Micro Measurements.

Potentiometers. Potentiometers are used to measure the joint angles of all the degrees of freedom the robot possesses. This information is necessary to servo the motors which control these various degrees of freedom to specified positions. Knowledge of the joint angles also gives the robot knowledge of its own physical configuration. This information can be used to determine the polygon of support for the robot. Once the configuration of the leg is known, the relationship between the forces reported by the strain gauges, and the actual inward, downward, and forward forces on the legs can be exactly determined, if required.

There are three potentiometers mounted on each leg: one to measure the rotation of the leg, one to measure the angle of the lead screw relative to the horizontal, and one to measure the angle between the lead screw and the leg link. These are shown in figure 6.3. A potentiometer is also used to servo the fourth degree of freedom, although the potentiometer alone cannot determine if the legs are vertical. Potentiometers are also used to measure joint angles on the pan/tilt head and the antenna. The pan/tilt head is a subsystem on the body of the robot which will be discussed in chapter 7. The antenna is a sensor system which will be described later in this chapter.

Inclinometers. Attila has both pitch and roll inclinometers mounted on it. The pitch inclinometer is used for servoing the legs vertical. The roll inclinometer is used to servo the body's roll angle equal to zero. The inclinometers are mounted onto the same axles that the legs are mounted onto and, thus, rotate with the legs. In this way, the pitch inclinometer is always trying to servo the legs back to its zero reading to accomplish vertical leg servoing. The roll inclinometer, which is mounted next to the pitch inclinometer and rotated 90 degrees, benefits from the vertical servoing. The only rotations the roll inclinometer sees are rotations about its sensitive axis. It does not have to deal with pitch rotations. Also, since the robot is trying to maintain a roll angle equal to zero, the pitch inclinometer is not subjected to large roll rotations. The inclinometers are manufactured by Spectron.

Battery voltage sensor. An analog sensor is attached to both the batteries supplying power to the motors and the batteries supplying power to the electronics and sensors. Thus, when the battery voltage drops, the robot can take appropriate action.

Digital surface contact sensor. While this sensor duplicates some of the function of the downward force sensor, it can be used in conjunction with or instead of the force sensor to determine whether the foot is on or off the ground. It is not strictly required by our minimum sensing requirement, but it provides valuable redundancy.

All of the above mentioned sensors form the basis for Attila's sensor hierarchy. Each of these sensors can be thought of as being at the bottom of tree of sensors which all work together to provide information to the robot. For example, the strain gauges are the simplest and most reliable of the group of sensors which detect obstacles. The position sensors are part of the motor control sensors. The inclinometers are the beginning of the robot attitude/ global positioning sensors. Figure 6.4 diagrams this organization.

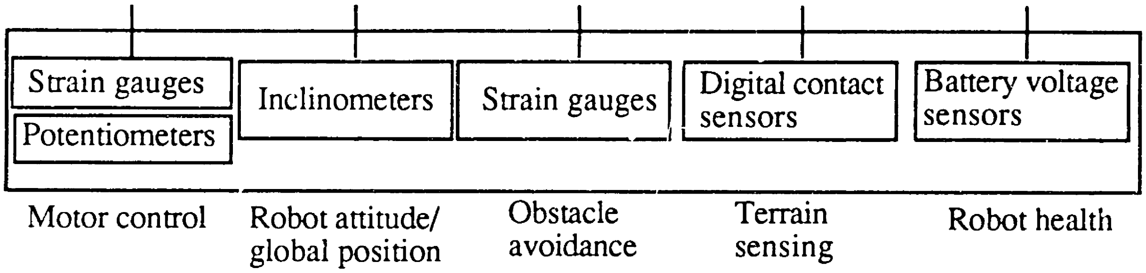


Figure 6.4 Basis of the sensor hierarchy

Now that the basis of the hierarchy has been determined, additional sensors can be added to each sensor category. Adding sensors improves the robot's ability to perform its tasks and makes its sensing abilities more robust. Below, each of the sensor branches in the sensor hierarchy tree is built up through the addition of sensors.

Motor Control Sensors

The motor control sensors are the sensors used by the robot to servo its motors. In addition to the strain gauges and potentiometers, velocity control is also added.

Velocity sensors. The joint velocity information is measured by analog differentiation of the joint position signals from the potentiometers. Velocity information can be used to help increase the dynamic response of the control loops servoing the motors. More importantly, it allows the robot to command, not just the joint position, but also the joint velocity. This is of utmost importance in achieving smooth walking gaits.

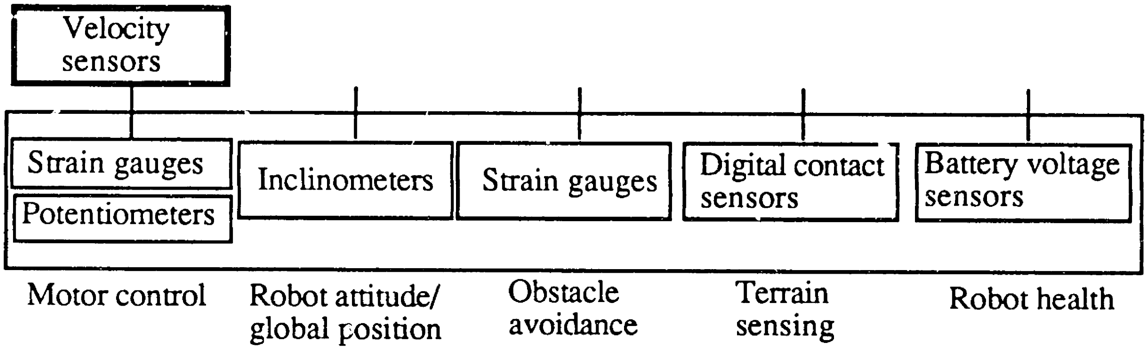


Figure 6.5 The motor control branch of the sensor hierarchy tree

Robot attitude/global position

The sensors in this branch of the tree are used to determine the attitude and position of the robot relative to the rest of the world. A description of these sensors is given below.

One bit orientation sensor. A mercury switch is embedded in the body of the robot. Its purpose is to determine whether the robot is on its front or on its back. This is important because, if there is a sudden dramatic change in the robot's orientation due to a fall or human intervention, the inclinometers can give misleading readings and it is difficult to tell whether the robot is right-side-up or upside-down. By using the one bit orientation sensor, the robot knows which orientation the legs should be in, and whether they must be brought back underneath the robot's body.

Accelerometer. The accelerometer is used to give the robot an inertial measure of whether it is going forward or backward and a crude estimate of how far it has gone. The velocity estimate is achieved by time integration of the accelerometer while the distance estimate comes from time integration of the velocity estimate. While this information is not assumed to be very accurate, the system does benefit from the ability to recalibrate at will. The robot needs only to stop moving and reset its current velocity estimate to zero. In this way, drift can be dramatically decreased. At this point in time, this sensor system has not been completed. The accelerometer used is manufactured by IC Sensors.

Rate gyro. The rate gyro serves two purposes. The first is as the second half of the two dimensional inertial system composed along with the accelerometer. The rotation of the robot is determined by time integrating the output of the rate gyro, and, just as with the accelerometer, exact accuracy is not expected yet the gyro can be recalibrated at will. The accelerometer and the rate gyro are mounted on a leg axle along with the inclinometers. Thus the acceleration measured is always in the direction perpendicular to gravity and the rotation measured is about the axis parallel to gravity.

The second use of the rate gyro is to stabilize the pan/tilt head. The pan/tilt head is able to scan back and forth, and up and down, and thus is an appropriate mounting for a CCD camera and an IR range finder discussed later in this chapter. It is desirable to keep the head, and therefore the CCD camera pointed at the same scene even as the robot rotates. In order to reduce the drift of the head while it is being controlled by the rate gyro, the CCD camera measures optical flow in its images and uses this additional information to help cancel the gyro drift. This method was developed by Paul Viola [Viola 90]. At this point in time, the rate gyro system is not yet complete. The rate gyro used is manufactured by Watson Industries.

