On the Design of a Biologically Inspired Hexapod Robot

by

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Declaration

I, Noel J. Rode, hereby declare that this dissertation contains no material which has been accepted for the award of any other degree or diploma in any university. Further to the best of my knowledge and belief, this dissertation contains no material previously published or written by another person except where due reference is made in the text of the dissertation.

Noel J. Rode	Date

Abstract

The area of study in this research involves the mechanical design and control of locomotion devices for legged robots. Robots that have either one, two, four, six or eight legs have been investigated. In particular, the emphasis was on robots that have six legs.

A small six-legged walking robot that is capable of producing relatively high walking speeds has been designed and built as part of this PhD research project. The robot is named "Strider" and was designed based on biological inspirations from the fast walking cockroach.

A new mechanical system, termed the "groove-slot mechanism", that was designed to propel the legs of a walking robot was developed in this research and is presented in detail.

Strider's walking speed has exceeded that of other similar sized walking robots researched. Due to the design of the groove-slot mechanism, the normalised amount of payload that Strider could carry far exceeded that of any other walking robot researched. These results have shown that Strider has a higher work capability than any of the previous walking robots researched.

The theory behind periodic walking patterns of insects and animals has been investigated. A new method of changing between walking patterns and hence changing the walking speed along a straight line for a walking robot is also presented.

Preface

This research had been carried out between 1993 and 1998 in the Department of Digital Systems (formerly Robotics and Digital Technology), Monash University, Clayton campus.

The work had been supervised by Dr. Andrew P. Papliński and co-supervised by Dr. Simon D. Hill for part of the research duration.

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- Noel J. Rode, Andrew P. Papliński, "Dynamic Gait Changing for Hexapod Walking Robots," in *Robotics and Manufacturing: Proceedings of the Fifth IASTED International Conference*, pp. 37-40, IASTED/ACTA Press, 1997. Held in Canún, Mexico, May 29-31.

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Special thanks to my friends and colleagues who gave me advice and help throughout, especially to Gary Evans who helped me create parts of my robot and Brendan Simon who advised me about the design and programming of the microprocessor board for the robot.

I wish to give a special thank you to my parents and the members of my family who supported me throughout my candidature. Their invaluable support and encouragement helped me to achieve the completion of this work.

Dedication

I specially dedicate this thesis to my father Carlyle and my mother Noeline. They began my schooling 22 years ago and now the writing of this thesis brings to a completion both my PhD work and a major part of what they set out to provide for me in my lifetime.

Forever grateful,

Noel.

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Chapter 1

Introduction

1.1 The Evolution of Legged Robots

Since the early 1800's people have researched the walking behaviour of animals for the purpose of creating mechanical walking machines [1]. Some animals use two legs, others use four. The coordination of their legs allow them to walk, climb, amble, trot, pace, canter, gallop and hop, depending on their leg structure [2]. Many different six-legged insects have also been researched in the past. In particular, the *Periplaneta Americana* (or the American cockroach), is one of the fastest invertebrates ever studied [3]. Other creatures such as eight-legged arachnids and crustaceans were also studied a great deal.

Interestingly, unconventional walking machines were designed in the past, such as the "Mechanical Horse" patented in 1893 [1], however these early designs were purely mechanical and did not make use of electricity and electronics. The Mechanical Horse and other similar mechanisms were difficult to control and did not provide the agility for smooth safe walking.

Probably the first mechanical walker is Jacques de Vaucanson's mechanical duck built in 1738 [4]. It seemed to be driven by fluid poured down its throat, turning turbines and making the legs move and the wings flap.

With the advent of steam power, inventors had a means of producing continuous mechanical oscillations that could be used to propel mechanical legs [5]. One such design was George Moore's "walking locomotive", built in the USA in 1893 [4]. It was a steam driven bipedal (two-legged) suit of armour that was allegedly capable of walking at about $12km/h$.

In 1968, a mechanical four-legged walking machine was developed [6] known as the General Electric Walking Truck. It was actuated by hydraulics and controlled entirely by a human operator. The Walking Truck was found to be too demanding for a human being to control and therefore new methods of control were required.

The introduction of electronics, computers and control systems either written in software or developed directly in hardware provided the necessary means with which to develop, control and experiment with the mechanical machines that the researchers designed. The quadruped (four-legged) robot known as the "Phony Pony" [7] was one of the first reprogrammable robotic platforms to be developed. The controlling computer for this robot was external to the mechanical platform.

In more recent years, microprocessors allowed entire robot control systems to reside directly on the robot. The additional use of light-weight power sources and tiny actuators made it possible to develop fully autonomous mobile robots.

In the last fifteen years or so, both small and large robots have been designed either for specific purposes or simply for research. The designers determine the size of the robots depending on such things as the type of terrain it is to walk on and its primary function. For some applications a large robot may be more suitable than a small robot. For example, one large robot used for land excavation purposes will perform better than many small robots.

Current research still deals with various mechanical designs that look and perform very differently to anything found in nature. The level of agility found in a cat that jumps, climbs and pounces, for instance, will not be found in any legged robot for a long time.

This is mainly due to the actuation devices that are typically used in such machines.

1.2 The Hexapod: Strider

A small walking hexapod (six-legged) robot that is capable of producing relatively high walking speeds has been designed for this research. The robot is named "Strider" and was designed and built based on inspirations from the fast walking cockroach.

The robot's body is about $30cm$ in length and it weighs just over $2kg$. It is constructed mostly of PVC, uses DC motors and has an on-board computer. The highest walking speed measured was $17cm/s$ using the fastest walking pattern, the *tripod*. The robot is shown in Figure 1.1.

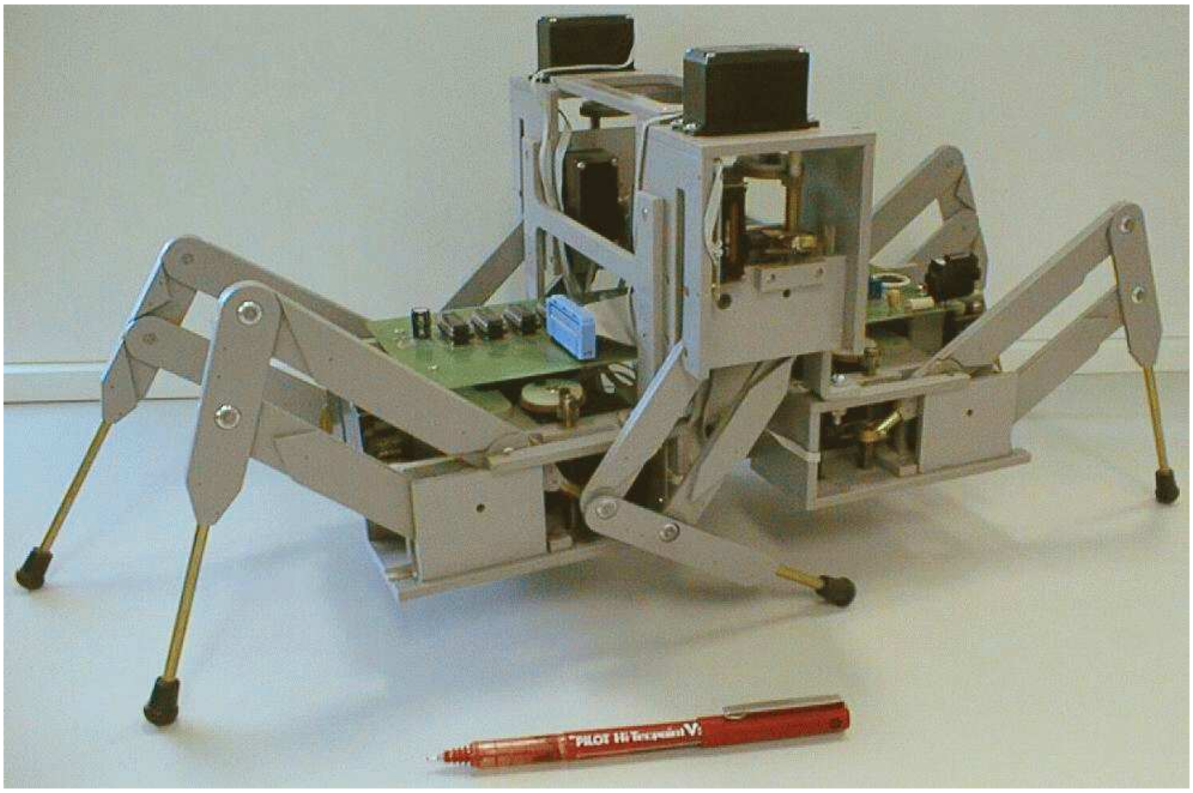


Figure 1.1: The hexapedal walking robot: "Strider".

The name *Strider* was obtained from the large, long-legged running creatures called *Land Striders* from the movie *The Dark Crystal*.

1.3 The Purpose of this Research

The work presented here describes a design for a small walking robot (shown in Figure 1.1) that is capable of producing high walking speeds and is able to carry larger payloads than many previous designs. A desired walking speed of about $20cm/s$ to $30cm/s$ has been found to be possible for a robot of about $30cm$ to $60cm$ in length.

Strider has two degrees of freedom (DOFs) per leg although it has been designed to walk on level ground using only one degree of freedom (DOF) per leg. Kaneko et al. [8] claim that using fewer DOFs for a hexapod walker will allow the robot to walk faster and be more energy efficient, as well as be less expensive in comparison to machines that require more coordination to control higher DOFs. They also developed a walking robot that uses only one DOF per leg to walk on flat ground.

Strider is designed to walk on what can be termed *perfect terrain* [9] where no obstacles are present in the robots path. However, small non-linearities in the terrain generally will not impede the walking of the robot. The robot is capable of climbing over small obstacles or through small ditches although it was not significantly dealt with in this work.

A summary of the contributions of this research is given below.

1.3.1 Faster Locomotion using Biological Inspirations

For any walking machine, rough terrain locomotion is fundamental [10]. Since the best rough terrain walkers are found in nature we searched for inspirations from biology to develop our walking machine.

The robot that was used in this research was designed and built based on inspirations from the leg structure of a fast walking cockroach such as the *Blaberus Discoidalis* or the *Periplaneta Americana*. The main inspiration taken from the cockroach was the approximate leg angles. It was found [11] that the leg angles used by the cockroach cause the legs to push against each other which in turn causes the overall muscle force production to be reduced. Also, walking becomes more coherent. Another inspiration obtained from biology was that of using six legs since the cockroach remains stable at all times while walking. The dynamic stability of quadrupeds, for instance, requires frequent body regulation which can slow the walking [12].

A simple drive mechanism (known as the *groove-slot mechanism*) was designed to propel each of Strider's six legs.

The groove-slot mechanism was designed specially for Strider. It enables the robot to walk on flat terrain by controlling only one DOF per leg. It also provides a large stride length for the robot's feet. High speed walking and a high payload capacity is the result of making use of the groove-slot mechanism.

The two features mentioned above, that of the cockroach leg angles used in the mechanical design and using the groove-slot mechanism, are what contribute to a faster walking machine.

1.3.2 Developing a Robot Control System

Several different robot control systems have been investigated and described in this work. In this thesis, the term "control system" refers to the *software* robot control system. It is the logic programming used to drive actuators, read sensors and perform higher levels of intelligence. Some of the control systems make use of rhythmic oscillators and central pattern generators. Other systems use subsumption architecture (developed at Massachusetts Institute of Technology (MIT), Cambridge) while others make use of neural networks or genetic algorithms. Out of these, the subsumption architecture was chosen to control our hexapod.

Previous robots exist that were controlled using the subsumption architecture, but due to the unique design of our hexapod using only one DOF per leg to walk, existing algorithms could not be directly used. A control system to make the robot walk using a variety of walking patterns was developed and is described in detail.

1.3.3 Dynamic Changing of Gait Patterns

The sequence of stepping patterns made by insects while walking is known as a *gait*. Strider is capable of walking using any periodic walking pattern (or gait) that has been observed in many insects including the cockroach. There are patterns that allow the insects to walk slowly or fast depending on the sequence of stepping.

In order for an insect to change from one walking speed to another it should be able to change its gait pattern. Some control systems have been developed for robots to change between gaits in a way similar to insects, but they require mechanical legs that have at least two DOFs per leg. A robot such as Strider that uses a fixed foot trajectory that is driven by only one DOF per leg to walk, must use a special approach to change between walking patterns, and hence change its walking speed.

A new method was developed to change between gait patterns for robots that use only one DOF per leg to walk. The method can also be used for robots that use two or more DOFs per leg. The control system used for Strider was further developed in this work to allow the robot to dynamically change between periodic gaits.

1.4 Related Research Findings - Literature Review

In the course of this research a large number of research papers, several theses and books have been investigated in the areas of walking robots, control systems for walking robots and entomology. Of the many research documents found, the discussion topics of several of them are closely related to the work presented in the following chapters. This section gives a brief literature review of these documents.

1.4.1 Walking Robots

"Walking Machines. An Introduction to Legged Robots" by D. J. Todd [13] is a book that gives a very good overview of many different walking robots developed from early years up to the mid 1980's. It gives descriptions of the robots as well as much of the theory involved in walking robots including mechanical design, actuation, sensing and programming.

"Leg Design for a Small Walking Robot" by M. B. Binnard [14] is a Masters thesis which discusses various mechanical structures that can be used for a walking robot. The author experimented with some previous leg designs and described the results of his own designs. His work led to the development of the robot Boadicea described in Section 2.5.9.

"Machines that Walk: The Adaptive Suspension Vehicle" by S. M. Song and K. J. Waldron [9] is a book that gives an in-depth overview of the mechanics, hardware and control system of the large six legged robot – The Adaptive Suspension Vehicle.

"A Six-Legged Telerobot for Nuclear Applications Development" by J. S. Byrd and K. R. DeVries [15] is a journal paper covering two of the large six legged robots developed by Odetics Inc. These robots are unique in their design and were very inspiring.

"A Cartesian Coordinates Manipulator with Articulated Structure" by S. Hirose and Y. Umetani [16] describes the use of the *pantograph mechanism* as a robot leg. The advantages of the energy efficiency of this mechanism is explained in the document.

"A Hexapod Walking Machine with Decoupled Freedoms" by M. Kaneko and M. Abe and K. Tanie [8] describes a robot whose legs follow a fixed semicircular trajectory similar to that designed for Strider.

"Analysis of the Dynamics of a Six-Legged Vehicle" by Q. Xiding and G. Yimin and Z. Jide [17] is a paper that also describes a robot whose legs follow a fixed semicircular trajectory. The legs of the proposed robot used the same mechanism as that used in the previous paper described above.

1.4.2 Control Systems for Walking Robots

"The Control of Walking" by K. Pearson [18] describes a biologically inspired locomotion control system based on that used by the cockroach. The paper also describes locomotion experiments with animals and insects.

"A Robust Layered Control System for a Mobile Robot" by R. A. Brooks [19] is a journal paper that introduces the theory of the subsumption architecture for use in a robot control system. It describes an early version of subsumption architecture to control and navigate a wheeled robot.

"A Robot that Walks; Emergent Behaviors from a Carefully Evolved Network" by R. A. Brooks [20] describes the newer, slightly modified version of subsumption architecture to control the walking and behaviours of a small six-legged walking robot named Genghis.

"An Artificial Insect" by R. D. Beer and H. J. Chiel and L. S. Sterling [21] is an article that describes a neural network based hexapod locomotion control system derived from Pearson's controller. A simple six-legged robot was used to test the controller.

1.4.3 Entomology

"The Co-ordination of Insect Movements. I. The Walking Movements of Insects" by G. M. Hughes [22] is an early paper describing the stepping patterns used by the cockroach. Issues relating to the leg angles and ground reaction forces of the legs are also discussed.

"Insect Walking" by D. M. Wilson [23] also deals with the walking of the cockroach. The various types of notation used to describe walking patterns are described. A definition of the rules for a simple insect walking model is also given.

"The Function of the Legs in the Free Walking Stick Insect, Carausius Morosus" by H. Cruse [24] describes various aspects relating to the stick insect such as geometrical relationships, various measured torques and angles of the insect's joints and ground reaction forces of the legs.

"Leg Design in Hexapedal Runners" by R. J. Full and R. Blickhan and L. H. Ting [11] describes the actual method of measuring the ground reaction forces of the cockroach legs while walking. The forces and angles are described in detail for each of the three pairs of legs. Much of the biological inspiration for Strider was obtained from this paper.

"Dynamics of the Walking Stick Insect" by F. Pfeiffer and H. J. Weidemann and P. Danowski [25] describes the physical biological structure of the stick insect and also describes a mechanical model for it. Various measured torques and angles of the insect's joints are also given.

"Leg Design Based on Biological Principles" by H. J. Weidemann and J. Eltze and F. Pfeiffer [26] continues the last paper mentioned by adapting the biologically derived mechanical model of a stick insect to develop a robotic leg mechanism. A simple control system is also described for use in the final robot.

1.4.4 Miscellaneous

"Mobile Robots: Inspiration to Implementation" by J. L. Jones and A. M. Flynn [27] was a very good source of information for designing small robots. It provided information on different types of sensors, actuation devices and various other hardware and software issues.

"Muscle Wires Project Book" by R. G. Gilbertson [28] was very useful to learn about Muscle Wire actuation. It covers a reasonable amount of theory and has many examples.

"VOGLE: A Very Ordinary Graphics Learning Environment" [29] is not a research paper but is rather a library of computer graphics routines. The documentation contained within the package was used extensively.

1.5 Thesis Outline

1.5.1 Chapter 2

This chapter covers the main issues related to legged locomotion. It introduces legged locomotion by explaining why it is studied and why nature has been used as a basis for many previous designs. The common types of mechanical structures and mechanisms used for legged robots are described and an explanation of the common actuation devices is also given.

Since many different walking robots were investigated for this research, several of them have been described. Most of the other robots are also described but in very little detail.

The chapter concludes with an explanation of why computer graphics has been used to simulate previous legged robot designs.

1.5.2 Chapter 3

In this chapter a complete description of Strider is presented. A detailed account of how the robot was designed and the reasons for choosing the appropriate materials, motors, sensors and other electronics is given.

The gradual development of the mechanical structure of the robot is shown, including the design of the legs. The on-board computer and other electronics is described and shown in detail.

An explanation of the physical inspirations that were obtained from the biological organisms is given. As mentioned above, the inspirations were taken from insects.

A detailed description of the drive mechanism (the groove-slot mechanism) that was specially designed for Strider is then presented. The mechanical description of the mechanism is described as well as reasons for its design. Various calculations are also given relating to this mechanism. The main advantage of this mechanism is that it allows the robot to stand without expending energy.

A comparison between the design of the robot and that of insects is then presented. Following this, a description of the robot's ability to climb obstacles is given and also its capabilities and overall performance.

1.5.3 Chapter 4

The various methods used by researchers over the last few decades to control six legged robots are described in this chapter.

The chapter begins by describing the previous research done in the study of locomotion of cockroaches, other insects and animals. The most popular hexapod control systems are then described in order to attain a reasonable understanding of how they work.

Of the methods described, one had to be chosen to control the legs of Strider. As described in the chapter, the control methods described could be used for Strider. Rather than implementing all or several of them, only one was chosen. The reasons for this will be explained.

A detailed description of the control system used for Strider is then presented. The method used to program the control system is described. The servo-controlling of the motors is described up to the stage of coordinating the legs to make the robot walk using any periodic gait, or walking pattern.

The last part of the chapter describes how the robot is capable of walking over small obstacles in its path. This however, was not a goal of our project.

1.5.4 Chapter 5

This chapter describes the theory that researchers have formulated regarding the walking patterns used by insects.

A description of the periodic gaits that cockroaches have been found to use is given and some of the mathematics that describe the patterns is also included. Apart from periodic gaits, non-periodic gaits are also briefly described, although Strider is incapable of using such gaits.

The following section of this chapter describes a method that Strider was able to use to make the robot change from one periodic walking pattern to another using the existing subsumption architecture-based robot control system described in Chapter 4.

Several examples are then given that show how the method developed allows Strider to increase or decrease its walking speed.

