Leg Design and Stair Climbing Control for the *RHex Robotic Hexapod*

Edward Z. Moore

Department of Mechanical Engineering
McGill University, Montreal, Canada
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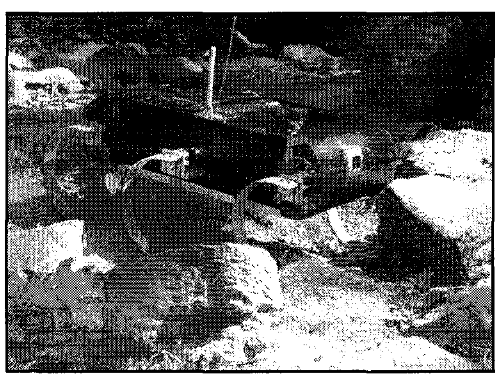

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Abstract

The goals of the research in this thesis are twofold. First, I designed and tested a stair-traversing controller, which allows RHex to ascend and descend a wide variety of human sized stairs. I tested the stair-ascending controller on nine different flights of stairs, and the stair-descending controller on four different flights of stairs. Rhex was run ten times on each flight, and met with only a single failure out of the one-hundred-and-thirty attempts. Second, we built and tested three competing leg designs. The second and third leg designs proved adequate for use on RHex, enabling dynamic and off road behaviors. The stair controller and leg design processes both drew on lessons from biology, in a process in we call "functional biomimesis". This framework guided us while we mimicked the functionally important features of animal morphology and behavior, while ignoring those features that are irrelevant to locomotion. We compared these advances with previous work in the field, including work on wheeled and tracked vehicles, as well as stair-traversing legged robots. Finally, RHex is a new robot, so we present an overview of RHex's basic mechanical and electrical designs.

Sommaire

Les objectifs de cette thèse se présentent en deux parties. En premier lieu, un contrôleur permettant le robot RHex de monter et descendre plusieurs types d'escaliers a été conçu et testé. Le contrôleur de monté a été testé sur neuf differents types d'escaliers et le contrôleur de descente sur quatre. Chaque ascension et chaque descente a été repétée dix fois par RHex. À la suite de cent quatre-vingts tentatives, RHex a échoué une seule fois. En deuxième lieu, trois differents types de jambes ont été conçus et testés. Le deuxième et le troisième design des jambes de RHex ont démontrés un fonctionnement dynamique adéquat et une bonne mobilité hors-terrain. Le développement du contrôleur et le design des jambes ont été inspirés du domaine biologique appelé 'functional biomimesis'. Par ce procédé, les comportements de l'animal et la morphologie de ses membres sont immités pour amener le robot à une mobilité semblable, tout autres comportements non-reliés à sa locomotion étant ignorés. Les résultats obtenus ont été comparés aux recherches publiées précédemment, incluant les recherches reliées aux véhicules sur roues et sur rails en plus de tous les robots mobiles sur jambes capablent de monter des paliers. RHex est un nouveau robot. Ce document présente ses principales caractéristiques mécaniques et électriques.

Acknowledgements

Foremost, I wish to express my deepest gratitude to my supervisor, Dr. Martin Buehler. Martin went the extra mile to get me into lab, and he went the extra mile to get me through. The shortest conversations with Martin can produce the most amazing results. It was a pleasure to work for a man who takes so much pleasure in his work, is so knowledgeable, and is so driven.

Now for the Supporting Cast

Montreal location

To Dave "go faster" McMordie, who pushed the robot where no one else thought it could go, including over that cliff. To Dave, who stood shoulder to shoulder with me while we confronted the big men with machine guns during the Paris episode. To Dave, who put blood, sweat, and ingenuity into making RHex the world's best robot. To Dave: my thanks, my respect and my admiration.

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U. Michigan location

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At the U. California at Berkeley location

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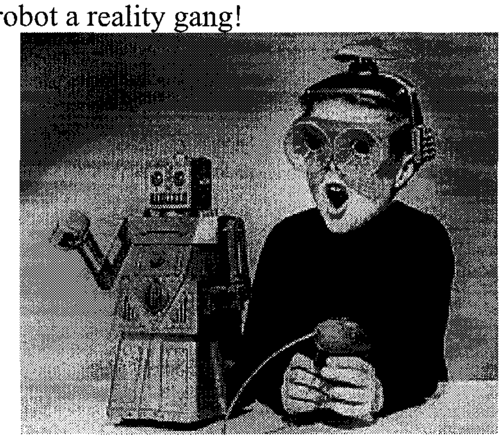
On the home front

Wicked big thanks, and my love, those who held down the fort and supported me: Mom, Dad, and Steve. Last, but not least, I owe my continued sanity to the incredibly patient Carolyn.

Special thanks to

H. B. Brown Jr. of Carnegie Mellon, for creating the geometry and prototype of the Four-Bar leg, and to Felix Grimminger, a visiting masters student at ARL from the Fachhochschule Karlsruhe in Germany, for creating the geometry and prototype of the Half-Circle leg for the RHex project.

Thanks for making the robot a reality gang!



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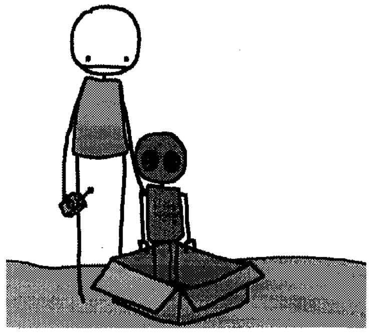
Chapter 1 Introduction



1.1 *Motivation*

The engineer's strategy for improving the lot of humankind is two pronged: constructing applications and devising theories that add to our understanding of our environment. These two facets of engineering are related; theory can lead to applications, but it is difficult to assess the value of theory in robotics without building and testing a real robot. At the Ambulatory Robotics Laboratory (ARL) of McGill University, we strive to work in both spheres. A theoretical mindset helps us to better understand the inner workings of animals, as well as to determine how little actuation and how few degrees of freedom (d.o.f.) are actually necessary for locomotion. But we do not build robots simply to test hypothesis about the mobility of animals. We wish to build machines that can be immediately useful too, and thus satisfy both criteria for an engineering project.

On the RHex team, we base our designs upon nature, but we are not ruled by it. Making compromises and trade-offs is the engineer's forte. For instance, materials must be chosen while considering the competing requirements of strength and weight. Nature makes trade-offs too, through evolution, yet where animals have muscles, robots have motors, where animals have bone, robots have steel, and where animals have fat, robots have batteries. Not only do our robots have different actuators, structural materials, and power sources than nature, but we are not even working towards identical goals. Nature's trade-offs involve many objectives, some of which are not relevant to RHex. Animals are not only running machines, but must also find food, and win mates. Thus we cannot copy nature blindly when weighing design decisions. *Functional biomimesis* is the term we use to describe how we arrive at the outline of a design through mimicry of selected animal features. It is a search for what can be pared away from the morphology of animals, whether it is DOFs, actuators, or even sensors, in order to leave a system built purely for locomotion. If we choose correctly and identify the important underlying principles of animal locomotion, and then verify our intuition through the production of a successful robot, we will not only have created a useful, engineered device, but we might also gain a greater understanding of the neurobiology of animals through simple deduction.

This design philosophy has been directly applied to RHex. The design and control of RHex was inspired by recent research into cockroach locomotion. Despite limited intelligence, cockroaches are one of the most mobile animals on earth, and so are very attractive role models for roboticists. Inroads have been made into understanding the strategies that cockroaches use to choose leg trajectories, increase efficiency, and maintain stability. We had hoped the success of RHex would augment these theories, and we believe that the ability that RHex already displays bears them out.

We envision RHex working in dangerous, dirty, or dull missions (the famous '3D' applications for robots) such as fire fighting, search and rescue, bomb disposal, planetary exploration, military action, and law enforcement. While RHex had been funded so far by the U.S. Defense Advanced Research Projects Agency (DARPA) for possible use in military scenarios, negotiations with NASA are ongoing towards the design of a mini-RHex for a Mars mission. We have received an IRIS (One of the Canadian networks of Centers of Excellence) grant to use a version of RHex for underwater exploration; work should begin soon. We have received a request for a quote to duplicate RHex for a U.K. military R&D department. However, many of the terrestrial mission scenarios, civilian and military, take place in urban settings. Of these, nearly all require RHex to have high mobility in buildings, which implies the capability to traverse stairs. These missions place other demands on RHex. RHex needs to be able to adapt to different terrains, to be reliable, and to be fast. Thoughtful leg design plays an important part in all of these requirements. Leg geometry even plays a part in stair negotiation: it determines the path of the hip, and the moment arm of the motor. The challenges of robotic stair climbing and leg design embody both theoretical and practical concerns, and our answers to them form the basis of this thesis.

1.2 *Authors Contributions*

- I designed legs that satisfy weight, ruggedness, compliance, and manufacturability requirements with H. Ben Brown of Carnegie Mellon University in the case of the Four-Bar legs, and with Felix Grimminger in the case of the Half-Circle legs. The designs are discussed in chapter three.
- I built an experimental apparatus, to determine the static force-displacement properties of three different types of legs: stiff Four-Bar, Hinged Four-Bar and Half-Circle legs. These

values will be used in future applications of theory to the robot as well as in simulations. The results and apparatus are discussed in chapter four.

- I designed simple, open loop controllers so that RHex can now ascend and descend a wide variety of human sized stairs. The behavior is quick, autonomous, reliable, and operates without prior knowledge of the stair geometry. The controller and the experiments that were run with it are discussed in chapter five.

1.3 *Organization of the Thesis*

In Chapter Two I give the reader the background necessary to appreciate the results presented later in the thesis, in chapters three through five. Drawing on the literature, I examine leg designs in animals and earlier robots. The literature also allows us to look at examples of other animals and robots with respect to their ability to traverse stairs. I conclude this background material by presenting the basic design of RHex in enough detail to expose strengths and weaknesses of the platform, and by including work on RHex for which others on the RHex team deserve credit.

Chapter Three starts with a summary of the leg design requirements suggested by the literature survey, and our own intuition. I then proceed to describe the very first 'compass' leg and the design of the three competing leg designs used on RHex.

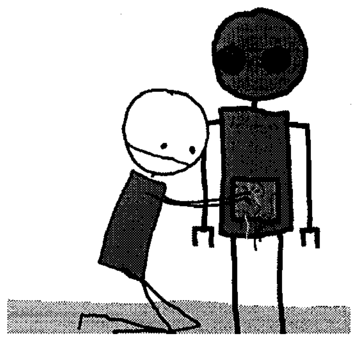
Chapter Four is concerned with the force versus displacement characteristics of the legs that we designed and built. I give results of the tests I performed on the legs to determine the values of these dynamic parameters. This chapter finishes with details of the setup used in the experiments.

Chapter Five begins with a discussion of the impact the geometry of each leg design has upon stair traversing. I then detail the controller developed to ascend and descend stairs. The chapter concludes with the presentation of the reliability, power consumption, endurance, and specific resistance results I gathered in experiments.

Chapter Six opens with a discussion of the results and implications of chapters three, four, and five. We then look forward to additional research avenues stemming from these results. We make hypotheses concerning new leg designs that incorporate additional actuated degrees of freedom, and potential improvements to the stair-traversing controller. Finally, we conclude with a summary of the contributions of this thesis.

Throughout this thesis personal the pronouns "I" and "we" are used repeatedly, in a conscious effort to make the text more readable. "I" refers to the author, of course. I try to make it clear to whom I am referring when "we" is used. I also believe that this will make it easier for me to give credit where credit is due. Contrast "RHex was accidentally dropped 3 m onto concrete" with "I accidentally dropped RHex 3 m onto concrete." It is important that I get credit for the experimental discovery that RHex can survive such a fall, much as my fellow researchers deserve credit for their- generally more insightful - discoveries.

Chapter 2 Background



Nature and engineers have built many walking systems, and by almost every measure, nature has proven to be the better engineer. There are laudable robot designs, but animals are more reliable, mobile, and efficient than men's best robots. We aim for our robots to have the abilities of animals, but we work with the tools of engineering, not of nature. Thus there are lessons for us both in the methods of nature, and the checkered results of engineering.

2.1 *Review of Leg Design*

We anticipated that not every strand of an animal's fur, or even the precise topology of its bones would be critical to locomotion. Our main task before building RHex's legs was then to decide which traits of an animal's leg contributes the most to its locomotion abilities, if they indeed factor into the equation at all. By comparing the features of robot legs with those of animals, and the resulting abilities of each, we tried to deduce the properties of RHex's ideal legs. We call this process "functional biomimesis"[1]. Other researchers have had the same goals as us, and used similar methods, and referred to the same biological research, but have not achieved all of the desired results. We have been wary of repeating their mistakes.

2.1.1 MAMMALIAN LEG DESIGN

Mammalian legs are worth examining because mammals display all of the characteristics in which we are interested: speed, agility, and reliability. In addition, RHex's weight of 7.5 kg places it in a class replete with mammals. We must ask some pointed questions, though, in terms of how mammals achieve their success. What are the most important determinants of a mammal's success in locomotion? Can the neurological system alone take credit for the amazing locomotion abilities of mammals? And if not the neurological system, what is responsible for the abilities we are trying to equal? Perhaps there is a common morphology among legs of the myriad species of mammals that aids in achieving excellence in locomotion?

Some elements of mammalian leg commonalities are readily visible. Some features, such as effective spring constant[2] and leg thickness[3], can even be predicted based on animal weight. They are simple relationships, based on exponentials. The precise formulas are not the issue; the fact is that they exist. The data for the relationship between body mass and effective leg spring constant is given in Figure 2-1. Gleaned from the tried and true methods of extrapolation and statistics, this type of information is the best guide we have to interpreting the infinitely complex morphology of animal legs, within an engineering framework.

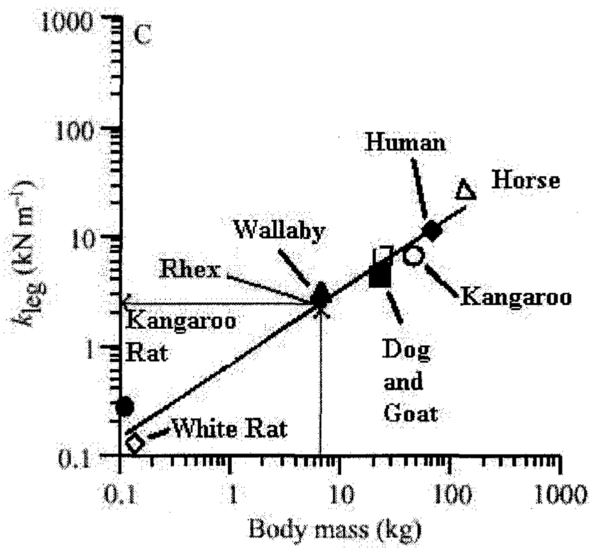


Figure 2-1 - A simple linear relationship between animal mass and effective leg spring constant can be seen on a log-log plot. Given RHex's weight, we can deduce nature's choice of spring constant, assuming that we know how many legs RHex will have on the ground at a time. If RHex uses all six legs, we need a soft spring: only 500N/m. With three legs on the ground, 1000N/m would be more appropriate.[2]

The first unifying feature of large mammalian legs is a common posture. Large mammals have a *cursorial* posture (Figure 2-2), which means that it is optimized for running. This stance is typified by each of the feet being positioned below the hip, and the width of the support polygon being small relative to leg length. Figure 2-6 contrasts this stance with that of animals not optimized for running: small mammals, which have a non-cursorial posture, and animals like insects and lizards, which use what is known as a sprawled posture. The rationale behind these other postures is left for later. A cursorial stance requires active control to maintain balance; it is like an inverted pendulum. Minimal muscle forces and energy is required to stand with this posture when balanced, because gravity loads are supported by the leg structure, not by muscle force. Hirose gave his sprawled posture robots this benefit by applying sound engineering principles. This was done by decoupling the motors required to move the robot forward from those that raise and lower the COM.[4] When the COM is at a constant height, a brake applied enough force to prevent the center of mass from sinking to the ground, while the propulsion motors did their job, preventing any energy losses from simply supporting the bulk of the robot, but still allowing forward movement.

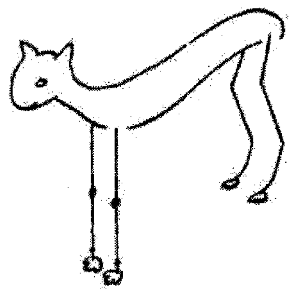


Figure 2-2 - Simplified mammal with a *cursorial* posture, that is optimized for speed and efficiency

The second common feature of mammalian leg morphology that is quickly apparent is the large number of joints. Seven d.o.f.'s (degrees of freedom) can be found in a human leg, not counting toes, as seen in Figure 2-3. Other mammals, such as a dog, require five per leg, but this is still a significant number if translated into motors on a robot leg.

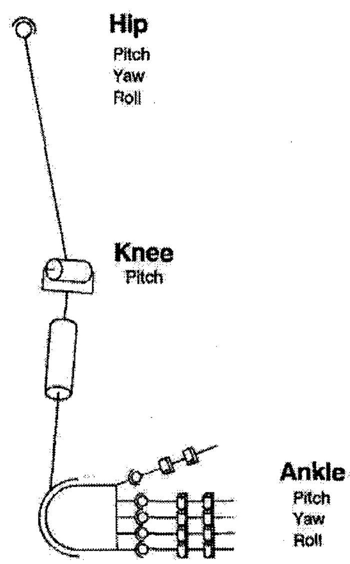


Figure 2-3 - The seven joints needed for rough approximation of a human leg. Seven d.o.f.'s per leg is impractical for a robot. [5]

Our classical training tells us that if we combine mammals' posture and complexity, mammalian locomotion will be an unstable, high d.o.f. system, that will requires significant control and coordination. If this is correct, a perfect imitation of animal leg design is only half of the solution required to build a robot that can equal animals. This prediction is contradicted by hard data pointing to the use of passive dynamics, and not high-level nervous system activity, as the source of high-efficiency animal locomotion[6][53] According to this idea, animals act as a simple-to-control spring mass system: they "bounce" on spring-like tendons to store and recover significant amounts of energy during each step. Of course this is something that has been understood before, in particular by Marc Raibert, whose pioneering work[7] is based on robots that implement literally the low DOF compliant pogo-stick model from Figure 2-4.

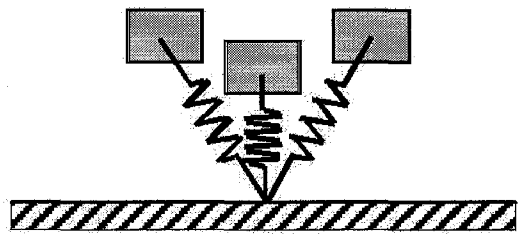


Figure 2-4 - The body and leg of a running animal can be reduced to a bouncing spring-mass system[9] [7] [53]

This would imply that, at least for locomotion on flat terrain, many of the d.o.f. in animal legs are redundant, and don't need to be reproduced in robots that don't need to eat or procreate, but only to bounce. It goes without saying that we could not immobilize a dog's knees and expect the same running behavior. The argument is that the motion produced by many joints can be replicated by a well chosen few. A model with few degrees of freedom, and with a simple, low DOF target dynamics coinciding with that preferred by natural dynamics is eminently controllable. This is a result that engenders hope for RHex.

If we can mimic structural features of mammals, such as thickness, during robot leg design, should we do so? While the spring constant may be important to our design, the thickness is not. We might need to approximate the spring constant to get the same behavior, but the thickness is only a function of the organic materials of an animal. We design with metals, so we are not interested in copying the thickness of an animal's leg. We will be better served by doing a engineering structural analysis on RHex's legs. While we want to imitate properties that increase speed or efficiency, we are not interested in copying every detail of animal legs.

We are left with several important design ideas.

1) We don't need to copy every detail of mammalian legs in our design.

2) We can predict from biological data what leg spring constant is desirable based on the mass of the robot.

3) While we want low energy consumption, which can result from a cursorial stance and bouncing behaviors, we do not have the tools to solve the control problem presented by a large d.o.f. leg.

4) At least for locomotion, many of the degrees of freedom in animal legs are redundant, and can be eliminated, though we should choose carefully those we wish to use.

2.1.2 ARTHROPOD LEG DESIGN

Based on population, insects comprise the most successful experiment in legged locomotion found on planet Earth. We expect that there is a reason for their success, and we hope we learn the right lessons from it. As insects are much smaller than RHex, we must take care in taking cues from insects, lest we are led astray by adaptations of insects that depend on their small size. Insects provide use with a model of animal leg design that is radically different than that of mammals, both in posture, and in the reduced complexity of the nervous system. We searched the literature for the answer to the same questions regarding insects as we did for mammals: how do they do what they do? What role does the nervous system play, and what role does mechanical design play?

The cockroach has proved that it has a very successful locomotion strategy due to its speed and stability over it's numerous and varied habitats add concrete performance examples: For example *Periplaneta Americana (cockroach)* speed > 10 Body lengths/s, maneuverability in terms of turning speed: > 10 rad/s, and efficiency for arthropods of 0.1-1 J/kg/m/s (specific resistance). Full demonstrated that cockroaches "bounce" in a manner similar to mammals. He then showed that cockroaches do not require high-level neural control to perform well in all types of terrain. Instead of high-level control, Full has found that there is a significant contribution to stability of locomotion from low-level neural reflexes, and from excellent passive leg design, which relies on simple mechanics for passive stability.[11]

An example of simplifying the control task through mechanical design can be found in the stance of the cockroach. The cursorial posture of large mammals differs from the posture of most insects, including the cockroach, in one very important way: an insect's stance is very wide, and its feet are not directly below its hip. This is known simply as a *sprawled* stance. The cockroach has passive stability, due to its stance, regardless of the terrain it is crossing over, and so it can rely on very simple leg trajectories for leg coordination. Cockroaches uses two groups of three legs each to form a pair of tripods. Either tripod can support the full weight of the insect, and the two alternate support periods. This gait is known as the alternating tripod gait. Low-level neurons, not high-level ones, define this, the only cockroach gait, and are responsible for many of the admirable abilities of the cockroach.

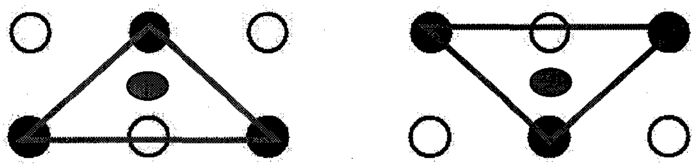


Figure 2-5 - The two phases of the alternating tripod gait. Full circles are legs in stance, open circles are legs in flight. Center of mass, oval dot, must stay inside the *polygon of support* (triangle) formed by stance legs.

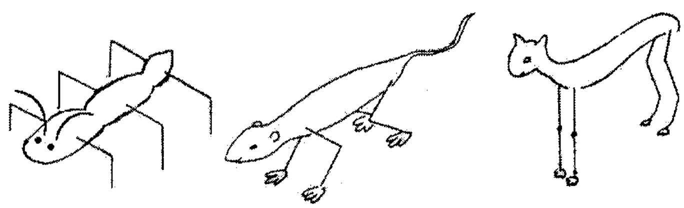


Figure 2-6 - Left to right, sprawled, non-cursorial, cursorial postures each have different leg configurations. Sprawled postures are most stable. Cursorial is fastest and most efficient.

Another positive result of the sprawled stance is that the joint torques of an insect are not as likely as a mammals to change sign. This is because they are always under some load simply to support the body. This idea is demonstrated in Figure 2-7. This eliminates the control problems due to backlash when standing, which is an important consideration for builders of legged robots[48], even if it is not for insects.

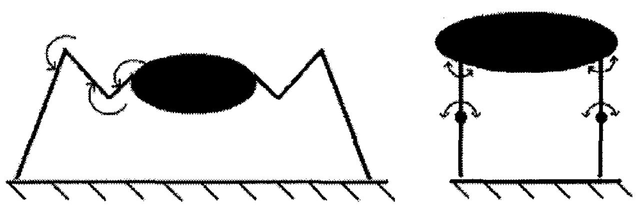


Figure 2-7 - Comparison of joint torques for a sprawled posture (left) and a cursorial posture (right) The sprawled posture requires constant effort to maintain, but the sign of the torque does not change, while the cursorial posture requires low torques that often change sign.

Recent research shows that the cockroach gives an example of how low-level neurological feedback can play an important role in locomotion. Consider the cockroach moving at high-speed over broken terrain. We might expect the cockroach to cross the terrain as humans do, carefully planning every step, and the best path through the area. It doesn't, and there is a serious impediment to the cockroach following this strategy: the speed of its neurons. When traveling over broken terrain, the cockroach has very little time to make complicated decisions relating to foot positioning and path planning. The nervous system has so little time that it isn't even able to relay information from the legs to the brain, and wait for an answer.[11] The brain must be taken out of the loop, and foot placement and leg trajectory decisions left to low-level neurons.[12] The low-level nervous system of the cockroach, known as the *Central Pattern Generator* (CPG), sends an open-loop signal to the cockroach's legs, that is known as the *Central Pattern.*[13] The CPG commands the legs to follow a set trajectory, and is repeated over and over again.