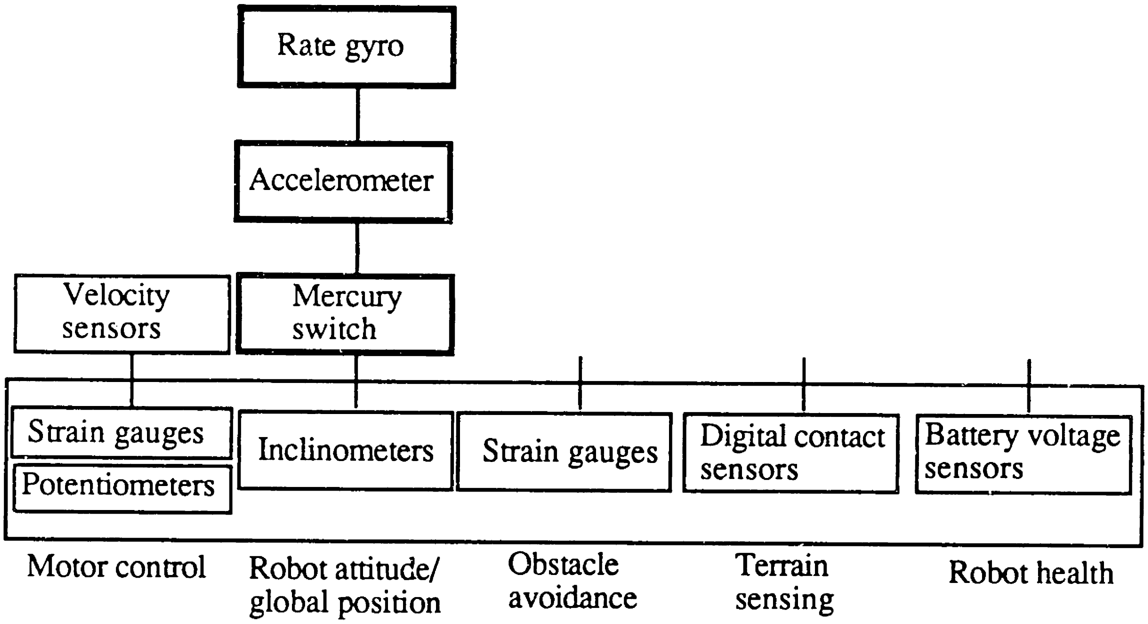


Figure 6.6 The robot attitude/global position branch of the sensor hierarchy tree

Obstacle avoidance

Obstacle avoidance sensors are used to determine when there is either an immediate obstacle in the way or there is an obstacle in a particular direction. Below is a description of these sensors.

Short-range IR proximity sensors. Short-range proximity sensors are mounted on the ankles of the legs. They can detect an object in front of them at a range of between 3/4 inch and 2 inches, depending on the color and shape of the object. This sensor is used to detect obstacles in front of the foot during the swing phase of the walking motion. This knowledge can be used to guide the foot smoothly over an obstacle without hitting it. The sensors which make up this system are manufactured by Hamamatsu.

Two degree-of-freedom actuated antenna. Attila has a two degree-of-freedom, motor-driven antenna. The antenna can be used as a "blind man's cane" to allow the robot to feel its way around obstacles. It can also be used to feel out the rough dimensions of an object in front of it.

This antenna was primarily designed by Michael Binnard. The antenna is ten inches long and can sweep out in front of the robot or store itself away by rotating underneath the legs, alongside the body. The antenna is equipped with two sets of strain gauges. The first set is mounted at the base of the antenna, while the second set is mounted two inches from the base. The strain gauges are used to determine when the antenna collides with an object. The separation between the two sets of strain gauges allows the robot to determine approximately where on the antenna the collision occurred.

Long-range point range finder. The range finder is an infrared triangulating device which can detect objects between ten inches and fifteen feet away with 0.7 inch resolution. The range finder is mounted in Attila's pan/tilt head. This mounting allows the range finder to be aimed at any point in front of the robot or scanned to provide a rough depth map. This sensor is manufactured by Hamamatsu.

165 x 192 pixel CCD camera. The CCD camera is a very versatile sensor. At this point in time, it is only used for cancellation of rate gyro drift, as mentioned in the rate gyro description, and sending video images to a monitoring station. Olaf Bleck designed the CCD camera system. Deniz Yuret designed the circuitry which converts the digitally stored image to an NTSC video signal. In the future, this sensor may provide much more information for the robot to use.

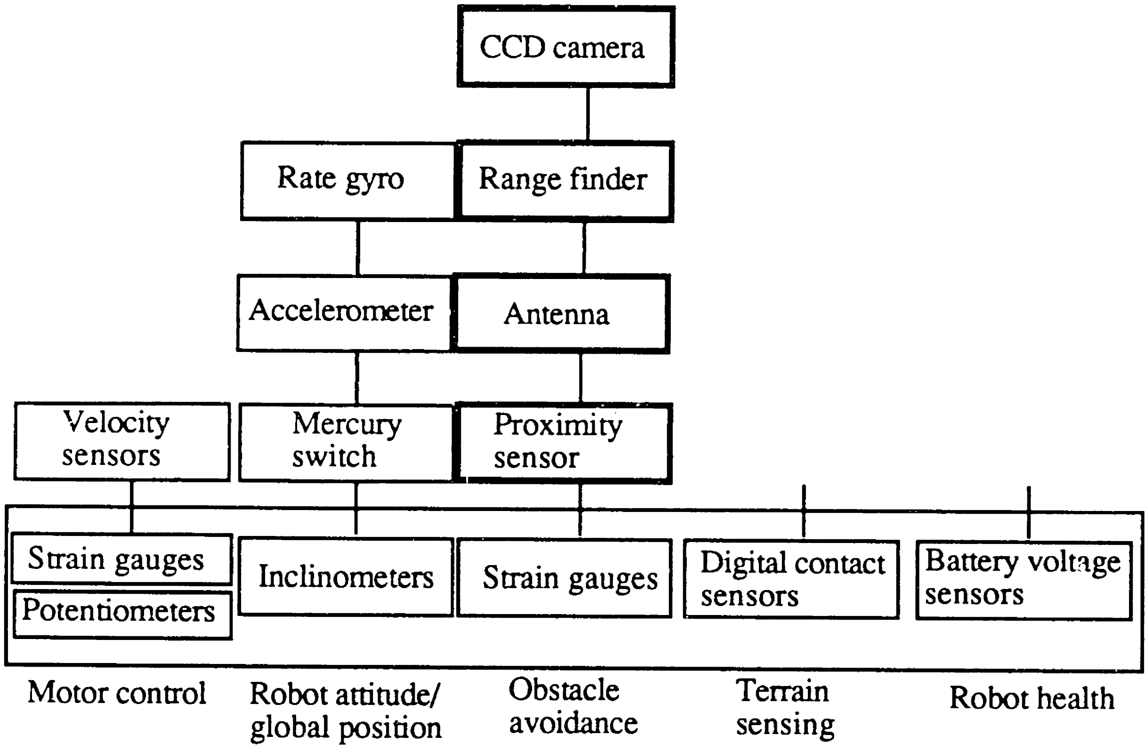


Figure 6.7 The obstacle avoidance branch of the sensor hierarchy tree

Terrain Sensing

The terrain sensors are a class of sensors which attempt to characterize the terrain underfoot. A description of the terrain sensors on Attila follows.

Optical contact sensor. The optical contact sensor is a sensor which detects a surface between 1/8 inch and 1/16 inch away from the bottom of the foot. This sensor is useful in determining when the robot is touching surfaces which cannot support any loads. The sensor can also be used to trace out the top surface of an object the robot is standing on and locate edges of that surface.