1.5.5 Chapter 6

This is the concluding chapter which provides a review of the results obtained from the design and implementation of the walking robot that was developed during the course of this research.

Following the conclusions, a discussion is given about the future of walking robots. Various aspects are considered such as the mechanical designs, construction materials and electronics. Methods of improving the control systems are also considered. Finally, a short discussion of the future possible applications of walking robots is given.

Chapter 2

Mechanical Legged Locomotion

2.1 Introduction to Legged Locomotion

For more than two hundred years it has been a great desire of mechanical engineers to develop a practical mobile machine that is fitted with legs similar to that of animals. The desire to transport cargo vehicles over terrain that could previously only be traversed on foot is a dream that researchers have yet to see realised.

The need for legged machines can be expressed by comparing them to the use of wheeled vehicles. According to a 1967 US Army report [30], the approximate percentage of area in certain countries that was unsuitable for wheeled vehicles is shown in Table 2.1.

As we can see, about half of the earth's surface is inaccessible to wheeled vehicles which shows the obvious need for rough terrain walking machines. Researchers have therefore studied and tried to imitate walking creatures found in nature.

Europe	50%
USSR	55%
Africa	25%
Asia	45%
North America	55%
South America	60%

Table 2.1: The percentage of land unsuitable for wheeled vehicles.

Most land animals have legs with which to transport their bodies over level or rugged terrain. There are several types of animal leg configurations including the human biped or the kangaroo “springy” biped. The quadruped structure of the dog or the horse are other examples of such configurations as well as the sprawled hexapod of the cockroach or the “stilt” hexapod structure of the stick insect. There is also the eight legged spider and other arachnids. Other insects such as centipedes and millipedes make use of several hundred legs.

There are several reasons that Raibert [1] had previously mentioned as to why we study legged robots. Firstly, we require legged vehicles to traverse where wheeled or tracked vehicles cannot. Studying legged robots will help us to further understand legged locomotion of animals and insects. The rhythmic movements and the rapid, ballistic and gymnastic maneuverability that legs can be capable of would provide robots with rich dynamical behaviours. Also, the active suspension that legs provide allow payloads to travel smoothly over uneven terrain [31].

Obviously, mechanical legs would provide greater mobility over rough terrain but they can also be useful to obtain information about the terrain itself that they are walking on or climbing over [32]. By adding even simple sensors on the legs of robots, they can detect obstacles, the height of obstacles, the texture and colour of the terrain, and so on.

A hexapod robot that has three DOF legs requires a total of eighteen DOFs to be controlled. Before digital computing was available, controlling such a large number of DOFs was difficult and therefore legged locomotion for robots was rarely used. As a result, wheeled vehicles were created since they generally require the control of only one DOF per wheel [30].

Graham [33] had expressed the basic mechanical requirements that legs should exhibit. They must support and stabilise the body so that it does not collapse. The legs must produce leverage in order to propel the body in the required direction. They must also lift off the ground and be returned to a particular position to propel the body again.

A robot fitted with suitable mechanical legs would ideally be able to manoeuvre itself smoothly over uneven terrain. It should be able to climb inclines and walk on smooth, rough, sandy or possibly slippery surfaces. Legged robots should be able to traverse terrain where it would be unsuitable to use wheels. Legs would therefore allow the robots to be far more universal than if wheels are used.

Researchers at MIT have determined a set of requirements that an autonomous (self-governing) walking robot should have in order for it to be more agile [32]. The robot should be able to locomote over rough terrain with respect to the size of the robot. It must climb up and down, and it must be able to recover from falls. It should be able to sense its immediate surroundings as well as further ahead for exploration and obstacle avoidance. It must be intelligent enough to avoid any obstacles while trying to reach a distant goal and should also monitor itself in order to maintain itself. It must be able to recover from various physical situations such as getting a leg stuck or wedged. It must maintain its own power supply, try to keep itself clean and be able to protect itself from high radiation.

Brooks [34], Angle [32] and McGhee [35] discuss the idea of sending many small autonomous robots to planets in our solar system for planetary exploration. The surface of the planets are usually sandy, rocky and contain craters. It has been argued that many small sized legged robots would be better suited for this application than using one large robot [36]. There are also many applications for use on our own planet. Small legged robots carrying video cameras can transmit images from locations that are dangerous for humans to be in. They could be used to inspect pipes or may be fitted with appropriate actuators to clean clogged pipes.

Smaller robots would have the advantage of having a better strength-to-weight ratio and hence will have reduced dynamic effects and lower power requirements [36] [10]. Also, depending on the terrain, a smaller robot with smaller feet would be able to find better footholds than robots with larger feet.

Larger versions of these robots could carry people and cargo over rugged terrain where wheeled vehicles cannot be taken. They would be better suited for agricultural and excavation purposes, as well as arctic transport, forestry inspection [37], fire-fighting and explosive disposal [35].

Many legged robot designs have been developed over the last few decades but there have been few legged vehicles that can be considered to be practical [38] in the sense of being more versatile as compared to biological organisms. The many species found in nature will continue to be the envy of many researchers until we can develop artificial creatures that can outperform them to a reasonable degree, both mechanically and intelligently.

2.2 The Pantograph Mechanism

In nature, muscles and skeletons are used to facilitate movement for creatures. Muscles appear to be best suited for the type of skeletons that exist although they are not ideal actuators from the standpoint of energy flow [39]. In order to use linear actuators efficiently mankind has developed several mechanical manipulators that have improved on energy consumption. One of these manipulators is known as the pantograph mechanism.

The structure and function of the pantograph mechanism is shown in Figure 2.1 (diagram adapted from [16]). The pantograph is constructed of four bars connected together as shown in the diagram with four pivot points. If the mechanism was to be used as the leg of a robot, actuators would be fitted to points Q and R. The end of the long bar labelled P would represent the foot of the leg.

With reference to Figure 2.1, the maximum magnification factor M, of the pantograph is given by Equation 2.1 [17].

$$M = \frac{\overline{RT}}{\overline{RS}} \tag{2.1}$$

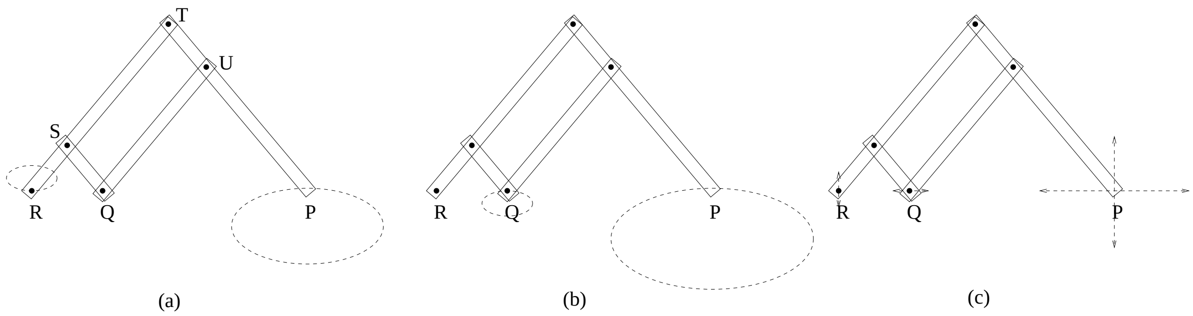


Figure 2.1: The function of the pantograph mechanism with magnification M. (a) Pivoting at Q, the trajectory at R will be inverted and scaled by M–1 at P. (b) Pivoting at R, the trajectory at Q will be scaled by M at P. (c) P is magnified by linear movements of Q and R.

In this particular diagram, the magnification factor has a value of 4. However, for any magnification factor, the length of the SQ bar is equal to the length of the RS bar, and the TU bar. The length of the QU bar is equal to the length of the ST bar, hence making a parallelogram. Also, the length of the RT bar is equal to the length of the PT bar.

In Figure 2.1(a) we see that by pivoting point Q and tracing a path ($\underline{x}(t)$) at point R, the path is magnified at point P by a factor of M–1 and is also inverted, thus producing a path given by $-(M-1)\cdot\underline{x}(t)$. Figure 2.1(b) shows the pantograph being pivoted at point R. The path ($\underline{x}(t)$) traced at point Q is now magnified at point P by a factor of M and is not inverted, thus producing a path given by $M \cdot \underline{x}(t)$. By adding vertical and horizontal linear movement at point R and Q as in Figure 2.1(c), point P will produce a large amount of equivalent movement in one plane.

It is also interesting to note that the ratio of the horizontal distances between points R and Q and points Q and P is constant and is equal to M–1, as shown in Equation 2.2.

$$\frac{\overline{RQ}}{\overline{QP}} = M - 1 \tag{2.2}$$

The most important feature of the pantograph mechanism is that it eliminates most of the excessive power consumption during use [16]. This can be explained using Figures 2.2 and 2.3 (diagram adapted from [16]), and is described as follows.

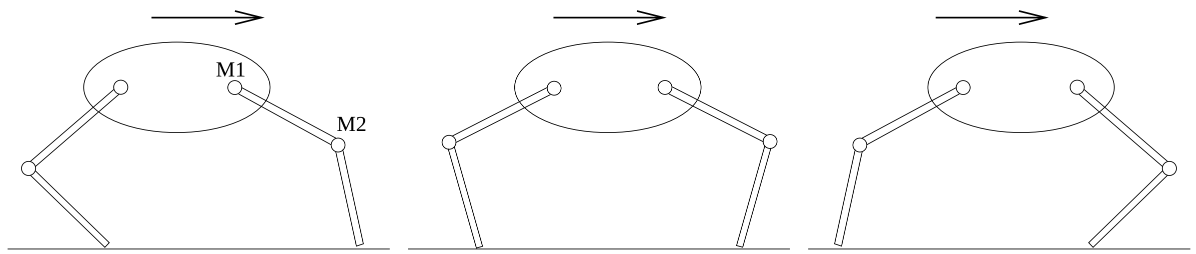


Figure 2.2: Moving a robot's body towards the right while it is standing on the ground.

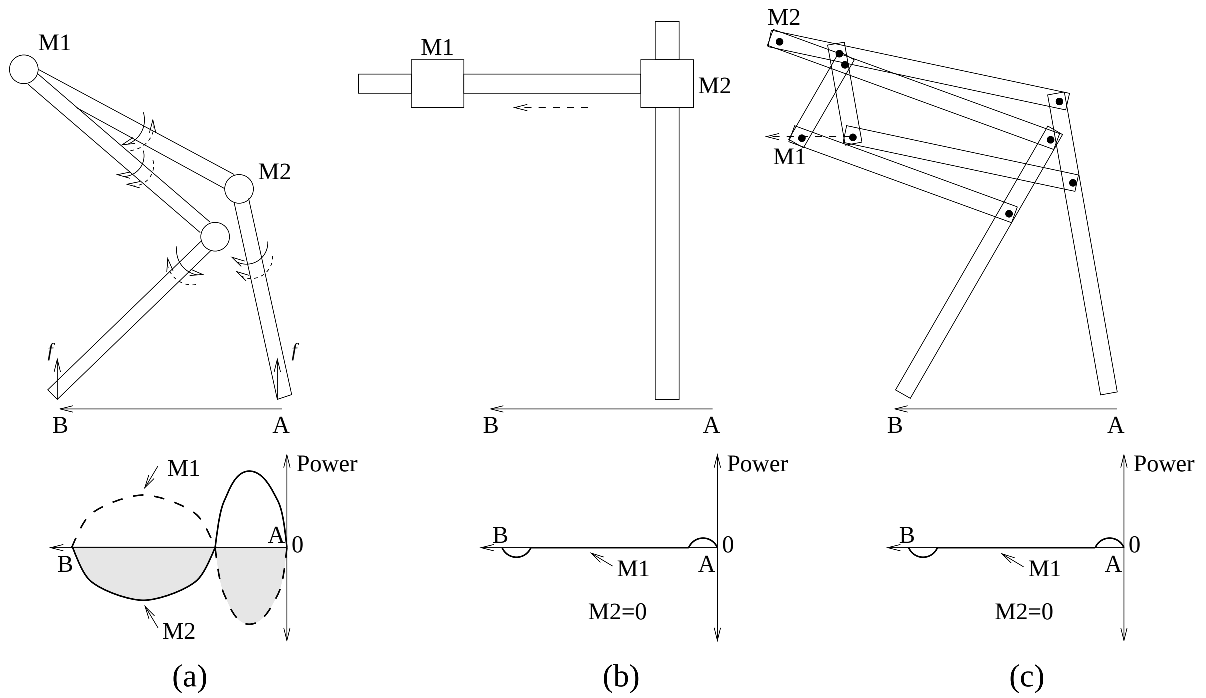


Figure 2.3: The power consumption of three types of leg configurations.

Figure 2.2 shows a robot body with two legs configured in a typical arthropod leg structure. An arthropod is a creature that has segmented legs such as a cockroach, spider or crustacean. The legs have two motors each, one for the hip joint (M1) and one for the knee joint (M2). The body is shown moving towards the right (or the legs moving towards the left) and gradually changing the angular position of the two motors.

Now, Figure 2.3(a) shows only the right-hand leg of Figure 2.2 performing the same leg motion, moving the leg (while it is on the ground) from position A to position B. The power that the motors use during this motion is shown below the picture of the leg. The dotted-line arcs drawn on the upper and lower bars of the leg represent the direction of the angular torque of the bar experienced by the ground reaction force, f. The solid line arcs represent the direction of the angular torque of the associated motors, M1 and M2.

Note that although in Figure 2.3(a) motor M1 is vertically above motor M2, if the body was lowered such that motor M1 was below motor M2, the direction of the resulting torques would be the same [16] [39].

When the leg is at position A, the upper bar experiences a counter-clockwise torque due to the ground reaction force f, and motor M1 at the hip joint must provide a clockwise torque to keep the robot standing. The lower bar experiences a clockwise torque and motor M2 must provide a clockwise torque since the robot body is moving to the right. The opposing torques on the upper bar shows that motor M1 is producing negative power. The non-opposing torques on the lower bar show that motor M2 is producing positive power. Hence, torques are required on both motors in order to maintain control of the leg.

As the leg changes to position B, the power used by the motors are reversed. The upper bar experiences a clockwise torque and motor M1 also experiences a clockwise torque producing positive power. The lower bar experiences a clockwise torque and motor M2 experiences a counter-clockwise torque producing negative power. Hence, the energy is consumed by the leg mechanism in both the positive and negative work mode [39], that is, power is being produced by both motors during use, which is very inefficient.

Weidemann et al. [40] have recently built a hexapod robot whose geometry is very similar to that of the *Carausius Morosus* (the stick insect). The legs each have three segments and are arranged in an arthropod stance, very similar to the actual insect.

Their purpose was to experiment with the insect's structure regardless of the energy inefficiencies described above.

Figure 2.3(b) shows another type of leg structure where motors M1 and M2 are linear and are gravitationally decoupled. Being gravitationally decoupled allows the leg to work irrespective of gravitational forces. The motors can work independently of each other, where motor M1 alone is used to propel the body of the robot to the right (as before) and M2 alone is used to provide lift. In this case, as the leg moves from position A to position B, motor M2 is fixed and only kinematic power is produced to accelerate and decelerate the body using motor M1.

Figure 2.3(c) shows a pantograph mechanism changing from position A to position B. The motors are again linear and gravitationally decoupled and therefore the same power consumption for this type of manipulator is experienced as in Figure 2.3(b). Due to the design of the pantograph mechanism, any rotations at the hip and knee are mechanically restricted. When one joint is driven and then has to brake, the excess moment (or energy) around the joint is mechanically transferred to the other joint by the linkage bars. Hence, the actuators would be absorbing the energy [38]. The advantage of using the pantograph mechanism to that of Figure 2.3(b) is that it allows the linear movement of the motors to be magnified. Also, the leg can be made light-weight since the actuators would be positioned at the hip-end (or base) of the mechanism rather than at both the hip and knee.

Hirose et al. [39] used the pantograph mechanism as a leg for a robot to provide movement in the horizontal x-axis and the vertical z-axis. They added an extra DOF to move the whole mechanism linearly in the horizontal y-axis. This allowed them to position the legs of the robot using Cartesian coordinates. They called this mechanism the PANTOMEC and is shown in Figure 2.4 (diagram adapted from [16]). The actuators at the base of the legs will be gravitationally decoupled as long as the robot's body is kept horizontal [39]. This would be necessary when transporting people or cargo but it would actually depend on the application as to whether posture control is required.

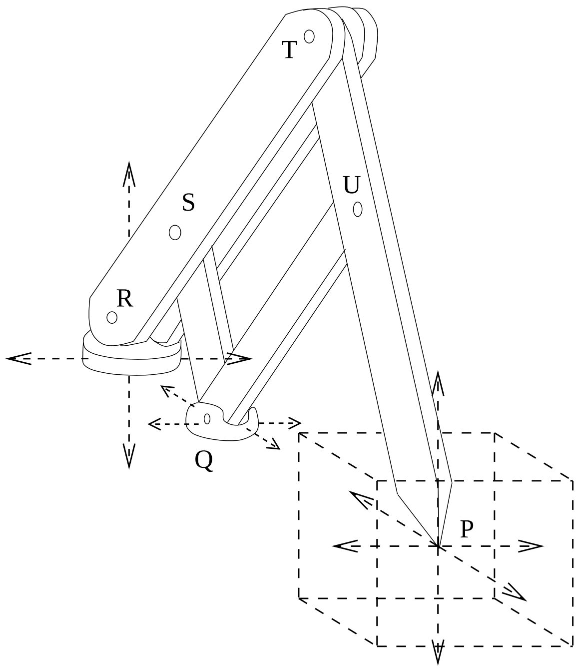


Figure 2.4: Hirose and Umetani's Cartesian pantograph mechanism, the PANTOMEC.

Some robots that use the pantograph mechanism for their legs include the Adaptive Suspension Vehicle [9], MECHANT I [37] and Boadicea [41], all of which are described below. Also, the Dante robot [42] used two groups of four pantographic legs.

2.3 Types of Leg Configurations

The overall design of the leg structure (or configuration) for a walking robot will have a strong bearing on its performance since it will determine the types of movements that it will be able to perform. It may have jointed legs such as those used by insects (like the stick insect), or it may be a non-biological design using telescopic legs. In any case, it is very important for the mechanism used to move the legs to be efficient [17].

One method of increasing the energy efficiency of a walking machine is to use springs. Alexander [43] proposed the use of springs in walking machines. Springs can save energy and reduce unwanted heat production by bouncing along to provide motion. They can also save energy by absorbing motion when halting legs and later returning the energy. Also, springs used in the feet help to reduce unwanted bouncing when the feet are rapidly placed down.

Another method used to make walking machines more efficient is to keep the weight of the legs as light as possible so that they will have low inertial effects. As mentioned previously, some robots, such as the Phony Pony [7] had the leg actuators within the structure of the legs, making them unnecessarily heavy. The weight of the legs can be reduced by locating the actuators at the base of the leg and then couple them to the joints by some kind of mechanical linkage, such as chains, cables, pulleys, push-pull rods, cams or levers [4].

A designer could obtain inspirations from biology in order to design the leg structure of a walking robot. For example, the leg structure of the cockroach can be used, although the designer would have to overcome any mechanical problems that may exist. One such problem is that the cockroach has its legs organised in a sprawled stance (described below) with the legs positioned laterally away from the side of the body. As the insect walks, the legs push on the ground in various angles causing the insect's body to yaw by deviating slightly from the line of travel [22]. In a mechanical version of the cockroach, this deviation would appear to the designer to be a problem that must be overcome since it would be better for the body to move more linearly. For example, a mechanical version of the cockroache's leg structure could be designed such that the legs move in straight lines in the longitudinal direction of the body, making the body also move in a straight line. This approach was actually used for Strider.

Another interesting leg structure is that used by kangaroos and various other animals that have three joints in their legs. The advantage of having three joints is that they allow the angle of the leg to change without changing the position of the body or the foot [44]. This is shown in Figure 2.5 (diagram adapted from [44]). Therefore, as the animal stands still, it can adjust the angle of its legs (shown by the dotted arrow) to keep itself stable and not fall over.