Important lessons from the world of insects include 1) a reinforcement of the bouncing hypothesis found in mammals, 2) the importance of a wide stance, and 3) the usefulness of gaits that use repetitive leg motions to improve stability during locomotion.

2.1.3 ROBOTS WITH STIFF LEGS

There are many robots that do not purposely store energy during some parts of the walking cycle, and release it during other parts. Included are robots that control leg trajectory with mechanisms, and robots that are designed to adapt to terrain using high d.o.f. leg kinematics. These robots generally have trouble reaching high speeds or negotiating obstacles, or both.

A common strategy in obstacle negotiating is to construct a robot with many degrees of freedom per leg, so that the robot can adapt to the terrain using kinematics. Legs with pointed toes need only three d.o.f. to have complete freedom in choosing touchdown position. In theory, at least, the robot should be then able to pick its way across even the most challenging terrain, by using isolated footholds, and a well-chosen path. Not only have toeholds and paths proven too difficult for autonomous machines to find reliably, but this technique also requires a stiff, over-actuated, high d.o.f. leg for precise toe control. This also requires a large number of heavy, inefficient motors, and leads to high impact loads. It is difficult to reach high speeds with these robots, as they are limited by their efforts to pick toe positions, and their slow, inefficient actuators. Several prominent vehicles of this type are shown in Figure 2-8.

An alternate approach to leg motion is to turn to simple mechanisms to produce a predetermined leg trajectory. Classic examples are shown in Figure 2-9. These machines have no ability to adapt to the environment, and so must rely on static stability if they are to cover broken ground.

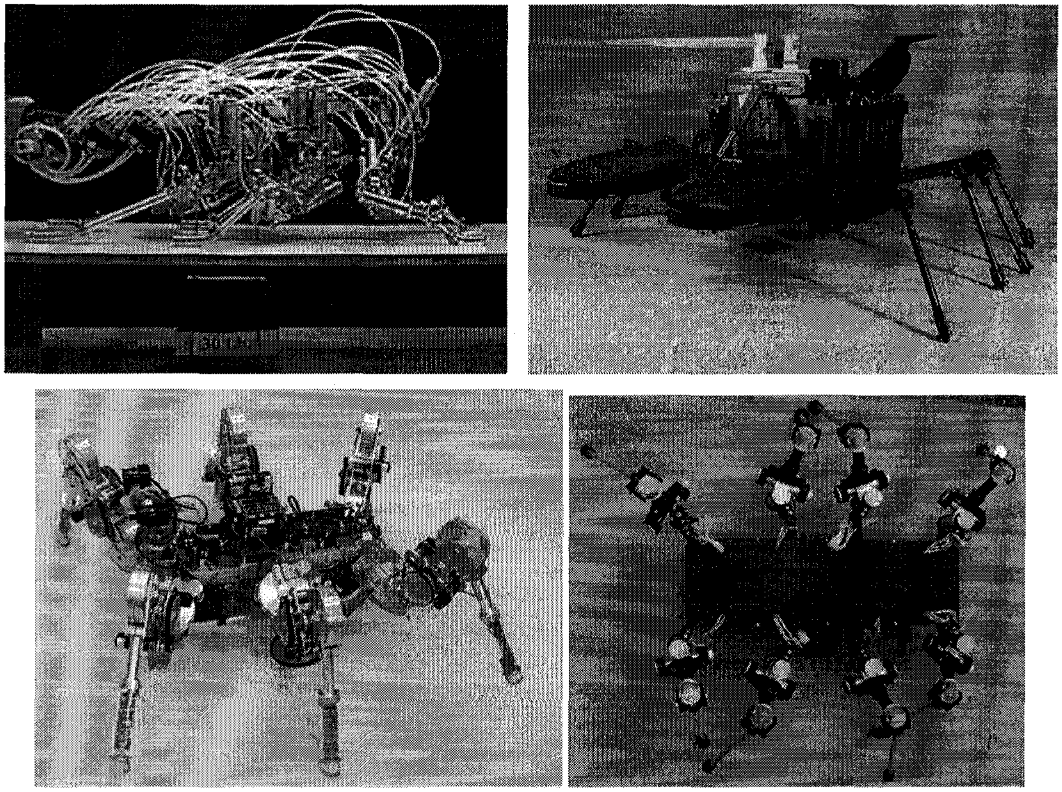


Figure 2-8 – Animal shaped robots with rigid legs. Clockwise from top left: Robot III of CWU[13]. BUR-001 of Northeastern[14], Lauron II of FZI [15], and Scorpion of Fraunhofer AIS [16]

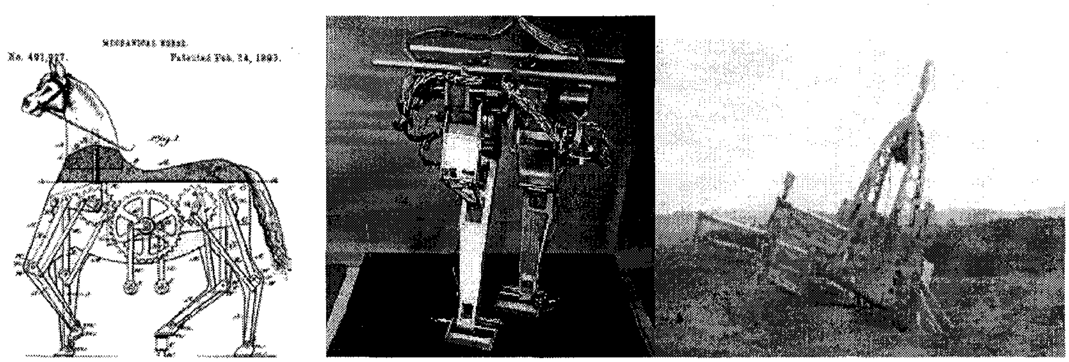


Figure 2-9 - Mechanism based robots, from left: Mechanical Horse from a 19th century patent[7], Meltran II of the AIST (Japan)[18], and Dante of CMU[19].

It is evident that mimicking the motions of animals is not enough if we want to duplicate the results achieved by nature. We could twiddle our thumbs until motors, power supplies, and control systems of unimaginable sophistication become available, but even then, it is not assured that brute force will win the day. Despite the geometric increases in the potency of the components we use to build robots, we have not seen a corresponding increase in the abilities of the whole robot. This can only lead us to conclude that there is a fundamental difficulty presented in the approach of the robots discussed here. We believe that much of the difference between success and failure of walking machines can be found in the opportunities presented for high speed, reliability, and efficiency by the exchange of energy during the walking cycle, and through the influence on reliability of low-level mechanical feedback.

Energy must be stored and released during the course of the walking cycle in order to make up for the inadequacies of the peak output power of actuators, and to increase efficiency. Some researchers over the last twenty years have focused their research on using stiff legs to store energy. These legs use gravity to passively store energy during parts of the walking cycle, as some animals do in walking. We believe that these robots represent a step forward, but they have not been able to emerge from the lab, and enter the real world. Examining the results of these projects should yield many clues to us as we designed RHex.

What are the strengths and limitations of using gravity to store energy? The idea is conceptually simple: the center of mass of the robot must be raised to store energy and lowered to release it. Most walkers have achieved this by having stiff legs that force the hip to change height as it passes over the foot during a stride. This is known as the *compass gait* and is illustrated in Figure 2-10.

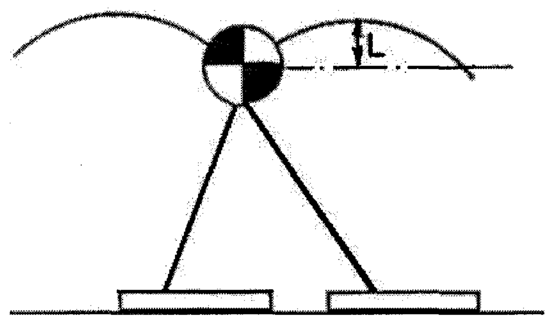


Figure 2-10. - Biped compass walker[33]. COM is highest when it passes over foot. Energy is stored in change in height.

While this technique can be found in nature for walking, it is not used for high-speed locomotion, because the rate at which energy can be stored and released is limited by gravity.[20] This is a useful model for efficient, low-speed locomotion, but it we will need another model to achieve our goal of high speed. Another way to store and release energy is to use compliant legs.

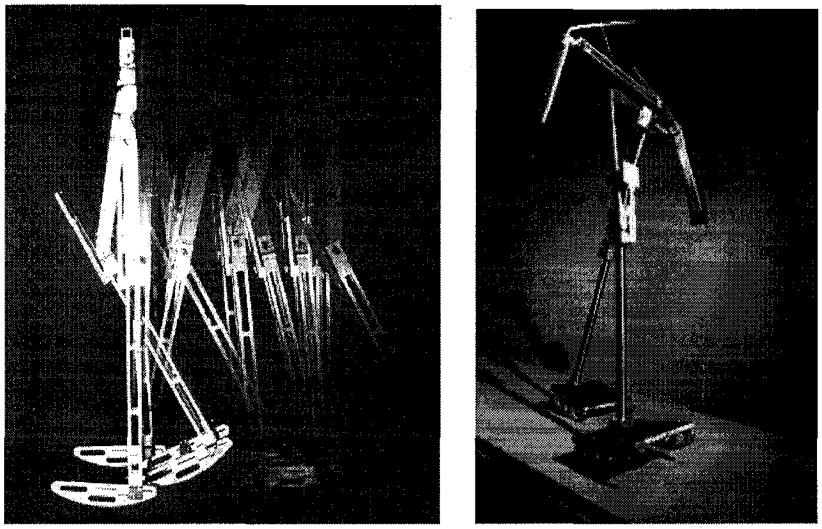


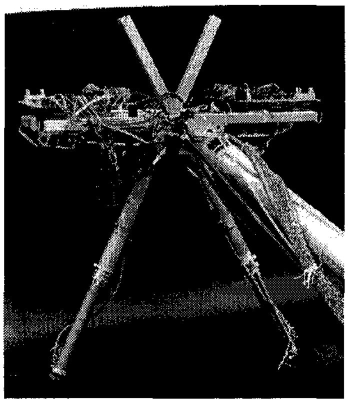
Figure 2-11 - Unpowered walkers that store and make use of potential energy. Left the Cornell Passive Walker[49], right Cornell Wisse/Collins Passive Walker[50].

2.1.4 ROBOT WITH COMPLIANT LEGS

Can springs help provide an effective model for legged machines? After viewing the success that animals have using their tendons as springs, we believe that they can. But storing potential energy in a spring, rather than gravity, poses a difficult set of engineering challenges to be overcome when creating a leg design. There are often problems with damping, reliability, and control of the exact spring constant used.

Several different spring technologies have been used to address the challenge of adding compliance to legs to allow a bouncing motion. Some robots have been built with pneumatic actuators, in which an air cylinder has served as both an actuator and a spring. Other robots have been built with telescoping joints, like the pneumatics, but with common coil springs inside. In addition to these broad, and more commercially available, categories of springs, there are many other prototype springs used by robotics researchers. These include custom leaf springs, shape-deposited rubber springs, and many more. Each class of spring has strengths and weaknesses, choosing a spring will determine which difficulties in our design will be most pressing.

The two most common spring designs, pneumatic and coil, have similar pros and cons. These designs have their strengths: the designs are commercially available, the designer has precise control over the value and direction of the spring constant, and off-axis stiffness can be made very high. These features allow for easier analysis of the robots dynamics. There are drawbacks of course. First, they are heavy. In addition, they do not react well to non-axial loads. During high non-axial loading conditions, such as under the impact loads of running, sliding friction can increase significantly, to the point where the mechanism ceases to function entirely. Another flaw is the high number of parts that both designs require, which can lead to reliability issues. Finally, these robots performed poorly on natural obstacles. So while this spring technology was selected for use on many running robots, including Raibert's monopods, biped, and quadruped[7], and ARL's Monopods, and Scouts[22],[23], we must view this design with some caution.



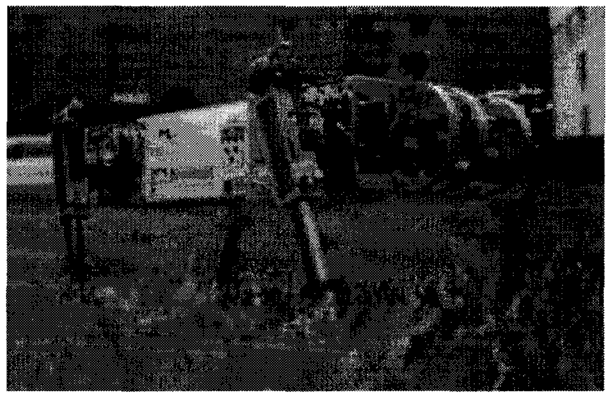


Figure 2-12 - Robots which use prismatic springs to store energy. Left - Raiberts Planar biped at MIT used pneumatic springs[7]. Right - McGill Scout II used coil springs[23]

We have little information concerning prototype spring designs used in other robots. We can only draw upon our engineering knowledge and extrapolate information. Pneumatic springs have been used with great success by almost all of Raibert's robots. However, in his pneumatic piston designs, a pneumatic pressure supply is needed to replenish pneumatic losses. This doesn't lend itself to autonomous robot designs. Hermetically sealed (bladder or muscle-type) pneumatic springs haven't been used successfully to our knowledge, even though this might be promising idea. Designs based on rubber or other polymeric materials, for instance, will probably have problems either with fatigue, or damping (not travel limitations, can get 300-600% strain for rubber extension springs). Rubber has been used successfully as a hip spring to provide leg swing motion and help improve running efficiency in ARL Monopod II.[9] Rubber springs share a drawback with leaf springs; the designer has less precise control over the magnitude and direction of the spring constant. On the other hand, these designs are generally lightweight, and compact. If the other engineering problems can be surmounted, these types of designs hold promise. Sprawlita, Patrush, Spring Flamingo, and the Bow-Legged Hopper exemplify good designs using non-standard spring mechanisms, and are shown in Figure 2-13 on the following page.

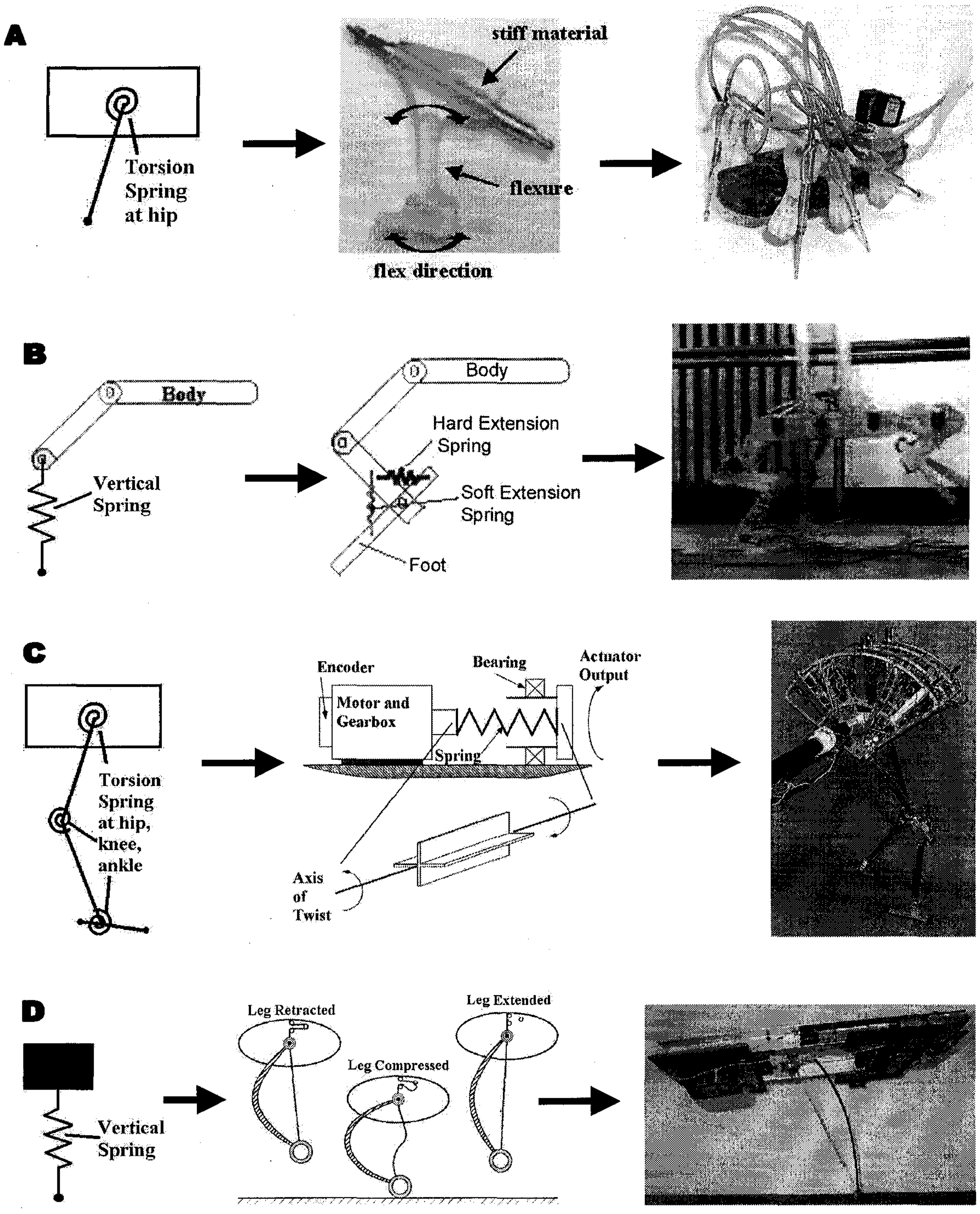


Figure 2-13 - Left to right - simplified models, more precise diagrams, and photos of robots with compliant legs. Top to bottom - Sprawlita[58], Patrush[56], Spring Flamingo[57], and the 3D Bow Legged Hopper[59]. Each of these leg designs is an attempt to overcome the problems of complexity, damping, and high mass that are common to telescoping spring designs.

Each of the four legs shown on the previous page has taken a different approach. Sprawlita[58] has compliance built right into its hip, since the hip is made with an elastomer via shape deposition. The shape deposition process gave the designers precise control over the composition and geometry of the hip spring. The designers of Patrush avoided exotic technology, and used extension springs with a mechanism,[56] thus avoiding the need to constrain the motion of the spring via a telescope. Spring Flamingo too uses old technology, but in a more interesting way. It puts a spring in line with the motor, and uses force feedback from the spring to not only store energy, but also to get force control[57]. Finally, the Bow-Legged Hopper uses a novel fiberglass leaf spring to store energy during stance. In addition the hopper can control the timing of the release of that energy through the use of a control string and a clutch mechanism[59]. The common denominator of these leg designs is that while they are fast and efficient in the laboratory, none have yet met the basic goal of any engineering endeavor - usefulness. Every one of these robots has some significant drawbacks, either needing tethers, information about the ground, or some other simplification.

2.2 *Stair Traversing*

2.2.1 STAIR TERMINOLOGY

Several sets of common terms need to have their meanings refined in order to facilitate later discussion. The terminology related to stairs geometry includes rise, run, and tread. These terms are illustrated in Figure 2-14. For this thesis, we will be concerned primarily with the rise and the run of the stairs. Our controller must be immune to problems arising from small variations in stair geometry in order to be practical, and the stair width is assumed large with respect to the width of RHex, so that it is not a factor during stair traversal.

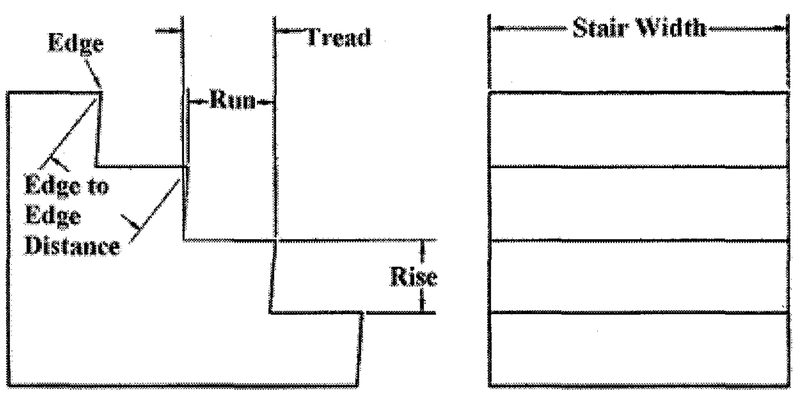


Figure 2-14 - Stair Geometry Terms [24]

Nearly all of RHex's leg motion occurs in the *sagittal* plane, (sagittal plane - a longitudinal plane that divides the body of a bilaterally symmetrical animal into right and left sections.[1]) which is the plane that divides RHex into a left and right half. Figure 2-15 gives a view of RHex in the sagittal plane. This figure illustrates other terms that will be important, such as hip, where the motor is attached, toe, the end of the leg, and body.

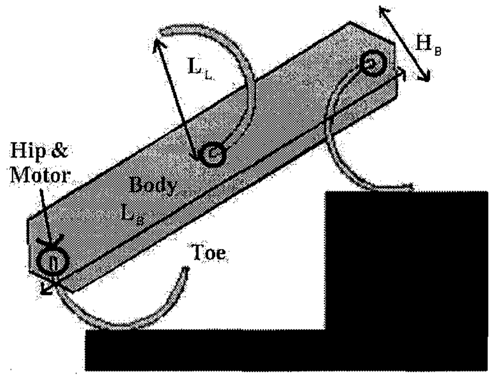


Figure 2-15 - Sagittal plane representation of RHex with circle legs.

2.2.2 Wheeled, Hybrid, and Tracked Robots

Wheeled, tracked, and wheel/leg hybrid vehicles have met with varying success in stair navigation. Stairs has generally stymied wheeled vehicles. Hybrid vehicles, such as Shrimp III have met with some success on stairs. Tracked vehicles such as Helios, Merlin, Andros Mark V-A, MRV-1, Packbot and others have all demonstrated degrees of stair traversing ability. Figure 2-16 shows some of these robots in action. A tracked robot needs several attributes to traverse stairs: treads with sizable teeth, powerful motors, a body that is at least two edge to edge lengths long, and a low center of mass. Some flights of stairs may thwart this simple strategy. Spiral fire escapes or older stairs with very round corners may not allow studs to grip the stair evenly.

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[1]Excerpted from *The American Heritage Dictionary of the English Language, Third Edition* Copyright © 1992 by Houghton Mifflin Company. Electronic version licensed from Lernout & Hauspie Speech Products N.V., further reproduction and distribution restricted in accordance with the Copyright Law of the United States. All rights reserved.

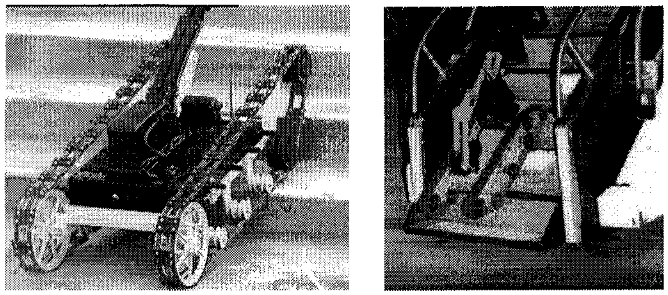


Figure 2-16- Stair climbing tracked robots - left to right the MURV[26], Vanguard[25]

Wheeled robots are a very large class. Wheels are very efficient, and universally acknowledged and accepted as a mode of efficient, high-speed locomotion. Simple wheeled vehicles based on automotive style designs have not had much success, however, on heavy terrain, or stairs. Some of the handful of existing examples relies on being able to move the axles relative to each other and the body, and others simply rely on being much larger than the stairs. They can still be effective. For instance, the DeKa wheelchair climbed the first level of the Eiffel Tower[29].