Peak force detection. On each footfall, the peak force is detected. This reading can be used to determine the approximate hardness of the surface being stepped on. If the foot impacts a hard surface, there is a very sharp impact force, while a step onto a softer surface does not cause such high forces upon footfall. This information can be used to differentiate surfaces.

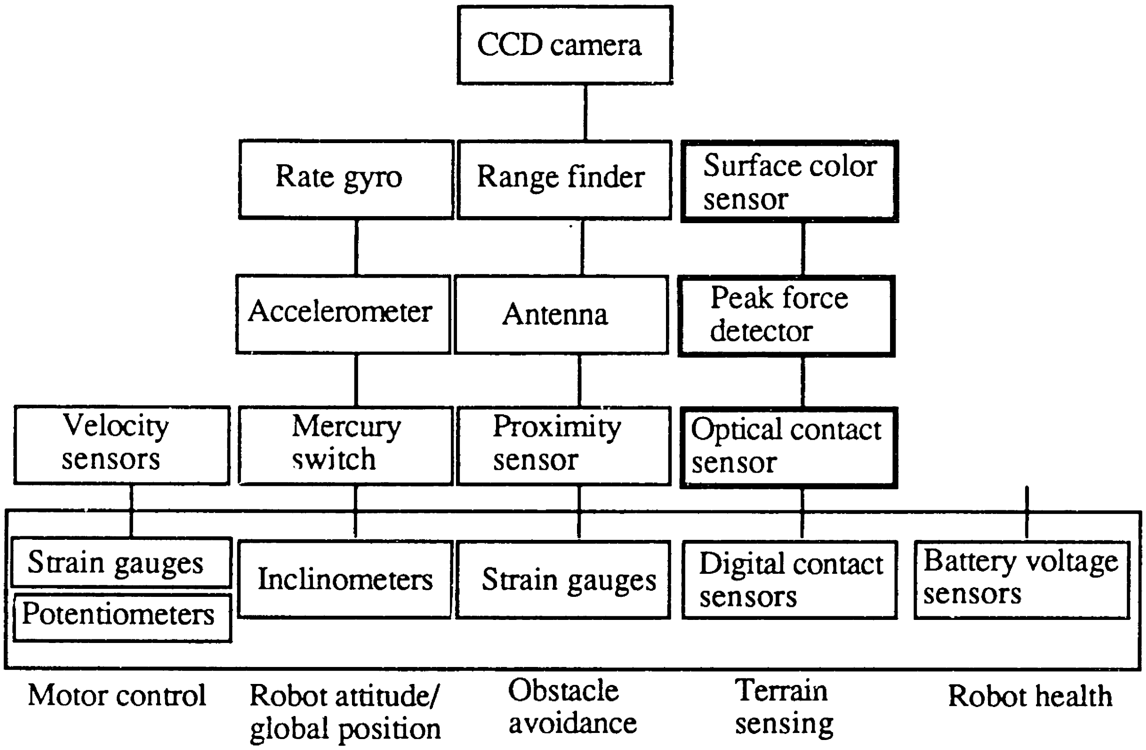


Figure 6.8 The terrain sensing branch of the sensor hierarchy tree

Surface color detection. The surface color detection system on the robot allows Attila to differentiate between various color terrains. The sensor measures light intensity through three different color filters: red, blue and green. The ratio of these intensities is taken in order to eliminate sensitivity to illumination intensity. This sensor was manufactured by Hamamatsu, and Angel DeLaCruz investigated its use for robotic systems [DeLaCruz 91].

Robot Health

Robot health sensors are sensors which monitor how the robot is functioning and if any systems have become damaged or dysfunctional. A health sensor is not necessarily a physical entity. For example, a procedure which attempts to move a leg from one mechanical stop to another while monitoring the range reported from the leg's potentiometer is not a physical sensor, but it can determine if that leg's degree of freedom is functioning properly. It can even auto-calibrate the leg's degree of freedom. This type of sensor is referred to as a virtual sensor.

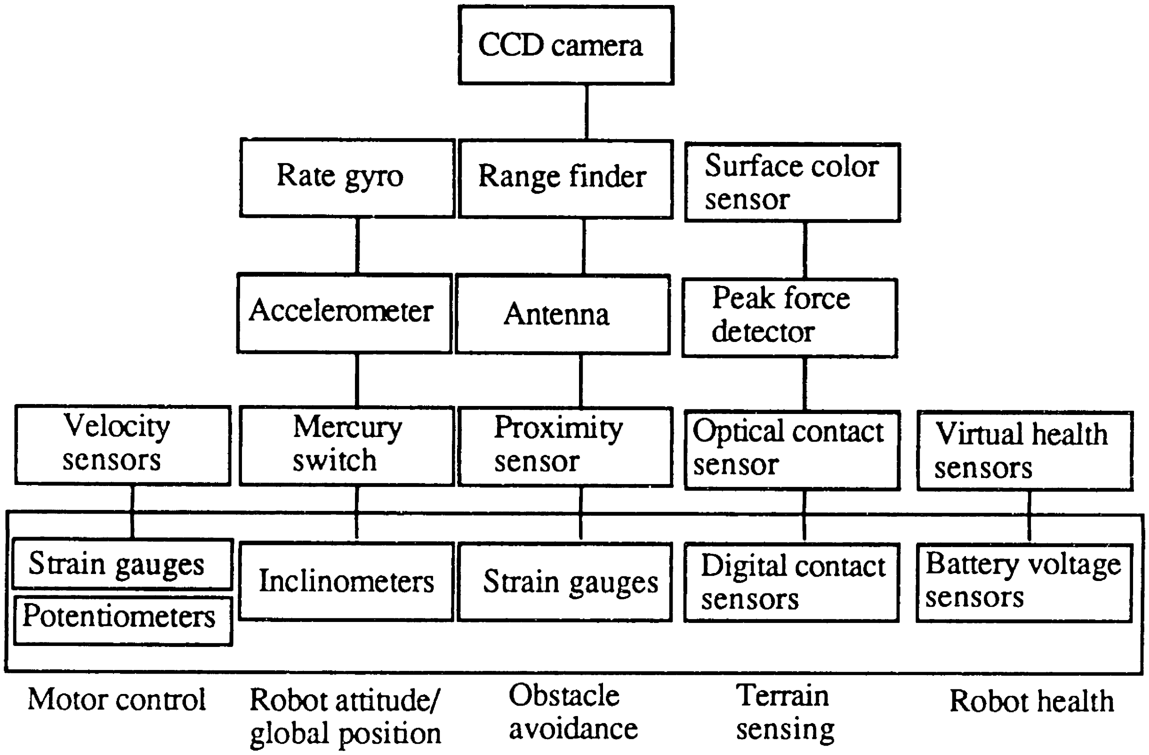


Figure 6.9 Attila's complete sensory hierarchy tree

Since these virtual sensors are manifestations of the control software, the details of their structure and operation are beyond the scope of this thesis. Attila is designed to allow for the auto-calibration and functional testing of leg position, the force sensors on the legs, velocity sensing on the legs, and position and force sensors on the antenna. As mentioned in the section on attitude and global position sensing, the robot can also recalibrate the inertial system.

SENSOR INTEGRATION

While Attila only relies fundamentally on its lowest level sensors, it uses all its other sensors to improve its performance. This section describes several methods in which sensors are combined to facilitate improved robot performance.