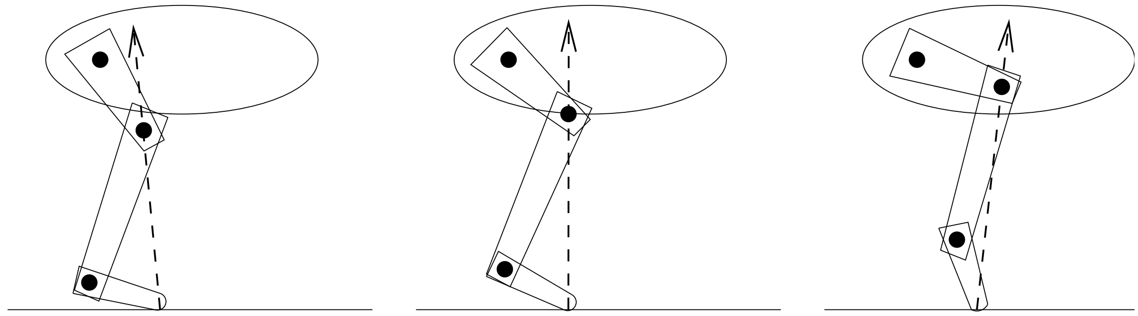


Figure 2.5: Balancing using three leg joints.
Three joints can be used to change the angle of the ground reaction force without changing the body and foot position.

The many different types of leg configurations found in nature can be simplified into three basic leg configurations [14]. These configurations (or stances) are shown in Figure 2.6 (diagram adapted from [14]). The volumes around the legs give an indication of the leg's workspace.

The *mammalian* stance shown in Figure 2.6(a) is used in most mammals, including humans. Some researchers have adopted this structure for their robots. One of these is the Adaptive Suspension Vehicle [45]. This stance has the advantage that the legs can act as pendulums when walking and hence improve the energy efficiency. Also, the knee joint can be locked allowing no energy to be expended by the joint actuators when the robot is standing upright. The arrows indicating the extension in this stance has also been termed *adduction* and *abduction* [22], where the leg swings towards and away from the body, respectively.

The *arthropod* stance in Figure 2.6(b) is typical of many insects such as spiders and the stick insect. Some examples of robots that have used this stance is Attila [32] and PV-II [39]. The main advantage of the arthropod stance is that the lift and advance DOFs are gravitationally decoupled, as described in Section 2.2 and hence can be actuated independently. This reduces the complexity of the controlling software. The mammalian stance, on the other hand, must use both actuators for the lift and advance DOF during

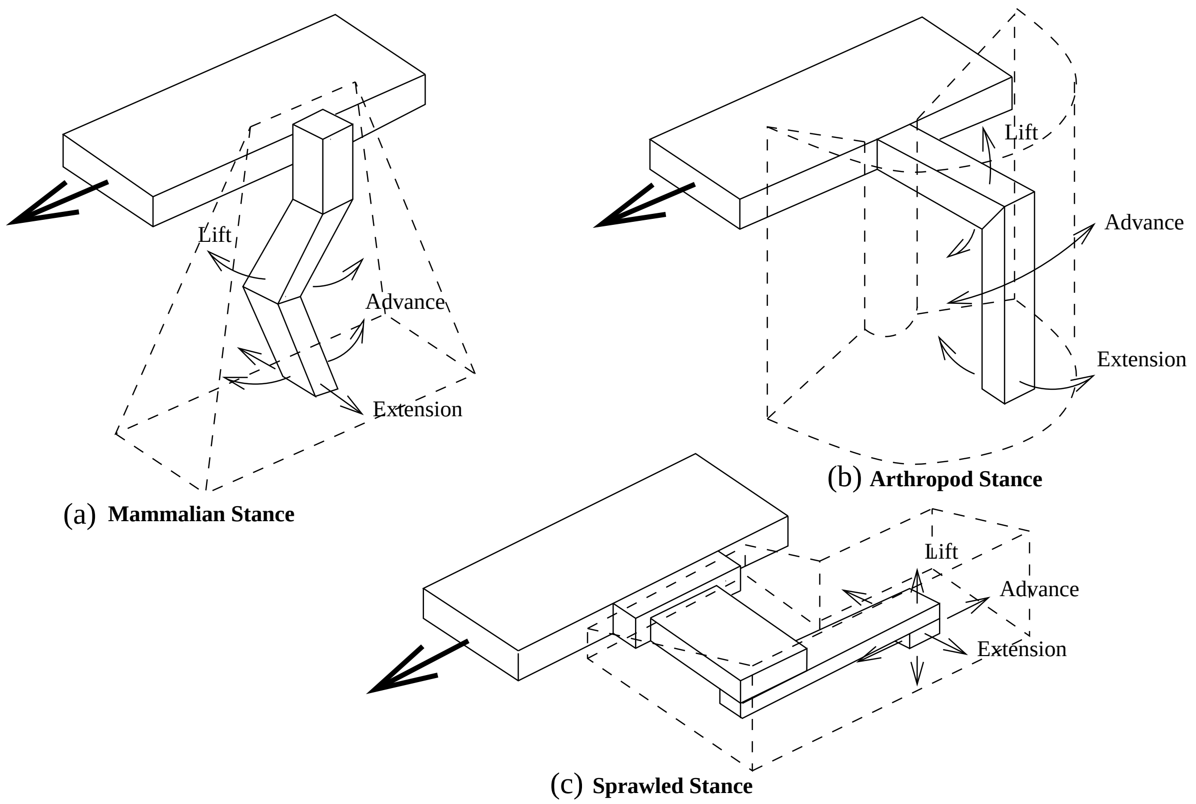


Figure 2.6: The three basic leg configurations or stances.

walking.

One of the problems with using the arthropod stance for robots is that when the leg is lifted or lowered significantly, the foot will be moved closer to the body. As a result the amount of forward/backward swing will be reduced which will also reduce the stride length. Therefore, the leg will produce less forward motion in each step cycle [36].

Also, the legs of robots that use the arthropod stance must move in an arc when they are propelling the robot forward. This produces lateral forces on the body causing the body to yaw [14]. This is the same problem that causes the cockroache's body to deviate slightly from a straight line walk using a sprawled stance, as mentioned above. According to Hirose and Umetani [38], the arthropod stance is better suited for rough terrain walking as compared to the mammalian stance because the legs are able to move a large distance away from the body.

The configuration shown in Figure 2.6(c) is known as the *sprawled stance* and is found in many insects and small reptiles. As mentioned above, the biological structure of the cockroach is a good example of an insect that uses the sprawled stance. The robots Boadicea [41] and Genghis [20] use this configuration.

Most of the leg movement using the sprawled stance is in the horizontal plane (as shown by the dotted plane in Figure 2.6(c)). A robot using the sprawled stance can be designed to have its body close to the walking surface. The body can pitch and roll to follow the contours of the terrain and will maintain more gravitational stability than the other two leg configurations. However, the strength-to-weight ratio of the leg actuators should be large compared to the gravitational forces acting on the robot. In the cockroach the musculo-skeletal forces generated in its legs are 20-30 times that of its body weight [11]. These large forces are needed since the muscle lever arms (i.e. the femur) are relatively short. The forces generated in the leg actuators must also be able to overcome the larger forces experienced by the legs when climbing an incline.

The sprawled stance shown in Figure 2.6(c) can be designed to use a pantograph mechanism in the horizontal plane to allow the foot to move in a straight line parallel to the longitudinal direction of the robot's body when walking forward. This could be one solution to the yawing problem mentioned above.

Other leg configurations do exist but they can generally be considered to be combinations of the three stances shown in Figure 2.6. Some other leg configuration methods have been observed in previously designed robots and are described below.

The Dante II robot [46] keeps four legs on the ground at a time keeping the body statically stable at all times on level terrain. Raibert's one-legged [1] and four-legged [47] robots use telescopic pogo sticks for their legs. These robots generally do not have a statically stable state and rely on dynamic balancing.

Another one-legged hopping machine was designed by John Nagle [48]. The foot of this robot used a lever similar to a human foot, hinged at the ankle and connected to a vertical spring-damper construction. An actively actuated horizontal balancing pole was used to maintain posture control.

As for the Odex robots (described in Section 2.5.2), they have six legs that need to be positioned accurately so that the centre of gravity of the robot remains inside the support polygon of the robot's feet. This would have been a difficult task since the upper part of the robots weigh about $360kg$ and the robot is about $2m$ high [49]. The leg structure for these robots had to be designed keeping these details in mind.

2.4 Types of Actuation

Actuators are used to produce the movement for mechanical systems in robotics. Some actuators produce rotational movement while others produce straight-line linear movement. Once movement is produced, the position of the movement as well as the speed of actuation must be monitored and controlled.

The amount of torque that actuators produce is very important for the design of a walking machine. The weight of the body and the legs are part of what determines the required torque of the actuators, especially for designs that require hopping or bouncing where the gravitational forces increase with the height of the oscillation.

In order to gain an understanding of the most common types of actuation devices used in robotics, they are briefly described below.

2.4.1 Electric Motors

One of the most commonly used types of actuation device out of all other devices is the electric motor. These provide continuous rotational motion, usually at high speed. Three types of electric motors exist that produce rotational motion. These include AC motors, DC motors and stepper motors.

AC (alternating current) motors are useful where AC power is readily available. AC may be generated by a gasoline engine on-board a large robot [37]. These motors generally produce a large amount of torque but it is very difficult to accurately control the acceleration and the deceleration [4]. Smaller robots usually do not have AC available and therefore these motors are hardly used.

For most smaller walking robots the DC electric motors are typically used since the DC supplies to power such motors are readily available. The motors are very fast and so can be geared down to produce slower rotation speed and hence increase the amount of torque. The speed and acceleration of DC motors can be accurately controlled and they can be connected to a gearbox and use a servo-mechanism to control the position of the output very accurately. DC motors are also reasonably energy efficient as compared to many other forms of actuation.

Some small walking robots that have been built recently have used servo motors for their actuators that are commonly used in radio-controlled cars and aeroplanes. These servo motors are a complete electric motor, gearbox and servo control system in a small package and are readily available. They provide fast and accurate position control over about $120°$ rotation.

Stepper motors are another alternative type of electric motor. These motors have many separate field-coil windings that allow the rotor of the motor to be aligned in discrete angular positions. By using logic control to switch between the coils the rotor can be made to rotate. The position, speed and acceleration can be accurately controlled although very high speeds are generally not obtained as compared to DC motors. Also, the torque of these motors are comparatively low.

Another type of electric device that (in this case) produces linear motion is the solenoid. The solenoid is not strictly a motor although it does use electricity to produce motive force. It is generally only used for two position requirements such as a single push-pull operation. Intermediate position control is very difficult for these devices.

2.4.2 Pneumatics and Hydraulics

Motive force can be produced using the transmission of fluid through hoses to actuating cylinders. Pneumatic actuation uses compressed air while hydraulic actuation uses pressurised oil [4]. Both systems are very similar in operation and the actuators are generally the same in structure. These systems produce linear movement and the speed of actuation is dependent on the pressure and the speed of the fluid.

A gasoline or electric compressor that is situated away from the actuators is usually used to create a high pressure containment of the air or oil. The fluid is transmitted to the actuators by flexible hoses.

An actuator consists of a piston inside a cylinder with a rod connected to the piston which extrudes from one end of the cylinder. Hoses connect to either end of the cylinder such that the fluid can be pushed into each side of the piston in the cylinder. By regulating the amount of fluid on each side of the piston, the linear position of the piston, and hence the rod can be varied.

Since hydraulics use highly pressurised oil as a transmission medium, the cylinders need to be very strong. They are typically made of stainless steel with brass fittings. Therefore, the actuators will be very heavy. Such systems produce very large motive force and are used in industrial excavators and dump trucks and have also been used in large walking robots such as the Adaptive Suspension Vehicle [9] and Sutherland's Hexapod [50], both of which carry a human driver.

Since pneumatics use compressed air as a transmission medium, the actuators will be lighter and can be used in cases where large forces are not required. Pneumatics are generally more difficult to control than hydraulics, although recently, researchers have been developing new valve systems to improve the control of the air flow [51].

2.4.3 Muscle Wires

Muscle Wires are a relatively new form of actuation that was evaluated in the course of this work for use in walking robots.

The name "Muscle Wire" is a commercial name given to what is actually known as a *shape memory alloy* (SMA) of nickel and titanium, extruded into very thin wires [28]. Other names for this alloy include BioMetal, Nitinol and Flexinol Wire.

SMA's can be deformed (or stretched) when they are "cold" using a small force and when they are "heated" they will return (or contract) to their original shape using a larger force. The original "cold" shape of the alloy is made by annealing it at high temperature.

The temperature that the wires contract is known as the *activation* temperature, typically around $70°C$. The temperature that SMA can start to be deformed is known as the *relaxation* temperature, typically below about $50°C$ [52].

The nickel-titanium wires have the ability to stretch (be deformed) about five percent their length at room temperature and shorten again to their original length by heating them using an electrical current.

The wires can heat quickly to their activation temperature and hence can actuate at reasonably high speed. However, the metal wires take a long time to dissipate the heat and cool down to their relaxation temperature. Therefore, when the wires are made to cycle by continuous stretching and contracting, the speed of the cycling is usually very low. Hence, this would limit the speed of some types of robotic movement.

Recently researchers have been developing ways to increase the cycle times [53]. The wires can be heated quicker by giving a short, large current pulse. They can be cooled quicker by making the wire rest on a metal block to dissipate the heat faster after the activation has completed. Another method is to immerse the wire in a cooling liquid. Much research is involved with designing micro-actuators using SMA [54] [55]. Most applications are for small scale projects.

The main disadvantage of Muscle Wires is that they have a very low energy efficiency, of the order of about 5%. This is because electricity is being used to heat the wires to produce the motive force. The wires can use power more efficiently by using Pulse Width Modulation (PWM) to actively control the length of the wires [28]. However, it depends on the application as to whether this approach is adequate or not. Also, heating the wires too much can cause them to anneal undesirably and lose the original recovery structure of the SMA.

Some of the advantages of these wires are that they have a very small size, they are very light weight and they have a very high strength-to-weight ratio. The strength of the wire depends on its thickness. They can be activated by either AC or DC. They have low magnetism and produce direct linear motion. They can lift thousands of times their own weight. A single $100mm$ long, $250\mu m$ thick wire can lift a weight of $1kg$ throughout a $5mm$ distance at a cycle speed of about $9cycles/min$ in still air, continuously, for millions of cycles using a current of about $1A$.

Two very small walking robots that use Muscle Wire actuators are Stiquito [56] and Boris [28]. These robots are very simple in design and are generally used for the purpose of experimenting with Muscle Wires.

In our research mechanical legs were designed based on Muscle Wire actuation. These legs are shown in Figure 2.7. The leg structure is based on the arthropod stance shown in Figure 2.6(b). The moving parts of the leg are produced by constructing two bars pivoted as shown, such that they form a parallelogram. The dotted lines represent the Muscle Wires connected from the inside of one end of one bar to the inside of the end of the other bar. By activating wire A in Figure 2.7(a), it will pull the bars closer together and lift the leg as shown in Figure 2.7(b). Conversely, by activating wire B the leg will be lowered. Figures 2.7(c) and (d) show a design that allows a leg to both lift and extend.

A prototype of this type of leg was constructed with a leg length of about $110mm$. The parallelogram leg segment was found to be very difficult to construct due to the

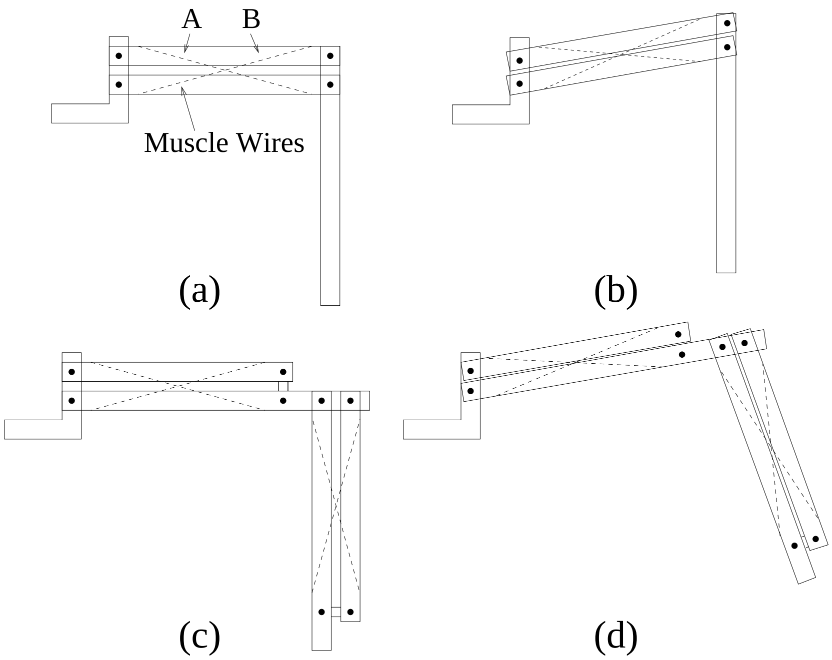


Figure 2.7: A leg design using Muscle Wires.
(a) and (b) shows a leg lifting by activating wire A. (c) and (d) shows a design to provide both lift and extension of a leg.

difficulty in handling the wires, which were $100\mu m$ thick. The leg segment did produce movement when the wire was electrically heated although problems were encountered with the current. The activation current that was used may have been too high. Having too high a current causes the wire to heat too much causing unwanted annealing and permanent deformation of the wire. Another problem encountered was that accidental stretching of the wires past their 5-8% limit also caused permanent deformation. If battery supplies were used to heat the wires they usually didn't last very long because of the low 5% energy efficiency of the wires.

It was concluded that Muscle Wires are only as yet suitable for very small and simple robots of about $10 - 20cm$ in length. Any more complexity in the robot's design, such as adding three DOF legs, requires intricate design by engineers. Larger robots may be able to use Muscle Wires in the future if special actuators are designed that make use of many, perhaps hundreds of such wires integrated in a small module that produces linear movement [28].

2.4.4 Polymer Hydrogels

Another new type of actuation makes use of polymer hydrogels that are capable of changing their volume by hundreds of times under certain conditions [57]. The gels are capable of both increasing and decreasing in volume when they are affected by stimuli such as a change in temperature, light, an electric potential, the pH acidity (or alkalinity) level or the type of solvent used [58].

Early research from Tanaka et al. [59] found that partially hydrolysed acrylamide gel can undergo discrete and reversible volume transitions when exposed to certain stimuli. They experimented with an electric field across the gel. The gel was immersed in a solvent of an acetone-water mixture. By applying a small electric field across the gel, it was found to reduce in volume.

A cylindrical gel about $6cm$ long and $1cm$ wide was used for experimentation. When $1V$ DC was applied the volume started to reduce. At $2V$ the gel was half its size. At $5V$ the gel was nearly all gone. This technology could be used to mimic the biological muscles in animals which also shrink and swell to provide actuation.

Currently, researchers at MIT are using changes in pH to modify the volume of poly acrylonitrile (PAN) filaments, a type of polymer hydrogel. pH levels are used because they provide faster actuation than other stimuli [58]. An example of a cylindrical actuator is given in [60] and is briefly described as follows. Commercially available PAN hydrogel fiber bundles are prepared using a procedure that involves annealing at high temperature for several hours. The long thin fibers are then fitted into a cylinder together with porous Teflon tubes that are used to irrigate the cylinder and immerse the fibers in either acidic or alkaline solutions. These solutions change the pH of the solution inside the cylinder making the PAN fibers either expand or contract. By fixing the fibres to a type of artificial tendon, the actuator can produce linear movement.

These polymer hydrogel actuators still require further research in order to develop a practical system. Once fully developed for universal use, it is quite possible that they may become a standard for use in robotics. Since they would be mimicking biological muscles, they will help to make the physical structure and performance of robots more like the creatures found in nature.