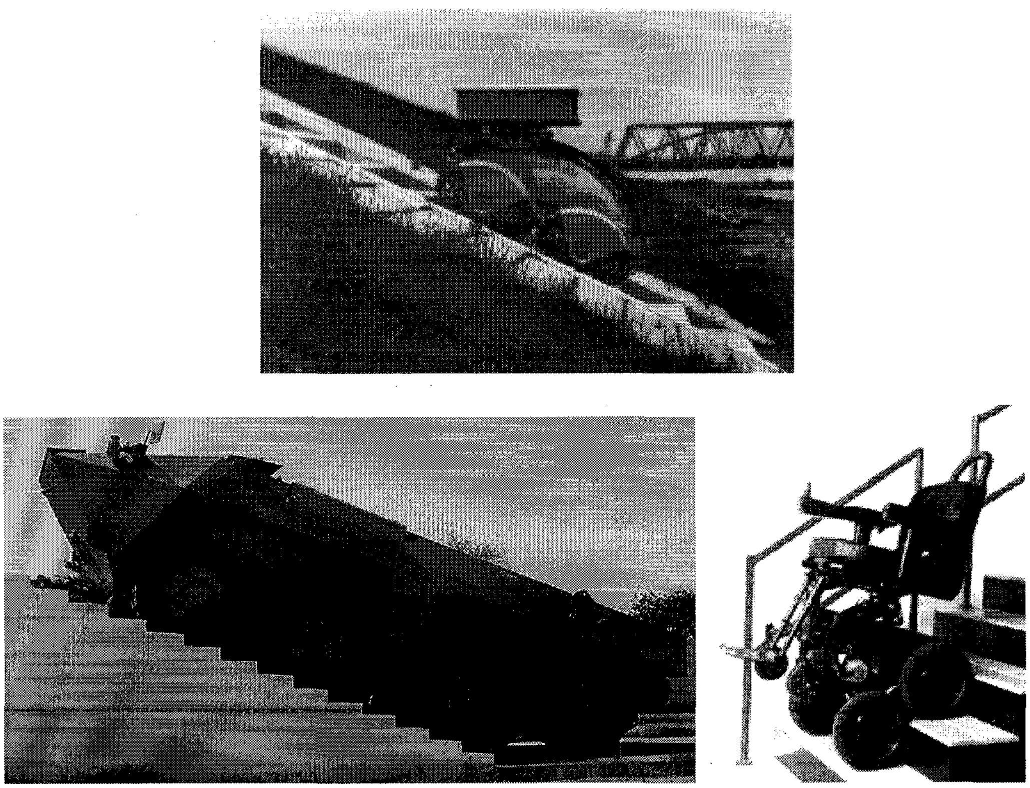


Figure 2-17- wheeled stair climbing vehicles, clockwise from top – Helios I, the DeKa wheelchair[29] and the al-Fahd[28].

The flat terrain speed and efficiency of wheeled robots has led some robotics researchers to blur the line between wheeled and legged machines. A wheeled vehicle can have very large travel in its' suspension, this travel can even be controllable, as is the case with Shrimp III. Shrimp III has displayed some of the most impressive rough terrain ability of any vehicle with wheels of which we are aware.[30]. It can traverse some stairs, and cross many types of terrain. It does require that the rise of the stair have a solid rise, so many wooden stairs and fire escapes would stymie Shrimp III. The power required to traverse with wheels forced Shrimp III and other hybrid vehicles to use higher gear reductions than normally found on wheeled vehicles; this counteract the natural speed and efficiency advantages of wheels.

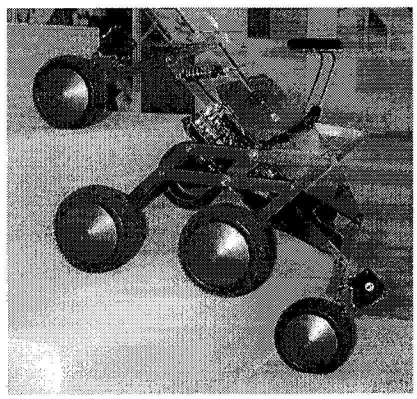


Figure 2-18- The Shrimp III - a very effective small wheeled robot. Shrimp III's suspension travel is so large, it effectively has legs.

The iRobot Packbot is an excellent example of tracked robot design. At the current time, it is the one of the most mobile robots ever built, though it still does not challenge animal's supremacy[31]. It uses a segmented body with two sets of tracks with ridges to grip and traverse a wide range of stairs. It can even turn in place on some stairs. It is unknown how even Packbot performs on especially challenging flights of stairs.

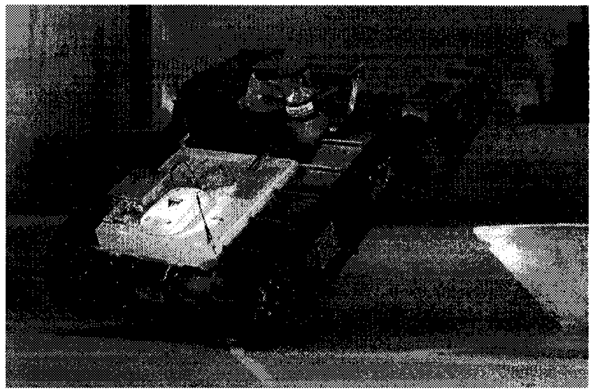


Figure 2-19 - the iRobot Packbot is one of the most mobile robot on earth, at the time of publication. It uses an articulated body and two independent sets of tracks.

2.2.3 LEGGED ROBOTS

Some legged robots have successfully demonstrated stair traversing, but they represent only a small percentage of walking vehicles. A variety of techniques have been used to endow each robot with the ability to traverse stairs. Some have approached the problem using a slow methodical approach, feeling out the stair like a blind man. Others have used advanced sensors or foreknowledge of the stairs to place feet precisely. A few have even used this knowledge to ascend and descend dynamically. Each of these approaches has advantages, and areas where we could hope for improvement.

The SD-2, built by Zheng and Golden in 1990, was the first biped to climb stairs[33] (Figure 2-20). It used a static gait, and relied on torso movement to keep the COM above the feet. It could only climb small stairs, and relied on tethers for computation and power.

Hirose built several quadrupeds, including the PV-II and the Titan series. An example of this group, the Titan VI, is shown in Figure 2-20. Their approach benefits from not requiring information about the stairs before traversing them. It is a trial and error approach that, while reliable, requires significant energy consumption. Hirose's robot, Titan VI required a tether for power and computation.

Matsumoto built a robot that could ascend flights of small stairs.[35] It is a hybrid biped, with wheels on its feet, and could roll to the end of each step, before proceeding to traverse the next step, but it should be considered a legged robot because the legs are so long, and the wheels so small. It was limited to very small steps, and required a tether for power, and computation.

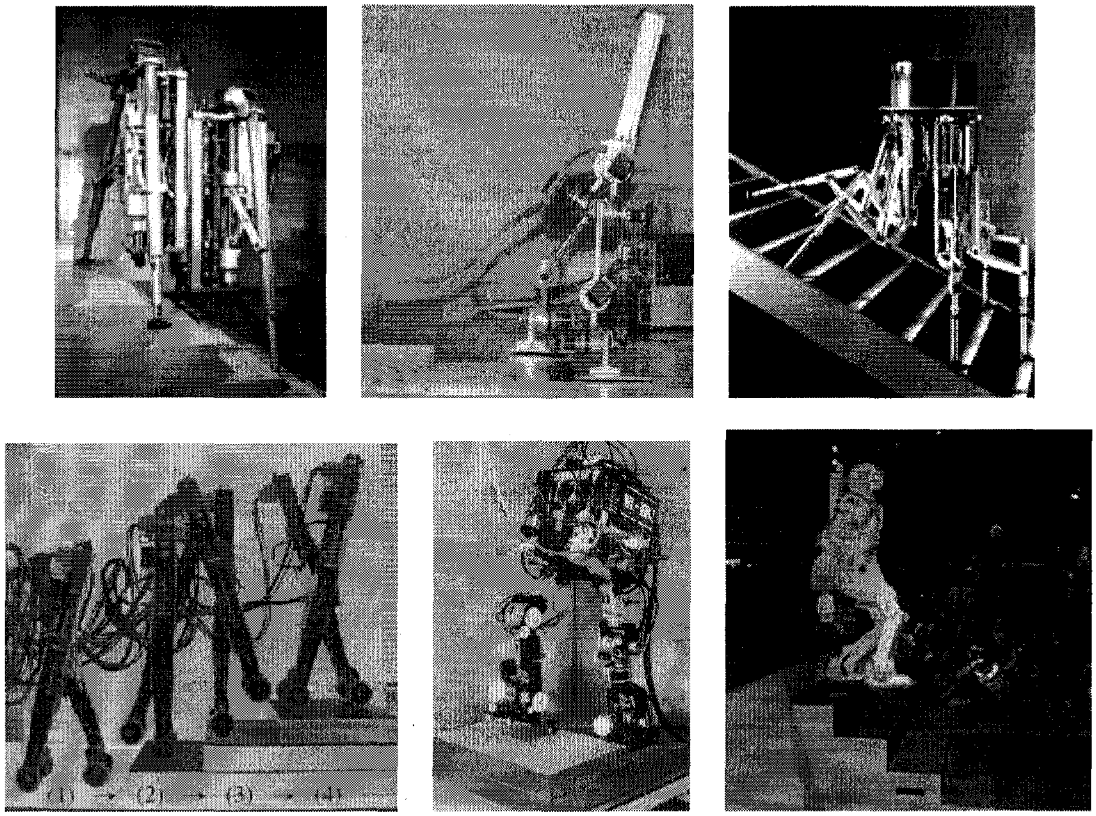


Figure 2-20- stair climbing robots, clockwise from top left: Titan VI[32], SD-2[33], Odetics[34], Honda P3 [35], WL-10RD[36], wheeled-leg type biped[35].

The WL-10RD ascended and descended stairs with a 10cm height at a rate of 2.6 seconds per stair[36]. Like the SD-2[33], it used significant trunk motion to maintain stability.

Recently the Honda humanoid traversed stairs quasi-statically.[37] Engineers at Honda recorded movies of humans ascending and descending stairs, and used them to determine composite trajectories for the robot. Using knowledge of the stair position and size, the P3 is thus able to ascend and descend stairs. While autonomous, P3 is not ready for the real world due to the limitations placed on it by its limited repertoire of motions.

Here at ARL, Yamazaki worked on ascending a single step with the Scout I quadruped.[8] This robot, had stiff legs, and stored energy in a rocking motion.[22] It was power, but not computation, autonomous, and required knowledge of the step *a priori*. Scout I was unable to climb multiple stairs.

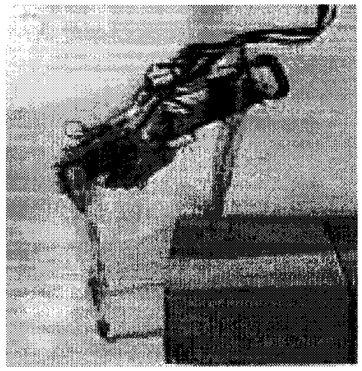


Figure 2-21- Scout I climbs a single step

Raibert built a tethered, planar biped that could hop up and down stairs dynamically, given knowledge of the stairs placement and size.[38] Raibert's robots made extensive and ground-breaking use of springs, as discussed in the leg design section. The speed of Raibert's biped represents the ideal case. Unfortunately, it also required power and computation tethers, and prior knowledge of the stairs.

There are many stair traversing legged robots, but we know of none that have met our goals of speed, efficiency, reliability, and autonomy from tethers. The only legged robots that we know of which can ascend and descend human scale stairs without a tether are the Honda P-2 and P-3 robots. It is interesting to note that knowledge of the stairs seems to be involved in the trade-off for higher speed and efficiency.

2.2.4 Biological Inspiration

Stairs are larger obstacles than the rocks and other natural barriers previously overcome by RHex. Insects use several different gaits, whereas RHex only has the alternating tripod gate. It is instructive to examine how insects traverse very large obstacles.

Whether on flat ground or during obstacle crossing, most insect gaits fall into a category known as the *metachronal* gaits. In these gaits, also known as back-to-front-wave gaits, all legs perform the same stepping motion, but some legs are out of phase with others. If the animal has enough legs, a back to front "wave" emerges because of this phase difference. Both millipedes and cockroaches use back-to-front wave gaits, such as the cockroach's alternating tripod gait. [1]

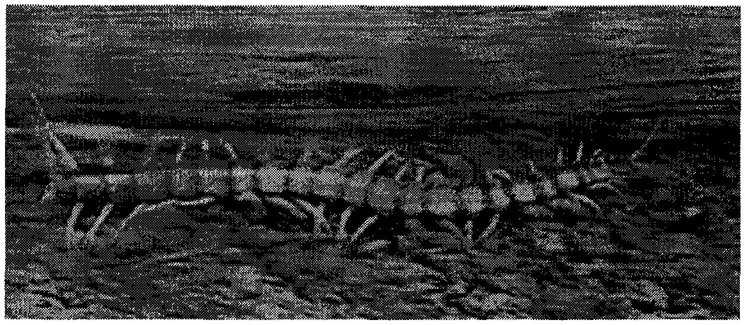


Figure 2-22 - A centiped using a back to front wave gait with contralateral legs out of phase. Similar to the alternating tripod gait.[40]

While the cockroach uses the alternating tripod gait at all times, the millipede changes its gait based on speed. Why do millipedes change the types of gaits that they use? Why don't cockroaches? The millipedes gait for medium and high-speed locomotion has contralateral legs out of phase with each other, which corresponds to the tripod gait of the cockroach.[14] When moving slowly, or crossing obstacles, however, the millipede's contralateral legs are in phase..

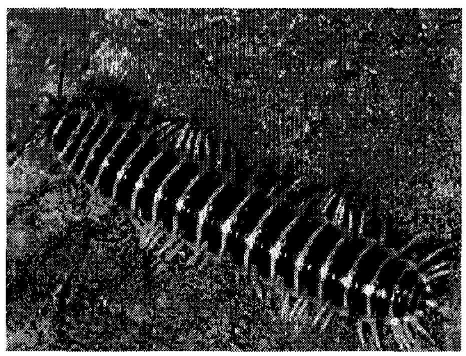


Figure 2-23 – A millipede using a slow, powerful gait in which paired legs work in phase, resulting in a back to front wave.[41]

Stability is not easy for the cockroach to maintain if its' contralateral legs are in phase, because it has only six legs, compared to the many in the millipede. It is difficult for it to keep its' COM over the polygon of support created by the other legs. When negotiating a significant obstacle however, the increased yaw stability inherent in such an arrangement gives the millipede an advantage over the cockroach. Slow and steady will win this race

> When slow patterns of gait are employed, with the backstroke of longer duration than the forward stroke, many legs are propulsive simultaneously, and paired legs move in similar phase (Diplopoda *[millipedes]* and Symphyla) thereby giving an even thrust from the body and no tendency to undulate in the horizontal plane. [39, p312-313]

Nature makes trade-offs in gait selection when obstacles become a factor. Slow speed is an acceptable trade for increased rough terrain ability.

2.3 *Previous Work on RHex*

Before I begin a discussion of recently completed work with RHex, I would like to present to the reader some basic information about RHex's geometry, electronic hardware, actuation, and power system. In addition, I would like to introduce the ongoing research of other RHex team members,

2.3.1 MECHANICAL DESIGN

RHex is a small robot, as is evident from the values for basic properties given in Table 2-1. A picture is shown in Figure 2-24. We adopted a simple aluminum space frame for the body, with a Lexan cover to protect the electronics from obstacles. RHex is a hexapod so it has six legs. Each leg has only a single motor attached to it at the hip. This allows each leg to rotate in the sagittal plane. In addition, each leg is compliant, giving it an additional, passive, radial degree of freedom.

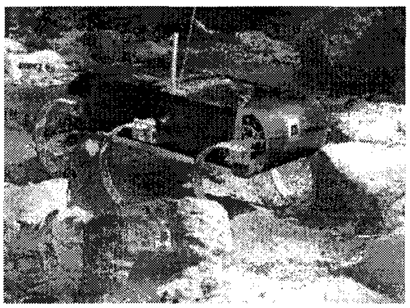


Figure 2-24 - RHex in rough terrain

Body Mass	M_B	~7.0	kg
Leg Mass	M_L	~0.1	kg
Body Length	L_B	0.51	m
Body Height	H_B	0.127	m
Leg Length (unloaded)	L_L	0.16	m
Hip Stall Torque	τ_{max}	~7	Nm
Hip No-Load Speed	ω_{max}	~5	rpm

Table 2-1- Basic RHex parameters

The commands of the CPG can guide us in our goal of reducing d.o.f.'s in our leg designs. If legs repeat the same motion without fail, we can, as stated earlier, supply that motion easily with a limited number of d.o.f.'s. Explicit knowledge of the CPG of the cockroach helped us pick the d.o.f.'s that we incorporated into RHex.

2.3.2 ELECTRICAL DESIGN

We must be aware of the strengths and limitations of the electrical system if we are to design controllers that use the motors, and mechanical systems to support the guts of the robot. More detailed information can be found in the RHex October 2001 Technical Report.

RHex is electrically actuated by brushed DC motors, and it is completely power and computation autonomous. RHex has Maxon Motors with a 33:1 planetary gearhead. Power is provided by a 24V NiMH battery pack with a nominal capacity of 3 Ah. These batteries can discharge at very high rates, and still maintain high efficiency. On-board computation is performed by a PC104 form factor Pentium II, running the QNX 4.0 real-time OS. This computer is powerful enough that our controllers can run at a rate of 1 kHz, and a real time OS prevents foolish problems due to timing issues in controllers. Coding is done in C++ with the Watcom compiler; C++ is flexible enough to allow us to design new controllers quickly. We write our controllers in a software environment called RhexLib, which was written for RHex by Uluc Saranli and Eric Klavins at the University of Michigan. The PC can be accessed through WaveLAN wireless Ethernet, which allows us quick and easy access to the robot. I/O is performed by the custom RHio PC104 card. The motor drives utilize SA60 single chip Pulse-Width-Modulation amplifiers, fitted with a custom heat sink. RHex is controlled with radio technology borrowed from remote controlled cars.

RHex uses several types of sensors. Leg angle is gathered from motor encoders on each hip. Encoders are reliable, and simple to use. They are the most important sensors on the robot. We have recently added a pair of new sensors, which are not utilized in any of the research presented here. In upcoming work, orientation data will be acquired with a Fizoptica three-axis fiber-optic gyro[51]. Precision cannot be expected from the gyros due to limits imposed by integration errors. We have also recently added temperature sensors, and we will monitor temperature of each motor and the computer power supply to prevent serious thermal failures. Tele-operation is provided via a pair of cameras, and a ¼ W transmitter. The cameras have a 165° field of view, which enhances the ability of the driver to orient himself. Six infrared range sensors are positioned around the robots body to allow autonomous wall following.

2.3.3 Previously Implemented Gaits

Uluc Saranli implemented a "flipping", or "self-righting" behavior that allows RHex to do a back flip. This is useful when the robot tumbles over an obstacle, and falls upside-down.

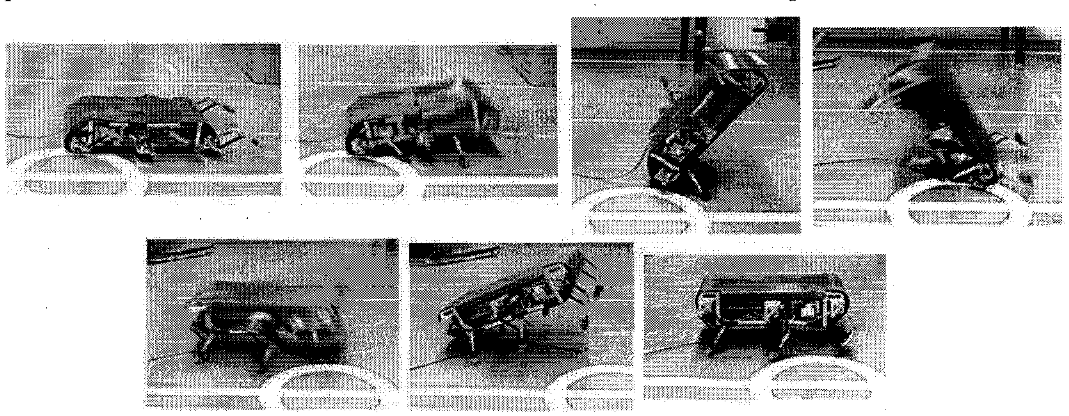


Figure 2-25 - Stop motion images of RHex doing a backflip. View from left to right, and top to bottom.

Dave McMordie built a simple swimming controller to allow RHex to propel itself through lakes and streams.

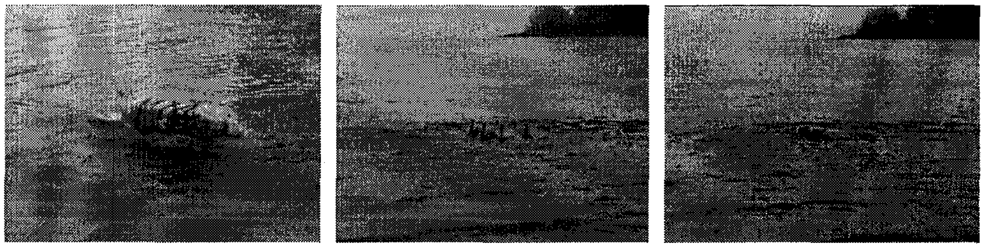


Figure 2-26 - Several pictures of RHex swimming off Cap-St-Jacques.

Martin Buehler and Uluc Saranli are responsible for the implementation of the alternating tripod gait, which was the first gait implemented on RHex. This gait has proved very successful, allowing RHex to traverse a number of obstacles previously impassible by walking robots.[1][42][43]

There is ongoing work at ARL by David McMordie investigating several dynamic gaits for RHex including pronking[44] and bounding. These gaits will be useful when speed and efficiency improvements using the tripod gait are exhausted.

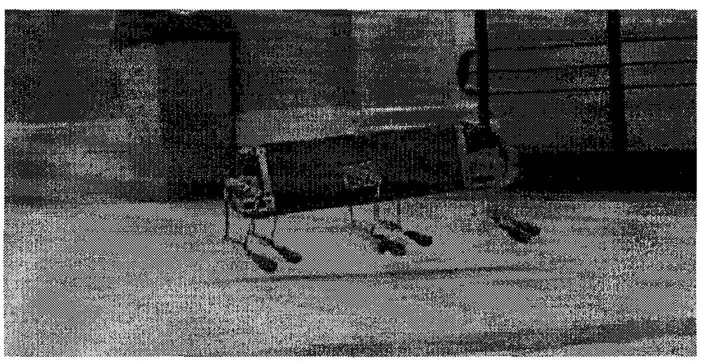
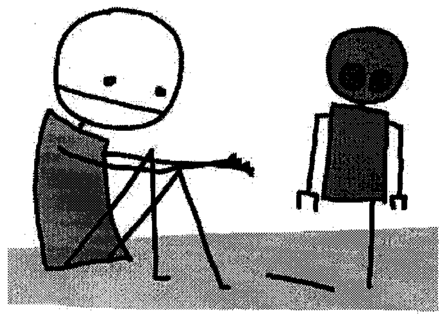


Figure 2-27 - RHex soars through the aerial phase of the pronking gait.

Chapter 3 RHex's Leg Design



Like all practical engineered devices, RHex's legs have to meet many requirements.

- Reliability > 100 hrs mean time before failure (MTBF) – While this value is somewhat arbitrary, reliability is extremely important for the missions we are considering, where lives are on the line. Four consecutive days operation without maintenance is a fundamental requirement for such a critical piece of equipment.
- Mass < 100 g – Even with this small mass, the total mass of the legs will still equal almost 10% of the robots total mass. Heavy batteries give more run time, heavy motors provide more torque, but there is no advantage to having heavy legs. This is a difficult target to reach, but worthwhile, because the smaller the leg mass, the lower the leg inertia. The basic tripod gait requires rapid leg accelerations, so low leg inertia results in power savings.
- Manufacturability < 5 hrs – While prototypes are worthwhile despite lengthy manufacturing processes, good designs minimize construction time. This saves money, and often dovetails with other design goals such as ease of maintenance and low mass.
- Based on the maximum output torque of the motor and gear-head combination, which is about 7 Nm, the legs must be able to transmit 7 Nm continuously. The legs must be able to transmit 15 Nm peak, because during ground impacts the legs can experience peak load about double the continuous load by being back driven, so 15 Nm peak is a reasonable design goal. No slipping of the leg on the motor shaft is permissible, or position control will become impossible
- Obstacle traversal – Whatever legs RHex uses, they must be able to traverse the obstacle course at the South West Research Institute[55], in San Antonio, Texas. This will depend

on a combination of the factors already mentioned, as well as geometry of the leg. The obstacle course is made up of a wide variety of common terrains and human constructed obstacles, and is a good measure of how ready RHex is for the real world.

- Enable stair traversal – as measured by the success of RHex on different stairs. (Results in Chapter 5) Stair traversal will contribute to the success of RHex in urban arenas. As in basic obstacle negotiation, successful stair navigation is a combination of several factors, especially geometry and weight.

- Desirable dynamic properties – this is important if dynamic behaviors such as running and leaping are to be possible. Force vs. deflection characteristic of the leg must be tuned to the mass of the robot to give the robot a natural frequency that allows it to bounce. The "spring constant" of tendons in animal legs suggest that a robot the size of RHex should have a vertical spring constant of about 1350 N/m.

- Lateral Stiffness > 10 kN/m – There are large non-radial loads on RHex's legs, from both falling, and normal walking. The legs cannot be allowed to deflect far into the lateral direction, or they could interfere with other legs, or even impact the body. Based on the mass of RHex, and the clearance of the legs, 10 kN/m should preclude any problems.

- Damping Ratio < 0.05 – The other main dynamic that concerns us is low damping. A low value of damping ratio will allow recovery of the energy in the leg during each hop, and avoid loss of energy to heat. 0.05 is not a magical target number for damping ratio, but it is a low value compared to the value for coil spring legs if sliding friction is considered, and so it is simply a good design goal.

Some of these design goals were meant to enable basic behaviors like standing and walking, and some were necessary only for more advanced behaviors. Of all the requirements, the most challenging was creating a design with the desired reliability and the desired compliance. The various approaches to solving these problems have strengths and weaknesses, and these differences warrant a closer look at each design.