The terrain filter

For Attila to travel across rough terrain, it should be able to pick and choose traversable routes. The obstacle avoidance senors on the robot do this. Attila's CCD camera is the only sensor that can collect information from beyond the range of 15 feet. This sensor will eventually give Attila information about interesting places to explore or similar information. At a range of 10 inches out to 15', the long range IR range finder can operate. By scanning its beam, the range finder can create rough depth maps of the terrain. With this information, the robot may recognize impassible slopes, or promising looking passes. Thus, the range finder can suggest a global direction to move in which is free from impassible terrain. 10 inches in front of the robot, the antenna sweeps back and forth. If the antenna hits an obstacle, the robot can be steered around it, and then continue on its course suggested by the range finder. Should the robot have to tread on rough terrain, the proximity sensors and the force sensors will allow the robot's legs to feel their way over the ground. What has been created in effect with all these sensors is a terrain filter. Given a global direction to head, the robot is able to choose a traversable path based on the arrangement of the terrain. Figure 6.10 shows this terrain filter.

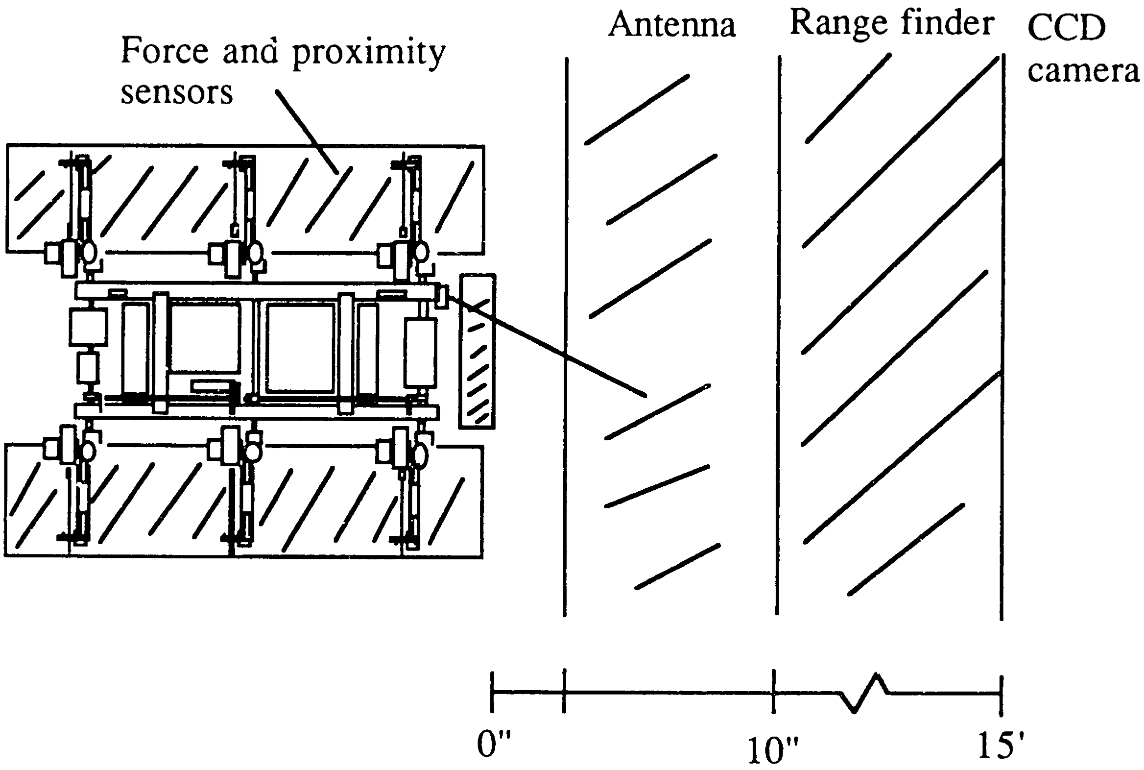


Figure 6.10 The Terrain Filter
This figure shows Attila and the effective ranges of the various sensors on it which make up the terrain filter.

Leg Recovery

The stepping cycle of the robot can make use of both terrain sensors, and obstacle avoidance sensors. The stepping cycle consists of lifting the leg off the ground, swinging it forward to a new foothold, loading the foothold, and driving the leg back. The lift-off of the leg can be sensed by the digital contact sensor, the optical contact sensor, or the strain gauges. As the leg is swung forward, obstacles in its path are detected by the ankle-mounted proximity sensors. The foot can then be lifted until it is over the obstacle and the proximity sensor no longer senses it. Then the leg can continue to swing forward. If the proximity sensors should fail to notice an obstacle, the strain gauges will detect it when the leg hits the obstacle.

In some cases, the proximity sensors are of no use, and the robot must rely entirely on its strain gauges. For example, if the robot walks in tall grass, the proximity sensor on the leg will detect an object in the leg's path even though the leg can be easily swung through the grass. This type of terrain hazard is termed a non-geometric hazard because, from the robot's point of view, it does not physically have the shape it appears to have. The robot can determine if its leg is in one of these types of terrain hazards because it has proximity sensors on both sides of its ankles. If it notices an obstacle in front of its leg, it can also check behind the leg. If there is an apparent obstacle there too, either the leg is in a hole or it is in one of these non-geometric hazards. This can be resolved by trying to move the leg forward despite the proximity sensor readings. If the leg moves without the strain gauges noticing a collision, then it is a non-geometric hazard and the robot can continue on if it so desires.

Once the leg has completed its swing forward, it can hunt for an appropriate foothold with its contact sensors and strain gauges. This done, the leg is driven back advancing the robot, and the whole cycle is repeated.

SUMMARY

This chapter has developed a structure within which to design a sensory system for a robot. It is often tempting to endow a robot with a vision system, or some other complex high level sensor, and assume it can solve all sensing problems the robot will have to face. In designing a sensory system, it is necessary to first analyze the environment the robot will be working in, and then work toward endowing the robot with enough sensors to at least survive in that environment. When this is done, more sensors may be added to enhance the performance of the robot.

By endowing the robot with many sensors, difficult problems such as path planning, or recognition of non geometric hazards can be removed from high level, computationally intensive programs and left in the hands of the sensors and simple reflexes.