2.5 Previous Legged Robot Designs

To gain a better understanding of the issues surrounding legged locomotion it was important to study many of the walking machines that were developed in the past. Most of the legged robot designs have been developed in the last ten to fifteen years, many of which were designed and built by very small groups of people for competition events such as the 1994 Singapore Robot Games [61] and the BEAM Robotic Games [62]. The more elaborate walking machines were mostly built at educational institutions.

A selection of the many robots that were researched are described below. Some of the robots are large while others are small. There are examples of having different leg structures and different methods of controlling them.

2.5.1 The OSU Hexapod

This six legged robot was designed by Dr. Robert McGhee of Ohio State University in 1977 who had also designed an earlier quadruped robot known as the Phony Pony [7]. The OSU hexapod was used for research purposes to develop control schemes and leg placement algorithms as well as being used to test new sensors and sensing systems [63]. The control systems for this robot were implemented on a PDP-11 computer. This robot was believed to be the first fully computer controlled vehicle [35]. It is shown in Figure 2.8 (picture obtained from [13]).

The robot was $1.3m$ long, $1.4m$ wide and weighed about $100kg$ [13]. Each of the six legs had three independent DOFs that were configured using the arthropod stance. Each

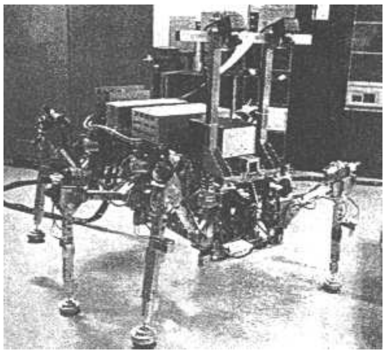


Figure 2.8: The Ohio State University Hexapod.

joint was driven by a geared-down electric drill motor that produced a walking speed of a few inches per second.

Mechanically, the legs were strong since worm gears were used after the reduction gears. As a result, the maximum torque of the leg joints were about $300Nm$.

The hexapod was able to climb over tables and other flat objects that were on the ground. The robot was also used as a test-bed to evaluate robot control systems that were eventually to be used on a larger robot known as the Adaptive Suspension Vehicle [9], described below.

2.5.2 Odex-1 and Successors

Odex-1 was built by Odetics Inc. of California in 1983. The robot is shown in Figure 2.9 (picture obtained from [64]). This six legged robot is very different to most other robots, not only by its appearance but also in its strength. It was built to test how appropriate the leg design would be for future robots. These robots were called "functionoids" by their creators.

The robot was controlled remotely by a teleoperator using a radio link. Although the robot does not appear to be designed to walk at high speeds, it is claimed to walk at about the "same speed as a man" [64]. A pair of video cameras are situated inside the glass sphere at the top of the robot. The Odex robots used a leg configuration similar to

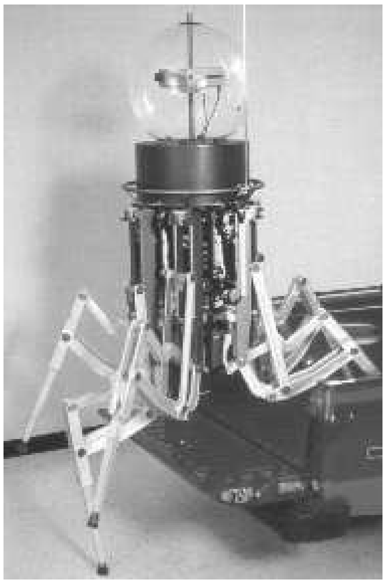


Figure 2.9: The Odex-1 "functionoid" from Odetics Inc.

an arthropod stance except that the six legs were arranged radially around the cylindrical body of the robot.

Odex-1 could vary its height between about $91cm$ to $2m$ using a unique leg structure [64]. The maximum step height for this robot is, impressively, about $1m$. The legs used a vertical lead-screw design that allowed each leg to lift about $200kg$. The strength of the robot was demonstrated by making it lift the rear-end of a utility truck via a brace positioned at the top of the robot. This was followed by making the robot walk while carrying the load, which was about $400kg$. The robot itself weighed about $200kg$.

One of the newer Odex robots was built for the Savannah River Laboratory in 1986 [65]. It was the third of the Odex generation and is named ROBIN (short for ROBotic INsect), and is also known as Odex-3 [66]. This robot was designed for nuclear plant maintenance [15]. It has a telescopic arm that resides in the cylindrical turret of the body that can lift about $14kg$ when fully extended to about $2m$. Other enhancements include a fiber-optic communications cable, an on-board data acquisition system and a three-camera TV system [67]. The robot performs operations semi-autonomously by on-board computers with the aid of a teleoperator.

Probably the most recent robot in this range is SHERPA [68] (short for Systéme HExapode Robotisé Pour Applications nucléaires, or robotised hexapod system for nuclear installations). This robot used the Odex-3 platform and had a few modifications to the walking control functionalities. The robot weighed $490kg$, could carry up to about $300kg$ and could walk at $5m/min$.

2.5.3 MELWALK MARK-III

This six legged robot was built around 1984 to demonstrate the effectiveness of using decoupled DOFs in its legs. Decoupled DOFs can allow a robot leg to use one DOF to propel the robot forward and use another DOF to separately adapt to the terrain. The body size (excluding the legs) was 50 x 50 x $10cm$ (width x depth x height), the maximum vertical extension of a leg was $20cm$, and it weighed $35kg$. The robot was used for research purposes such as experimenting with walking over soft ground using force sensors on the feet [69]. It is shown in Figure 2.10 (picture obtained from [8]).

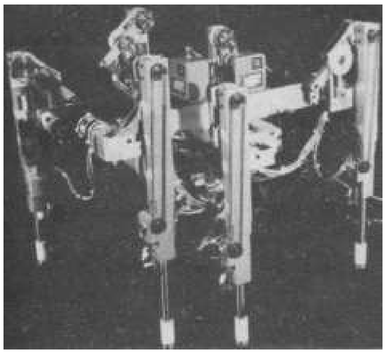


Figure 2.10: MELWALK MARK-III.

Three types of linkage mechanisms were used for the legs of MELWALK as shown in Figure 2.11. Figure 2.11(a) uses a four-bar linkage mechanism (described below) to produce an approximate straight line motion while the leg is on the ground. The leg is connected directly to position E in this diagram. As the leg is moved from the front to the rear of the robot, the leg will be on the ground propelling the robot forward. As the leg is

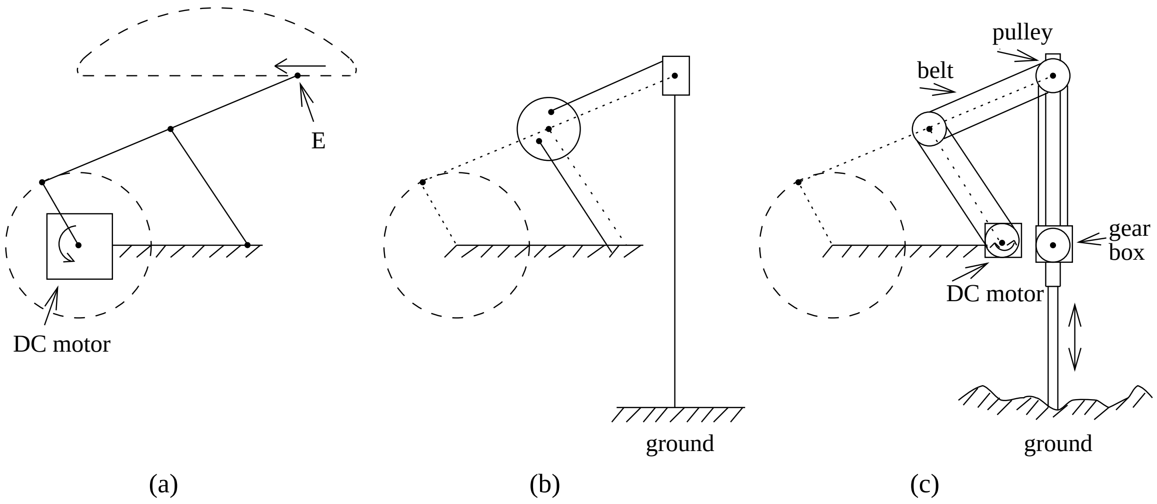


Figure 2.11: The three leg mechanisms used in MELWALK MARK-III.
(a) The four-bar linkage mechanism. (b) The sublinkages used to keep the leg vertical.
(c) The mechanism used to provide vertical lift.

moved from the rear to the front, it is automatically lifted by the mechanism and hence decouples the body-propelling DOF from the lift DOF. In order to keep the leg vertical at all times, the sublinkages shown in Figure 2.11(b) were used. Finally, the vertical lift DOF was obtained using a separate motor mounted on the body and connected to the leg using belts and pulleys as shown in Figure 2.11(c).

The four-bar linkage mechanism produces the semicircular trajectory shown in Figure 2.11(a) using a single DOF. The mechanism that is used to propel the legs of Strider (described in Section 3.4) also produces a semicircular trajectory using a single DOF. This is what makes the four-bar linkage mechanism similar to that used to propel the legs of Strider. For this reason the four-bar linkage mechanism is briefly described below.

The four-bar linkage mechanism is shown in more detail in Figure 2.12 (diagram adapted from [8]). This mechanism was originally designed by the famous Russian mathematician Chebyshev [31]. The semicircular trajectory that is produced by this mechanism is useful for walking robots since it is similar to the trajectory a foot would follow in an animal. In Figure 2.12 we see the four bars; AD, CD, DE and BC. The lengths of these bars are given by the following.

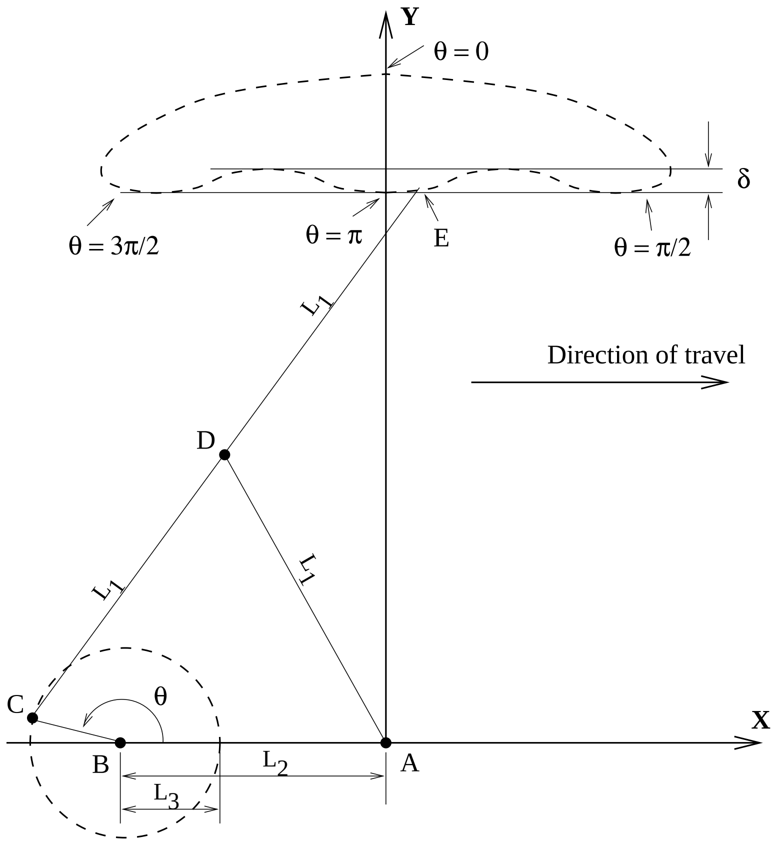


Figure 2.12: The four-bar linkage mechanism.

$$\overline{AD} = \overline{CD} = \overline{DE} = L_1$$
$$\overline{BC} = L_3$$

Bars CD and DE are actually joined together to produce a single bar CE. The distance between points A and B is given by L_2. Joints A, C and D are pivots. The semicircular trajectory that produces the stepping motion is produced by a single DOF by positioning a motor at point B. The leg is connected to position E, as mentioned above.

As the motor rotates around point B, the trajectory of point E is determined by Equations 2.3 and 2.4 [17].

$$X_E = L_1 \sin\theta \sqrt{\frac{4}{({k_1}^2 - 2k_1\cos\theta + 1)} - {k_2}^2} \tag{2.3}$$

$$Y_E = L_1(k_1 - \cos\theta) \sqrt{\frac{4}{({k_1}^2 - 2k_1\cos\theta + 1)} - {k_2}^2} \tag{2.4}$$

where

$$k_1 = \frac{L_2}{L_3}$$
$$k_2 = \frac{L_3}{L_1}$$

As can be seen in Figure 2.12, the mechanism produces a small oscillation, with amplitude δ, in the horizontal section of the resulting trajectory. δ can be minimised by choosing appropriate lengths for L_1, L_2 and L_3, and hence k_1 and k_2. For values of $k_1 = 2$ and $k_2 = 0.4$, where $l_1 = 17.5mm$, for example, the trajectory in Figure 2.13 is produced. As can be seen, the oscillation in the horizontal section is very small and would therefore allow the robot to walk smoothly along a flat surface.

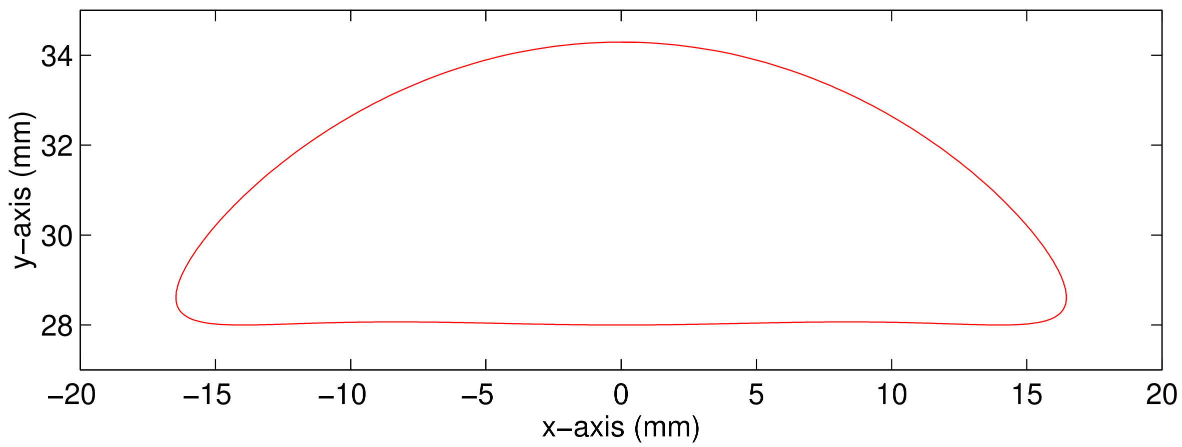


Figure 2.13: The four-bar linkage trajectory for $k_1 = 2$ and $k_2 = 0.4$ and $l_1 = 17.5mm$.

Further discussions of the four-bar linkage mechanism is given in [8] and [17].

MELWALK used a fixed alternating tripod gait for simplicity. The tripod walking pattern moves the front-left, rear-left and middle-right legs rearward while they are on the ground to propel the robot forward. The other three legs are in the air moving towards the front. The sequence is then reversed. This is repeated continuously to produce the periodic tripod walking pattern.

Turning was obtained by mounting three legs on a lower base plate and three on an upper base plate. The front and back legs of one side and the middle leg of the other side were mounted on one plate and the other three legs were mounted on the other. The two plates overlapped and were pivoted in their centre and connected to a motor to rotate each plate and hence make the robot turn.

The robot's average step time was 12 seconds on irregular terrain using the lift DOF on its legs. It could walk faster on flat ground since it used only one DOF per leg to produce the semicircular foot trajectory. Also, it could make a $90°$ turn in about 20 seconds.

2.5.4 The Adaptive Suspension Vehicle

The Adaptive Suspension Vehicle (ASV) was developed at Ohio State University around 1985. The main goal was to develop a human-controlled six legged walking machine to be used on rough terrain [30]. The human operator would sit in a cockpit and use a joystick to control the robot's low-level movement, including simple forward, backward and twist movements. The ASV is shown in Figure 2.14 (picture obtained from [45]). The cockpit can be seen at the front of the machine.

The ASV's leg structure used the mammalian stance except that the legs were not driven at the knee. Rather, a pantograph mechanism was used for each of the six legs to perform the lift and advance functions. Each leg was also able to swing laterally (adduction and abduction) to allow the machine to turn. The legs were controlled by hydraulic actuators which were powered by a $900cc$, $0.25kWh$ motorcycle engine.

Since the vehicle was to be used within unstructured environments, a large amount

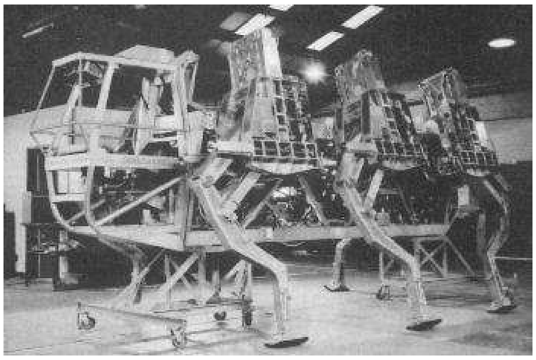


Figure 2.14: The Adaptive Suspension Vehicle.

of sensing was required. An infra-red scanning rangefinder was used to obtain terrain information in front of the vehicle. It had a resolution of 128x128 pixels and scanned at $2 frames/s$. Other sensors include position, velocity and hydraulic differential pressure sensors for the actuator servos, and gyroscopes to measure the roll, pitch and yaw position and acceleration.

Eight Intel 80386-based computers were used for general purpose processing [70]. Other processors were custom designed for devices such as the rangefinder.

The ASV was $5.2m$ long, $3m$ high, $2.4m$ wide and weighed 2.7 tonne. It could accept a payload of $220kg$ for sustained operation. It was reported to walk at $2.2m/s$ in 1989 [31] and it was designed to have a maximum speed of $3.6m/s$.

The ASV was previously funded by DARPA (Defense Advanced Research Projects Agency) and has since ceased development due to lack of funding.

2.5.5 MECHANT I

The MECHANT (or MECHanical ANT) hexapod robot was developed in the early 1990's. The main goal of this project was to develop a semi-autonomous walking robot whose purpose was to walk through uneven natural terrain in a highly unstructured environment such as a forest [71]. The leg configuration of the MECHANT is based on the arthropod stance as can be seen in Figure 2.15 (picture obtained from [71]). It is controlled via a radio link by a human operator.

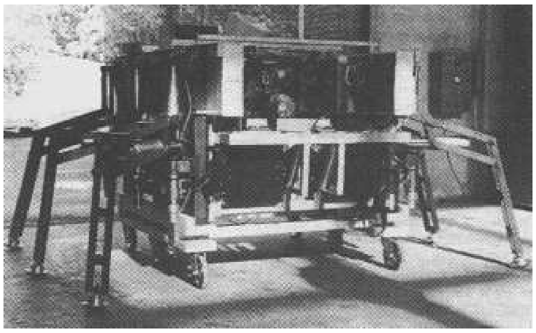


Figure 2.15: MECHANT I.

The six legs have three DOFs each and are all hydraulically actuated and powered by a small aeroplane combustion engine. The legs use a pantograph mechanism for the lift and extension DOFs. The third DOF rotates the pantograph mechanism to provide an advance DOF as shown in Figure 2.6(b).

The robot is $2.1m$ long, $1.6m$ high, $2.4m$ wide and weighs about 1.1 tonne. Its maximum walking speed was about $70cm/s$ and could carry a payload of about $100kg$.

MECHANT was used primarily for research purposes to experiment with terrain adaption and also to develop control systems for gait control.