3.2 Compass Leg Design

The first legs used on RHex, were very stiff in comparison with later designs, but they did possess some compliance. A rough estimate of the spring constant, which assumed a linear spring, was 4600 N/m, as compared to values as low as 1600 N/m for other legs, which are introduced in the next sections. The low compliance led us to term them "compass legs" because of the energy-storing gait enabled by high leg stiffness, which stores energy as potential energy in the body elevation, instead of in elastic energy in the legs themselves. These legs were barely sufficient for RHex in all design categories, and have been replaced by more recent designs, but those designs did benefit significantly from the experience gained working with these legs.

3.2.1 Mechanical Design

Compliance in the compass leg arose from the curved shape, which created a leaf spring. The final shape resulted from heating and bending of straight rods into a custom built mold. The spring material used in the compass leg was the commercially available plastic Delrin, in the form of 3/8" diameter rod. Quality control of the final shape of the parts was poor due to "spring-back" after the parts left the mold. Pads were added to the foot to give better traction than that offered by the bare plastic. The torque transmission mechanism consisted of two friction clamps, each with a set screw tightened against the flats of the gear-head shaft and a flat on the leg. The two clamps are then bolted to each other. Figure 3-1 shows the compass leg.

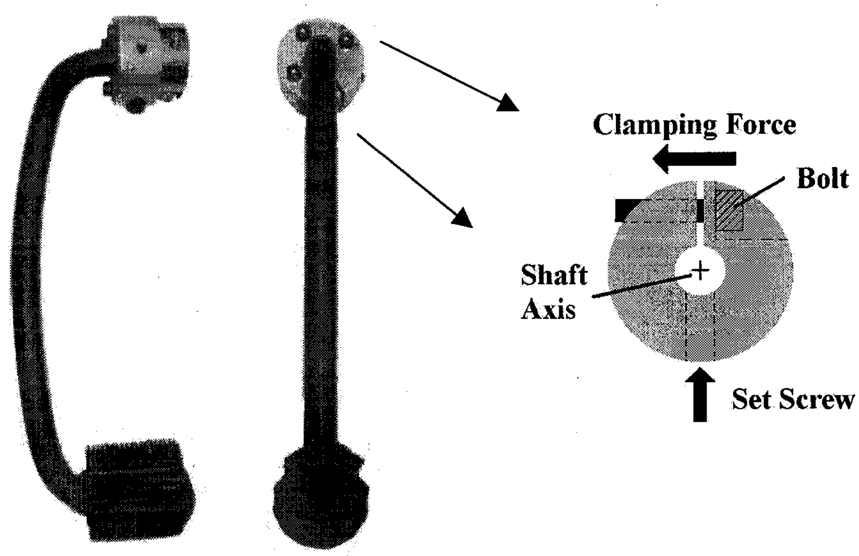


Figure 3-1 - Left - Plate of compass leg. Right - diagram of torque transmission mechanism. Set screw on flat of shaft, and friction from the deformation of the clamp both help to transmit torque, but there is no effective mechanical lock. Slipping occurred under peak loading.

3.2.2 Lessons Learned from the Compass Leg

The compass had the following shortcomings:

- The radial stiffness was too high
- The torsional and lateral stiffnesses were too low.
- The legs' MTBF was only about 4 hours.

- Torque transmission mechanism was imperfect. The friction clamps and set screws slipped often, allowing significant change in angle between the leg and the motor.
- Traction of the rubber foot pad was insufficient.
- Poor moldability of the material led to legs of different length.
- Manufacturing involved significant manual labor, and was very time consuming.
- Creep was observed which changed the shape of the leg.

We kept all of these problems in mind while designing more advanced legs

3.3 *Hinged Four-Bar Leg Design*

The second design that we implemented was the Four-Bar leg. The name succinctly describes the basic geometry of the leg, which is shown in Figure 3-2. The initial prototype had clamped end conditions for both of the leaf springs, as seen in the following picture.

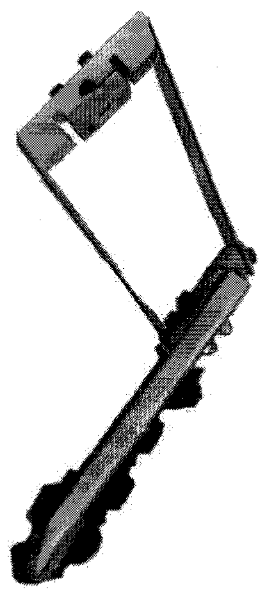


Figure 3-2 - A prototype of the Four-Bar Leg design, before hinges were added.

The design of the Hinged Four-Bar legs represents an improvement over the other legs previously designed at ARL, and seen in the literature, in several ways:

- Improved MTBF of about 150 hrs
- Robust torque transmission mechanism
- Low mass (120 g)
- Very little sliding friction during spring displacement (only in hinges)

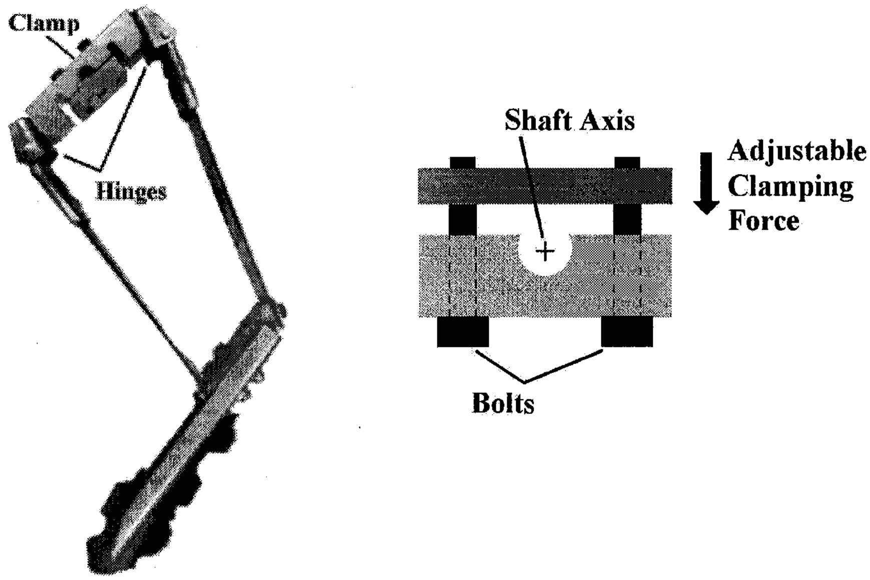


Figure 3-3 - Plate of Hinged Four-Bar Leg. Right - diagram of torque transmission mechanism. Two bolts force key (dark gray) onto flat of the gear-head shaft. The displacement of the clamp could be adjusted to account for deformation of the gear-head shaft.

There are still some drawbacks; the parts require significant time to build, up to twelve hours per leg, plus time to maintain. The are two main features of the leg design which are worth further discussion: 1) the transmission design, which is vastly superior to earlier ARL designs, and completely eliminates mechanical slip between the motor and the leg, and 2) the spring design, which makes novel use of leaf springs to ensure low-friction, nearly radial toe travel.

3.3.1 Transmission Design

Good torque transmission relies on a positive mechanical lock between a driving motor shaft, and a driven leg in order to avoid slipping between the two. Conditions such as high impact or oscillating loads make this lock more difficult to achieve and maintain because the components of many transmission designs can deform, and fail to operate properly. High loads are usually accommodated via a spline, but this was not an option for RHex, because the commercial gear heads we chose utilize a round shaft with a simple flat. In addition, the shaft material is soft low-carbon steel, not a hardened alloy. These two features lead to failure via the "rounding", or plastic deformation, of the flat on the shaft under high loads when the fit between the two shafts is imperfect. To eliminate this failure, we designed the shaft on the leg to be a clamp. The clamp is detailed in Figure 3-3. The clamp allowed the driven shaft to maintain a good fit with the driving shaft, even if the driving shaft was not machined to tolerance, or had begun to deform.

3.3.2 SPRING DESIGN

The Four-Bar leg makes use of a pair of cantilever springs. To specify the design of the spring, we had to choose the material, the geometry, and the end conditions of the cantilevers. These choices were made with two main goals: the path that the foot travels during displacement, and the force required to displace the spring.

A torsional spring in series with the hip actuator not only makes precise control of the toe position in the torsional direction very difficult, but it makes it difficult to apply the animals-as-pogo-sticks theory; the theory only utilizes a radial spring, not a torsional spring. Any torsional deflection by the foot implies that there is a torsional compliance, and so should be avoided. We made the remaining elements of the leg orders of magnitude stiffer than the cantilevers to avoid torsional stiffness as much as possible. A side effect of this choice is that the entire compliant structure is made easier to analyze, because the cantilevers dominate the compliance of the structure. We used trial and error to produce the geometry of the leg design, resulting in a displacement path that is primarily radial.

Material choice has a significant impact on the compliance of the final leg structure. We had to select a material that would allow for appropriate displacement, without failure, under the severe impact loads of a running robot. We chose unidirectional S-Glass for the leaf springs, with the symmetrical lay-up [0,-45,45,0,45,-45,0] (where 0 is the longest direction on spring) that was 0.052" thick and with a 35% resin content. Fiberglass is much more compliant than easily available and machinable materials, such as plastics, metals and other composites. (To view support for this statement, please refer to Appendix B) It possesses an excellent balance of yield strength and Young's modulus. In addition, fiberglass does not suffer from plastic deformation and creep as quickly as pure plastics, and it is lighter than metal.

Even with proper material selection, and spring geometry that minimized safety factor to increase compliance, the choice of the cantilever end conditions is critical to the leg design. It effects not only the maximum deflection, but also the distribution of stress in the cantilever. We choose to give the free end of each cantilever a pin joint. A pin joint prevents the application of moments to the free end of the cantilever. This also lowers the stress for a given deflection, and thus allows for a greater maximum deflection. We found that this choice, in combination with the geometry and the material selection, resulted in acceptable total leg compliance.

3.4 *Half-Circle Leg Design*

The most recent leg designed for RHex is the Half-Circle leg. Felix Grimminger, a visiting masters student, did nearly all of the design work, although I, and everyone on the RHex team, did some consulting. This material is presented in this section for archival purposes, and as a useful comparison with other designs. The name succinctly describes the basic geometry of the leg, which is shown in Figure 3-4. The design of the Half-Circle legs improves on the success of the Four-Bar leg in some ways, and required trade-offs in others:

- Improved MTBF of at least 200 hours – there have not been enough failures to date to determine this value precisely.
- Same robust torque transmission clamp as Four-Bar leg
- Low mass (80 g)
- Easy to build and maintain. With only three parts, only four hours are needed to build a leg, most of that time is machining the clamp. Fewer parts mean much less maintenance. They can be run for most of their life without maintenance, with only occasional tightening of the bolts.
- No sliding friction during spring displacement, as in the Four-Bar leg.

There is still one major drawback to this leg design: the spring displacement is not purely radial. The two main feature of this leg design which are worth further discussion are: the spring design, which uses leaf springs to ensure low-friction, radial toe travel, and the future plans for the Half-Circle leg design, which include a second actuated degree of freedom.

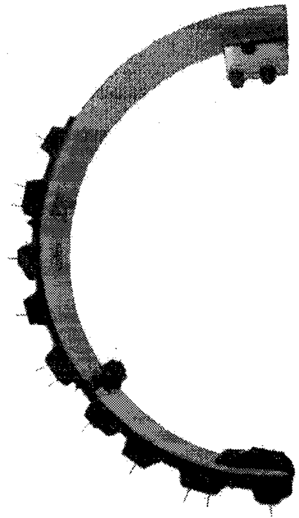


Figure 3-4 - Plate of the Half-Circle leg. Uses the same torque transmission mechanism. Spring is light green. Bike tire tread is added to leg to add traction, and protect the spring.

3.4.1 Special Design Requirements

In addition to the requirements that we set for any RHex leg, two additional requirements helped shape our design of the Half-Circle legs. The first requirement stemmed from our wish to be able to actively control leg length, which means we must add an actuator to each leg of RHex. The second requirement we considered was our desire to build legs which could be altered using the leg length changing mechanism, to allow a rolling motion, instead of a walking one.

We hoped to address the extra requirements placed on this design with a single solution. We plan on adding a second degree of freedom that will change leg length by moving the center of rotation of the leg from the tip of the Half-Circle to the center of the Half-Circle arc. At the extreme position in the center of the arc, the leg will become a half wheel, with the main drive motor at its' center. This orientation is shown in Figure 3-5. The second motor will be de-coupled from the loads of driving the leg, or the wheel, but should be powerful enough to change the length of the leg quickly. Grimminger has built a prototype of this mechanism, but we have not implemented it fully on RHex, and so this mechanism is a footnote to the current work.

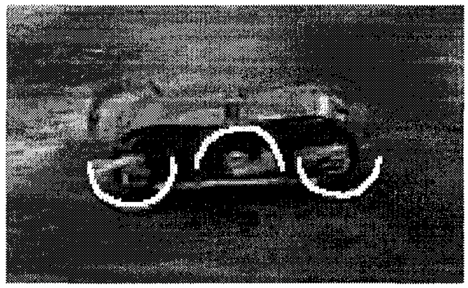


Figure 3-5 - RHex with Half-Circle legs in "Wheel mode". This test was performed with legs that were unable to change length, as a proof of concept. The test was a success, with high speeds of ~ 1.5 m/s attained, and 40° slopes climbed on the campus of McGill University. Legs are highlighted for clarity.

3.4.2 SPRING DESIGN

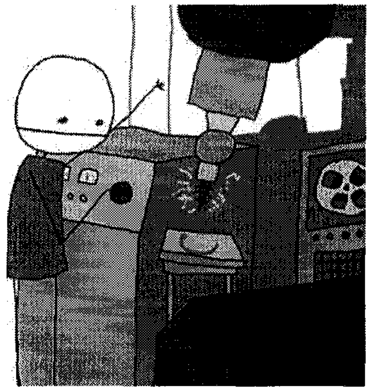
The special requirements for this design dictated much of the geometry and the end conditions, and we followed the logic used in the design of the Four-Bar leg for material selection. Still there are some features of interest in this spring, 1) the size of the spring, 2) the orientation of the layers, and 3) the impact that small amounts of torsional and lateral stiffness have on actual operation.

The goal of compliance is achieved through a single composite cantilever, one fewer than in the Four-Bar leg design. We used bi-directional, plain-woven E-Glass with 45% resin content in a [45,0,-45,0,45,0,-45,0,45,0,-45] lay-up. The high resin content helped lower stiffness, but it also decreased the yield strength, and plastic deformation was a problem in early designs, especially in the lateral direction. Numerous 45° layers were required to increase the lateral stiffness of the leg to fix this problem. This step was unnecessary in the Four-Bar design because it's geometry generated lateral stiffness, but the Half-Circle offers no such benefit.

The use of a very large spring allowed us to achieve ruggedness in the design. The sheer size of the spring allows the strain energy to be distributed over a larger volume than in the Four-Bar leg. This results in lower stresses, and thus fewer failures. The design is so much more rugged, in fact, that we have difficulty quantifying the MTBF; there haven't been enough failures.

Unlike the Four-Bar design, this design does not give us much direct control over the path that the foot travels during energy storage and release, and so we cannot specify primarily radial motion. While the lateral and torsional compliances are higher than in the Four-Bar design, it does not prevent successful performance. In fact there are benefits to higher compliance in all directions: the increased lateral and torsional compliance of the Half-Circle leg design helps to mitigate shocks to the leg and the motor from ground impacts. This implies a trade-off in performance, not simply a degradation of properties.

Chapter 4 Experimental Leg Characterization



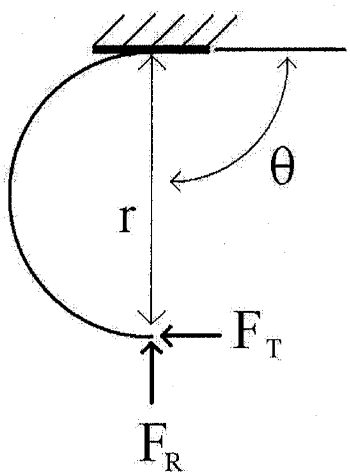
The legs we built for RHex have proven successful with respect to durability and obstacle traversal. As the RHex team became more concerned about the dynamic behavior of the robot, the experimental dynamic characterization of the legs became important. The purpose of obtaining these values is to predict the behavior of the robot during dynamic behaviors and to compare the competing leg designs. In order to make any assumptions clear, we discuss the experimental procedure before presenting the results.

4.1 *THE TEST*

Stiffness can be tested using static measurements of load and deflection. It can be found in a linear spring by taking the slope of a line that relates the two. The plots of deflection versus force of RHexs legs are not linear, because the legs are complex leaf springs. We took measurements of radial and tangential forces at the toe at many different toe positions in the sagittal place. We then used Matlab 6.0[54] to interpolate and filter the data, and then plot the data for both of the forces measured. Once the plots are available, we can examine them for trends that allow us to model the leg as a collection of rigid bodies and tractable springs, a *pseudo-rigid mechanism*.

4.2 *Experimental Setup*

We built an experimental test jig to collect the data that we needed. The layout used, the sensors, and the method of data collection had to be determined as part of the design. We need two position values and two force values. During experiments, the hip of the leg is fixed, and the toe is allowed to move freely. The layout is shown below in Figure 4-1. While this setup is quite adequate for static force vs displacement tests, there is too much friction in the system to be used for dynamic tests that could determine damping properties.



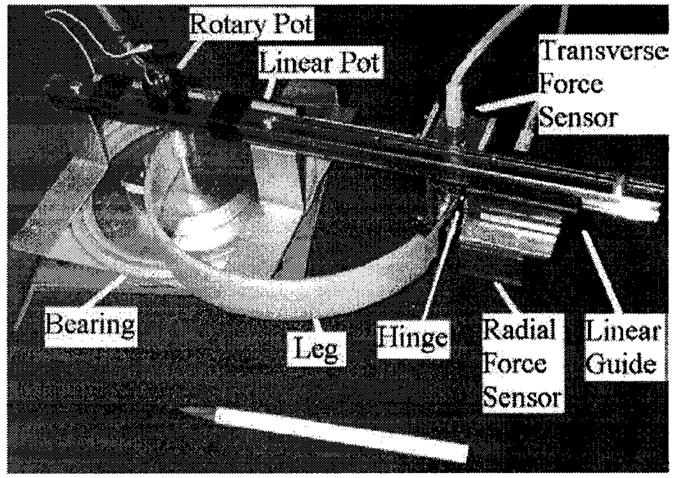


Figure 4-1 - Left - a simplified diagram of the quantities being measured with respect to a Half-Circle leg. Right - The experimental apparatus, the physical implementation of the diagram on theleft.

4.2.1 SENSORS

The sensor suite of the set-up consists of two force sensors, and two position sensors. We used two uniaxial force sensors, which are based on Hall effect sensors[45]. The force sensors are mounted in series. The toe is mounted through a hinge to the tangential force sensor, and the tangential force sensor is mounted on the input to the radial force sensor. The axis of the hinge is placed in line with the radial force sensor axis to minimize cross talk between the two sensors. The force sensors are mounted to a linear guide, and the displacement of the guide is measured by a linear potentiometer.[46] A rotational pot measures the rotation between the linear guide[46], which rotates on a bearing plate, and the hip, which is fixed in space.

4.2.2 DATA ACQUISITION

Data was collected on RHex through spare analogue input ports. I modified a small test program written by Uluc Saranli to record the data with a sample frequency of 1 kHz. We designed and built a simple buffer, voltage divider, and level shifter to make all of the sensor outputs between zero and five volts. The electrical hardware is shown in Figure 4-2. All of the data we collected was filtered twice. First using a Butterworth filter to reduce time dependent noise, and then using a special filtering Gaussian filter. The Butterworth filter had a cutoff frequency of 10 Hz. The Gaussian filter had a width of 7 points, which with our grid size of 1 mm, makes a window of 7 mm, and a standard deviation of four.

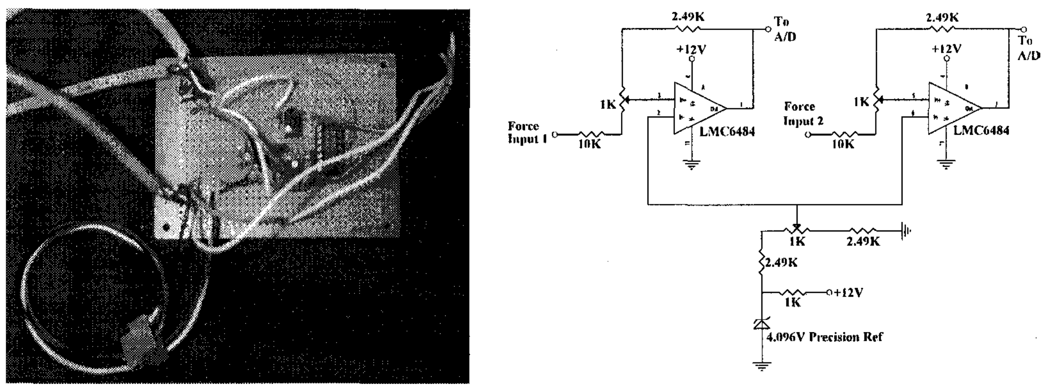


Figure 4-2 - The electronic hardware and corresponding schematic used to prepare the force sensor output for input into RHex's onboard data aquisition system.

4.3 *Results*

Once the leg has been mounted upon the test apparatus, and data from each of the sensors is recording, we applied displacements to the toe. We applied force to the radial force sensor, so as to measure all reaction forces. The displacement was changed slowly in order to minimize dynamic forces. The toe traced a path over a polar grid with squares of approximately 3 mm x 1°. Small areas of travel were inaccessible due to mechanical interference of the apparatus, but these areas are not critical to the results we seek.

Using the sensors, apparatus, and RHex's data acquisition system that we just described, we were able to collect data on the load vs. deflection characteristics of each leg that we designed. We looked for trends with mechanical underpinnings in the force vs. deflection plot to use as the basis of models of the leg. In some cases, we developed models that are both accurate, and based on mechanical reality. In other cases, while clear trends existed, we do not present models, because there was no dominant physical basis for the trend. In such cases, if the data is needed for an analysis, a look-up table or simple algebraic fit may be used.

Any model is an attempt to simplify a complicated system. In our case our models use rigid body linkages and springs to approximate leaf springs. Under large deflections, the ends of cantilever beams, like our leaf springs, trace out paths that are nearly circular. In nearly every case, the circle traced out will not be centered on the fixed end of the beam, so the trick to predicting the position of the free end is to find the center of the circle, known as the *characteristic pivot,* about which the free end orbits. Once it is found, we can use a rigid link to connect the circle center to the beams base, and another link, with length equal to the *characteristic radius,* to connect the circle center to the free end. Connect the two rigid links with a carefully chose torsion spring, and a good model of the cantilever's force versus deflection characteristics will result. The following figure shows the transformation, from a simple cantilever, to a *pseudo-rigid* mechanism.

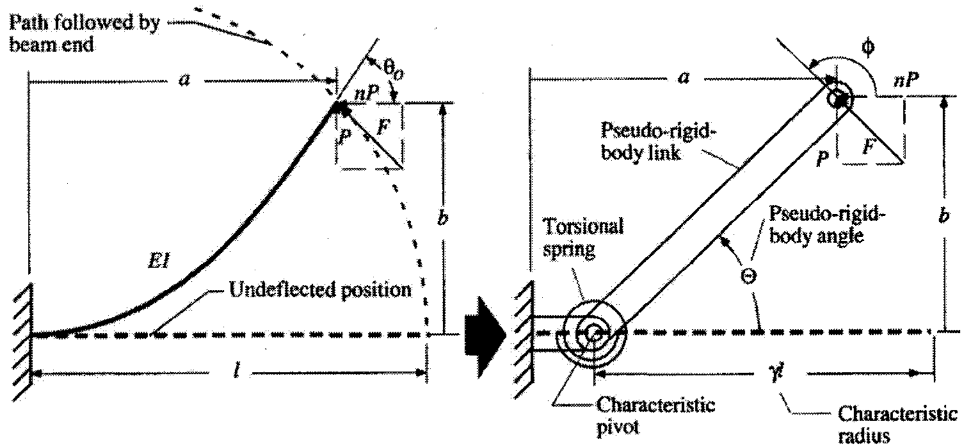


Figure 4-3 - Demonstration of simplifying a large deflection compliant beam (Left) into a pair of rigid links, joined by a torsion spring. (Right) [47]

4.3.2 Clamped Four-Bar Leg

We tested the force vs. displacement properties of a Four-Bar leg without the hinges mentioned in the leg design chapter. This leg is a prototype only, and can be seen in Figure 3-2. Without hinges, the springs are doubly clamped cantilevers, and are very stiff. We did this test to verify our assertion that the hinges add to the compliance of the design, and for comparison purposes with the other legs. The raw data that resulted from the test is in Figure 4-5, and the data after the application of a filters is shown in Figure 4-6. Like the hinged Four-Bar leg, we do not present a physical model to compare with the results because, while there are clear trends that could aid or provide an alternative to look-up tables, the physical basis of such models are not clear. Creating models for this data could be the subject of future work.