Chapter 7
Connectors, Modularity, and Computers

WHY THESE THREE GO TOGETHER

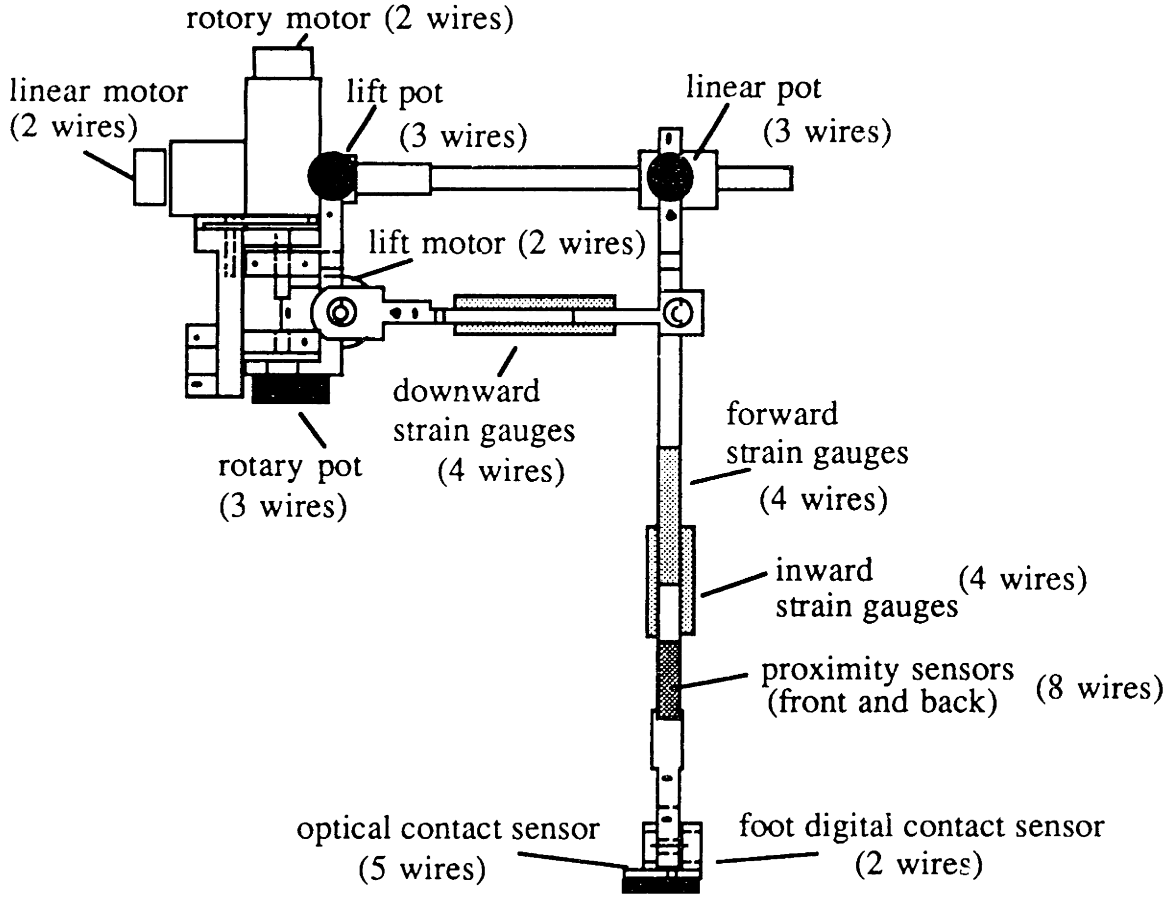


Figure 7.1 42 wires per leg!

Attila is a complex robot. It has over 150 individual sensors of 14 different types. The robot's legged system has 19 degrees of freedom. With the addition of a two-degree-of-freedom antenna and a pan/tilt head, the robot has 23 motors. This is a huge connector problem, not to mention a difficult control problem. If all the computation was done in a central control processor, then approximately 42 wires would need to be brought off each leg! This is shown in figure 7.1.

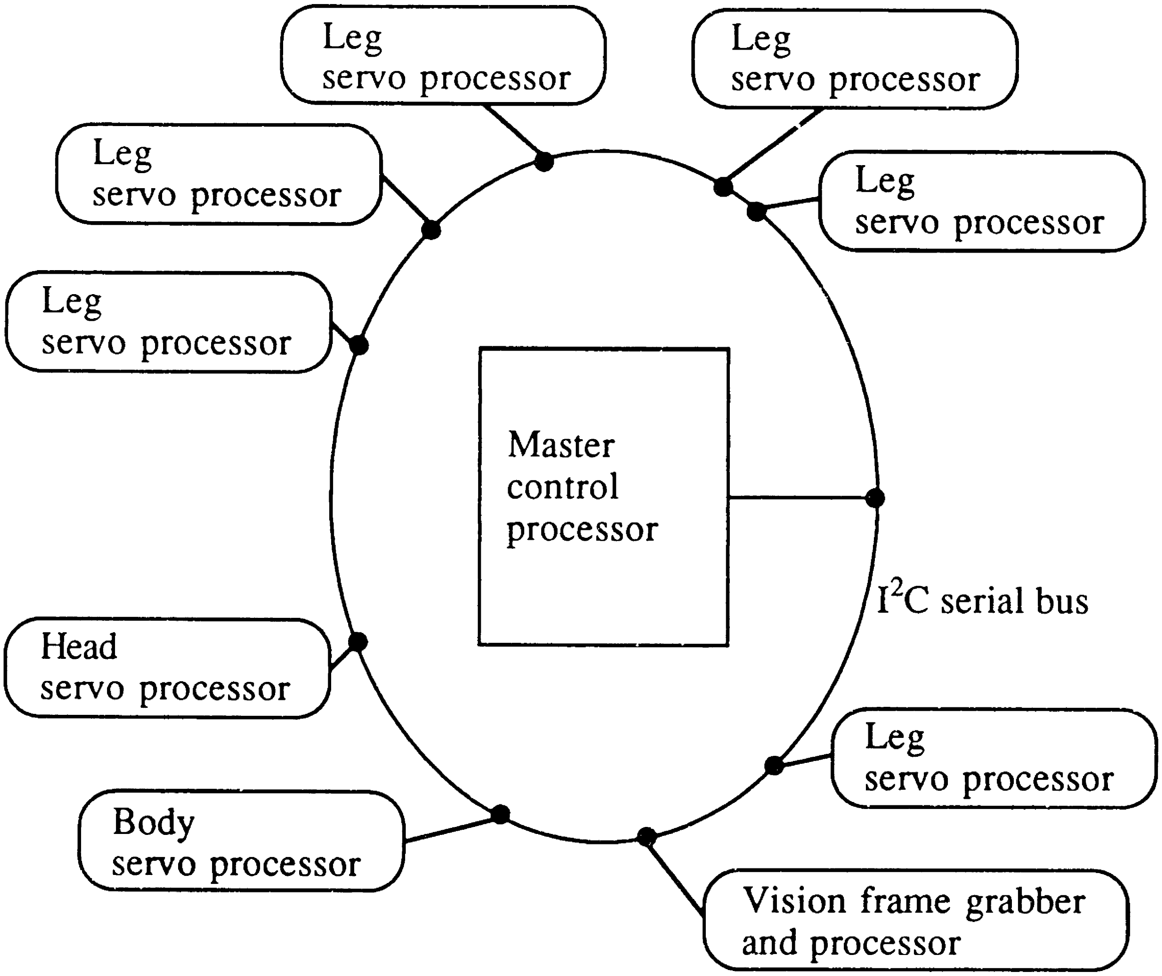


Figure 7.2 Attila's control network

In order to bring things under control, the robot was broken up into smart subsystems and then linked together with a medium speed serial network. By placing a servo processor on the leg itself, all the wiring could be routed to that processor and only power and communication need to be sent to the leg. As shown in figure 7.2, Attila is organized with a single central processor to which 10 subsystem control processors are attached. This allows high bandwidth communication and motor servoing to be handled locally, with only high level communication making it onto the serial network.

ENABLING TECHNOLOGY

In order to create the smart subsystems on Attila, several microcontroller boards had to be designed. The local satellite processor board is an 87c751 based board used on every subsystem except the vision system and the master processor. The heart of the master processor and the vision system is the Signetics 68070 processor.

The local satellite processor. The local satellite processor is a general-purpose analog information acquisition and motor-control board. It was designed by Cynthia Ferrell and Chuck Rosenberg. The board combines a 16 Mhz 87c751 microcontroller with 19 channels of 8-bit A/D conversion, three 3 amp peak motor drivers, and a I^2C serial bus.

On the legs, the processor is connected to an analog signal processing board which amplifies the strain gauges, peak detects the force measurements, differentiates the potentiometers, and drives the proximity sensors. The program running on the processor board for the legs, written by Cynthia Ferrell, allows the three motors on a leg to be servoed to a position at a specified velocity or force. The processor also communicates the legs' state information to and receives motor servo setpoint commands from the master processor.

There are also satellite processor boards which drive the pan/tilt head, the antenna and the global forth degree of freedom, and the inertial navigation system. Each of these systems has its own analog signal processing board into which the satellite processor connects.

The master processor. The master processor is a 15 Mhz 68070 based microprocessor board. It has Brooks's Behavior Language operating system resident in ROM [Brooks 90], 64K bytes of electrically erasable PROM for program space, and 256K bytes of RAM. This processor board serves as the computational engine for the robot. It has an expansion port into which new cards can be plugged. To date there are three such cards.