2.5.6 Genghis

Genghis is a small hexapod walking robot developed at MIT in 1989. It was designed to test the use of a control system for a robot with many DOFs [20]. The control system used for the robot was based on the subsumption architecture, developed by Rodney Brooks, which will be discussed in Section 4.3.6. It was one of the first six legged robots developed by the MIT Artificial Intelligence Laboratory's Mobile Robotics Group. The robot is shown in Figure 2.16 (picture obtained from [20]).

The leg structure used for Genghis can be thought of as similar to the arthropod stance of Figure 2.6(b) although it actually uses the sprawled stance of Figure 2.6(c) without the extension DOF.

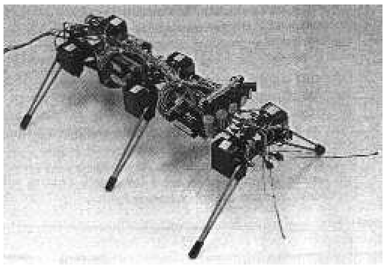


Figure 2.16: Genghis.

Each leg has two DOFs and is driven by two standard position controlled "radio control" servo motors that are mounted orthogonally for leg lifting and a forward/backward swinging motion. There are two whiskers on the front of the robot which are used to detect high obstacles in the robots path. Two inclinometers mounted on the body are used to detect the pitch and roll while walking. Six front-facing infrared sensors are positioned on the top of the robot and are used to detect and locate infrared sources.

The body of Genghis is about $30cm$ long, $10cm$ wide and $4cm$ high. When the robot is in a standing position its total height is about $10cm$ with a leg span of $15cm$.

Although Genghis wasn't the first small walking robot to be developed or the first to use subsumption architecture, it became very popular throughout the world and at the same time made the subsumption architecture well known. It inspired many other small walking robots to be developed around the world in the following years.

2.5.7 Attila

Attila was the next walking robot developed after Genghis at MIT in 1991. The main goal of the project was to develop a small autonomous walking robot that could locomote itself over rough terrain, climb steep inclines, recover from falls and make use of lots of different types of sensors. These are the same requirements for an autonomous walking robot as mentioned in Section 2.1. Its main use was as an experimental platform for future planetary exploration. A picture of Attila is shown in Figure 2.17 (picture obtained from [72]).

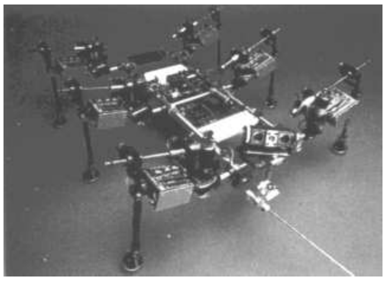


Figure 2.17: Attila.

Attila was about $30cm$ long, $25cm$ wide, $18cm$ high and weighed $2.9kg$ [32]. The robot had over 150 sensors of 14 different types [73]. The leg structure used for the robot was the arthropod stance. Each leg had three DOFs and the body had a DOF that rotated all the legs together when walking on an incline. A two DOF antenna was used to detect objects in front of the robot. The robot also had a head with a range finder and CCD camera mounted on it that could pan and tilt.

Many of the problems with the mechanical design of Attila were addressed in [14]. The leg design had the problem of making the body yaw as mentioned in Section 2.3. The legs were able to lift high for climbing up, but due to its design they only had a small step-down height. Nevertheless, Attila was used for many tests for possible use on rocky planetary surfaces. The same robotic platform was also used for research purposes to evaluate various control systems for a walking robot [10].

2.5.8 CWRU Hexapod

The Case Western Reserve University Hexapod robot was developed in 1991. Its main use was for research purposes to evaluate a neural network based control system developed by Beer et al. for insect locomotion, described further in Section 4.3.5. The robot is shown in Figure 2.18 (picture obtained from [21]).

The six legs were configured using the mammalian stance where each leg had two DOFs. The legs had no knee joint and therefore one DOF could only swing the leg in the longitudinal direction of the robot's body. The other DOF linearly lifted the leg off

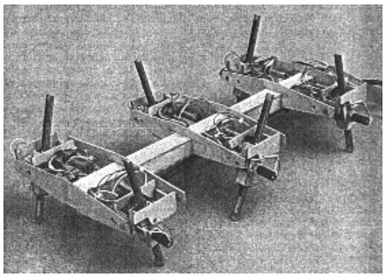


Figure 2.18: The Case Western Reserve University Hexapod.

the ground. As a result the legs could only move the robot forward or backward and not turn. Since the robot was built only to test Beer's neural control system, the ability to make the robot turn was not necessary.

The robot was $50cm$ long, $30cm$ wide, about $10cm$ high and weighed about $1kg$ [74]. The power and electronics were kept off-board the robot in order to keep it simple. This made the robot light-weight and hence reduced the inertial properties and the need for powerful motors.

2.5.9 Boadicea

One of the latest small walking robots from MIT, developed in 1995, is Boadicea. This robot was built for research purposes to examine the mechanical capabilities of combining lightweight pneumatic actuation, the use of specialised materials and the mechanical structure design based on that of a cockroach (the *Blaberus Discoidalis*) [41]. The robot is shown in Figure 2.19.

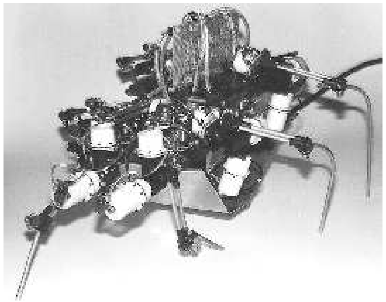


Figure 2.19: Boadicea.

The robot was 50cm long, about 25cm wide and about 25cm high. It also weighed about 4.5kg. The pneumatic actuators were custom designed and produced high force using compressed air at 100psi. Most of the mechanical structure used injection molded fiber reinforced plastic. The air flow of the pneumatics used solenoid poppet valves that were controlled using PWM by an MC68332 microprocessor.

The leg design shown in Figure 2.19 is actually the sprawled stance of Figure 2.6(c). A pantograph mechanism was used in the horizontal plane to provide the forward/backward advance DOF and the extension DOF. Another lift DOF was added to the two middle and two rear legs. The front legs only had two DOFs. Hence, in total the robot had 16 DOFs.

2.5.10 Other Walking Robots

Many other walking robots were investigated in this research in order to gain a better overview of the styles used for mechanical designs and the methods used for controlling the robots. Information for over forty different robots have been found, some of which did not have anything more than a photograph. However, a picture of the robots is all that is usually required to gain a general understanding of how the robot had walked. Very brief descriptions and references are given in Table 2.2 for most of the robots investigated.

The size of the robots are considered *small* if they are about 30cm long or less. They are considered *medium* if they are less than 1.5m long, otherwise they are considered to be *large*. Some of the leg structures of these robots were difficult to describe as being either of the mammalian, arthropod or sprawled types. The closest description has therefore been given in the table. The "Year" column gives an approximate indication of when the robots were developed.

Other walking robots can be found on the internet at [82].

Name	No. of Legs	Leg Structure	Size	Year	Ref.
Airratic	six	other	medium	1992	[75]
Ambler	six	other	large	1989	[76]
AQUAROBOT	six	arthropod	medium	1996	[77]
Ariel	six	arthropod	small	1997	[78]
Boris	six	arthropod	small	1994	[28]
COLLIE-1	four	mammalian	small	1984	[79]
CWRU Hexapod Robot II	six	arthropod	small	1996	[80]
Dante	eight	arthropod	large	1993	[42]
Dante II	eight	arthropod	large	1995	[81]
Four-Legged Running Machine	four	mammalian	medium	1984	[47]
Genghis II	six	sprawled	small	1995	[78]
Geo 2 (MENO II)	four	arthropod	small	1996	[82]
Heg	six	arthropod	medium	1995	[83]
Hermes	six	sprawled	small	1995	[78]
HexWalker	six	arthropod	small	1995	[84]
Hexax-I	six	arthropod	medium	1991	[85]
JTUWM-II	four	arthropod	medium	1991	[86]
KAISER II	four	arthropod	medium	1993	[87]
KUMO-I	four	arthropod	medium	1978	[38]
Lurch	four	other	medium	1987	[75]
Marv	six	sprawled	small	1996	[88]
MASCHA	six	arthropod	medium	1990	[89]
NCTU Quadruped	four	arthropod	medium	1985	[90]
One-Legged Hopping Machine	one	other	medium	1983	[31]
Phony Pony	four	mammalian	medium	1967	[7]
Platontic Beasts	four	other	small	1996	[91]
PV-II	four	arthropod	medium	1979	[16]
RIMHO	four	arthropod	medium	1993	[92]
Robotic Insect	six	sprawled	small	1994	[93]
Robug III	eight	arthropod	medium	1997	[94]
Rodney	six	sprawled	small	1995	[95]
Stiquito	six	arthropod	small	1992	[56]
The Iron Mule Train	eight	arthropod	medium	1968	[96]
Thing	four	arthropod	small	1994	[97]
Three-legged walker	three	mammalian	medium	1975	[98]
Titan-III	four	arthropod	medium	1984	[12]
TUM	six	arthropod	medium	1994	[40]
Ursula	six	sprawled	small	1996	[78]
Walking Truck	four	mammalian	large	1968	[31]
X-Plorer	four	other	small	1994	[75]

Table 2.2: A list of most other walking robots investigated in this research.

2.6 Simulating Robots using Computer Graphics

In certain circumstances it would be an advantage, and sometimes necessary to perform experiments on an artificial representation of a robot. If a designer finds it necessary to experiment with physical interactions of robots then it is necessary to physically build the robot. However, if the designer only needs to test certain control theories or behaviours related to the control of the robot then computer graphics can be used to generate artificial creatures to represent them. The speed of modern-day computer technology and computer graphics has allowed researchers to develop real-time animations which aid in the design of mobile robots [99].

For most computer simulations the best way to observe what is happening is to actually see moving objects with your eyes. A non-graphical simulation that only produces a set of numbers printed on a terminal screen is far more difficult to visualise. If, however, the numbers could be used to control a graphical model of the system being simulated then an observer would not require much previous knowledge of the internal mechanisms of the system and the simulation could be appreciated by a greater number of people. This is analagous to comparing a text adventure game to a graphical flight simulator.

As an example, Lin et al. [100] used a graphical simulation of a quadruped to examine the performance of a Cerebellar Model Articulation Controller (CMAC) neural network. The animated movement is far easier to observe than the data that the CMAC produces.

Previous attempts have been made to simulate walking robots with reasonable realism [101] [102] [48]. Some researchers used computer animations to simulate walking patterns of insects and animals such as horses [103]. The physical information used in the simulations were obtained from the biological organisms. In some cases computer graphics was used to create virtual environments for mobile robots. The robot Dante II [104], for example, used graphical simulations of the landscape it would be walking on.

Stoner et al. [105] simulated a quadruped walking vehicle to test the stability of particular walking patterns based on the robot's centre of gravity. The simulation successfully showed when the robot was stable or unstable and would have been very useful to use before implementing the walking patterns on the real robot.

Some of the things that may never even be considered when simulating a robot that would most likely be experienced in a real robot include obtaining false infrared readings, false sonar echoes and sound absorption, motors can stall and power supply voltages can vary [106]. Simulating every possible fault can be much too difficult. In such cases, the robot should be built and tested with minimal simulation. The reasons for this are explained as follows.

Brooks et al. [107] mostly deal with the interaction of robots in the "real world". They typically try to avoid doing any computer simulations of their robots and tried to work in real environments and deal with real issues [73]. Two reasons for this were given. Firstly, simulations may deal with circumstances that a real robot may never experience. Secondly, a simulated robot will almost definitely perform very differently in real life [107].

In Brooks' earlier research they felt that is was important to have realistic simulations that try to simulate all the errors and uncertainties that exist in the world of the real robot [19]. They eventually realised that the simulations must be limited since everything in the robot's true environment cannot be fully and accurately simulated. Trying to fully simulate the complexity of a robot's environment would require more work than to actually build the robot itself [108]. That is why they built the robots to perform their tests in the real world. One of their robots, Genghis (described in Section 2.5.6), was built without any previous computer simulations. By discovering the actual problems that were encountered with the real life interactions, the control system was able to be further developed [20]. Many of the problems encountered may not have been discovered if simulations were used.

Beer et al. [21] used computer graphics to simulate an artificial cockroach. The neural network locomotion controller used for the simulated cockroach was found to produce a wide range of walking patterns. The researchers were not sure that the large range of patterns were simply an accident of computer simulation so they eventually built a small walking robot (described in Section 2.5.8) to assess the utility of the controller [74] [109]. They found that the real robot still produced the large range of walking patterns that were simulated. They also found that if they chose instead to further develop their computer simulation, they may not have discovered various other problems that became apparent using the physical robot [109].

There are many CAD packages available which can be used to graphically draw and animate robots. Alternatively, a graphical model can be created using a graphics library of routines to draw the shape(s) of the robot's structure and then program the various mechanical motions required. In some ways this approach could be more difficult than using a graphics modelling package but it can provide more flexibility to the programmer.

In the course of this research a graphical simulation of the robot Genghis was developed in order to test the subsumption architecture control system mentioned previously (described in Section 4.3.6) [110]. The control system was limited to only making the robot perform a simple walk in a straight line.

The graphics package used for the Genghis simulation was called VOGLE [29] which stands for Very Ordinary Graphics Learning Environment. VOGLE is a public domain graphics library which is loosely based on the Silicon Graphics graphical programming language. It allowed simple drawings to be made such that a wire-frame representation of the robot could be drawn.

Only the main, visually obvious parts of the robot were modelled including the body, six of the servo-motors which represent the so-called "beta motors" that were used to lift the legs, and the six stilt legs. A pair of whiskers are also shown but the control system for them was not implemented. Their only purpose was to show where the front of the robot was. A small floor was also drawn to make the walking motion easier to observe. The graphical model of Genghis can be seen in Figure 2.20 which shows the robot standing and walking using a tripod gait. The resulting image resembles the original robot in Figure 2.16 reasonably well.

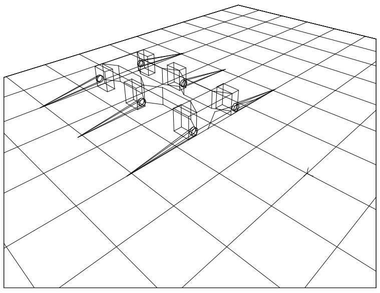
Since the simulation had been designed to simulate the mechanical motions produced from a subsumption control system, the physical interactions that the robot experiences within its environment had been limited. The graphical body of the robot was able to lift itself above the floor when its legs were lowered. Also, its body could move forward when its legs were projected backward. Gravitational forces and friction were not simulated. As a result, the body of the robot glided smoothly above the floor in an unrealistic manner. Any feet movements on the ground would have normally produced lateral forces on the body that were not shown in the simulation. The simulation only provided a good visual demonstration of how the subsumption architecture control system could be used to control a robot with many DOFs.

2.7 Summary

This chapter introduced legged locomotion by examining its properties and applications of legged machines. A common mechanical design used in walking robots (the pantograph mechanism) was described showing the advantages it has over several other mechanisms. A description of the main leg configurations used by most walking machines was given explaining their advantages and disadvantages with respect to their mechanical design and energy considerations.

The various types of actuation used in robotics were described, some of which are currently in use while others are still being developed at other institutions. Muscle Wires were evaluated for use in small walking robots and were found to be inappropriate due to their low energy efficiency of only 5%.

A description of various legged robots that were designed and built by other researchers in the past were presented. Over forty walking robots had been investigated in this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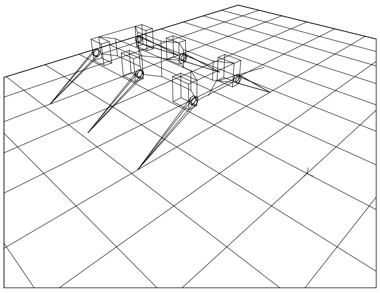
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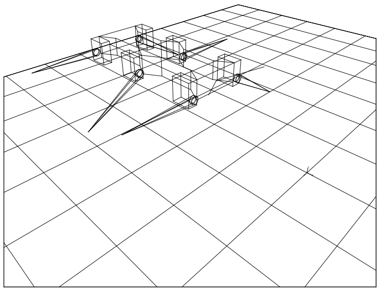
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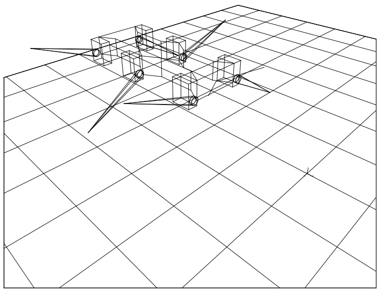
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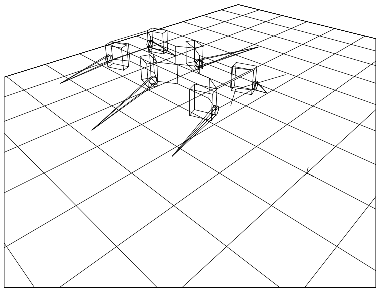
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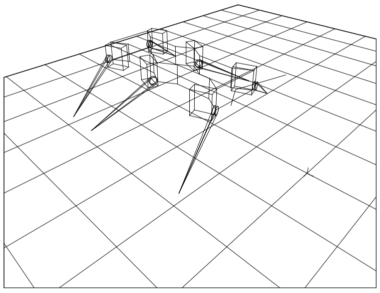
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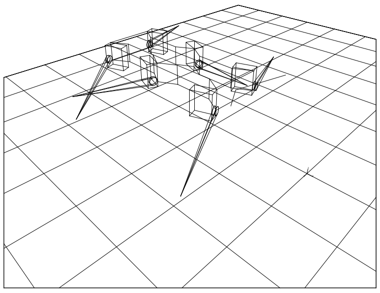
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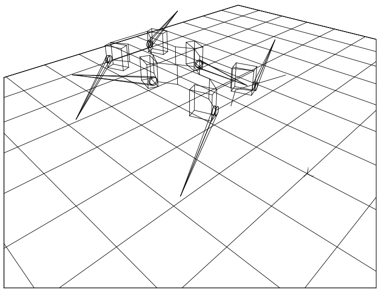
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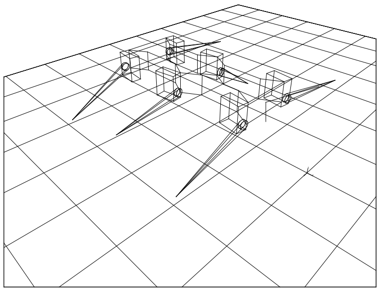
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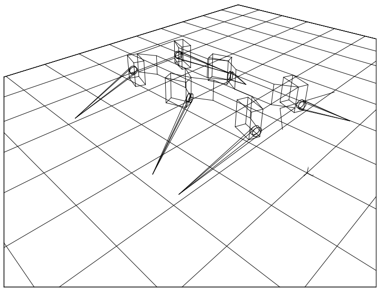

(j)

Figure 2.20: Graphical simulation of Genghis.
(a)–(b) Standing. (c)–(j) Performing a tripod gait.

research. Most of these were described in little detail in this chapter. Nine robots were discussed in more detail.

The application of computer graphics to the design of walking vehicles was evaluated based on results from this research as well as previous researcher's work. Is was concluded that computer graphics is best used to evaluate the control systems that are to be used on a real walking robot. Building and testing the robot can produce far more information about how the robot would behave in the real world that is almost impossible to simulate.

Chapter 3

The Biologically Inspired Walking Robot

Although the small walking robots that were described in Section 2.5 were sophisticated in their mechanical design and the way that they were controlled, their walking speed was relatively low. Out of the robots described, Boadicea (Section 2.5.9) had the highest walking speed of about $10cm/s$. One of the main purposes of this work has been to develop a walking machine capable of producing relatively higher speeds than previous designs, that may lead to newer designs for both small and large scale robots.

Our study was based on the six-legged walking of the cockroach, such as the *Periplaneta Americana* or the *Blaberus Discoidalis*. This insect is one of the fastest invertebrates ever studied relative to its mass, reaching speeds of up to $1.0 - 1.5m/s$ [3].