We will now present a number of plots showing the force vs. displacement characteristics of the clamped Four-Bar leg. As a point of reference, see Figure 4-4, which shows how the leg relates to a sample data set.

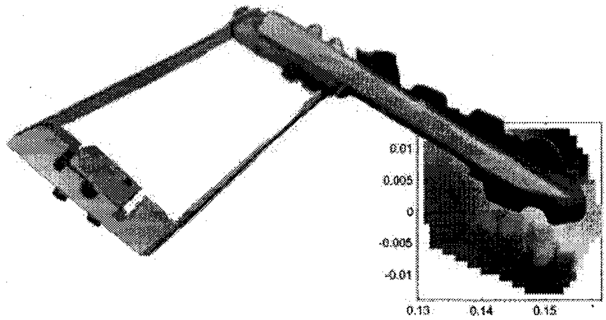


Figure 4-4 - Sample data set of stiff Four-Bar leg force vs. deflection. Photo of leg is superimposed to give sense of magnitude of deflection. Photo is roughly to scale, and is placed near the no-load position.

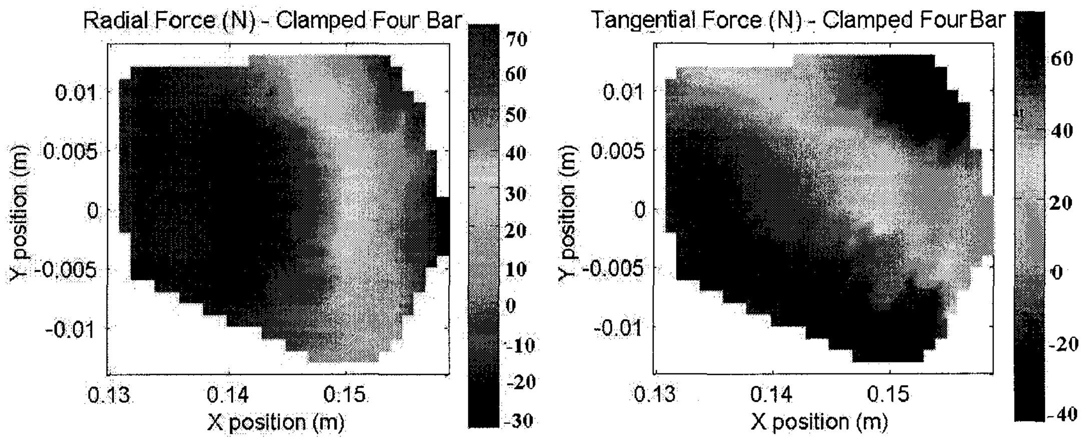


Figure 4-5 - Raw data for a force vs displacement test on a doubly clamped Four-Bar leg. Note that range of motion is small, and reaction forces are high. This leg is very stiff. Hip is at (0,0) and Toe is at (0,0.15)

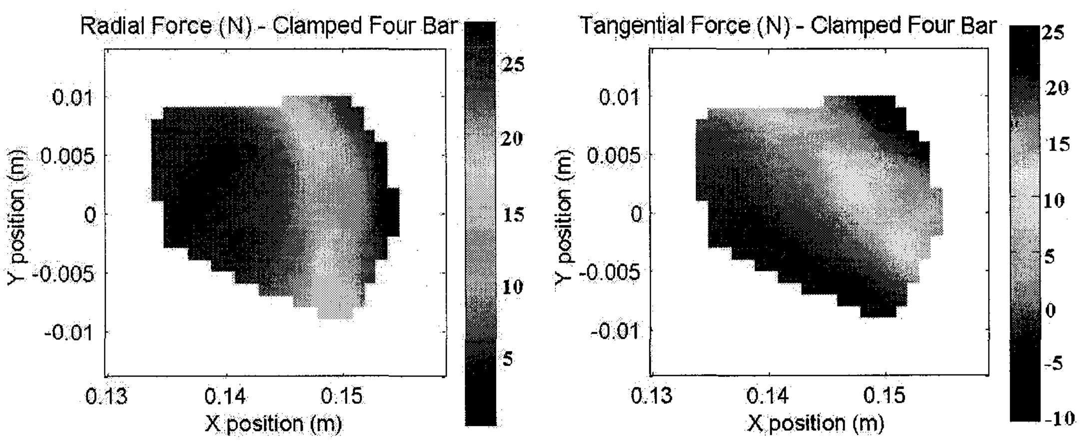


Figure 4-6 - Results of a force vs displacement test on a doubly clamped Four-Bar leg after a Gaussian filter is applied. Hip is at (0,0) and Toe is at (0,0.15)

The contour lines of the filtered data are shown in Figure 4-7. Like with the other legs, the contour lines provide convenient ways of visualizing possible models that involve radial and linear springs.

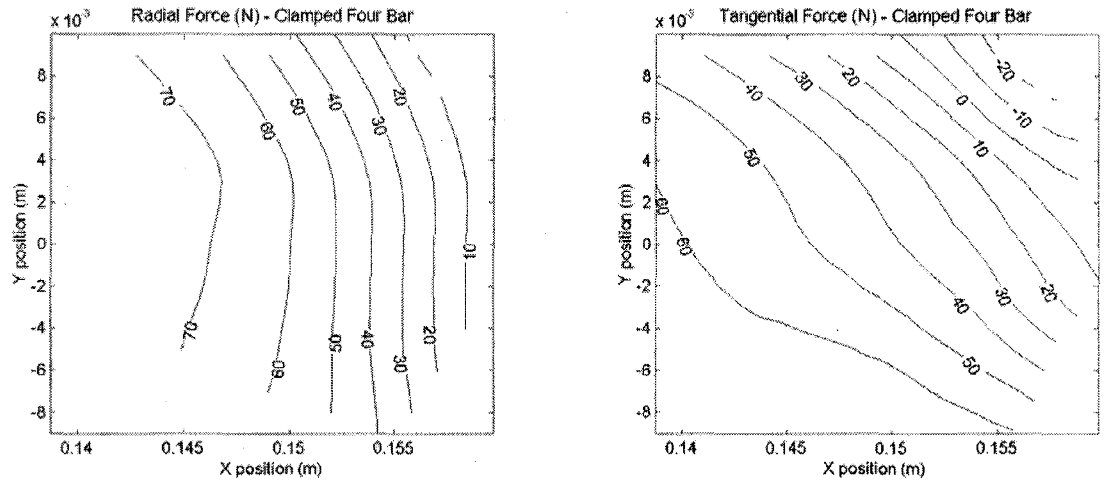


Figure 4-7 - Contour plot of a force vs displacement test of a clamped Four-Bar leg, after the application of a Gaussian filter. Hip is at (0,0) and Toe is at (0,0.15)

4.3.1 HINGED FOUR-BAR LEG

The unfiltered data from the hinged Four-Bar leg experiment can be seen below in Figure 4-9. Some trends can be guessed at, but the following figure, Figure 4-10, plots data after a Gaussian filter has been applied, and is much smoother. While some data was lost in the filtering, the remaining plot is much smoother, and trends more noticeable. While the patterns are clear, we were unable to relate them in a simple manner to a pseudo-rigid model of the leg. This is likely because the leaf springs in this leg begin to undergo buckling when under large deflections, which is not a part of the pseudo-rigid model, and because there are two springs at work, which complicates the model.

We again present a sample data set with leg to convey approximate deflection, and to relate the trends to the physical leg, see Figure 4-8.

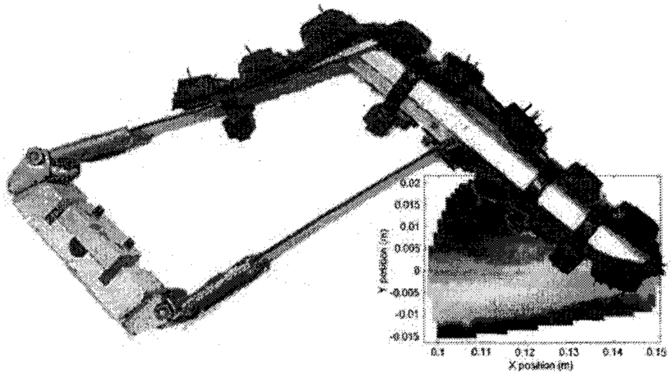


Figure 4-8 - Sample data set of Hinged Four-Bar leg force vs. deflection. Photo of leg is superimposed to give sense of magnitude of deflection. Photo is roughly to scale, and is placed near the no-load position.

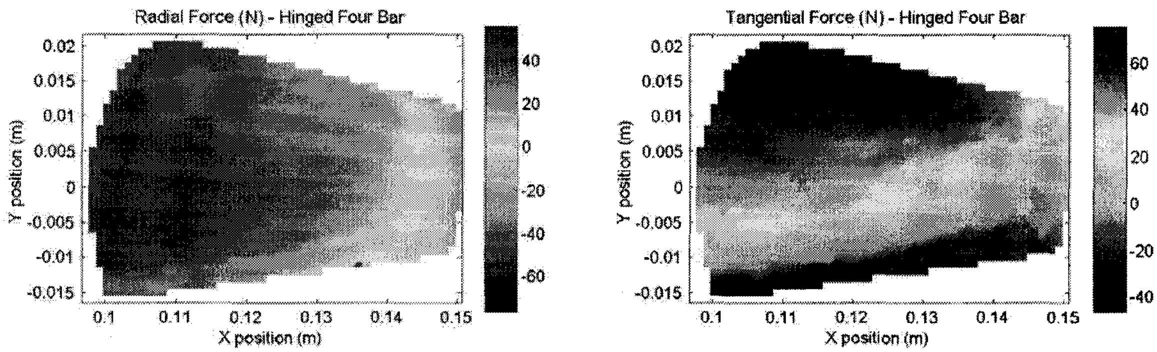


Figure 4-9 - Raw data from the force versus displacement test of a hinged Four-Bar leg. Hip is at (0,0) and Toe is at (0,0.15). See color electronic version for easiest interpretation of plot.

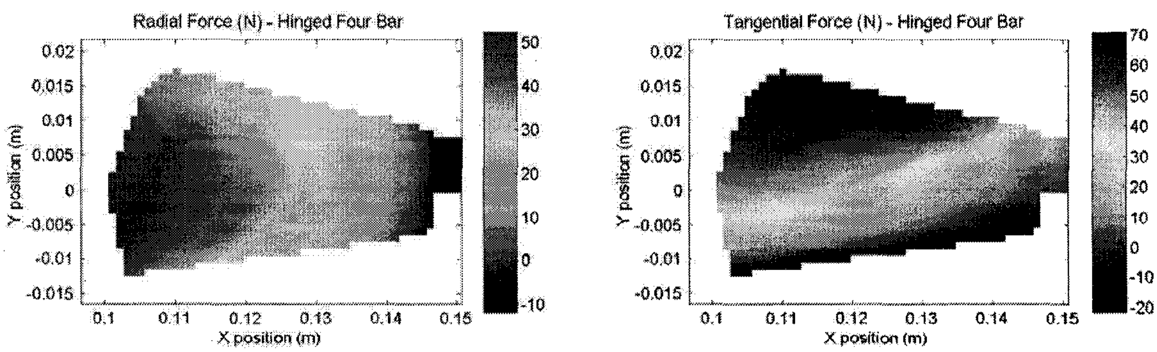


Figure 4-10 - Results of a force vs displacement test on a hinged Four-Bar leg, after a gaussian filter is applied. Hip is at (0,0) and Toe is at (0,0.15).

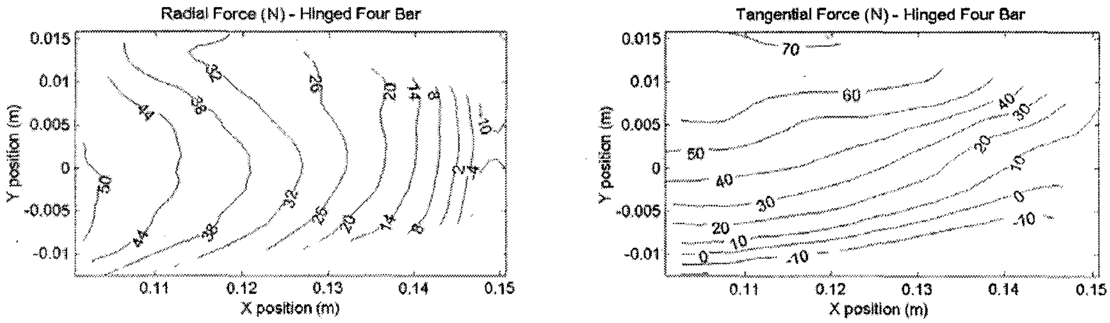


Figure 4-11 - Contour plot of the force vs displacement test on a hinged Four-Bar leg. Hip is at (0,0) and Toe is at (0,0.15)

The contour plots are very interesting because we are able to see the path of zero tangential force, which is the path the foot would have to travel for the leg to be approximated by a radial spring. We can see that the hinged Four-Bar leg has a more radial trajectory than the circle leg. It is not, however, perfectly radial, it deflects about 1 cm from the perfect radial path.

4.3.2 HALF-CIRCLE LEG

A comparison of a sample data set with the actual leg will aid in interpretation of results.

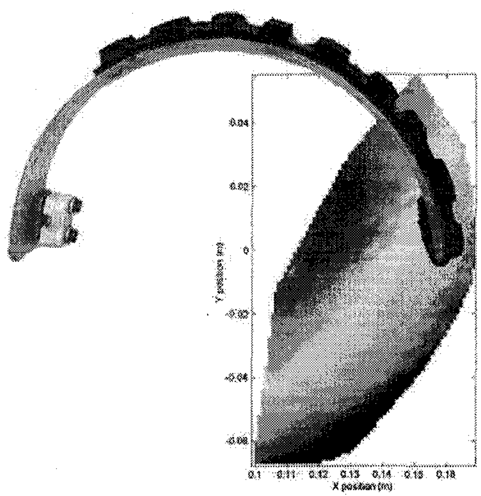


Figure 4-12 - Sample data set of Half-Circle leg force vs. deflection. Photo of leg is superimposed to give sense of magnitude of deflection. Photo is roughly to scale, and is placed at about the no-load position.

The unfiltered data from the Half-Circle leg experiment can be seen below in Figure 4-13. Some trends can be guessed at, but the following figure, Figure 4-14, which plots data after a Gaussian filter has been applied, is much smoother. While some data was lost in the filtering, the remaining plot is much smoother, and trends more noticeable.

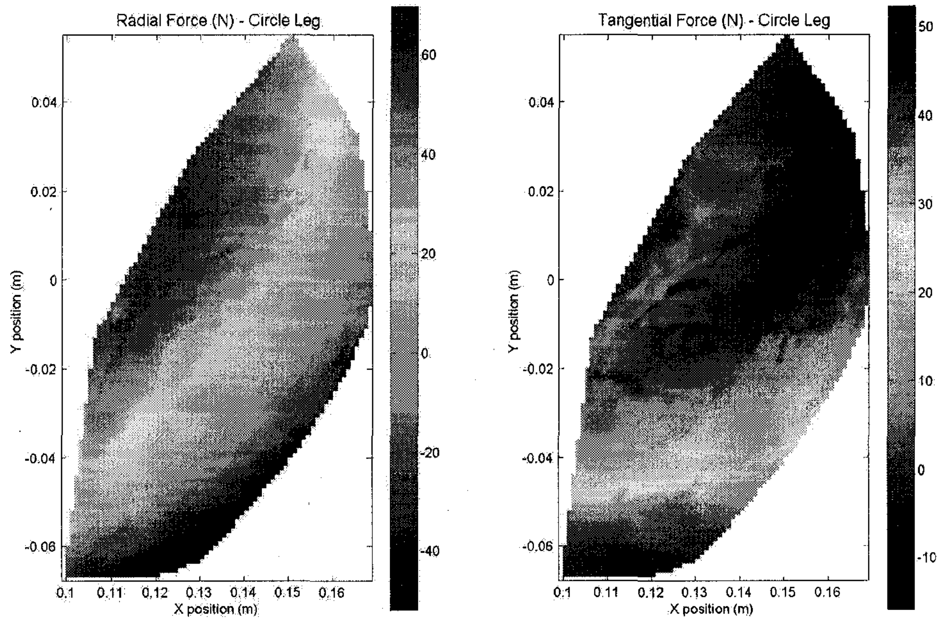


Figure 4-13 - Raw sensor output for force versus displacement tests on a Half-Circle leg. Radial force is on the left; tangential force is on the right. Hip is at (0,0) and Toe is at (0,0.15). See color electronic version for easiest interpretation of plot.

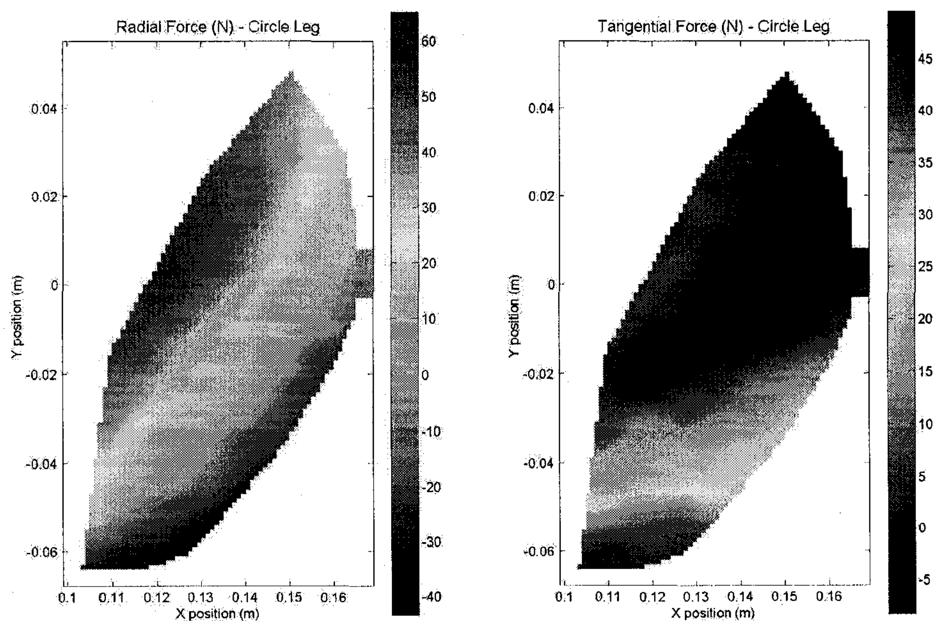


Figure 4-14 - Force vs displacement of a circle leg after Gaussian and Butterworth filters are applied. Hip is at (0,0) and Toe is at (0,0.15). See color electronic version for easiest interpretation of plot.

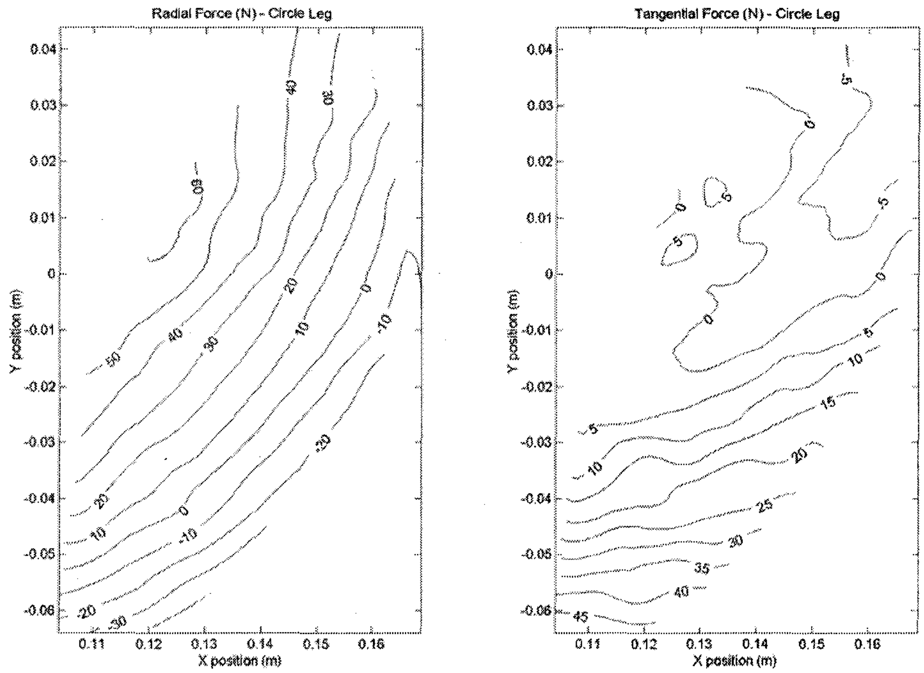


Figure 4-15 - Contour plot of the force vs displacement test on a Half-Circle Leg. Hip is at (0,0) and Toe is at (0,0.15)

We used the circle center and radius defined above to create a pseudo-rigid model of the Half-Circle leg. Because of the trend seen in Figure 4-14, we added a linear spring to the model. The linear spring proved to allow a good model of the force in the radial direction, but we found no simple corresponding trend for the tangential forces. Still, the radial spring force appears regularly in the models of the entire robot, and so a good approximation is valuable. The model of the leg is superimposed over the data in Figure 4-17, not only to show the model, but it is also useful to view the range of motion of the toe when compared to a structure the size of a leg.

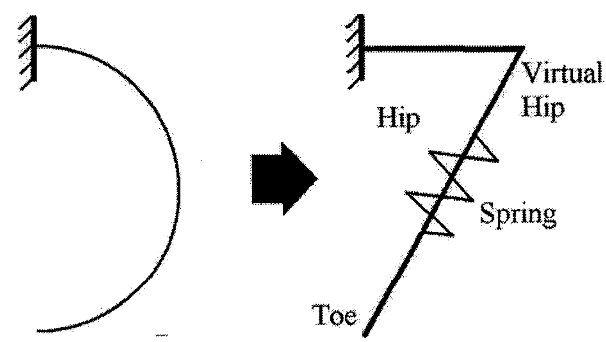


Figure 4-16 - Simplification of the Half-Circle leg using a pseudo-rigid link.

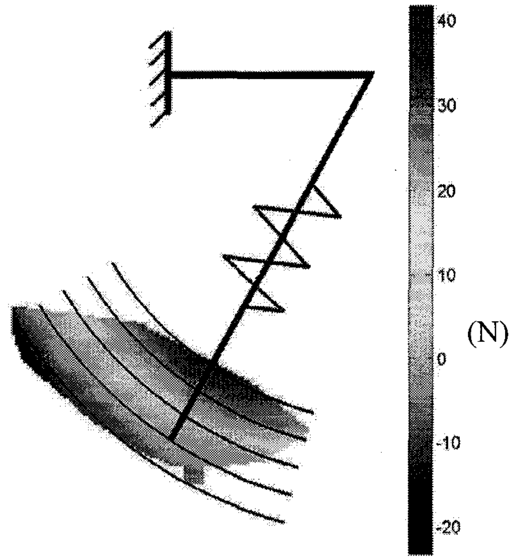


Figure 4-17 - The simplified Half-Circle leg model is overlaid on the radial force data. It appears that a linear spring on the model could give a good prediction of radial force. See color electronic version for easiest interpretation of plot.

The model used has link lengths of 0.079 m and 0.172 m, which were calculated from equations in [47]. Trial and error was used to determine a reasonable spring constant for the model. The slope of the linear spring that we found is 1270 N/m, and the standard deviation of the data from this prediction is 2.62. The difference between the linear spring force and the radial force is shown in the next plot, Figure 4-18. Only in small areas is the force prediction of the simple linear spring off by more than 2 N.

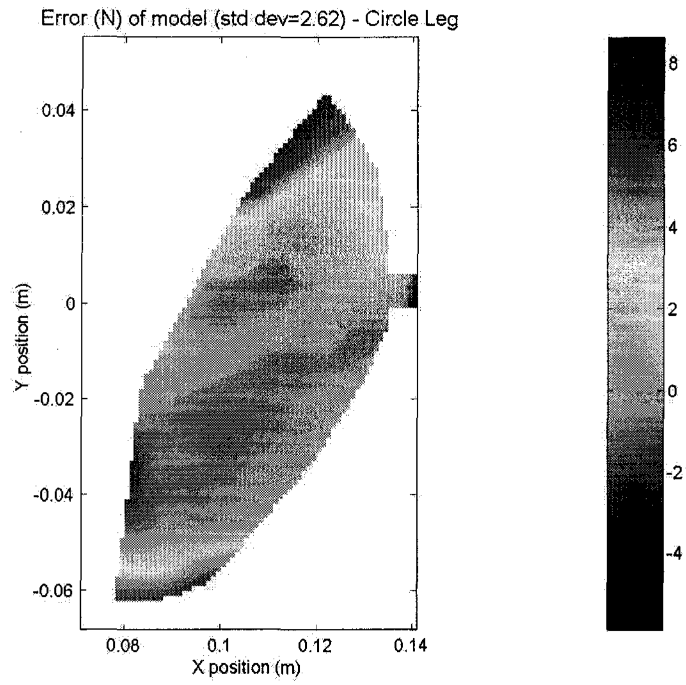
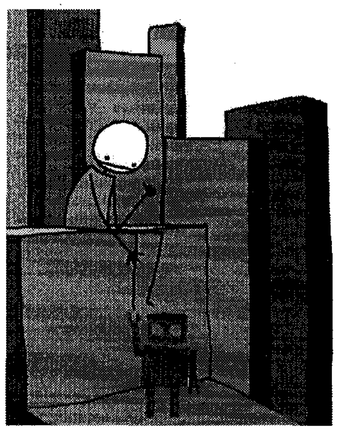


Figure 4-18 - Error of the pseudo-rigid link with linear spring model in prediction radial force. R^2 = 2.6. Hip is at (0,0) and Toe is at (0,0.15). See color electronic version for easiest interpretation of plot.