The extended memory card expands the electrically erasable PROM space up to 312K bytes and extends RAM by up to 8 Megabytes. With the addition of the camera card, a master processor card is turned into a frame-grabber for the robot's CCD camera. Because grabbing frames only uses a fraction of the processor's computing power, the vision system which is formed can also do some simple machine vision computation, such as the rate gyro drift compensation described in chapter 6. A third board can be added to the vision system which allows a monitor to be plugged into the robot and the images from the CCD camera be displayed on it. All of the boards in this section were designed by Olaf Bleck, except for the video display board which was designed by Deniz Yuret, as referenced earlier in chapter 6.

The I^2C serial bus. The I^2C serial bus is a 100 K bit communication system which is used to hook all the various subsystems on Attila together.

The I^2C serial bus is not fast enough to do real-time motor servoing or to transfer images at any reasonable frame rate. This limitation in effect, forces modularity on the robot. Anywhere that high bandwidth communication is required, a local processor must be used. The local processor can, internal to its own subsystem, run very high bandwidth operations. But in order to satisfy the I^2C serial bus bandwidth limitations, the local processor must boil down the information it generates and the control commands it needs to a few bytes.

Since it is impossible for the vision processor to send the master processor an image, it must locally determine what in the image is interesting, and just report that. For example, the world shifting to the right or an interesting terrain feature on the left are interesting pieces of information from an image.

SMART SUBSYSTEMS

The result of the I^2C serial bus forced modularity is the breakup of Attila into smart subsystems. Each subsystem has one of the processors described earlier, some sensors, and in many cases, some actuators to control. The subsystems are connected together with a standardized connection which gives the subsystem the power it needs, and the I^2C serial bus hookup.

These modular subsystems are the method through which complexity has been controlled on the Attila project. Each subsystem is complete enough to be developed and debugged on its own. Once that subsystem is complete, it can be treated as a black box with well defined functionality and a high level set of commands used to operate. Attila's smart subsystems mark only the beginning. For as easily as one of Attila's subsystems could be used on a different robot, so could a new subsystem be added to Attila. All it would have to do is conform to the I^2C serial bus protocol, find a place physically to be mounted on the robot, and be interfaced with the master processor so that it can be queried for information or commanded to do something. In this way, robot building blocks are created. As more of these blocks become thoroughly debugged and made robust, more and more can be incorporated into new robots, thereby creating better, more sophisticated artificial creatures. Below is a list of the smart subsystems which make up Attila.

Figure 7.3 Attila's Leg system

The Leg Subsystem

Processor - Standard 87c751 satellite processor board

Sensors - 3 axis force measurement
Peak detection of downward and forward force axis
Joint position sensors for all 3 degrees of freedom
Joint velocity sensors for all 3 degrees of freedom
Proximity sensors mounted on either side of the ankle
Digital surface contact sensor
Optical surface contact sensor

Mechanical - 3 degree of freedom leg
9" leg step height
Supports up to 35 oz in normal walking configuration
Foot moves at speed up to 17 in/sec

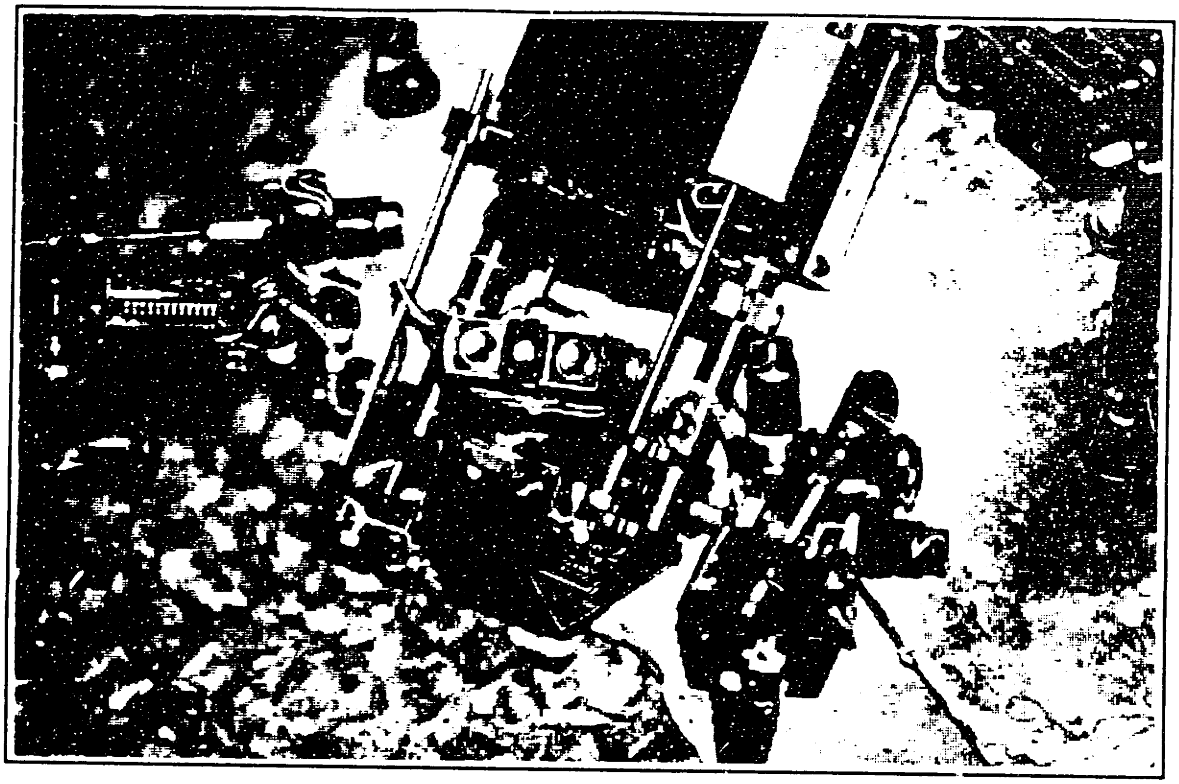


Figure 7.4 Attila's Pan/Tilt Head

The Pan/Tilt Head

Processor - Standard 87c751 satellite processor

Sensors - CCD camera chip and lens with direct connector to the vision system frame grabber.