Strider, developed in this work and shown in Figure 1.1, used a simple design for a small robot and was built based on inspirations from the leg structure of a cockroach. A simple drive mechanism (known as the *groove-slot mechanism*) was also designed to propel each of the robot's six legs. It is these two features of the robot that contribute to a faster walking machine.

As mentioned in Section 1.4.1, Xiding et al. [17] designed concurrently with our research, a six legged robot with a similar leg structure to that used by Strider. The legs use the four-bar linkage mechanism (described in Section 2.5.3) to propel the legs in a semicircular trajectory. The pantograph mechanism was used to magnify the semicircular trajectory. The main difference with their robot and ours is that their robot uses only one DOF to propel all the legs at the same time and it was designed to only walk using a fixed tripod gait. The legs of Strider and most other walking robots can be controlled independently allowing a variety of gaits to be produced.

3.1 A Word About the Design Process

In some cases researchers try to fully design their robots before they start to build them. This is usually done using simulations to eliminate as many errors as possible. After the machines are built they are often different in some ways to what was originally designed. Also, the time taken to do the theoretical design is typically large and more time may have to be allocated to redesign the systems if necessary [97].

During the design process for Strider, sections of the robot were first designed, usually by drawings, and then tested experimentally. In some cases sections of the robot had to be designed and tested after other sections were completed. This incremental approach of alternating between theory and practice was found to be very beneficial.

In some situations the order of the design process is also important. The legs used for Strider, for instance, were only partially designed before the rest of the body was designed. As a result, the gearboxes that the legs were connected to were designed specifically for those legs initially designed. The leg construction was found to be inadequate after the body was built and had to be redesigned. The final legs that were designed were not as good as they could have been if the gearboxes could accommodate more changes to the legs. This shows that the legs should have been fully designed and tested before the body and gearboxes were designed. This also shows that the order of designing the sections of a robot is very important.

In the next section the mechanical design of Strider is presented including the electronics used to control the robot. The following sections discuss some parts of the robot in more detail and various other aspects regarding the mechanical design.

3.2 An Overall Description of Strider

3.2.1 The Materials Used for the Mechanical Structure

One of the first stages in the design process for Strider was to investigate various materials that could be used to construct the mechanical sections of the robot. The main sections include the chassis and frame, the gearboxes and the legs. Several different materials were investigated at the same time that the mechanics of the robot were being designed. A suitable construction material that is light weight, strong and easy to handle had to be chosen by the time the mechanical designs were completed.

The many different parts that make up the mechanical sections of the robot were to be cut out from thin sheets (about $4mm$ thick) of the chosen material using a computerised milling machine. The milling machine was originally designed to create circuit boards by milling out the copper cladding. Instead the various shapes would be drawn on the computer to be cut out with the high precision cutting tool. Once cut out, the parts were connected together using screws.

The chosen material had to be easy to mill on the milling machine. Some materials, such as nylon, could not be used since the high-speed milling drill bit melted it instead of neatly cutting into it.

Some of the materials investigated included acetals, polyethylene, polypropylene, nylon, Teflon, polyvinyl chloride (PVC) and fibreglass. The most impressive material found was described by several material engineers as a glass-reinforced polypropylene. This material was light-weight, very easy to mill, reasonably hard and had low friction. Only a small sample of this material was available and unfortunately a manufacturer for it could not be located in Australia. Due to the lack of availability of this material, the next best alternative had to be found. After much investigation the chosen material used was PVC. The milling machine did melt the PVC slightly at times but was adequate for the purpose.

Apart from the PVC, a small amount of thin brass tubing was also used for part of the construction of the legs.

3.2.2 Using Two Degrees of Freedom Per Leg

The ability to walk over rough terrain is an obvious necessity for a walking robot. Two DOFs is the minimum a robot leg should have if it is to walk over rough terrain, as is the case with Genghis (Section 2.5.6). One DOF must be used to lift a leg off the ground or to lift over an object. Another DOF must move the leg forward and backward to propel the robot. When the robot turns, however, the forward/backward movement of a leg is insufficient to keep the feet in the same positions as the body rotates. Therefore, at least a small amount of foot slippage can be expected. By adding another DOF the location of the foot placement positions can be more accurately chosen and the foot slippage can be minimised. Therefore, for a walking robot to be "fully terrain adaptive" its legs must have at least three DOFs [30].

Since Strider was designed for research purposes, only general walking using two DOF was necessary. One of the advantages of Strider's design is that it can walk using only one DOF per leg. The groove-slot mechanisms (described in Section 3.4) are driven by these DOFs to provide general walking on level terrain. The other DOF in Strider's legs lift the foot vertically when necessary for climbing over obstacles and into small ditches, as will be explained later.

3.2.3 Dimensions of the Robot

Figure 3.1 shows the dimensions of Strider's body. It is 29.5cm long, 14.5cm wide and 19.5cm high. With the legs fully extended in the longitudinal direction, the overall length is about 63cm. Also, with the legs fully extended vertically, the overall height is about 28.5cm.

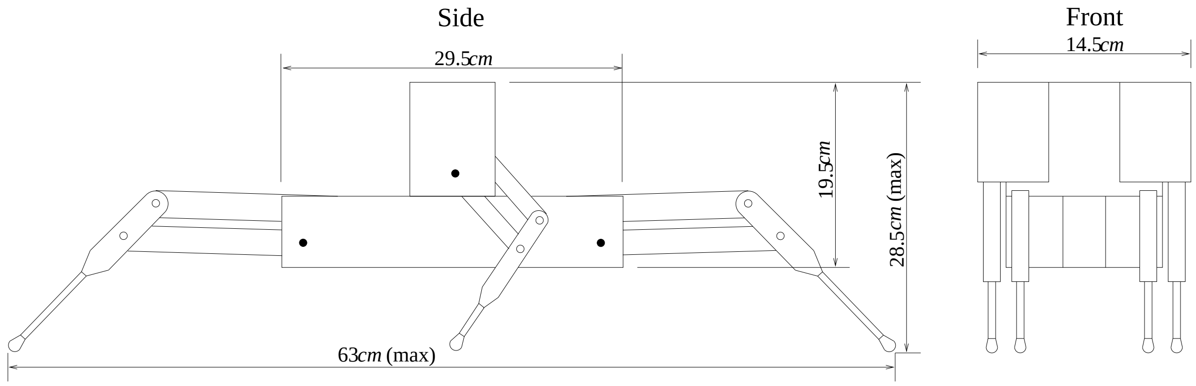


Figure 3.1: The dimensions of Strider.

3.2.4 Strider's Pantograph Legs

Each of Strider's mechanical legs use a planar pantograph mechanism in the longitudinal axis of the robot. The pantograph is used to magnify the semi-circular motion that is produced by the groove-slot mechanism (described in Section 3.4 below). The large horizontal strokes of the pantograph legs help to provide fast walking speeds.

As mentioned above, our first design for the robot's legs was not used in the final product. The first design was used as a guide to design the gearboxes. The other designs were made after the body and gearboxes were built.

The first design for the legs consisted entirely of brass tubing and brass joints. Small thin pieces of brass rod were used make the pivoting hinges and thicker pieces of rod were inserted into the tubing at the joints to give them more strength. This leg is shown in Figure 3.2(a). The leg was light-weight and narrow but the small joints produced too much lateral play which would have caused the robot sway sideways while walking. The swaying would have caused the joints to bend and damage the legs. The amount of play had to be reduced.

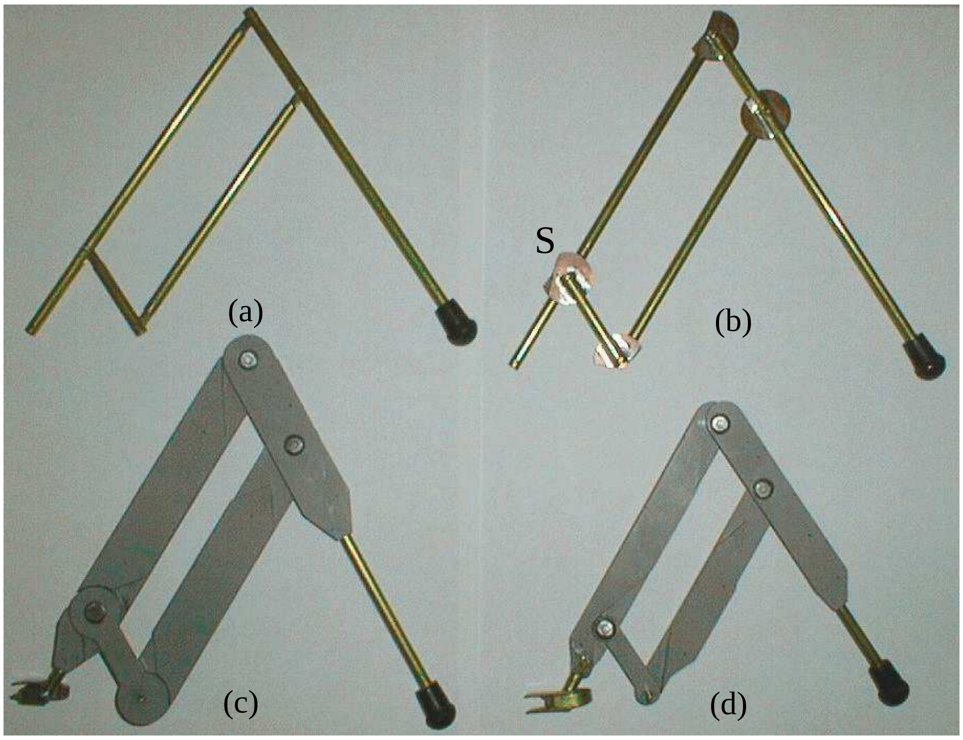


Figure 3.2: The different versions of pantograph legs used for Strider.
(a) The first leg designed. (b) The second leg designed with reduced lateral play. (c) The final design used for the front and rear legs. (d) The design of the smaller sized middle legs.

The next step chosen was to use the same construction material for the legs but to add reasonably large flat disks on the joints. Two disks would be used per joint where each would be mounted onto each bar. The joint was again hinged using a small piece of rod. The resulting leg, shown in Figure 3.2(b), had much reduced lateral play as compared to the first leg due to the large sliding surface area of the disks. However, when the legs were used to hold the weight of the robot's body, the brass tubing at joint S (shown in Figure 3.2(b)) began to bend since the metal was too thin in that region. Another design was necessary that would maintain the reduced lateral play as well as be able to withstand the weight of the robot's body.

The final leg that was designed is shown in Figure 3.2(c). The leg segments were made of PVC pieces cut from $4mm$ PVC sheet on the computerised milling machine described in Section 3.2.1. The pieces were made double the thickness where possible by gluing the PVC pieces together using PVC pipe glue (as used by plumbers). The segments were then hinged together using reasonably wide rivets. The same $5mm$ brass tubing used in the earlier designs was used to connect the leg to the foot. The feet themselves were made of rubber and were connected to the end of the brass tubing. They were made using rubber mushroom buffers that were glued to standard rubber table feet.

Since the gearboxes were designed based on the first legs, which were narrow, and the final legs were about the same width, the final legs were still a little flexible and caused some unwanted lateral swaying of the body.

The orientation of the two middle legs were positioned vertically for reasons that will be explained in Section 3.3.1. The height of the robot was therefore dependent on the size of the two middle legs. These legs were reduced in size as much as possible while still keeping the same magnification factor of the other four legs. A picture of one of the middle legs is shown in Figure 3.2(d).

Strider's legs use a 4:1 magnification factor. The length of the longest leg segment for the front and rear legs is $15cm$ as shown in Figure 3.3. The length of the longest segment for the middle legs is $12cm$. The lengths of the other leg segments can be determined using Equation 2.1. These dimensions were chosen to allow for a stride length of $12cm$.

Figure 3.3 also shows the forces that the leg will experience while standing. The leg is pivoted at point R and a trajectory that is traced at point Q will be magnified four times at point P (the foot). While the robot is standing, the ground reaction force f_p is experienced at the foot.

As a consequence of having a 4:1 magnification, the forces at joints Q and R will be multiplied by the magnification factor of the pantograph [81]. Due to the nature of the pantograph mechanism (as described in Section 2.2), the ground reaction force (f_p) will be magnified by four times at joint Q (given by f_q). Also, the reaction force (f_r) that

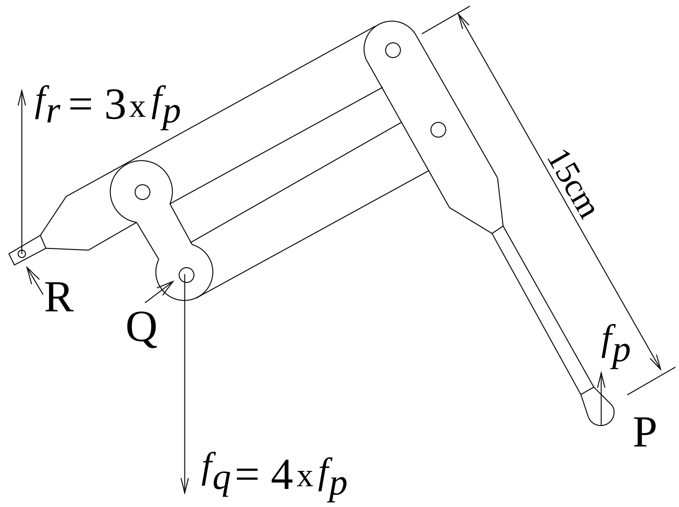


Figure 3.3: Strider's pantograph leg showing the reaction forces experienced while standing.

will be experienced at joint R will be three times higher than f_p. The direction of these reaction forces are also shown in Figure 3.3.

The reaction forces, f_r and f_q, are important since these forces will relate to the friction that is produced at the corresponding joints, R and Q. The strength of the gearboxes that house the legs must be able to cope with the frictional forces at these joints. The leg will be mounted into gearboxes as described in the following section.

3.2.5 The Drive Mechanisms

The drive mechanisms (or gearboxes) are the physical structures used to house the servo motors, the groove-slot mechanism (described in Section 3.4 below), the vertical lift gears and to connect the legs to the chassis.

As described in Section 3.2.1, the gearboxes are composed of PVC pieces that were cut out from PVC sheets. Examples of these pieces are shown in Figure 3.4.

The PVC pieces on the left of Figure 3.4 are for the middle, right-hand gearbox. A duplicate of these parts are used for the middle, left-hand gearbox except that the position of the parts will be exactly opposite when it is constructed. In other words, the left-hand gearbox is the mirror image of the right-hand gearbox. The pieces on the right are for the

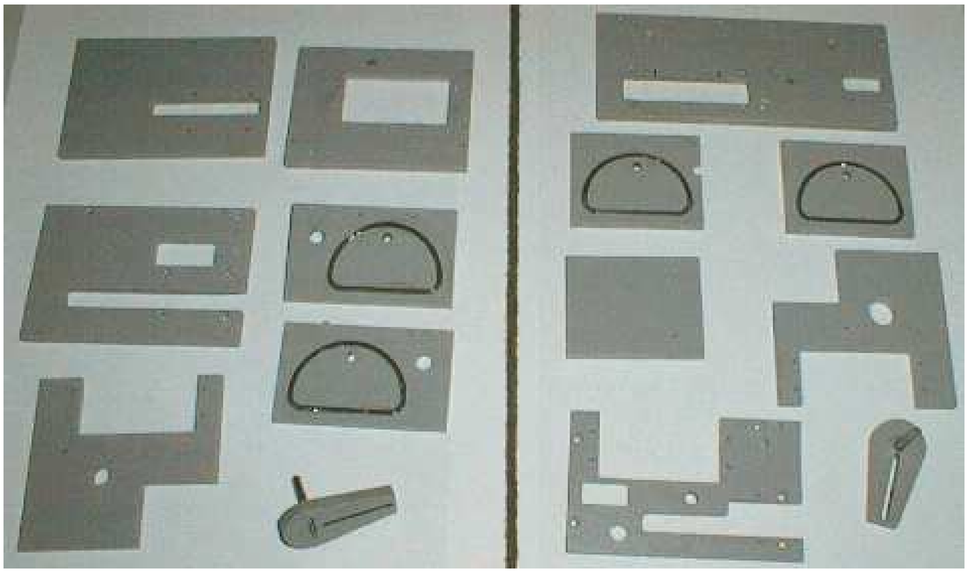


Figure 3.4: Examples of the PVC pieces used to construct the gearboxes. Left: the pieces for one of the middle gearboxes. Right: the pieces for one of the two front or two rear gearboxes.

front, right-hand gearbox. A duplicate of these parts are also used for the front, left-hand gearbox and the two rear gearboxes. The pieces were screwed together using small, $6mm$ long countersunk screws.

The other parts that are housed within the gearboxes include gears, sensors and the motors. The gears and other miscellaneous parts are shown in Figure 3.5. The sensors and the motors are shown later.

The gearboxes were designed by drawing orthographic projections of them using a 2D drawing program. The drawings are shown in Appendix B. These drawings were adequate to work out the shapes of all the PVC pieces. The shapes were then redrawn on computer to be cut out using the computerised milling machine. The six constructed gearboxes are shown in Figure 3.6.

A few more PVC pieces had to be made to join the six gearboxes together to form the chassis of the robot. A picture of the completed chassis without the legs is shown in Figure 3.7.

Figure 3.5: The other parts used in the gearboxes.
The long screw is the lead-screw used for the lift actuators (described in Section 3.2.6). The gears and brass coupling are used as part of the robot's actuators. The plastic washers are used as spacers where necessary and the screws are used to join the PVC pieces together.

3.2.6 The Motors Used on the Robot

One of the first steps in the design of a robot is to determine what type of actuation to use. In the case of Strider, the small and compact servo mechanisms commonly used to control radio-controlled aeroplanes and cars (described in Section 2.4) have been used. The robot required twelve such actuators, two per leg. The DC motors and high ratio gearbox in these servos produce a reasonably fast, high torque actuator that was acceptable for our purpose. Many different servos exist ranging in different size, speed and torque characteristics. An appropriate servo had to be chosen. The method of choosing which servos to use is described below.

For most legged robots that use the strength of the leg actuators to keep the robot standing, the weight of the body and legs had to be estimated at an early stage so that the required actuator torques could be determined [97].

The torque of the motors mentioned below are actually the output torque of the motor/gearbox combination of the servos.

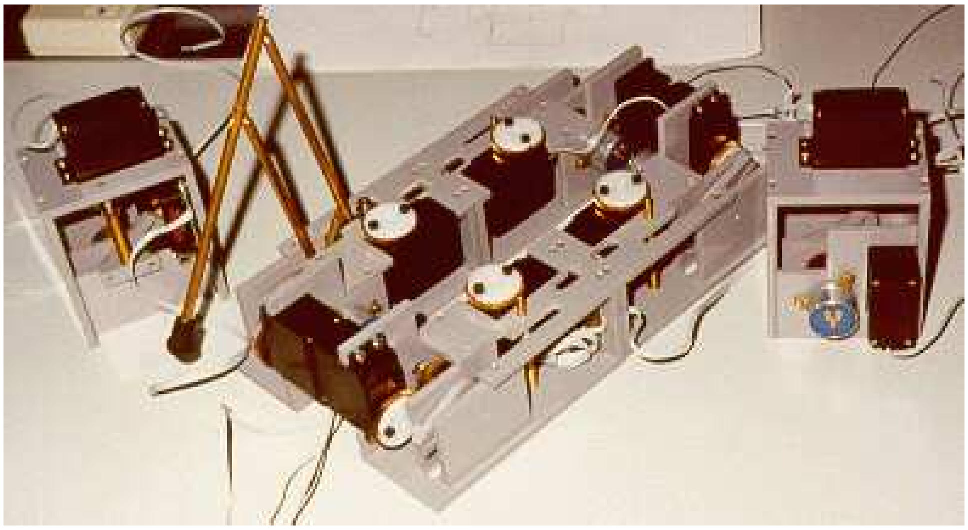


Figure 3.6: The constructed drive mechanism gearboxes.

As will be explained later in Section 3.4, Strider does not use its actuators to stand on level terrain. However, the actuator torque calculations are necessary when Strider is standing or walking on an inclined surface. Therefore, the required actuator torques were determined assuming that the robot is standing on an incline.