Chapter 5 Stair Traversal



We elected to use a back to front wave gait, with RHex's contra lateral legs in phase with each other. Our design is based upon analysis of the robot leg and stair geometry, which suggest such a gait, and the low reliability and performance achieved by using the alternating tripod gait. The analogy with the millipede that we presented in the introduction provides support for this gait, though it is far from a proof that this gait is optimal.

5.1 *Influence of Leg Design Upon Stair Traversing*

RHex has sported legs with three different geometries. They were introduced in chapter 3, and are shown for reference in Figure 5-1. They vary in compliance, geometry, and ruggedness, but all enabled RHex to perform on rough terrain. Stair Traversing introduces new requirement for the legs. Whatever leg is chosen must be able to grip the stair, but two main factors affect the suitability of each leg geometry for stair traversing: the horizontal distance between the hip and the ground contact point during a stance phase, and the degree to which the hip trajectory parallels the slope of the stairs.

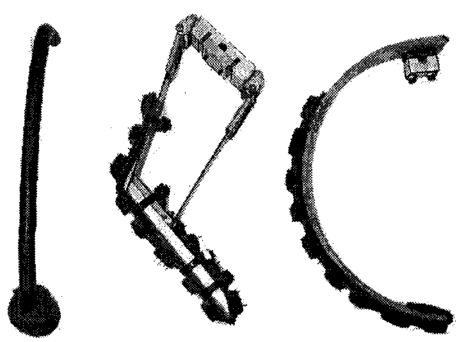


Figure 5-1 - The three leg geometries that have been used on RHex - at left is the Delrin compass leg, center is hinged Four-Bar leg, and at right is the Half-Circle leg. Geometry has a large impact on how well RHex can ascend and descend stairs.

The horizontal distance between toe and hip determines the hip torque required to support the robot against gravity. This contributes substantially to total energy cost, and so must be minimized. Not all the legs are able to minimize this distance effectively. The compass leg was not suitable for stair traversing as the horizontal distance between the foot and the hip can be quite large, as long as the leg itself Figure 5-2.

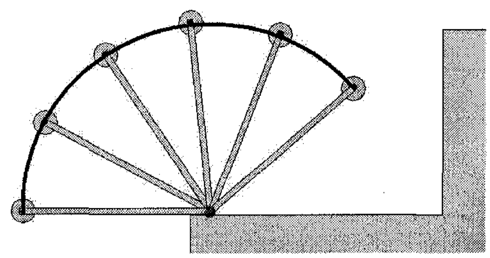


Figure 5-2 - A Compass leg during stair climbing, shown in stop motion. Black line is hip position, red dot is toe contact point

The Four-Bar leg improved upon the performance of the compass leg by changing the contact point of the leg as the hip moved during stance. This is best illustrated in Figure 5-3. The Half-Circle legs take the multiple contact point action of the Four-Bar leg a step farther by using a rolling foot contact that allows for added reductions of the horizontal toe-hip distance, as seen in Figure 5-4.

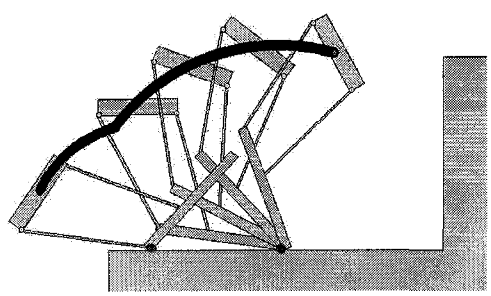


Figure 5-3 - A Four-Bar leg shown in stop motion. Black line is trace of hip motor shaft position. Red dots are leg contact points. Discontinuity in trajectory stems from change in contact point.

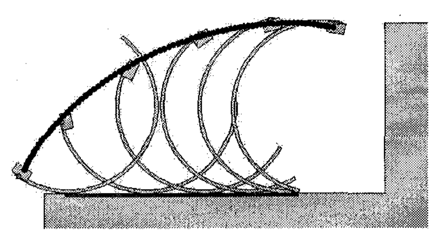


Figure 5-4 - A Half-Circle leg shown in stop motion. The black line is a trace of the hip motor; red line is leg contact points.

Of the three legs we have designed, the Half-Circle legs engender the least horizontal toe to hip distance during stance.

In stair traversing, the hip would ideally follow a straight-line trajectory along the flight at stair inclination. While it is beneficial in terms of energetics to avoid motions that do not move the robot towards its goal, there is another reason to follow such a trajectory. If all six hips follow it, then the pitch of the robots body will remain constant, reducing the chance that the robot will pitch over backwards, a catastrophic failure mode. The difference in the trajectory that the hip of each leg traces can be seen when they are compared in Figure 5-5.

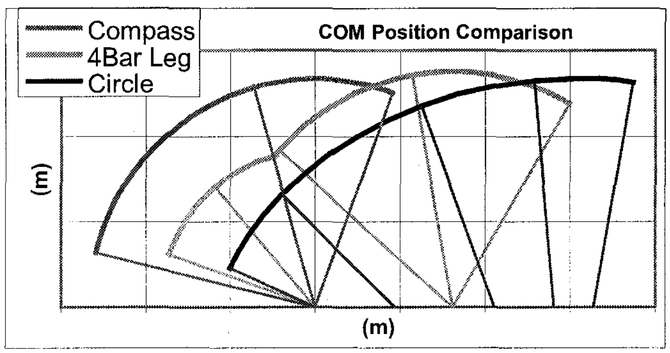


Figure 5-5 - Each of the three legs traces a different hip trajectory during the stance phase. Thick lines are these trajectories. Thin lines are selected leg positions during stance. Grid is 6 cm squares.

To follow the ideal linear trajectory perfectly, the leg would need multiple actuated d.o.f. Multiple d.o.f. legs have many advantages. A single d.o.f. leg cannot compete easily with such specialization, at least with respect to trajectory. A line-tracing, two d.o.f., leg is shown in the Figure 5-6. Limits of modern technology, however, restrict effective use of many d.o.f. robot legs, and we can also see in Figure 5-6 that the horizontal toe to hip distance can be large, a defect that causes more difficulties than the linear path fixes.

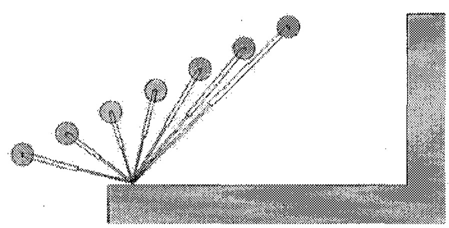


Figure 5-6 - A stop motion image of a two d.o.f. robot leg following a linear trajectory up a stair, the trajectory is excellent for stair traversing, but the hip to toe distance can be very large.

Stair traversing is a repetitive action, and so the infinite freedom of leg angles and lengths offered by a multi d.o.f. leg is not required. We can see in Figure 5-5 that the circle leg forces the hip to follow a trajectory that, of the three legs we built, is closest to the ideal. The Half-Circle legs, and to a lesser extent, the Four-Bar legs, give RHex the advantages in stair traversing of a multi-d.o.f. leg, without the disadvantages in weight, reliability, and power consumption. They change effective length, the distance between contact point and the hip, by using more than one contact point on the leg. Because the Half-Circle leg rolls, it does not suffer from a discontinuity in hip trajectory, as the Four-Bar leg does when it changes contact points. A final benefit of the Half-Circle leg is that the rolling contact of the legs allows for efficient touchdowns and liftoffs.[13]

Not surprisingly, we found that the Half-Circle legs offer improved performance in stair ascending compared to the hinged Four-Bar legs. Using the same controller as an early stair ascending paper[52], which had been tuned for ascending with the hinged Four-Bar legs, power and specific resistance decrease by 37%, from 183 W to 135 W, and 10.9 to 8.0, respectively, simply by using the Half-Circle legs. Reliability also increased from 90% to 100% over ten runs on flight #5. The Half-Circle leg design is not simply a stair-traversing gimmick. Early tests show that they provide an advantage in top speed, slope ascending, and walking efficiency as well as these found in stair ascending.

5.2 *Stair Ascending*

5.2.1 NSAA (Ned's Startup Ascending Algorithm)

The algorithms presented below allow RHex to climb human sized stairs, but it is implicitly assumed that RHex is already on the stairs. We use another algorithm in order to bring the robot to a pose where either of the stair-climbing algorithms described below can be safely activated. This algorithm can be seen in Figure 5-7. Figure 5-8 plots the actual and target position and estimated motor current of the hips from an experiment.

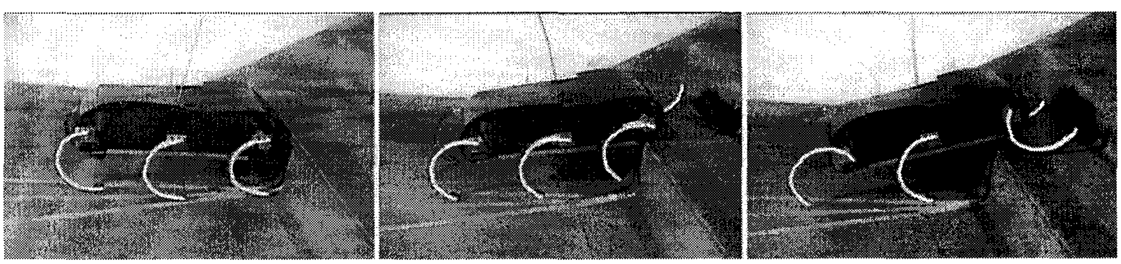


Figure 5-7 – This is a stop motion sequence for ascending first stair from standing position. A single front leg raises body up onto the stair. The other front leg follows, and the robot is ready to enter the main algorithm. Legs are highlighted for clarity.

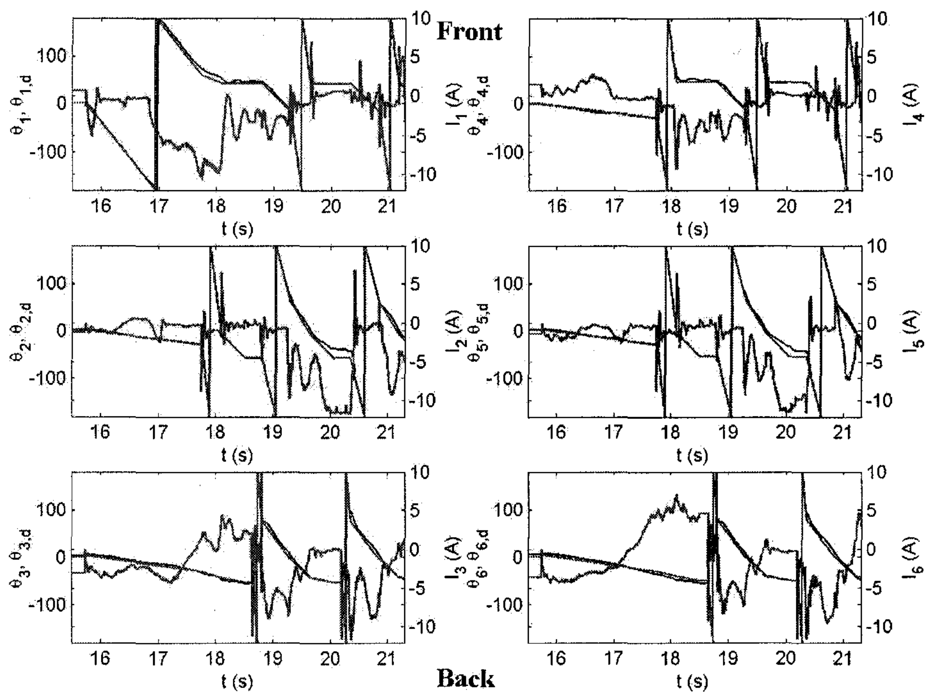


Figure 5-8 - The target (blue) and actual (green) hip trajectories and estimated hip motor currents (red) for Ned's First Stair Algorithm. Tracking is good. Motors are rarely saturated.

5.2.2 NBAA (Ned's Basic Ascending Algorithm)

As discussed above, we chose to use a back to front wave gait, with contra lateral legs in phase with each other. This choice increases the number of legs in stance at any time, compared to the tripod gait. In addition, because there are always four legs forming rectangle, and because of stair geometry, RHex tends to follow the gradient of the stair, which is a very valuable, as well as simple, attribute. We found the angles and phase differences used in the algorithm via intuition and video analysis while ascending a particular flight of stairs (stairs # 5, see Table 5-4 and Figure 5-19). The target leg angles are not altered using feedback. Motor encoders provide enough feedback to ensure that the legs are on moving along the desired trajectory. The controller is effectively open loop. While designing the controller, we placed an emphasis on maintaining a body pitch that is parallel to the slope of the stairs, a high, steady body velocity, and a moderate body ground clearance. The cycle time for the NBAA is only 1 s per step. Figure 5-9 shows the robot as it ascends stair #5. Table 5-1 gives the exact angles and times used for each pair of legs, the front, the middle, and the rear.

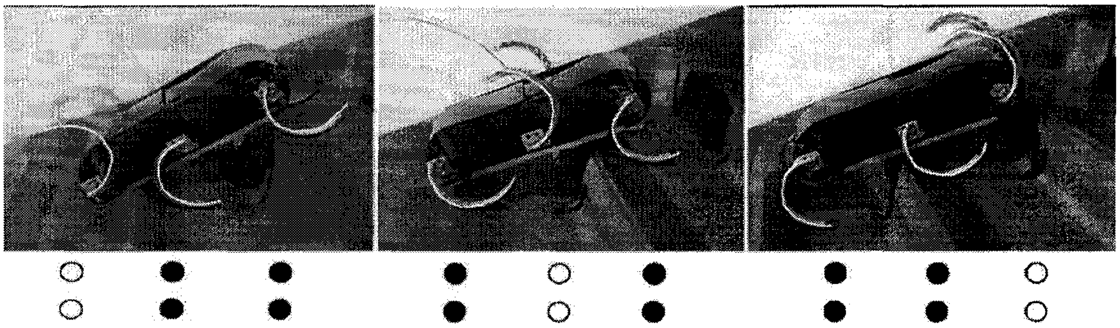


Figure 5-9 - Ned's Basic Algorithm shown in stop motion on flight #5. Each pair of legs recirculates in turn, from back to front. Legs highlighted for clarity.

NBAA	Phase Time (sec)	Rear Legs (°)	Middle Legs (°)	Front Legs (°)
Phase 1	.15	80	-30	45
Phase 2	.35	20	0	45
Phase 3	.4	-45	40	-15

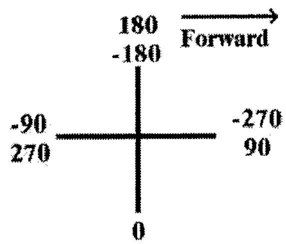


Table 5-1- Leg target angles and phase times for the NBAA. At right is the key for the leg angles. Only three sets of angles are given, since the legs work in pairs

While the Basic Algorithm worked very well on the stairs for which it was tuned (Table 5-4, flights #4 and #5). The success rate dropped of sharply, however as the stair geometry varied from the target stair geometry. Failure was either fatal, when RHex flipped about the yaw axis, or merely an exercise in futility, when the rear legs failed to reach the next stair as they recirculated, so that RHex slipped backwards one step. Neither failure mode was acceptable, so we had to improve upon the NBAA.

What is at the root of Ned's Basic Ascending Algorithms dependence upon stair geometry? The success of Ned's Basic Algorithm relies upon the robot being "in phase" with the stairs. By this I mean that when the rear legs recirculate, for instance, it is assumed that there will be a stair for it to touch down upon, at a predetermined approximate angle. Thus, successful ascending with Ned's Basic Algorithm requires some tuning of the controller to particular stair geometry. The geometry of other stairs may be such that the robot is not stable, i.e. at the completion of an ascending cycle, RHex does not have the same pose as it did at the beginning. The visible consequence of this is that the rear legs may finish their stance phase too far from the next stair to reach it at the end of their next recirculation. This will produce a failure via flipping over or by simply not progressing, as was seen in initial tests with the NBAA. This condition may not occur during every step of a flight, as the de-synchronization between robot and stair may grow over several steps.

With the NBAA, I have shown that RHex can avoid this problem if the gait parameters are carefully chosen, and climb a particular flight of stairs. If RHex is to climb any given flight, however, there must be a more general method for adapting to the stairs than arduous parameter tuning. The search for such an idea led to the creation of the following: an improved stair-ascending algorithm.

5.2.3 NIAA (NED'S IMPROVED ASCENDING ALGORITHM)

To make the NBAA more general, did we tune NBAA to many different stairs, and add sensors and a look-up table? No, too complicated. To resolve this problem, we made the following modification: at the completion of the NBAA cycle, the robot can extend the final phase, continuing to move the rear and middle legs very slowly. This effectively gives RHex an "extra push", moving RHex forward, until the body of RHex touches the next stair, and the rear legs are in the correct position to reach the next stair. Ned's Improved Algorithm can be seen in Figure 5-10 and Figure 5-11. The actual leg target angles and times are given in Table 5-2. This modification lengthens the period of the algorithm to about 1.55 s/step. The NIAA does not control RHex's body trajectory or body pitch as smoothly as the NBAA on the flight for which the NBAA is tuned, but it significantly increases the range of stairs the robot can ascend. This is an acceptable trade-off. The experimental data shown in Figure 5-11 represent three full cycles of stair ascension, on flight #6. Two of the cycles shown are of the basic algorithm, and the middle cycle is the modified algorithm. This, along with Figure 5-10 is the best visual description of the simple change we made to the NBAA in order to make RHex a much more reliable stair ascender. This algorithm was used on all stairs reported in the results section, except #4 and #5. Unless we have foreknowledge of a flight of stairs, and know them to be of the same size as flights #4 and #5, we use the Ned's Improved Ascending Algorithm for ascending stairs.

NIAA	Phase Time (sec)	Rear Leg (°)	Middle Leg (°)	Front Leg (°)
Phase 1	.15	80	-30	45
Phase 2	.35	20	0	45
Phase 3a	.4	-35	-40	-15
Phase 3b	.55	-45	-50	45

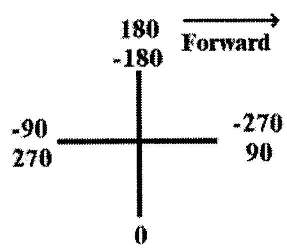


Table 5-2 - Leg angles and phase times for the NIAA stair ascending algorithm. Leg angle key is at the right. Right and left side angles are identical.

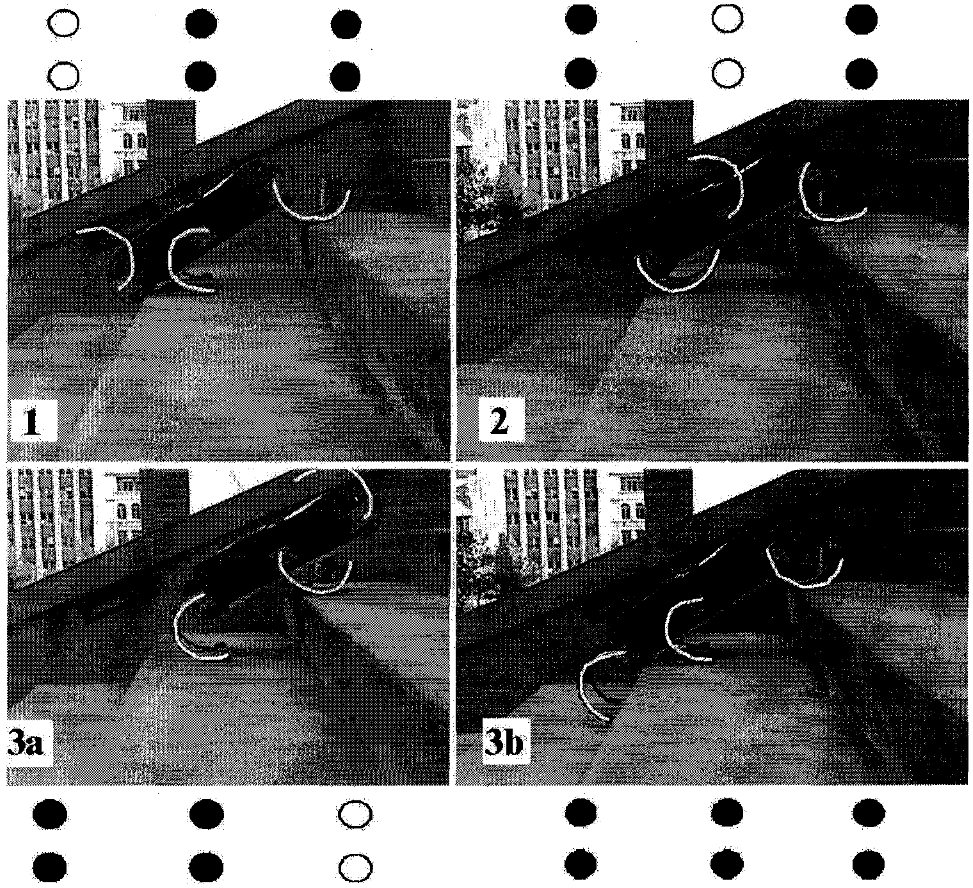


Figure 5-10 - NIAA shown in stop motion. 1,2 and 3 are identical to the NBAA. 3b is the additional phase that adds generality by maintaining posture from one step to the next. Legs highlighted for clarity. Filled dots indicate legs in stance; open dots indicate legs in recirculation.

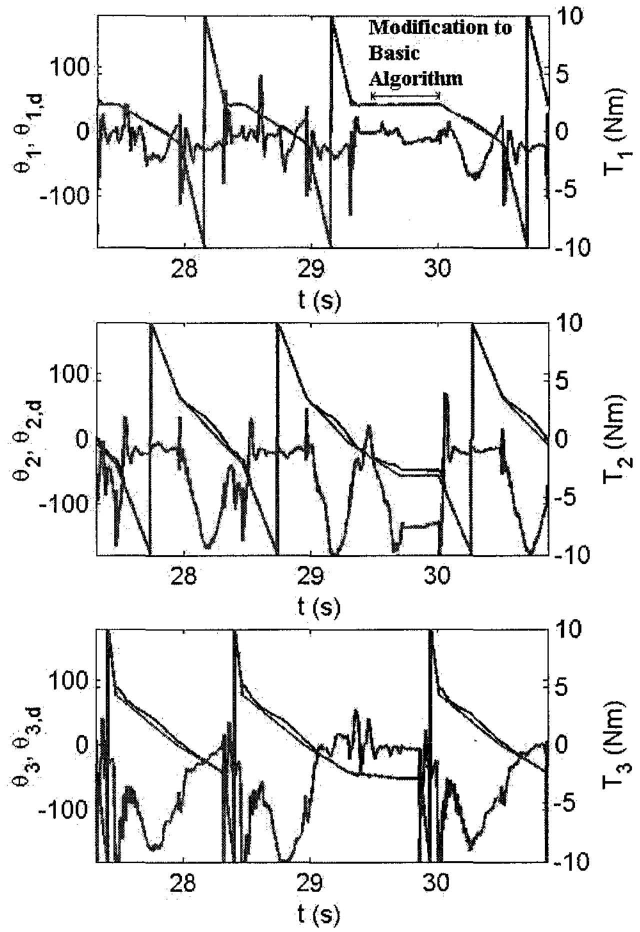


Figure 5-11 - The target (blue) and actual (green) hip trajectories and hip torques (red) during experiment that used NBA and NIA on successive stairs. NBAA is at first, NIAA is used second. Only left side motor results are shown, since robot is symmetrical. Tracking is good. Motors are rarely saturated. Best viewed in electronic version of thesis.

5.2.4 EXPERIMENTS RUN ASCENDING STAIRS

We tested RHex on nine different flights of stairs (Table 5-4 and Figure 5-19) that we found on the McGill University campus. As all stairs are designed for humans, the variation in height, length and average slope was not extreme. We believe these flights to be a good representation of the range of stairs encountered in everyday life. This assertion is backed up by the specifications of the North American building codes, given below.