10" - 15' point range finder

Forward pointing close proximity sensor

Downward pointing surface color sensor

Pan/tilt joint angle sensors

Pan/tilt joint velocity sensors

Mechanical - 2 degree of freedom pan and tilt

Max pan velocity 600 degrees/sec

Max tilt velocity 100 degrees/sec

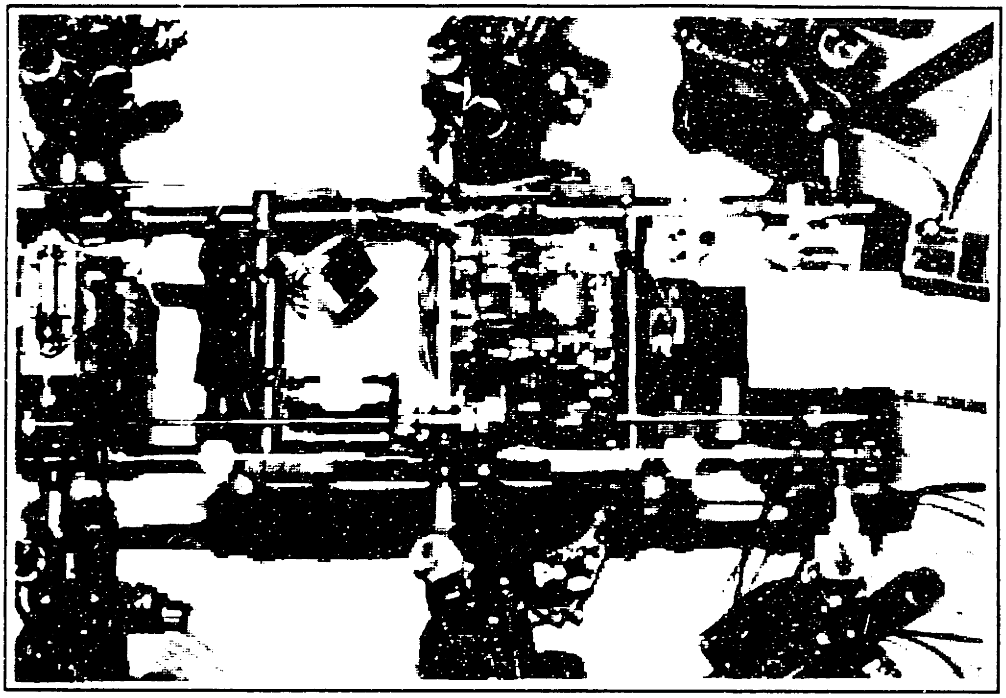


Figure 7.5 Attila's Body

Attila's Body

- *Processor* - Standard 87c751 satellite processor
- *Sensors* - 2 axis (pitch, roll) inclinometers
- 2 degree of freedom actuated antenna
  - phi, theta joint position sensors
  - phi, theta joint velocity sensors
  - antenna collision and location sensor
- Global degree of freedom position sensor
- Motor and electronic battery power level sensor
- 1 bit orientation sensor
- *Mechanical* - Vertical leg servoing actuator
- 2 degree of freedom actuated antenna
- *Special* - 7.2 volt 1.3 amp hour battery pack

4.8 volt 1.8 amp hour battery pack
Power regulation for +5v, +15v, and -15v
Connection network for all subsystems

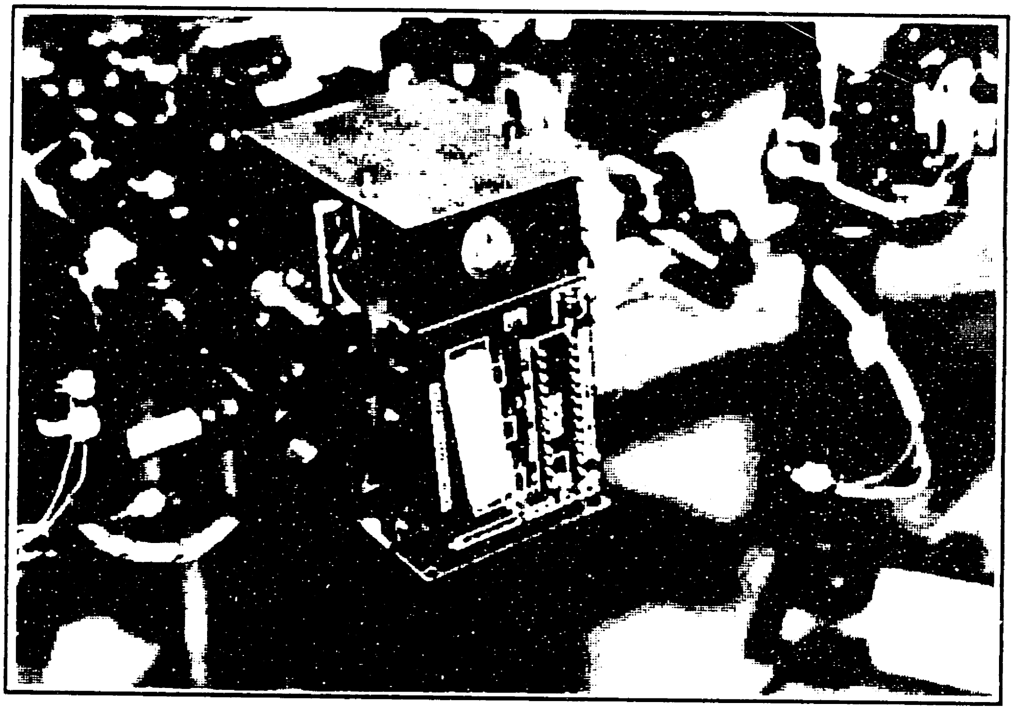


Figure 7.6 Attila's Inertial system

Attila's Inertial system

Processor - Standard 87c751 satellite processor
Sensors - 5g max Accelerometer
300 degree max rate sensor
Note - not functional yet