In other previous work the same method of estimating the weight of the robot was also used. The weight distribution for the robot Attila (described in Section 2.5.7) was estimated based on the weight distribution of the previous robot Genghis (described in Section 2.5.6). However, the distribution was found to be very different. The weight distribution for the robot Thing [97] was estimated based on the weight distribution of Attila and Genghis but was found to be closer to Attila's distribution. Therefore, the estimated weight distribution for Strider was based on these three robots. Table 3.1 shows the weight percentages of the main sections of the three robots as well as the initial estimated weight distribution for Strider. Strider does not carry batteries and therefore the other areas have a higher percentage.

Now, assuming the total weight of the robot to be $2.0kg$ the torque of the actuators can be determined. Since Strider only uses one actuator per leg to drive the groove-slot mechanism, only the torque of these actuators need to be found.

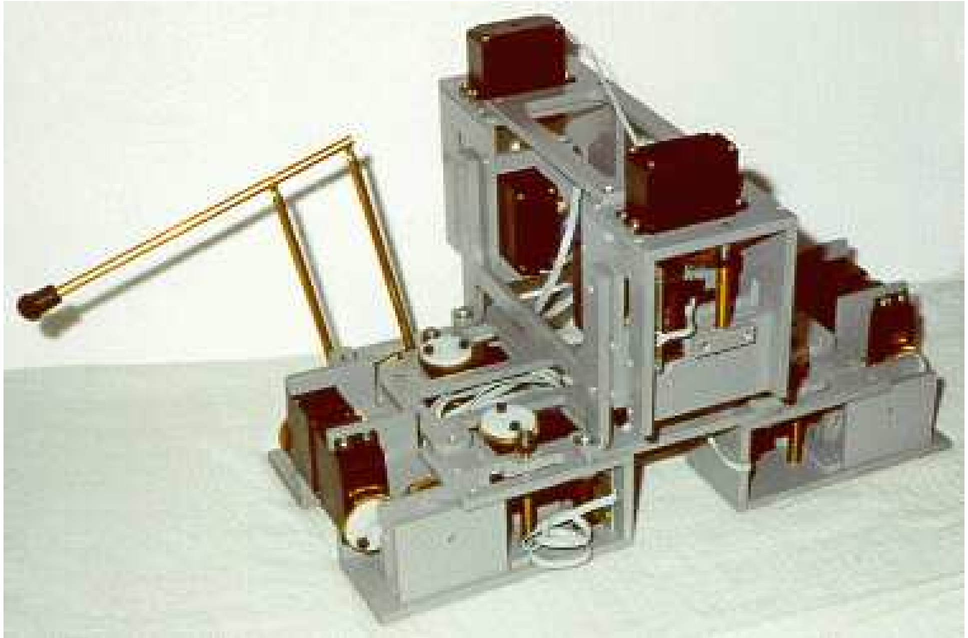


Figure 3.7: Strider's completed chassis showing an early version of a leg.

% of weight	Genghis	Attila	Thing	Strider (estimate)
structure	25	43.5	42	55
electronics	35	22	22	15
motors	30	20	22	35
batteries	10	14.5	14	—
total weight	$1.13kg$	$2.95kg$	$2.02kg$	about $2.0kg$

Table 3.1: Weight percentages for three robots and estimations for Strider.

Due to the design of the groove-slot mechanism the motor torque must be determined as a function of the angle of the maximum inclined plane that the robot can climb. If we assume a maximum climbing angle θ of $40°$, and a robot weight W of $2.0kg$, then the weight acting along the slope W', can be calculated using Equation 3.1 as shown in Figure 3.8.

$$W' = W \sin(\theta) \tag{3.1}$$

which for the parameters as above is

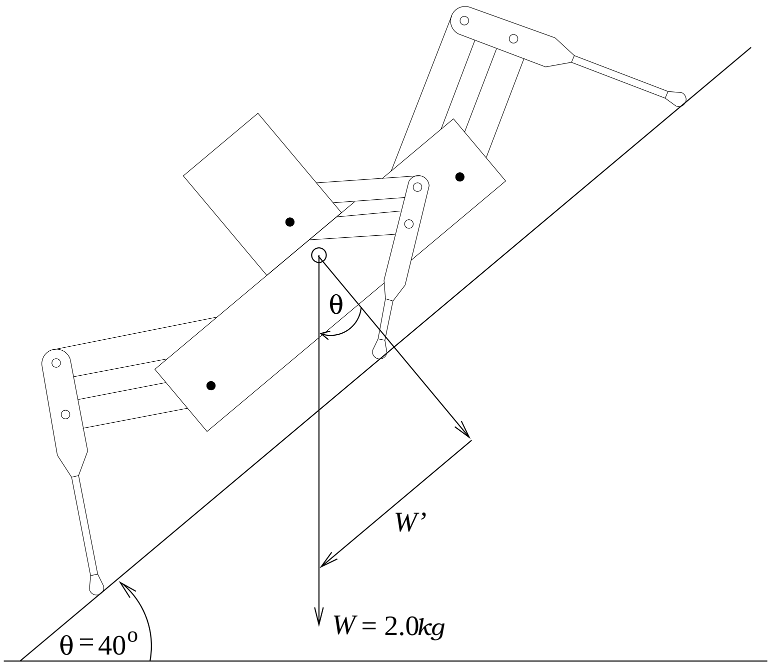


Figure 3.8: Strider on an inclined plane at angle θ.
W is the weight of the robot and W' is the weight acting down the plane.

$$W' = 2.0 \times \sin(40°) = 1.3kg$$

The number of legs that the robot is using to stand or walk should be known. Using fewer legs means that the actuators need to hold more weight. A hexapod robot must be standing on at least three legs to maintain stability. However, since we are assuming a maximum inclination of 40° we must assume that the robot would be standing on five legs at a time while walking. Therefore, each leg must be able to support at least $1.3(kg)/5(\text{legs}) = 0.26kg$.

As will be explained in Section 3.4, the groove-slot mechanism does not require actuators to keep the robot standing on a horizontal surface. This means that when the robot is on an inclined plane, the force perpendicular to the slope, $W\cos(\theta)$, will be absorbed by the groove-slot mechanism.

The magnification factor of the pantograph legs must also be taken into account. As

Model No.	Torque ($kg \cdot cm$)	speed (sec/60°)	weight (g)	Price ($AUD ex. tax)
HS-101	1.7	0.20	26.5	$48
HS-80	2.2	0.15	17.5	$56
HS-422F	2.2	0.15	45.5	$34
HS-300	3.0	0.19	44.5	$24
HS-422	3.1	0.20	45.5	$32
HS-205BB	3.1	0.20	28	$52
HS-605BB	5.5	0.16	49	$72
HS-75BB	6.6	0.5	35	$72
HS-615MG	7.7	0.23	60	$80
HS-700BB	9.5	0.22	102	$55
HS-705MG	11.5	0.27	115	$74

Table 3.2: A list of the range of servo actuators investigated.

shown in Figure 3.3, the vertical force component, f_q, experienced at joint Q (where the groove-slot actuator is used) is four times larger than the force at the foot. Therefore, the weight experienced at this joint will be about $0.26kg$ x $4 \approx 1.0kg$. Also, while a leg is in the standing position, the maximum leverage radius of the groove-slot mechanism is $2.5cm$. This is the maximum distance from the centre of the motor spindle to the position of joint Q.

This shows that the torque of the actuator should be able to support at least $1.0kg$ at $2.5cm$, or $2.5kg$ at $1cm$ radius. Therefore, the motor/gearbox torque of the servo must be at least $2.5kg \cdot cm$.

Table 3.2 shows a list of various servos investigated and their specifications. The ratings given were measured using $4.8V$ across the motors. The servos are ranged in order of ascending torque and the approximate (ex. tax) price per item is also given in Australian currency.

According to this table, the best servo to choose would be the HS-300 since it has the closest torque specification that is greater than the required torque calculated above. The speed of the HS-300 is given as $0.19seconds/60°$ or $0.88rev/s$ at a voltage of $4.8V$. However, a higher speed would have been more appropriate. In an attempt to increase this speed, one of the HS-300 servos were purchased and the normal supply voltage was increased. By increasing the voltage on the motor, both the speed and torque had increased. Using a voltage of $11V$ to $12V$, the speed increased to about $2.0rev/s$ using only about $120mA$ current, and hence consuming only $1.4Watts$. The motor was kept turning for a long time but the high voltage did not cause any damage or excessive heat on the motor. The resulting torque was about $4.0kg \cdot cm$ and therefore the HS-300 servos could be used for Strider's actuators. The HS-300 servo is shown in Figure 3.9.

Figure 3.9: The HS-300 servo used for Strider's twelve actuators.

The design of the groove-slot mechanism requires that the servos turn 360° continuously. Since the servos were originally designed to turn with about 120° angular movement, they had to be modified. The gearing system had to be modified slightly to rotate continuously and this meant that the servo control circuit inside the unit could not be used. As a result, an external position sensor had to be used and the microprocessor on the robot had to control the position of the actuators separately as described later in Section 3.2.8. Therefore, the main use of the servos was to only make use of the small and compact motor and gearbox.

The weight distribution of Strider is shown in Table 3.3. The final weight of the robot was $2.25kg$, a little higher than initially estimated.

The actuators used to lift the legs vertically had to produce linear motion. The

% of weight	Strider (actual)
structure	72
electronics	7
motors	21
batteries	—
total weight	$2.25kg$

Table 3.3: The actual weight percentages for Strider.

rotational movement of the servos had to be converted to the vertical linear movement using a type of screw mechanism.

It was initially intended to use ball-screw devices for the vertical lift gears [36]. Ball-screws consist of a threaded screw and a special nut that contains ball bearings. As the screw is rotated the nut moves linearly along the screw and the ball bearings ensure that nearly all the rotational motion is converted to linear motion with minimal energy waste. Without the ball bearings there would be considerable energy waste due to friction between the threads of the screw and the nut.

The ball-screw approach was not used for Strider, however, for two reasons. Firstly, the ball-screws were very costly per item. Since six such devices were needed for the robot they would have been too expensive. Secondly, ball-screws can be back-driven, that is, the screw can be made to rotate by moving the nut along it. This would be undesirable for Strider since any vertical leg force would make the screw rotate and the actuator would have to be used to prevent it from turning.

An alternative method was to use a lead-screw/nut combination for the lift actuator's linear gears. The lead-screw (shown in Figure 3.5) is a bolt that was shaped at either end on a lathe so that it would be suitable to fit into the gearboxes. Point R of the pantograph leg in Figure 3.3 was then connected and pivoted to a nut that was on the screw. Therefore by turning the screw using the servo, the nut (and hence joint R) would move vertically. It was eventually found that the friction between the lead-screw and the nut was reasonably small and could easily be overcome by the lift actuator. The friction was also adequate to stop the gear from being back-driven. The lead-screw mechanism for the four front and rear legs is shown in Figure 3.10. The lead-screw mechanism for the two middle legs is shown in Figure 3.11.

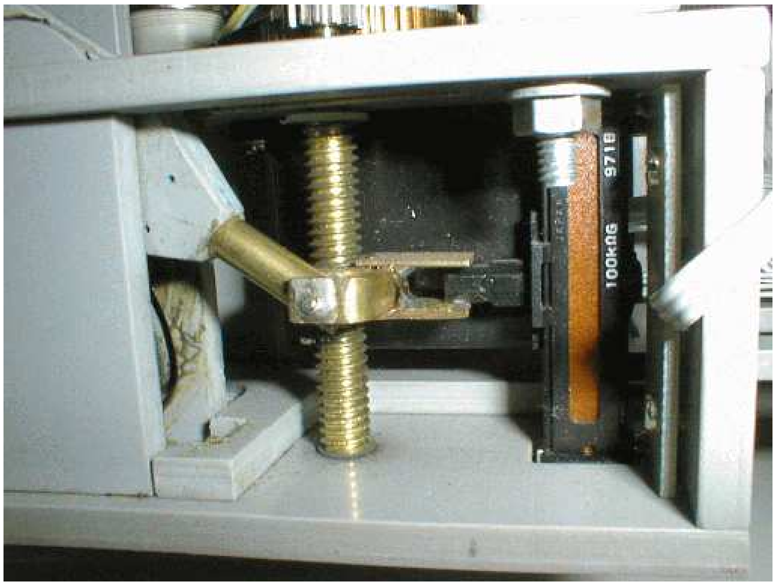


Figure 3.10: The lead-screw mechanism used for the two front and two rear legs.

Since the actuators used to lift the legs vertically did not need to be very powerful to lift the weight of the legs, the same HS-300 standard servos had been used.

3.2.7 The Sensors Used on the Robot

Many of the small walking robots mentioned in Section 2.5 were designed to navigate either autonomously or semi-autonomously in their environment. Strider however was not designed with any navigation in mind and was only meant to walk in straight lines, the same as the CWRU Hexapod (described in Section 2.5.8). Therefore, no special navigation sensors were needed. The only sensors that Strider required were the absolute position sensors for each DOF of each leg and a foot contact sensor for each leg. Hence, there are a total of twelve position sensors and six contact sensors.

The sensors used for the groove-slot mechanism use continuous-turn potentiometers. These replaced the "limited-turn" potentiometers that were removed from the servos as

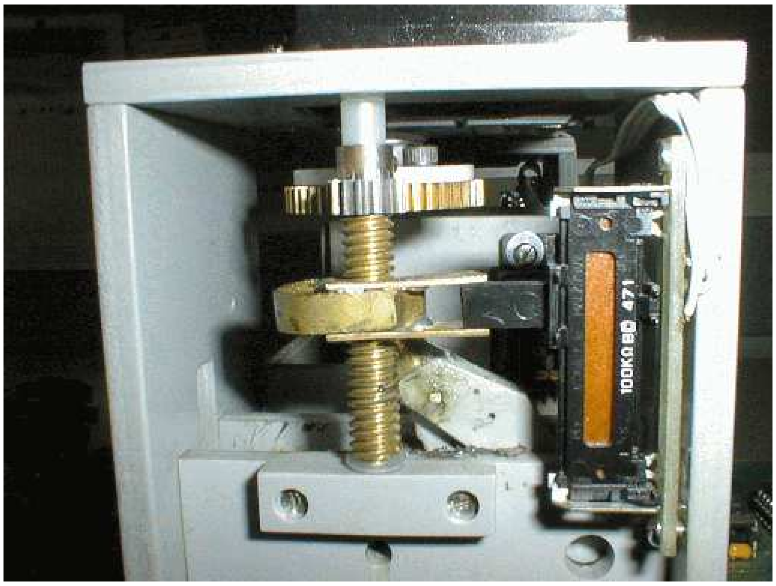


Figure 3.11: The lead-screw mechanism used for the two middle legs.

mentioned above in Section 3.2.6. A $5V$ supply was maintained across the potentiometers and the analogue slider voltage was converted to digital values using an 8-bit analogue-to-digital converter (ADC). These variable voltages are directly proportional to the rotational position of each leg.

The continuous-turn potentiometers have a linear resistance over 340°. A blank 20° region exists where no voltage and hence no position can be read. This did not cause any problems since the 20° region was kept in a fixed position where the leg position was unimportant. The most important leg positions are where the leg is on the ground, just before the leg is placed down and just after the leg has lifted off the ground. The least important position is when the leg is lifted off the ground and is midway in its return stroke. This is where the blank region was kept.

The vertical lift actuators each uses a linear slider potentiometer position sensor. The voltages applied to the sensors were configured the same as the rotational sensors where the vertical position is measured by converting the variable ($0V$ – $5V$ approx.) voltage to a directly proportional digital value. The two types of sensors used can be seen in Figure 3.12.

Figure 3.12: The two types of position sensors used in the gearboxes.
Left: The continuous turn potentiometer used for the groove-slot mechanism. Right: The slider potentiometers used for the lift actuators.

The six contact sensors mentioned above are necessary to detect when a foot has touched the ground or an object. A simple switch contact sensor was designed for the feet but was not implemented due to its small size. An alternative method of detecting foot contact was used instead. A small amount of vertical play was always present in the legs. This small movement was sufficient to move the vertical slider potentiometer sensors described above, about $1mm$. By monitoring these sensors, the small change in vertical position was sufficient to detect when the foot had made contact with the ground. Although the one physical sensor was used for two purposes, the foot contact sensor must be considered as a separate sensor. This shows that Strider has a total of eighteen sensors.

3.2.8 The On-Board Computer, Electronic Circuitry and Power Supply

The design of Strider's electronics is explained in this section. Many problems were encountered during the development of the embedded system and are mentioned where necessary.

In order to control Strider's twelve DOFs and also be able to control the sequence of stepping patterns of the six legs, a small logic controller and associated hardware had to be designed and built to be fitted to the body of the robot. Since it was necessary to perform so many operations in real-time it was obvious that a microprocessor would be needed. Apart from the microprocessor, other devices were also needed to read the sensors and control the motors.

The main requirements were to have a microprocessor to execute programs, at least twelve ADC's, twelve H-bridge drivers, communication with a host computer and a power supply. The ADC's are used to read and convert the analogue sensor readings to digital numbers for the microprocessor. The H-bridge drivers are used to supply power to the motors and to determine their direction. The communication with a host computer allows programs to be downloaded to the robot and commands to be given to the programs from the host computer keyboard.

Since the robot was designed for research purposes only, it was not necessary to have an on-board battery power supply. Therefore, an external $12V$ DC power supply was used in order to reduce the weight of the robot. A standard IBM compatible switch-mode power supply was modified slightly and used to power the robot. Although this power supply provided four different voltages, only the $+12V$ DC supply was used and could supply up to $8.5A$.

Many configurations for the microprocessor and motor control circuits were initially designed using block-diagrams. Some of the designs used field-programmable gate-arrays (FPGA's), analogue multiplexors, digital-to-analogue converters, sample-and-hold devices and 8-bit and 16-bit microprocessors. In the final circuit design all of these devices were omitted. Instead a fast 16MHz 32-bit microprocessor (the MC68332) was used to control all twelve motors, as shown in the block diagram in Figure 3.13. However, the processor's bus was used in 8-bit mode to make the circuit design simpler. The on-board computer also incorporates EPROM, RAM, two 8-channel ADC's and six dual H-bridge drivers for the motors. The board has a connection for serial communications and external power. A host computer can communicate with the 68332 for development and downloading of programs. All the main components used are listed in Table 3.4.

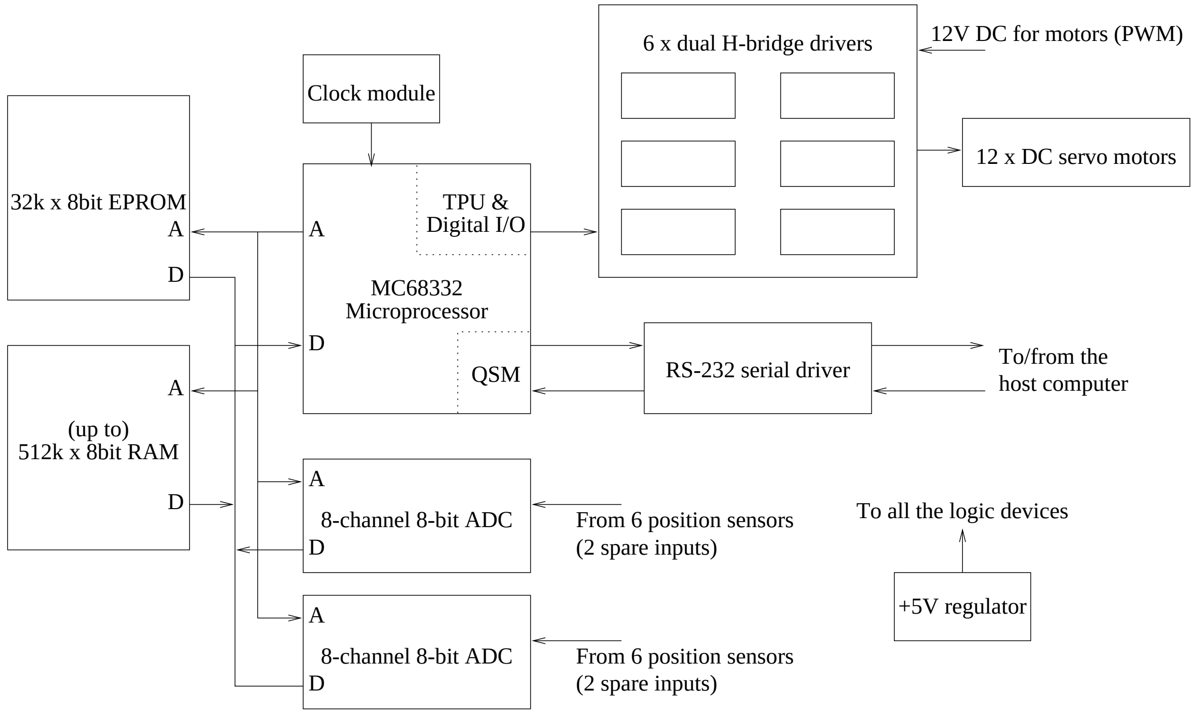


Figure 3.13: The block diagram of the microprocessor and associated circuitry used for Strider.