	National Building Code of Canada (1995)	**BOCA (USA) 1990**
Rise (mm)	125-200	102-178
Run (mm)	210-355	279
Tread (mm)	235-355	279

Table 5-3 - Government Stair Geometry Standards

Flight #	Rise (m)	Tread (m)	# of Steps	Material	Slope (°)
1	.13	.33	12	Smooth concrete	21.5
2	.15	~.35	10	Old stone – 90° circular flight	24.0
3	.16	.338	10	Rough concrete	25.3
4	.16	.285	13	Worn wood	29.3
5	.16	.28	10	Smooth stone	29.7
6	.175	.285	15	Rough concrete	31.6
7	.18	.29	12	Smooth stone with metal lip	31.8
8	.19	.26	12	Industrial carpet w/ rubber lip	36.2
9	.20	.22	18	Metal Grate (fire escape)	42.0

Table 5-4 - Physical features of the stairs used in stair ascending experiments. Stairs of varied materials, shapes, and sizes were used to show adaptability of the NIAA.

5.2.5 EXPERIMENTAL RESULTS

Figure 5-10 shows the implemented and desired leg trajectories along with the actual leg torques for ascending experiments. Low tracking errors are exhibited, except during temporary torque saturation, primarily in the back and middle legs. For each test, RHex was started at a standing position a short distance (0-6cm) from the first stair, and was directly facing the flight.

Basic abilities

RHex ascends stairs at a rate of 1.55 s/stair using the NIA. This is a slow ascent for a human, I sprinted flight #5 at a rate of 0.18 s/stair and walked up it at a rate of 0.60 s/stair. RHex is still faster than many of the robots found in the literature. Some of the few published speeds are given in Table 5-5. When there is no speed data along with claims of legged robot stair traversal by other robots, we expect that the robots are relatively slow. Rhex can traverse a wide range of stairs in an efficient and reliable manner, as discussed in the following sections. As an additional test of endurance, we used the NIA to ascend the 292 steps of varying sizes and geometries of Montmartre in Paris, France, twice in a row, without difficulty. Pictures of this ascent are shown below. Stair ascending was also demonstrated numerous times at the CLAWAR 2001 conference in Karlsruhe, Germany.

Robot Name	Ascending Speed (sec/stair)
Raibert Biped[++]	0.6
Honda P3[**]	~1.5
RHex	1.0-1.55
WL-12RIII	2.6
Wheel-Leg Biped	3.0
MelCrab II	10+

Table 5-5 - Comparison of stair ascending rates of different legged robots. [++]Value based on published average velocity and stair size. [**]Value found by timing a movie

Figure 5-12 - Left – RHex starts climbing stairs next to funicular at Montmartre in Paris. Right - Onlookers stop to stare, as RHex makes final ascent.

Energetics

Energetic cost of ascending stair is substantial, based on an average total electrical power consumption of between 94 and 203W on the various stairs. While the power varied widely, we are also interested in how efficiently we are climbing stairs. A measure of efficiency in a walking vehicle must consider weight, power, and speed. Gabrielli and von Karman proposed a general method for measuring efficiency, using a cost function known as *specific resistance.* Specific resistance is defined by the following equation:

$$\varepsilon = \frac{E}{m \cdot g \cdot d_x} \tag{1}$$

Where E is total energy used, m is the mass of the robot, g is gravity, and d_x is the horizontal distance travelled. A smaller specific resistance corresponds to lower energy requirements to perform task. Our calculation of specific resistance is conservative on three points. First, we need a long time to climb the first stair, and this increases the total energy used by RHex because of the significant overhead imposed by the computer and other systems, whose power consumption does not vary with mechanical work. Second, we do not consider the added potential energy of the system when the robot reaches to top of the stairs. Finally, the total distance that the robot has travelled is much greater than the horizontal distance. The success rate, power consumption and specific resistance results for each flight are given in Table 5-6.

This specific resistance values found are at least four times that for walking on even terrain. On the other hand, the raw power consumption is less than twice that of walking. The robot simply moves more slowly when ascending stairs. It would be interesting to compare this energetic cost to that incurred by other robots during stair ascending. Unfortunately, to our knowledge, no such data is available in the literature. While Ned's Basic Algorithm provides an advantage in speed over Ned's Improved Algorithm, it was not more cost effective, due to corresponding increases in power consumption. In Figure 5-13, we can compare with what data is available for other robots, and even though only RHex is ascending stairs, it is comparable to other legged robots. The data for flight #5 is the average of data taken over ten runs. The energetic results for all other flights represents data from a single experiment.

Flight #	Success (%)	E (W)	S.R. ε
1	100	100	4.8
2	90	94	4.8
3	100	96	5.6
4	100	122	5.7
5	100	106	4.7
6	100	111	7.5
7	100	102	6.8
8	100	185	13.6
9	100	203	19.4

Table 5-6 - Success rates, power consumption, and specific resistance data for the 90 experiments run ascending nine different flights of stairs. Stair parameters are in Table 5-4.

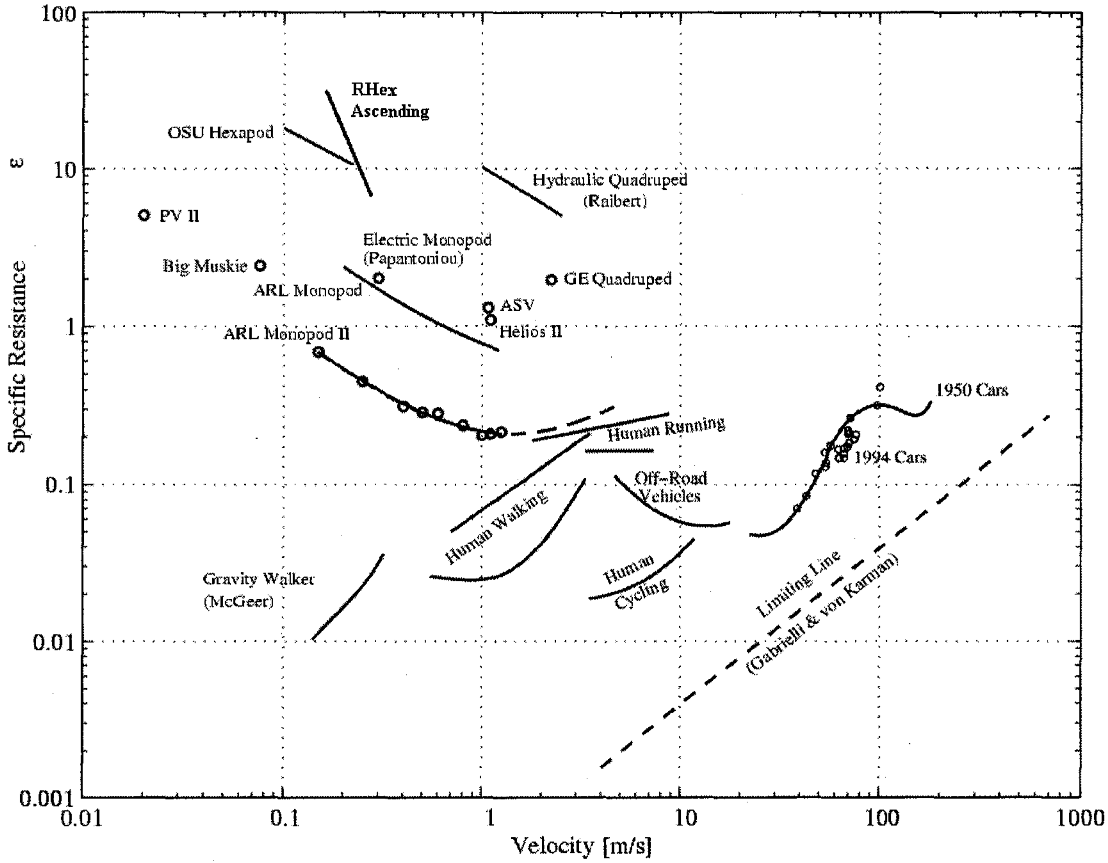


Figure 5-13 - Comparison of specific resistance for people and various machines, only RHex is traversing stairs, but its specific resistance is still comparable to some other robots.[9]

The specific resistance recorded for stairs eight and nine are substantially higher than the other stairs. This is due to the higher frictional coefficients of the surfaces of these stairs. During the "extra push" phase of the ascent, the legs get locked in position, instead of slipping a small amount, as happens on the other flights. This leads to high joint errors, and high torques, and thus higher specific resistance.

There is some energy wasted during the "extra push" phase correction of all stairs, as can be seen in the large torques of the middle legs in Figure 5-11, and the power spike at 29.2 s in Figure 5-14, while the spike at 30.8 s is that of a normal cycle.

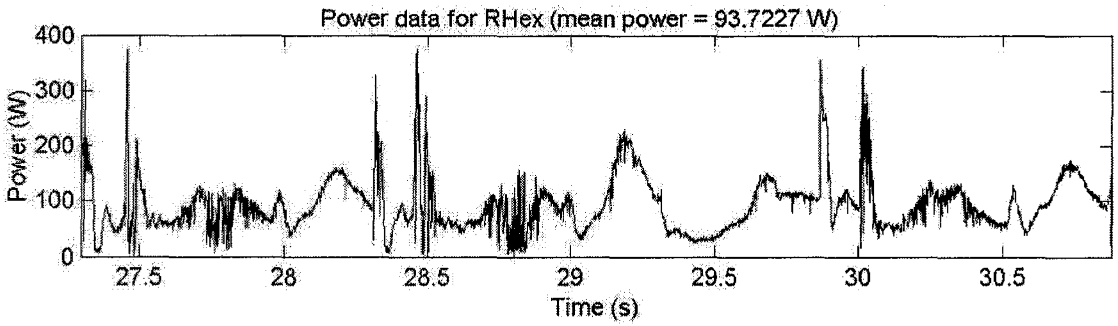


Figure 5-14 - Power used during ascending of flight #5. This data is from the same set as Figure 5-11 the large spike at 29.2 s is due to use of NIAA, while smaller spikes at 28.2 s and 30.8 s correspond to the NBAA.

Reliability

We found during development that the best predictor of success was the rise of each step, not the tread length, average slope, or surface finish. There are classes of stairs that RHex cannot yet ascend, such as circular stairs and stairs with very round corners. The results were good, in general. The reliability over ten runs as is given in Table 5-6. The single reported failure did not involve Ned's Starting Ascending Algorithm, but instead occurred once the robot was on the stairs, and was using Ned's Improved Ascending Algorithm. Reliability can be affected by factors such as weather, rain can make the stairs slippery for example, or by extremely warm weather, as the motors will be more likely to overheat, and provide insufficient torque to ascend the stairs.

5.3 *Stair Descending*

The stair-descending algorithm was created after the completion of the work presented above on ascending stairs. This allowed us to learn from the results of ascending. We elected to immediately use a contralateral, back to front wave gait, and so the design relied less upon video analysis of experiments.

5.3.1 STARTUP ALGORITHM

As in the stair descending algorithms above, the open loop target angles used in the stair descending algorithm presented below are able to descend human sized stairs. Again, it is implicitly assumed by these algorithms that the robot already is on the stairs. In order to bring the robot to a pose where the main stair-descending algorithm can safely be activated, two sets of target angles are implemented before the main controller. It can be seen in Figure 5-15. This controller has the simple goals of changing the pose of RHex from standing at the top of the flight of stairs to resting in a position similar to that shown in phase 1 of Figure 5-16, which allows the robot to transition to the main stair descending algorithm that RHex uses. The positions and leg torques are also shown in Figure 5-15.

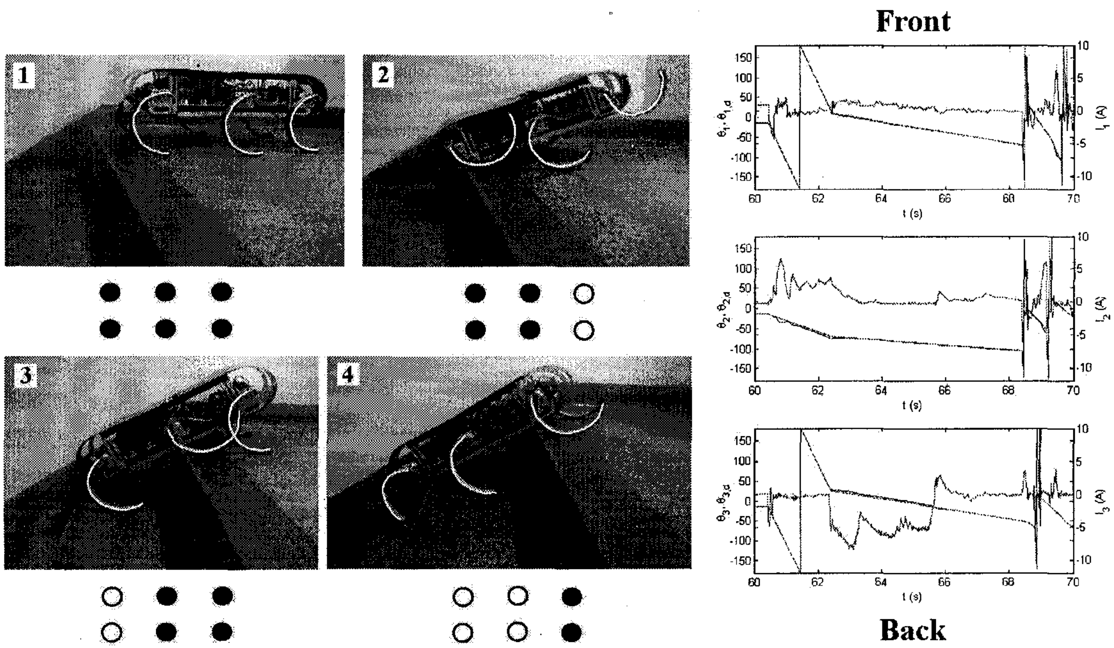


Figure 5-15 - 2 stage starting algorithm for stair descending shown in stop motion (left) and leg positions and motor current (right)

The first stair algorithm lasts about five seconds. Low speed helps to prevent RHex from falling over the edge of the first stair. In image one of Figure 5-15, the robot is standing in front of the stair. Image two shows the first phase of the descending starting controller. The front legs recirculate, while the middle and rear legs lower the body, and move it towards the stair. The rear legs finish this stage at the end of their recirculation, and so the middle legs are the only pair to remain in contact with the ground throughout the phase. The rear of the robot rests on the ground as a result. During the second phase of starting, shown in image 3 of figure 15-2, the middle and front legs lower the body onto the next stair. The rear legs point towards the ground, but are not able to reach the stair. At the end of the phase, the middle and rear legs perform a recirculation to bring the robot to image four, which is the same position as position one of the main descending algorithm, and RHex is thus ready to descend.

5.3.2 Ned's Descending Algorithm (NDA)

In this gait, the legs work in pairs, just like in the ascending gaits. There are six sets of target angles, but this was done to make certain aspects of the development easier, and I prefer to think of the NDA as having three distinct phases. The rear legs recirculate in the first, followed by the middle legs, and then the front legs. Each of the three leg pairs recirculates in only 0.15 s. The fast recirculations result in significant lengths of time were all six legs are on the ground, about 1.1 s out of a 1.55 s cycle. This is done to enhance stability, and explains why there are six phases; there are three for recirculation for each of the three leg pairs, and three for full stance phases between recirculations. In order to take advantage of the leg geometry, RHex descends the stairs "backwards". The gait is shown being used on flight #5 in Figure 5-16. The corresponding joint angles and torques are shown in Figure 5-17.

In the NDA, the body slides along the lip of each stair, resulting in an effective, if somewhat graceless stair descending algorithm. Because the body is nearly always in contact with the stair, the movement is not as smooth. The main difficulty in allowing the body to slide down the stairs is that any load taken by the body is not applied to the legs. With small loads on the legs, it is difficult for them to apply propulsive force to the tread. In order for RHex to move forward, its legs push off the rise of the stair, instead of the tread humans do. This works well on stairs that have rises, but is a serious problem on stairs that don't, such as many outdoor wooden and metal stairs, such as fire escapes.

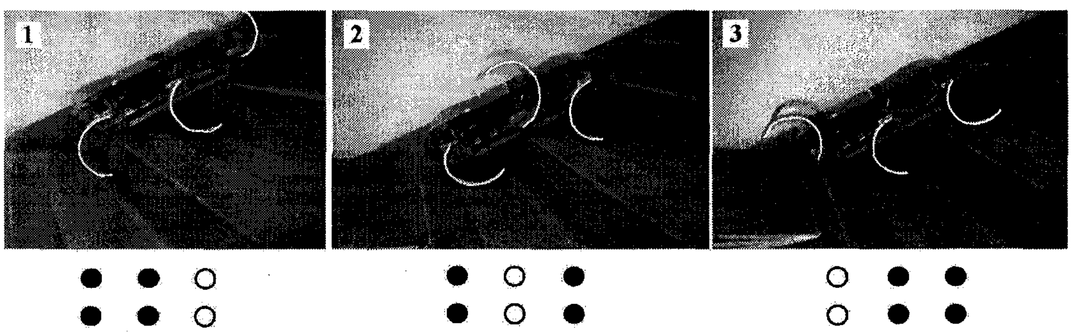


Figure 5-16 - Stop motion sequence of RHex descending flight #5. Rearmost legs recirculate first, followed by middle and front. Legs in stance represented by black dots, legs in phase by open circles. Legs are highlighted for clarity.

NDA	Phase Time (sec)	Rear Leg (°)	Middle Leg (°)	Front Leg (°)
Phase 1	.25	55		
Phase 2	.15	-25		
Phase 3	.2		60	
Phase 4	.15		-40	
Phase 5	.3			80
Phase 6	.15			-55

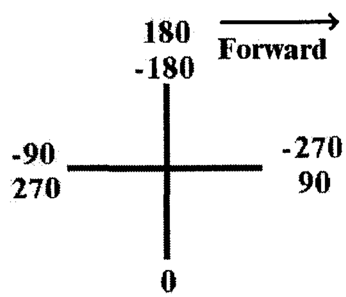
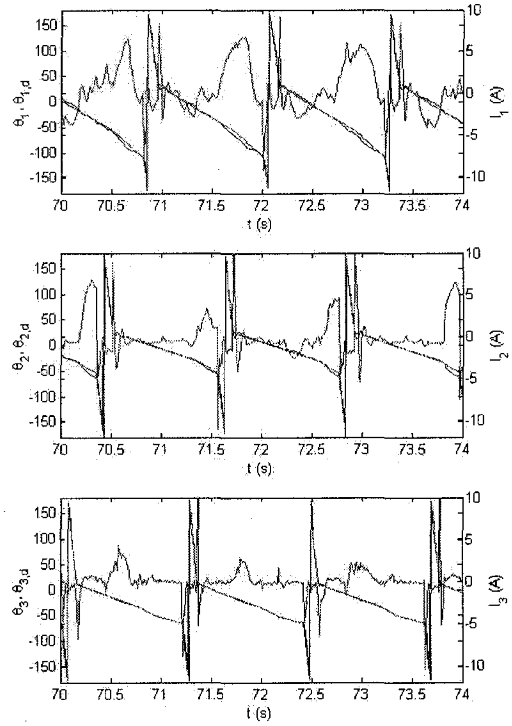


Table 5-7 - Leg Angles and Phase times for Neds Descending Algorithm. Many spaces left blank on purpose. Each leg pair works in a two-stroke mode, where they move between two targe positions. Intermediate joint angles are linearly interpolated. This method allows us to choose the phase difference between leg pairs, while retaining a two-stroke controller for each pair of legs. At right is joint angle key.

Front



Back

Figure 5-17 - Data for stair descending: actual leg position (green), target leg position (blue) and motor torque (red) for stair descending. Only left side is shown, as this gait is symmetrical in the sagittal plane. Front legs are legs that lead the body during stair descending, although these legs are used in rear for most other gaits.

5.3.3 Experiments Run Descending Stairs

We experimented with the descending controller on the same stairs that we used in the ascending experiments. Because the descending algorithm relies on pushing off of the rise of each stair, RHex was not able to descend flights # 2, 4, 7, 8, and 9 successfully. These flights are ignored during this section. While the smaller set of flights does reduce the variation in geometry and surfaces that are examined, the remaining flights of stairs still vary significantly from each other in geometry and surface finish. The variation is large enough that the success of RHex on these stairs demonstrates a robust ability, not merely a trick.

5.3.4 Experimental Results

Basic Abilities

RHex descends stairs at a rate of 1.2 s/step. This is slow compared to a human, but not by too much. We were unable to locate descending speeds of any other legged robots in the literature. While several robots, including the Honda P3, Sony Asimo, and the SD-2 can all descend stairs, there is no published information about the precise attributes most of these controllers. We only know that the Raibert biped descended stairs at the same rate that it ascended: 0.6 s/stair. Because there are even fewer stair descending legged robots than ascending, this dearth of information is not surprising.

Even in failure, RHex reaches the bottom of the flight of stairs, and RHex is reliable enough to survive a tumble. I have accidentally dropped RHex three meters onto concrete, without visible result. We do prefer the more elegant NDA, however.

This controller is more sensitive to initial distance from the first stair than the ascending NIAA, and so driver skill is required to prevent RHex from starting poorly. In all forty tests that I ran of the NDA, RHex descended the stairs without relying on tumbling.

Energetics

The measure of cost for legged vehicles that was introduced in section 5.2.5, specific resistance, is actually slightly higher for descending than ascending using the NBAA, but is lower than that of NIAA. The comparison between the NIAA and the NDAA is fair because they operate on a similar range of stairs, while the NBAA only works on a narrow range of stair geometries. This difference is important because it is likely that the NBAA exploits details of the stair geometry through tuned parameters to reduce cost.

There is at least one factor that will increase the specific resistance of descending compared to ascending: in the interval between the testing of the ascending and descending controllers RHex lost a full kilogram, when the electrical hardware underwent an overhaul. Mass appears in the denominator of specific resistance, and so a heavier robot can be more efficient, all other things being equal. This effect is overwhelmed by several other factors that increase the efficiency of descending. At the very least, RHex must increase its potential energy while ascending, and must lose it while descending. The direction of energy flow probably effects energy consumption from the batteries. Second, the descending algorithm causes RHex to slide on the stairs, removing the need for the legs to spend energy to simply support the body for portions of the cycle. Finally, RHex descends 30% faster than it ascends, and so uses less total energy for baseline operation, such as computer operation. Specific resistance during stair descending is given in Table 5-8.

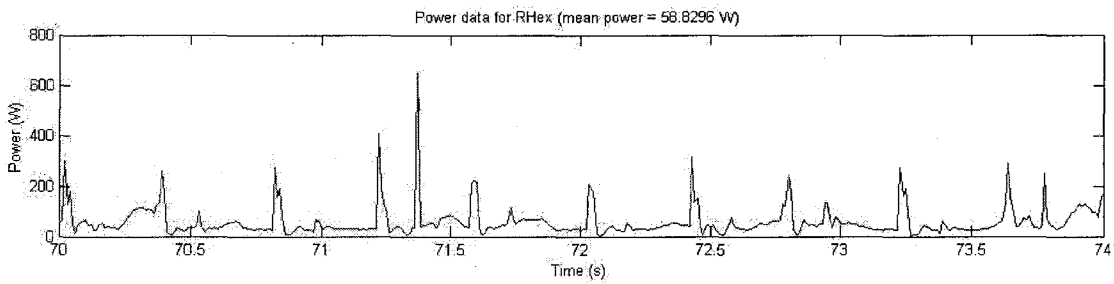


Figure 5-18 - Power consumption during a descent of flight #5. Spikes are of the same magnitude as the NIAA, but are less frequent, so power use is only about 60% that of the NIAA.

Flight #	Success (%)	E (W)	S.R.
1	100	92.24	7.1
3	100	57.94	4.3
5	100	62.9	5.1
6	100	48.28	4.0

Table 5-8- - Success rates, power consumption, and specific resistance data for the 40 experiments run descending four different flights of stairs. Stair parameters are in Table 5-4.

Reliability

The NDA is more susceptible to initial conditions than the NIAA. The errors that do occur while descending do not tend to be as fatal as those that happen while ascending. RHex sometimes skips stairs while descending, but overall performance is not affected by this tendency. It still reaches the bottom of the stairs, and does not suffer any damage.