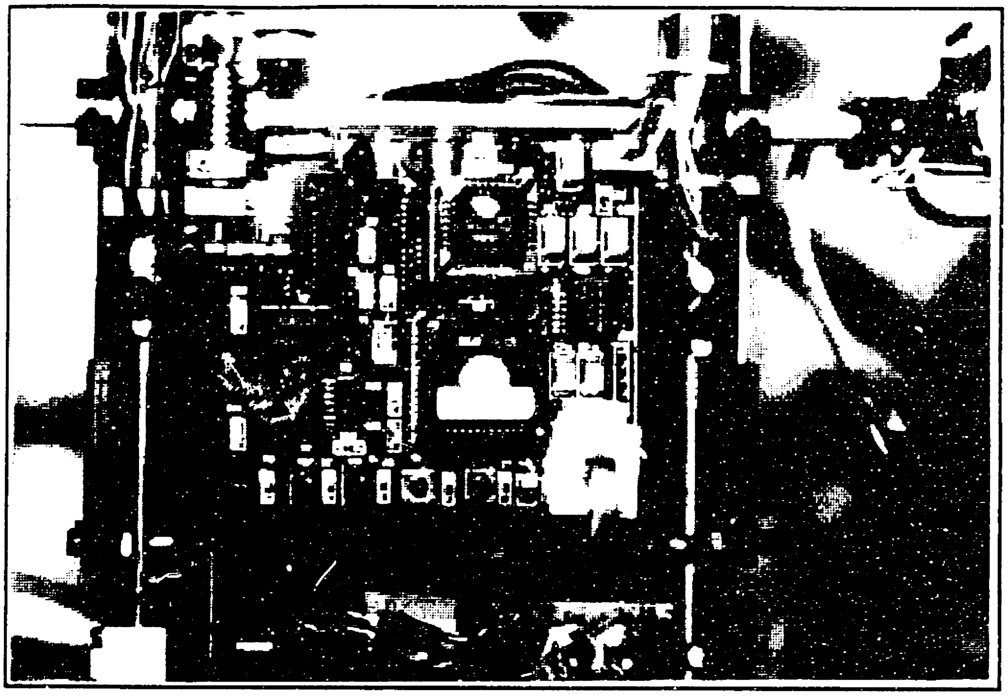


Figure 7.7 Attila's Master Processor

The Master Processor System

Processor - 68070 based microprocessor

Extended memory card

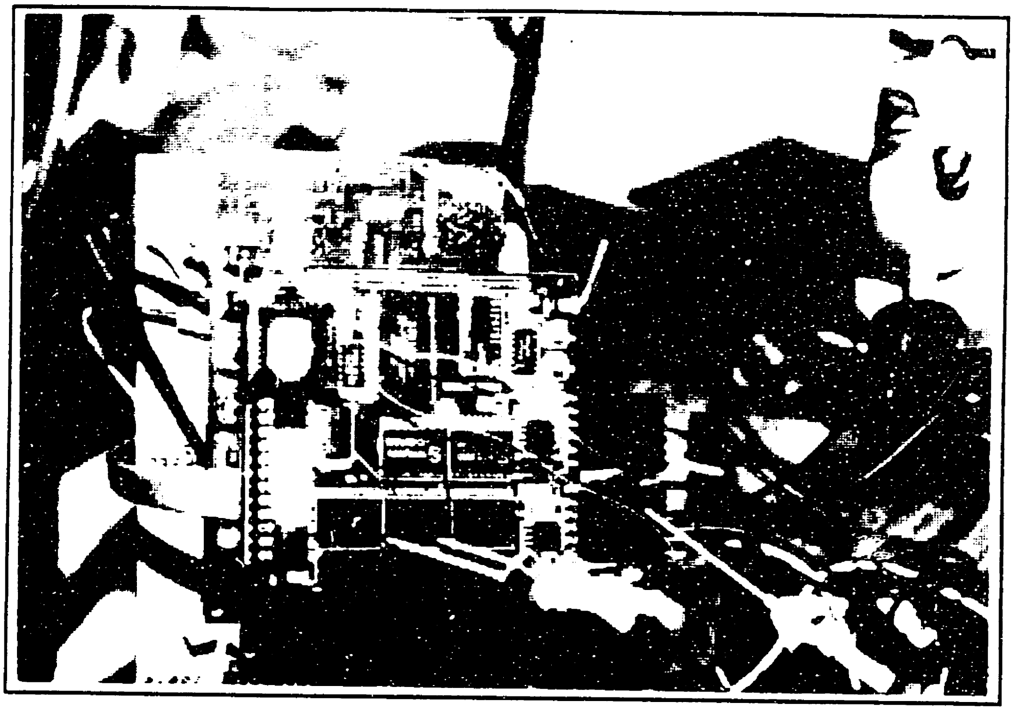


Figure 7.8 Attila's Vision System

The Vision System

Processor	-	68070 based micro processor Frame grabber expansion board NTSC converter board

SUMMARY

The need to control the complexity of Attila has led to a very modular approach. The design of the robot was broken up into many different subsystems. Each of these subsystems was given enough functionality that it was a stand alone device. Thus, is was possible to independently develop and test each of the subsystems. The further-reaching implication of developing high functionality subsystems is that, since they are stand alone units with reasonably simple interfaces, they can be easily transferred to new systems. In this way, artificial creature evolution can be accelerated.

Chapter 8
Summary and Future Work

SUMMARY

Building an artificial creature was an immense undertaking. Every system needed to fit nicely with every other system. No mechanical design decisions could be made without looking at the ramifications it would have to the electrical system and vice versa. Despite all this, Attila has come together and stands as one of the most richly sensored and dexterous robots built today.

Attila has incorporated several important new ideas which have made its construction easier or increased its performance. The first of these has to do with the robot's size. The smaller the robot is, the easier it is to make it durable and resistant to falls. This fact has far ranging benefits. The most important, perhaps, is that the programmer of the robot can feel safe trying out control programs without having to be certain ahead of time that they will not cause the robot to fall down. A second effect of the robot's scale is that the programmer can be sitting at a computer in a normal office with the robot on the floor by his feet while programming it. There is no special need for large spaces to work in.

The second major idea is that climbing over an object and walking on flat ground are two very different things. While walking wants to be efficient and quick, when faced with an obstacle, it is permissible to slow down and carefully place each foot. This realization allowed a kinematic leg design in which performance and speed depended on which portion of the workspace the leg was in. The leg could be optimized to both walk quickly and climb powerfully. When the robot is walking, the leg is in the portion of the workspace which allows for very quick movements. Lifting the leg in the air to climb moves the leg into the region where the leg moves slowly and powerfully.

Vertical leg servoing was the most important mechanical idea incorporated into the robot. Adding the global degree of freedom allows the robot to walk up slopes in the same manner as it walks on flat ground. The center of mass is brought closer to the surface being climbed as the slope becomes steeper. This fact increases the robot's stability and may allow Attila to climb the steepest slopes ever attempted by a robot. Unfortunately, this attempt will have to wait for more software. Attila's ability to get up off its back represents a crucial ability for a rough terrain traversing robot because it will be out of reach of physical human assistance in the event of a fall.

Attila takes a step back in the sensory domain. There has been a trend in building robots to use nothing but, or to depend fundamentally on, a camera or laser range scanner to yield enough information for a robot to operate. This may be because, for large robots, the designers felt that any collision between the robot and the world would result in grave damage to either the robot or the environment. This should not be a concern for an exploring robot which is meant to poke around its environment and, more importantly, feel its way through terrain perhaps too confusing and filled with non-geometric hazards for range sensors to operate sufficiently well. Attila approaches the terrain sensing problem from a very different perspective. It has a minimum set of sensors required to assure its safety. These sensors are primarily tactile sensors. Only when the minimum set was complete did we add on more sensors, such as cameras and range finders, and then only to improve the robot's performance. The ultimate safety of Attila always rests in the fundamental sensor's hands.

The most significant idea incorporated into the robot was the development of modular smart subsystems. In order to control the complexity on the robot, the robot was broken up into fully functional subsystems. Each of these subsystems, once its mechanical and electrical interface was specified, could be developed and tested independently. The result of this modularity is that it is very easy to remove and replace systems on the robot. To date there has been many times where a malfunctioning leg has been unscrewed from the robot and replaced or all but one of the legs disconnected if one leg sufficed for the current test. It takes 20 seconds to remove or reattach a leg on Attila.

Not only has the use of modular smart subsystems allowed for easier development and debugging of the robot, it also facilitates easier improvements. It is possible to take just one leg, the pan/tilt head, or any other subsystem and work on making it better. The scope of the improvement project is nicely constrained, and, as long as the interfaces are maintained, when the project is finished, the subsystem can be incorporated directly back onto the robot.

TIME ESTIMATION

Things take longer than you think they will, especially when you are designing completely new systems. This fact causes problems when trying to come up with time estimates. To illustrate this, Attila was supposed to be a one year long project. Below is a table which tries to show how much was accomplished on the robot in various time frames. Take into consideration that the Mobot Lab is a near ideal place to develop robots. The purchasing system is fast and efficient, there are lots of people to ask for help, there is no shortage of computers to work on, and there is an excellent machine shop across the hall.

Time frame	An example of an accomplishment
1 day	wire 1 leg
1 week	design and build the on/off/recharging switch box
1 month	design and build the mechanical portion of the pan/tilt head
6 months	design and build a leg prototype
3 people for 2.5 years	Attila

Table 8.1 Time frames

The more I think about the problems I've had estimating times, the more I am reminded of a conversation involving one of the great mythical engineers of future. It is a conversation between "Star Trek's" Scotty and Captain Kirk, and went something like this:

> Kirk: How do you do it Scotty? You always come through. You even fix things in half your required time when we really need it.
>
> Scotty: That's because when you ask me how long something will take, I take my best estimate and triple it. That way I know I can get it done, and if you say it must be done in half that time, there is a good chance of doing that, as well.

"How long will Attila take, 3 years? Why you finished in 2 1/2. That's 6 months early!" I think Scotty's got the right idea.

FUTURE WORK

Now that Attila exists, it can be improved. The starting point will be the hardening of existing systems. In order for the robot to meet its goal of exploring harsh terrain, its body must be sealed to the elements, and perhaps even made waterproof. Who knows what Attila might find wandering along on the bottom of the ocean?

Once Attila systems are hardened, it will be time to expand once again. There are three projects in particular which I see as most important. The vision system, in its current form, does not have enough computational horsepower to do much in the way of serious machine vision. The addition of a digital signal processor or two would go far in alleviating this problem. There is already space in the body cavity for this and the DSP cards could plug in to the expansion connector on the existing vision system boards.

The robot could also use a manipulator for the collection of samples. While the legs can move rocks around, even into position to be picked up, they cannot actually be used to lift the samples.

The third addition to the robot will be solar panels. In order for the robot to be truly autonomous, It must be able to recharge itself when needed. The solar cell array would fold up on the robot when not in use, and could be mounted on the top or bottom of the robot.

By the time these systems are built, there will be twenty more things that the robot "needs." As long as the robot remains modular, new systems can be easily added, while old, out of date, systems, are retired or improved. I hope the result of all this is the development of artificial creatures which will push the envelope of artificial intelligence, provide the world with robots which can be used to explore the frontiers of our universe, and inspire the minds of young scientists, engineers, and dreamers to go ahead and build the coolest thing that they can imagine.

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