5.4 *Stairs used in Experiments*

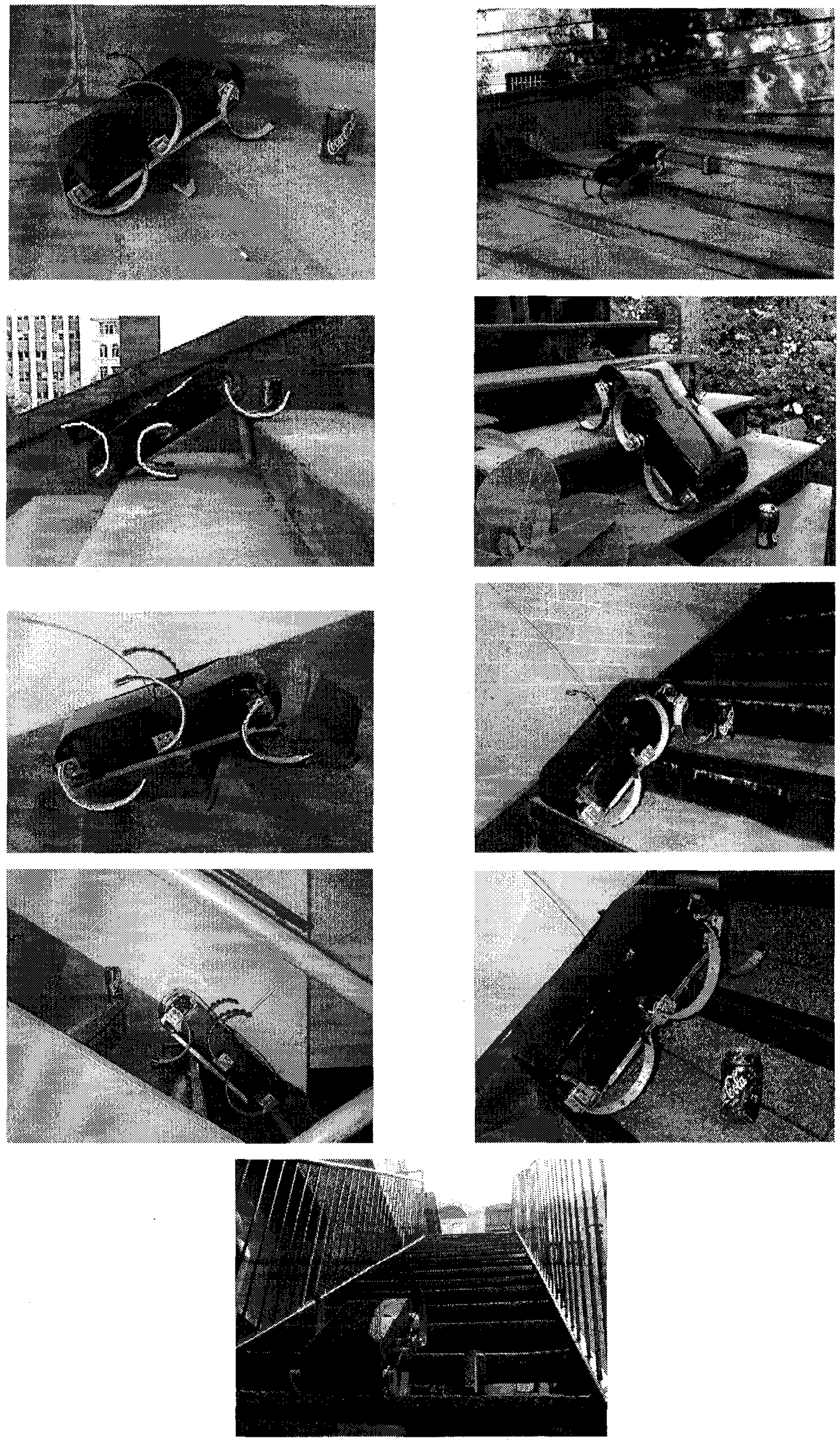


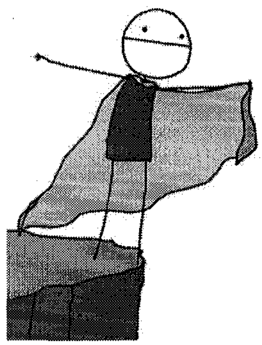
Figure 5-19 - Stairs used in experiments, left to right, top to bottom, stairs #1-#9

5.5 Summary

Based first on intuition, and tuned with insights from biology and video analysis, I have designed a stair ascending and descending controller for RHex. I tested it on a wide variety of human sized stairs, and measured power consumption and speed, and calculated a measure of efficiency, specific resistance, for comparison purposes. The tests also were used to indicate the reliability of the controller, and it was found to be excellent, resulting in only a handful of failures during hundreds of experiments.

I integrated the above behaviors into a single controller in the standard RHex control library. The controller is simple to use, the driver must only position the robot near the first stair. The controller is reliable, experiencing only a handful of failures during hundreds of tests on many different stairs. The controller is energy efficient, with specific resistance values as low as 4.0. These attributes make RHex one of the most able stair traversing legged robots in the world. It is the smallest robot of which we know which can climb human sized stairs. That it can do so autonomously, reliably, and efficiently only adds to the accomplishment.

Chapter 6 Conclusions



This thesis presented the development and successful implementation of several different compliant leg designs. Composite leaf springs were used in the leg designs, and the force versus deflection characteristics of the legs are known from experiments. A controller that enabled RHex to ascend and descend human sized stairs quickly, reliably, and efficiently was designed, coded, and tested. The success of this controller demonstrates that a seemingly complex problem can be solved in using a simple, open loop control strategy. In conclusion, we highlight the achievements, and motivate future work.

6.1 *Summary*

- Several leg designs have been built and evaluated with respect to many practical criteria, including reliability and torque transmission capabilities. The Half-Circle legs and the hinged Four-Bar legs have proved sufficient for use on RHex.
- We determined the force vs. displacement properties of the legs that we designed, using experiments. We then found simple models to give predictions of the static leg reaction forces. This information can be used for creating more accurate simulations of RHex.
- RHex can ascend and descend nearly any stair it encounters, using only a simple open-loop controller. We measured speed, power and efficiency while ascending a wide variety of stairs, including fire escapes, wooden stairs, carpeted, and both indoor and outdoor stone and concrete. We measured the same quantities while descending stairs on a smaller set of flights that varied widely in size, but not in material. RHex is now the only robot of its size that can climb stairs reliably, and is one of very few legged robots that can climb stairs autonomously, without an external source of power or control. It is also nearly the fastest legged stair climber, and certainly the fastest in its weight class.

6.2 *Suggestions for Future Leg Designs*

The leg designs presented here have been successful at their stated goals of reliability, compliance, and other metrics. But it is folly to think that they are optimal. Some of the improvements listed below will improve performance, and others will increase our understanding of RHex.

Combining the uniform cross section, the spring kinematic constraints, and the loading conditions of each spring yields an uneven stress distribution when the springs are loaded. An even stress distribution is desirable so that both compliance and durability can be optimized. We could achieve an even distribution of stress by varying the cross section area of the spring. A perfectly even distribution may not be possible due to space limitations on RHex, but an increase in performance is certainly attainable.

6.2.1 LEG DAMPING

Determining the damping will lead to improved models of RHex. This parameter is especially important for modeling and simulation of dynamic behaviors, such as bounding or pronking. Dynamic tests are required to determine damping coefficients. It is unlikely that the damping ratio would vary significantly with leg length, so it would be easy and beneficial to test the damping at a single leg length. The same setup as used in the force versus displacements tests could be used if the friction of the test apparatus could be reduced. From this a simple approximation of the damping ratio could be found based on the decay of a free vibration using, given the assumption of a second order spring mass damper system. Initial tests that I performed indicate that this assumption might be valid.

6.2.2 ADD SECOND D.O.F.

In our publications, we have made much of the fact that RHex does what it does with only a single actuated d.o.f. per leg We value the reliability, simplicity, and other benefits associated with a minimally actuated system. Adding more d.o.f.'s, however, may provide benefits to certain behaviors through additional flexibility of control. One such behavior is slope ascending, which would be helped through the ability to shorten the legs, and thus lower the center of mass. Running could be made more stable by being able to choose the touchdown angle more precisely, and by being able to shorten the legs during the swing phase. Finally, one of the long-term plans for the Half-Circle legs involves adding a second actuated d.o.f., which would enable a special behavior: rolling. If the main drive shaft, currently at the hip, is moved to the center of the Half-Circle, RHex could roll on the leg. By using a modified tripod gait, we expect that speeds up to 2 m/s could be achieved. While the addition of a second actuated degree of freedom will have to be done carefully in order to preserve current features, it has the potential to significantly enhance the capabilities of RHex.

6.2.3 CAM LEG

While picking the best leg to use for stair climbing, we noted that a linear trajectory is desirable, but not valued as highly as a short horizontal distance between the hip and the toe. We could design a leg that would give a nearly linear trajectory, and low hip-toe distance, if we modify the Half-Circle leg to have a cam profile. Since stair traversing is successful with the circle legs, it is unclear if RHex should have legs that have been designed with such a specialized purpose in mind. A "cam-leg" would have a pointed toe, which should make running simpler to analyze, because it would give a point, not a rolling, contact. It is evident that the cam leg will not allow for a "wheel mode" as the circle legs do. If the "wheel mode" becomes important to overall performance, this design will not offer enough benefit to warrant construction.

6.3 *Suggestions for Future Stair Traversing*

While the basic question of stairs has been answered to our satisfaction, there exist certain subclasses of the problem that might be interesting to explore.

6.3.1 MAXIMUM SINGLE STEP CAPABILITY

There are many examples of single steps, rather than entire flights of stairs, as obstacles in every day life, such as roadside curbs. It might be possible to tune the algorithms described above to traverse a single step that is taller than any that could be traversed repeatedly as part of a flight.

Alternately, entirely new "leaping" algorithms might be devised that would forgo the ponderous statically-stable wave gait, in favor of something more drastic, that could clear a single step quickly by jumping. This kind of behavior will become more of a possibility once RHex acquires fast dynamic gaits, which will likely happen in the near future. This will allow RHex to build up the significant kinetic energy that can be turned into potential energy by changing the touchdown angle, as described by Raibert.[7] This is in fact a behavior that is currently being developed by our RHex team colleague at the University of Michigan, Haldun Komsuoglu.

6.3.2 ENHANCED TURNING

Right now, RHex tends to follow the gradient of a flight of stairs because its legs are used in pairs. It might be desired to turn at an even steeper angle in an emergency. It may be possible to turn through larger angles by modifying the stair-traversing algorithm discussed above. It was mentioned that the limiting factor is the ability of the legs to reach the next stair during recirculation. This problem may be overcome by adding a phase shift between contra lateral legs. Thus the leg that can reach the stair in a tight turn should do so, and help to move the body up the stairs until the other leg can also reach the stair. This idea will have problems if the sole leg touching the next stair is unable to provide the necessary force. Still, we believe that this idea has some merit, should such steep turning be required.

6.3.3 FEEDBACK

By not relying information about the stairs garnered from sensors, we avoid many potential pitfalls, such as sensor noise, range, speed, and reliability. That isn't to say that there are not benefits to be reaped from using sensors to improve the stair ascending and descending. Sensors would be especially suited to tasks such as automatic steering, power optimization, or automatic positioning before the first step, which are not critical to operation, but are bells and whistles. It should also be possible to tune the controller over several steps to increase speed, given information and some metric, describing how well RHex is climbing. Body pitch angle, distance from the stair, vision information, and motor torque could all be used to improve the stair traversing algorithms we have presented here.

Bibliography

[1] R. Altendorfer, U. Saranli, H. Komsuoglu, D. E. Koditschek, B. Brown, D. McMordie, E.Z. Moore, M. Buehler and R. Full, "Evidence for Spring Loaded Inverted Pendulum Running in a Hexapod Robot", *Int. Symp. Experimental Robotics*, 2000.

[2] C. T. Farley, J. Glasheen and T. A. McMahon, "Running springs: speed and animal size", *Journal of Experimental Biology,* 185: pp. 71-87, 1993.

[3] T.A. McMahon, "Using body size to understand the structural design of animals: quadrupedal locomotion", *J. of Applied Physiology,* 39(4): pp. 619-627, Oct. 1975.

[4] S. Hirose and A. Rattipat. "Design of a stair-climbing vehicle", in *Proc. Of the 13th Ann. Conf. RSJ,* pp.153-154, 1995.

[5] M.E. Rosheim, *Robot Evolution – The Development of Anthrorobotics*, John Wiley and Sons, New York, 1994.

[6] R. Blickhan, and R.J. Full, "Similarity in multilegged locomotion: Bouncing like a monopod", *J. J. Comp. Physiol,* A 173, pp. 509-517, 1993.

[7] M.H. Raibert, *Legged Robots that Balance*, MIT Press, Cambridge, MA, 1986.

[8] K. Yamazaki, "Design and control of Scout I", M. Eng. Thesis, McGill University, 1999.

[9] Mojtaba Ahmadi, "Stable Control of a One-Legged Robot Exploiting Passive Dynamics", Ph. D. Thesis, 1998.

[10] R.J. Full, K. Autumn, J.I. Chung, and A. Ahn, "Rapid negotiation of rough terrain by the death-head cockroach", *American Zoologist*, vol. 38, pp. 81A, 1998.

[11] T.M. Kubow and R.J. Full, "The role of the mechanical system in control: A hypothesis of self-stabilization in hexapedal runners", *Phil. Trans. Royal Society London*, vol. B. 354, pp. 849-862, 1999.

[12] H. Cruse, "What mechanisms coordinate leg movement in walking arthropods?", *Trends Neuroscience,* 13, pp.15–21, 1990.

[13] D. Graham, "Pattern and control of walking in insects", *Advanced Insect Physiology,* 18, pp. 31–140, 1985.

[14] G.M. Nelson and R.D. Quinn, "Posture Control of a Cockroach-like Robot", In *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, Leuven, Belgium, May 18-21, 1998.

[15] J. Ayers, J. Witting, N. McGruer, C. Olcott, and D. Massa, "Lobster Robots", In *Proceedings of the International Symposium on Aqua Biomechanisms,* T. Wu and N. Kato, Eds., Tokai University, 2000.

[16] K. Berns, S. Cordes, and W. Ilg, "Adaptive, neural control architecture for the walking machine lauron", In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1172-1177, 1994.

[17] D. Spenneberg and F. Kirchner, "Omnidirectional Walking in an Eight Legged Robot", In *Proc. of the International Symposium of Robotics and Automation*, 2000.

[18] S. Kajita and K. Tani, "An analysis of experimentation of a biped robot Meltran II", In *Proc. of 3rd International Workshop on Advanced Motion Control*, UC Berkeley, pp.417-420, 1993.

[19] J. Bares and David S. Wettergreen, “Dante ii: Technical description, results, and lessons learned”, *Int. J. Robotics Research,* 18(7), pp. 621-649, July 1999.

[20] T. McGeer, “Passive Dynamic Walking”, *The Int. J. of Robotics Research*, 9(2), April 1990.

[21] M. Ahmadi and M. Buehler, “Stable Control of a Simulated One-Legged Running Robot with Hip and Leg Compliance”, *IEEE Transactions on Robotics and Automation,* 13(1), pp 96-104, Feb 1997.

[22] M. Buehler, R. Battaglia, A. Cocosco, G. Hawker, J. Sarkis, and K. Yamazaki, "SCOUT: A Simple Quadruped that Walks, Climbs, and Runs", *IEEE Int. Conf. Robotics and Automation*, pp. 1701-1712, 1998.

[23] D. Papadopoulos and M. Buehler, “Stable Running in a Quadruped Robot with Compliant Legs”, *IEEE Int. Conf. Robotics and Automation*, pp. 444-449, April 2000.

[24] R. Battaglia, “Design of the scout II quadruped wuth preliminary stair-climbing”, M. Eng. Thesis, McGill University, March 1999.

[25] EOD Performace Inc. - http://www.vanguardrobot.com

[26] HDE Manufacturing Inc. - http://www.hdemfg.com/news.htm

[27] S. Hirose, S. Aoki, and J. Miyake, “Terrain Adaptive Tracked Vehicle HELIOS-I”, In *Proc. 4th Int. Conf. on Advanced Robotics*, Springer-Verlag, pp. 676-687, 1989.

[28] EADS N.V. - http://www.army-technology.com/projects/al_fahd/index.html

[29] DeKa Research - http://www.dekaresearch.com/

[30] Bluebotics Corp. - http://www.bluebotics.com/products/shrimp/

[31] iRobot Corp. - http://www.irobot.com/rd/p08_Packbot.asp

[32] S. Hirose, K. Yoneda, K. Arai, and T. Ibe, “Design of Prismatic Quadruped Walking Vehicle TITAN VI”, In *Proc. 5th Int. Conf. Advanced Robotics*, pp.723-728, 1991.

[33] J. Golden and Y. Zheng, “Gait Synthesis for the SD-2 Biped Robot to Climb Stairs”, *International Journal of Robotics and Automation*, 5(4): pp. 149-159.

[34] T.G. Bartholet, “Odetics makes great strides”, *Nuclear Engineering International*, 31(381): pp. 37-38, Apr. 1986.

[35] O. Matsumoto, S. Kajita, M. Saigo and K. Tani, “Dynamic Trajectory control of passing over stairs by a biped type leg-wheeled robot with nominal reference of static gait”, In *Proc. IEEE/RSJ Int. Conf. Intelligent Systems and Robots,* pp. 406-412, Victoria, BC, Canada, Oct. 1998.

[36] H. Takanobu, A. Takanishi, I. Kato, “Development of a Biped Walking Robot Adapting to a Horizontally Uneven Surface”, In *IROS*, pp.1156-1163, 1994.

[37] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, “The development of Honda humanoid robot”, In *Proc. IEEE Int. Conf. Robotics and Automation,* pp. 1321-1326, 1998.

[38] J. Hodgins and M. Raibert, “Adjusting step length for rough terrain locomotion”, *IEEE Trans. Robotics and Automation,* 7(3): 289-298, June 1991.

[39] S. M. Manton, *The Arthropoda: Habits, Functional Morphology and Evolution*, Clarendon Press, Oxford, 1977.

[40] Insectia Television show website - www.insectia.com.

[41] University of Georgia – Dept. of Entomology – Advice on Pest Management - http://www.ent.uga.edu/ipm/homeowner_ipm.htm

[42] M. Buehler, U. Saranli, D. Papadopoulos and D. E. Koditschek, "Dynamic Locomotion with four and six-legged robots", *Int. Symp. Adaptive Motion of Animals and Machines*, Montreal, Canada, Aug 2000.

[43] U. Saranli, M. Buehler, and D. E. Koditschek, "Design, Modeling and Preliminary Control of a Compliant Hexapod Robot," in *IEEE Int. Conf. on Robotics and Automation,* 2000.

[44] D. McMordie and M. Buehler, "Towards Pronking with a Hexapod Robot", *4th Int. Conf. on Climbing and Walking Robots*, 2001.

[45] AMTI http://www.amtiweb.com/industrial/fd-1_2.htm FD-1-2000.

[46] Midori Corp. - http://www.midoriamerica.com/ LP-75-FP Green Pot and green rotational 5K potentiometer.

[47] L. L. Howell, *Compliant Mechanisms,* John Wiley and Sons, New York, 2001.

[48] Idea gleaned from conversation with Jonathon W. Hurst, Ph.D. student at CMU.

[49] M. Garcia, A. Chatterjee, and A. Ruina, "Speed, Effciency, and Stability of Small-Slope 2-D Passive Dynamic Bipedal Walking", in *Proceedings of the 1998 International Conference on Robotics and Automation*, 1998.

[50] S.H. Collins, M. Wisse, A. Ruina, "A 3-D passive-dynamic walking robot with two legs and knees", *IJRR*, April 2001.

[51] Fizoptika Corporation - http://www.fizoptika.ru/products/catalog/vg941-3d.html

[52] E.Z. Moore and M. Buehler, "Stable Stair Climbing in a Simple Hexapod", *4th Int. Conf. on Climbing and Walking Robots*, 2001.

[53] R.J. Full and D.E. Koditschek, "Templates and anchors: Neuromechanical hypotheses of legged locomotion on land", *J Exp Bio*, 202, pp. 3325-3332, 1999.

[54] The Mathworks – Matlab 6.0

[55] SWRI – Small robotic vehicle testbed

[56] H. Kimura, K. Sakurama, and S. Akiyama, "Dynamic Walking and Running of the Quadruped Using Neural Oscillator", In *Proc. of IEEE&RSJ IROS98*, pp.50-57, 1998.

[57] J. Pratt and G. Pratt, "Intuitive Control of a Planar Bipedal Walking Robot", In *Proceedings of the IEEE International Conference on Robotics and Automation,* 1998.

[58] J. G Cham, S. A. Bailey, and M. R. Cutkosky, "Robust Dynamic Locomotion Through Feedforward-Preflex Interaction", In *ASME IMECE Proceedings*, 2000.

[59] H.B Brown and G.Z. Zeglin, "The Bow Leg Hopping Robot", *IEEE International Conference on Robotics and Automation*, 1998.

Appendix A Spring Material Selection

The discussion in the thesis did not completely eliminate any material from consideration. There is a seemingly endless supply of materials that would have to be considered, if we did not use our engineering judgment. Based on our familiarity with various plastics, metals, and composites, we elected to use a composite material for the spring. This was done for reasons outlined in chapter 3, including weight, stiffness, and resistance to creep. Exact material properties for composites cannot be found in a textbook, but must be found through experimentation. Lacking time to evaluate many different materials, we could use a simple series of calculations to narrow the selection. We examine a simple cantilever beam with a force at one end, with is a fair approximation of the leaf springs used in our legs. It is of length L, height h and width b, and the beam is diagramed in Figure A- 1. .

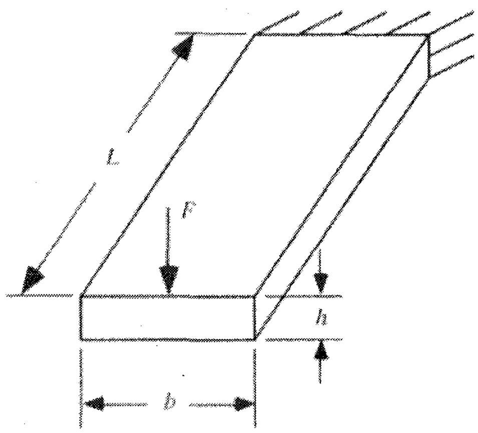


Figure A- 1 - A simple cantilever beam with a force at one end.[47]

We start by finding the spring constant of the cantilever beam as a function of material and geometry. Basic solid mechanics tells us that the deflection at the end of the beam, δ, is

$$\delta = \frac{FL^3}{3EI} \tag{A.1}$$

Where E is the Young's modulus, and I is the cross sectional inertia of the beam. The inertia can be written in terms of beam geometry as:

$$I = \frac{bh^3}{12} \tag{A.2}$$

Thus the deflection can be rewritten as:

$$\delta = \frac{4FL^3}{Ebh^3} \tag{A.3}$$

Spring constant, k, is defined as deflection of the end of the beam per unit force applied to the beam. Thus we solve for the spring constant as a function of geometry and material properties by rearranging the last equation to get deflection per force:

$$\frac{\delta}{F} = \frac{4L^3}{Ebh^3} = k \tag{A.4}$$

We see that the spring constant will be a cube function of length and height, but only a linear function of width and Young Modulus, E. As a result, the best parameters with which to tune the spring constant of our legs will be the length of the springs. Length will be especially easy to tune, since we are able to simple grind the spring to shorten it.

We will find the maximum deflection of a rectangular cantilever beam in pure bending as a function of its geometry and mechanical properties. This will tell us which material will deflect the most before failure. This is the other quantity that must be optimized for the leg to perform well, and reliably. In pure bending, the stress, σ, is

$$\sigma_{MAX} = \frac{M_{MAX}c}{I} \tag{A.5}$$

Where the M_{MAX} is the maximum moment applied to the beam, and c is the maximum distance from the centerline of the beam. $M_{Max} = FL$ and $c = h/2$. Then maximum stress, which we will set equal to the yield stress, σ_Y, in order to find the maximum stress before failure as a function of applied force and geometry is equivalent to the yield stress, is:

$$\sigma_{MAX} = \frac{6FL}{bh^2} = \sigma_{YIELD} \tag{A.6}$$

Solve for Force, F, and substituting this into the deflection equation A.3 gives us the maximum deflection before failure:

$$\delta_{MAX} = \frac{2}{3}\frac{\sigma_{YIELD}}{E}\frac{L^2}{h} \tag{A.7}$$

We see that the maximum deflection depends on both the material and the geometry of the beam. We can use the ratio of yield stress to Young's modulus to pick the material that will permit the largest deflection before yield for a given geometry. A material with a higher value of σ_Y/E will be a superior spring, because it will deflect further before yield than a similar spring of another material. If we use length and height to tune the spring constant, we are left to maximize the possible deflection, and thus the robustness of the spring, using the material properties. The following table gives approximate values for a range of materials. We see that E type fiberglass, based on the criteria defined here, is the best material for a compliant mechanism.

Material	Youngs Modulus E [Mpsi (Gpa)]		Yield Stress σ_Y [kpsi (MPa)]		$(\sigma_Y/E) \times 1000$
Steel (1010 hot rolled)	30.0	(207)	269	(179)	0.87
Steel (4140 Q&T@ 400)	30.0	(207)	238	(1641)	7.90
Aluminum (1100 annealed)	10.4	(71.7)	5	(34)	0.48
Aluminum (7975 heat treated)	10.4	(71.7)	73	(503)	7.00
Titanium (Ti-35A annealed)	16.5	(114)	30	(207)	1.80
Titanium (Ti-13 heat treated)	16.5	(114)	170	(1170)	10.00
Beryllium copper (CA170)	18.5	(128)	170	(1170)	9.20
Polycrystalline silicon	24.5	(169)	135	(930)	5.50
Polyethylene (HDPE)	0.2	(1.4)	4	(28)	20.00
Nylon (type 66)	0.4	(2.8)	8	(55)	20.00
Polypropylene	0.2	(1.4)	5	(34)	25.00
Kevlar (82% vol) in epoxy	12.0	(86)	220	(1517)	18.00
E-Glass (73.3% vol) in epoxy	8.1	(56)	238	(1640)	29.00

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