A wire-wrap board was going to be used to construct the circuit. However this was not done since the clock speed of the microprocessor (16MHz) was quite high for wire-wrap. Also, there would have been too much wiring and the board would have been too large. Therefore, it was decided to design a printed circuit board (PCB). The EEDesigner circuit design package was used for this purpose.

A detailed circuit diagram of the block diagram shown in Figure 3.13 is given in Appendix A. The layout of the printed circuit board is also given in Appendix A. A picture of the final circuit board used for Strider is shown in Figure 3.14. This board was 25cm long and 9cm wide. This is actually an early version of the PCB that contained errors and was modified until it was working properly. The final circuit board layout for the updated circuit diagram in Appendix A was not actually redesigned and built since the modified board was already working.

The Motorola 68332 microcontroller unit (MCU) is an updated version of the 68000

Quantity	Part Description	Part Number
1	16MHz, 32-bit microprocessor	MC68332CFC16
1	32k x 8-bit of EPROM	NM27C256Q
1	up to 512k x 8-bit of RAM	EDI8F8512C
2	8-channel, 8-bit ADC	AD7828
6	dual H-bridge drivers	L293D
1	$+5V$ RS-232 driver/receiver	MAX232CPE
1	16.384MHz clock oscillator module	—
1	$+5V$ voltage regulator	MC7805CT

Table 3.4: The list of the main components used for the on-board processing system.

processor [106] [111]. Its central processing unit is the 32-bit CPU32 [112]. It has several integrated coprocessors including a Queued Serial Module (the QSM) for communications, a 2kB static RAM module and a Time Processor Unit (TPU) [112]. The TPU had 16 independently programmable channels that could perform up to 10 different I/O time-related functions [106]. The TPU operates independently of the CPU32. Twelve of these channels were use to control the speed of the motors using PWM. The mark-space ratio and the period of the PWM signals were set by assigning values to certain registers in the TPU memory map. The complete memory map for Strider's on-board computer is shown in Appendix A.

When power is first applied to the MCU, it is reset using a simple resistor-capacitor circuit. The clock oscillator module provides a continuous 16MHz square-wave for the 68332's clock input. Certain pins on the 68332 had to either be pulled high or low during reset in order to configure various functions of the MCU so that it could be used with the other associated circuitry shown in Figure 3.13. This was done using a $10k\Omega$ resistor tied to either $+5V$ or ground for each pin. These particular pins and the effect these pins have on the operation of the MCU are given in Table 3.5.

The V_{DDSYN} pin (an external physical pin) is the MCU's clock synthesizer power input and had to have $+5V$ directly applied to it at all times for the MCU to operate. Also, by applying $+5V$ to the V_{STBY} (another external physical pin) when the MCU power is turned off, the contents of the MCU's 2k Byte of internal RAM could be maintained.

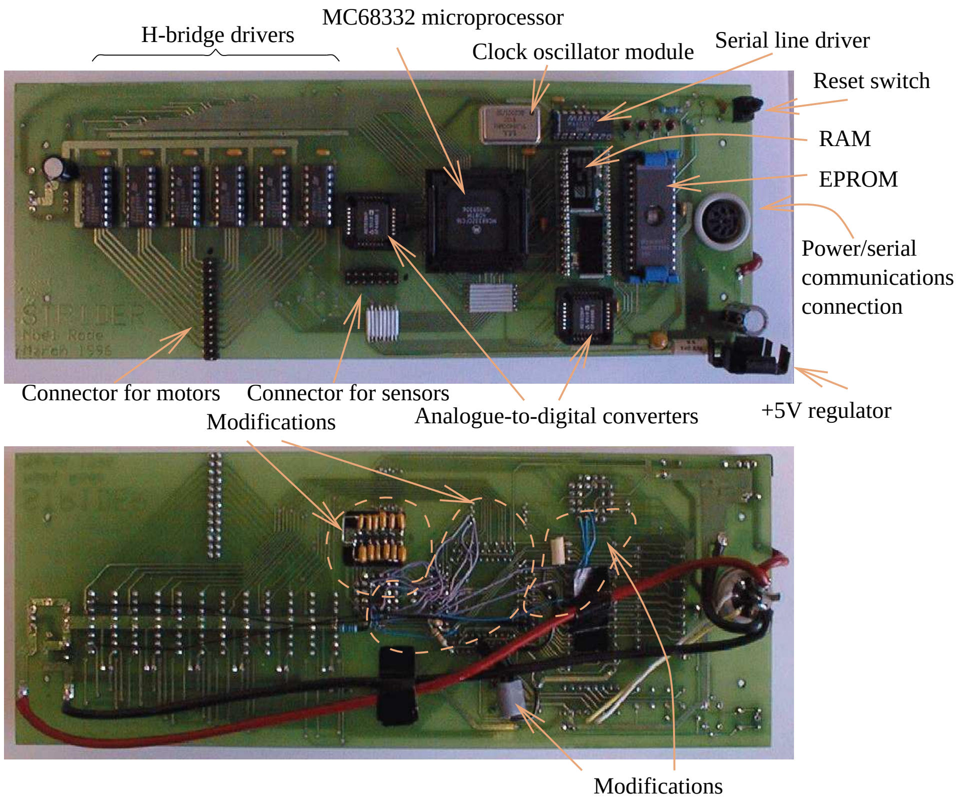


Figure 3.14: The actual printed circuit board used for Strider.
Top: the top-side of the board. Bottom: the under-side of the board showing the modifications made.

However, since this option was not used the pin had to have $+5V$ applied to it only when the MCU was powered.

Power was supplied to the motors using the H-bridge drivers which were controlled using logic levels from the microprocessor. The PWM lines were connected to the enable inputs of the H-bridges. The direction of the motors were controlled using several of the outputs from the discrete output ports of the 68332. Two discrete outputs were originally used per H-bridge. Hence, for twelve motors, a total of twenty-four discrete output lines were used. Using two outputs gave the motors the ability to turn clockwise (binary signal: 01_2), counter-clockwise (binary signal: 10_2) or to brake (binary signal: 00_2 or 11_2). Therefore, the motor could be made to electrically brake by applying an equivalent voltage on both sides of the motor. Unfortunately, it was found at a later stage that the braking force was too weak when coupled with the high gear ratio in the servos and hence

Pin label	Pin Description	Pulled	Effect
D0	First data line	Low	Enables reading of an 8-bit EPROM
D9	Tenth data line	Low	Configures PORT F as an output port
$\overline{BKPT}$	Hardware breakpoint	High	Disable hardware breakpoints
$\overline{HALT}$	Debugging line	High	Prevent suspension of MCU
$\overline{BERR}$	Debugging line	High	Ignore external bus errors
$\overline{DSACK1}$	Data size acknowledge	High	Allow for 8-bit data transfers
$\overline{DSACK0}$	Data size acknowledge	Low	Allow for 8-bit data transfers

Table 3.5: The pins of the MCU that needed to be pulled either high or low for the MCU to operate.

the motors did not brake to any great extent. As a consequence, instead of using twenty-four output lines from the 68332 ports, the H-bridge drivers could have been controlled using only twelve discrete outputs and using two hex inverter IC's to obtain the opposing logic levels for the H-bridges. This approach would have reduced the routing complexity around the microprocessor.

The EPROM is read by the microprocessor when the power is first turned on. The 68332 does this by activating its $\overline{CSBOOT}$ output which is connected to the EPROM's chip enable pin. Code is then executed starting from address $\texttt{000000}_{16}$ as can be seen in Appendix A.

During the design of the board, it was not known how much RAM would be needed. It was difficult to judge how large the final executable files would be once the programs were compiled. Using C libraries, the final executable files would be larger than if the code was only written in assembly language, but again the executable file size was still difficult to estimate. Although the amount of RAM on the board is limited to 512k Bytes, this amount was found to be very sufficient. The largest file size of the compiled programs was about 50kB (using C libraries). Thus, a 64kB or 128kB RAM module would have been sufficient. Hence, instead of having nineteen address lines, either fifteen or sixteen address lines could have been used. This also would have reduced the routing complexity in the circuit board layout.

As shown in Figure 3.13, only six of the channels from each of the two 8-channel

ADC's were used to read the robot's position sensors. The four spare channels could be used at a later stage for any additional analogue sensors.

The ADC's were configured such that the address given to them by the microprocessor during a read cycle indicated the channel to be read. By giving the same address to each ADC, they could read pairs of sensors at a time. Therefore, only six read operations were necessary to read the twelve sensors. Also, the ADC's were configured such that the actual ADC value read on the data bus is the result of the *previous* ADC conversion. Hence, the current read would start the ADC conversion of the given address but would not be read by the microprocessor until the next read operation. This was necessary so that the ADC's could be given enough time to perform their conversion. Otherwise, the microprocessor would have to wait until each conversion was complete before proceeding.

The output data lines of one ADC were connected to lines D7-D0 of the microprocessor, while the other ADC was connected to lines D15-D8, as shown in Figure 3.15. Therefore, the microprocessor had to read a 16-bit word value to read the two ADC's. This meant that the address given to the ADC's used the address lines A3, A2 and A1 of the microprocessor. A0 was not used since it could only be used to read 8-bit (byte) values. The six ADC inputs were therefore addressed from $\texttt{10000}_{16}$ to $\texttt{1000A}_{16}$ as shown in Appendix A.

One of the problems encountered with the ADC's is that when the microprocessor was reading the sensor values and then one sensor was adjusted, the values of some of the other sensors would drift rapidly. The ADC's have an inherent sample-and-hold feature built into their analogue input switching. The voltage being sampled must remain constant for about $1\mu s$. Since the microprocessor uses a 16MHz clock speed, it is likely that the analogue switching was occurring too rapidly causing the held voltages of the other channels to drift when one sensor was adjusted. This problem was overcome by adding $0.1\mu F$ capacitors on each analogue input to the ADC's. The capacitors held the sensor voltages for a longer duration such that they did not interfere with each other, and the

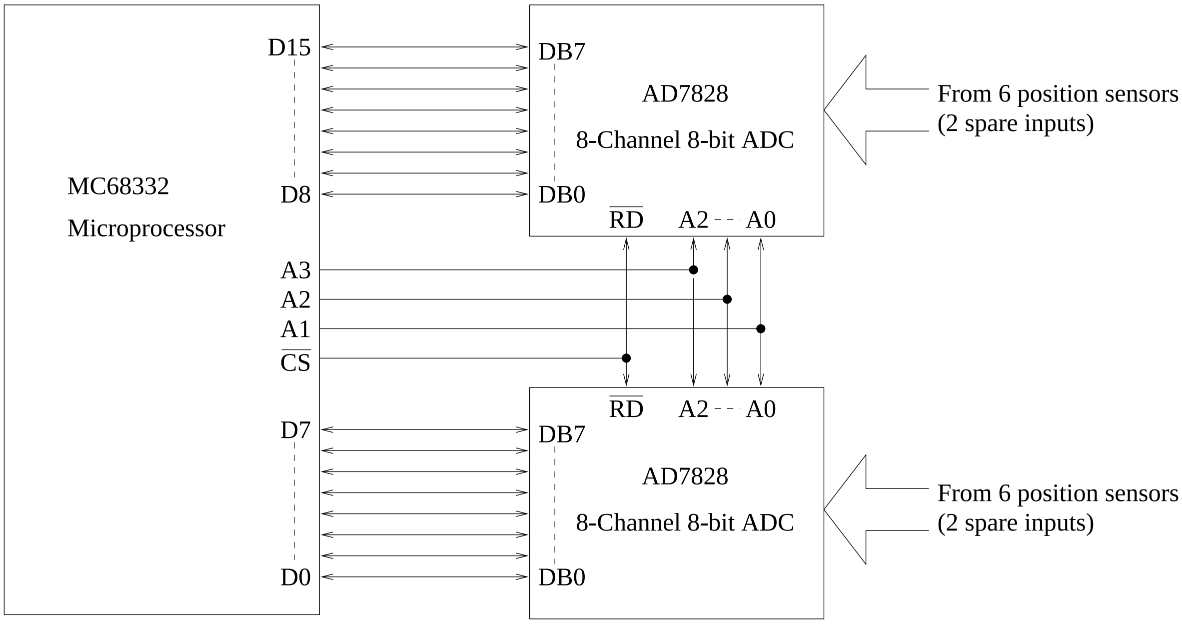


Figure 3.15: The connection of the two ADC's to the microprocessor.

ADC's could then perform their conversion.

The RS-232 serial line driver was used to convert the microprocessor's logic levels to RS-232 logic levels and vice versa.

3.3 Structural Biological Inspirations

If we were to compare the walking of current legged robots with the walking of animals there will be obvious and significant differences in the way they move [26]. Animals walk with so much more agility than any robot ever built. Since nature has (so far) produced the ideal rough terrain locomotors it only seems natural to study the creatures we have in the world and use the information to inspire our new creations. Therefore, it should be obvious why many researchers are looking more towards these biological organisms for inspirations to create mechanical, robotic equivalents.

As an example, Weidemann et al. [113] [25] used biological research findings from Cruse et al. [24] to develop a hexapod robot based on the stick insect (*Carausius Morosus*).

As previously mentioned, the study of the cockroach has played a role in our research.

The structure of the legs of the cockroach and the effects that the leg angles have on the kinematic behaviour of the insect have been investigated in detail by researchers such as Full et al. [11]. This information inspired the design of Strider.

Apart from the biological structure of the cockroach, researchers have also investigated the gait generation of these insects [41] as will be discussed further in Chapter 4.

3.3.1 Leg Angles

The legs of a cockroach are generally positioned such that the front legs are angled towards the front of the body at all times while walking. The rear legs are always angled towards the rear and the middle legs change from pointing forwards to pointing rearwards during a complete stride or step. In effect, while in motion, the front legs decelerate the insect's body, the rear legs accelerate the body and the middle legs both decelerate and accelerate the body [11].

Figure 3.16 shows a lateral projection of a cockroach. When the feet hold the weight of the insect's body a ground reaction force is produced. The vertical component of the force is about 1.5 times the body weight [11]. The angle or direction of this force changes as the legs move from their most forward position to their most rearward position. As can be seen in Figure 3.16, the ground reaction force of the front leg is always pointing forward, just as the leg itself is also pointing forward [22]. The middle and rear legs also experience similar ground reaction forces corresponding to the direction that each leg is pointing.

Full et al. [11] showed that the front, middle and rear legs of a cockroach each play different roles in accelerating and decelerating the centre of mass of the cockroach. They argued that legs that push against one another, which generate horizontal accelerating and decelerating ground reaction forces, can reduce the overall force production. This would cause both the joint moments and the muscle forces to be minimised. This is contrary to the larger joint moments that are produce in the legs of birds and mammals

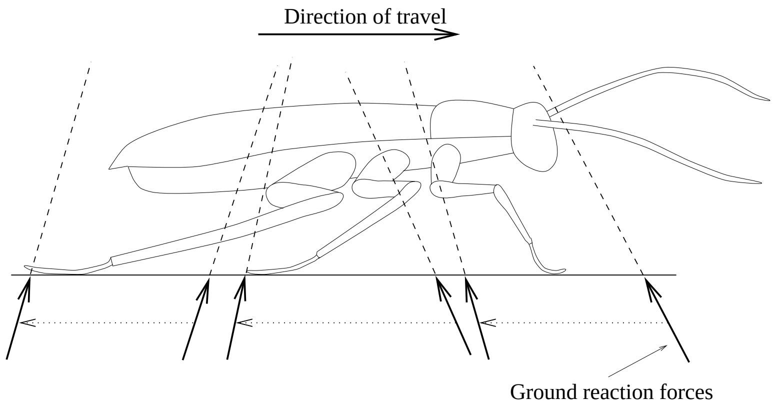


Figure 3.16: A lateral projection of a cockroach showing the change in direction of the ground reaction forces of the legs while it walks forward.

whose legs are vertically oriented. They also mention that by reducing the horizontal ground reaction forces, the energy fluctuation of the insect's centre of mass would also be reduced. These observations were made primarily from the *Blaberus discoidalis*. Also, a set of three legs angled in this way together perform the same function as one leg of a biped. Hence, normal walking would be more coherent.

The legs of Strider were angled in a similar way to the legs of the cockroach in order to approximate the acting forces. Although the legs of the cockroach operate in three dimensions, the legs for this robot were simplified by restricting them to two DOFs. The legs can move in a vertical plane, in the longitudinal direction, parallel to the body. Movement in the lateral direction (away from the sides of the body) was restricted in order to simplify the operation of the robot. Hence, only the forces acting from a lateral view of a cockroach have been adapted to this robot.

Figure 3.17 shows the maximum area of movement that the legs can move in two dimensions. The front and rear legs always point towards the front and rear respectively during a complete stride. The angle of the middle legs change from pointing forward to pointing rearward in a complete stride, although they are angled less. This, however should not affect the performance of the robot.

Having the legs of Strider angled in a similar way to that of the cockroach is one of the

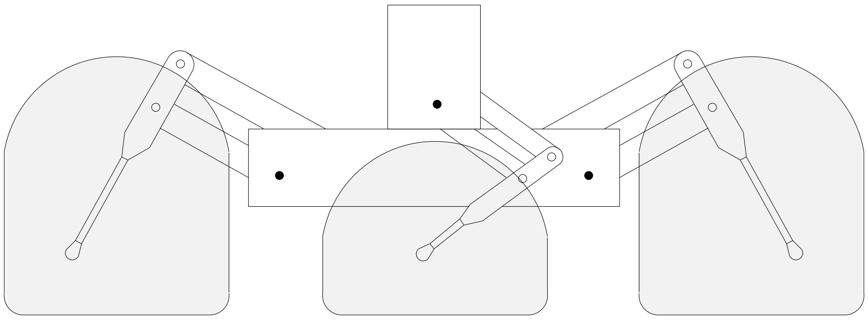


Figure 3.17: The leg workspaces shown from a lateral projection of the robot.

biological inspirations for the design of its mechanical structure. Another walking robot that incorporated this same feature was Boadicea, described in Section 2.5.9.

3.3.2 Leg Sizes

Another biological inspiration that can be obtained from a cockroach are the leg sizes. The front, middle and rear legs each have different sizes which vary in different species of the cockroach. The front legs of the *Blaberus Discoidalis*, for example, are smaller than the others while the rear legs are the largest. The rear legs on the *Periplaneta Americana* are also the largest but it has longer front legs than the *Blaberus* [41]. Generally, the larger (or longer) the legs, the greater the physical strength.

There are several reasons for the cockroach to have long rear legs. Firstly, large strong rear legs are needed to produce fast accelerations when propelling the insect forward. Another reason is that since the insect's abdomen protrudes towards the rear of the insect, the long rear legs help to keep it from dragging on the ground. Also, since the workspace (or area of movement) of the rear leg overlaps the workspace of the middle leg, the rear legs, being long, can be used in place of an amputated middle leg to maintain stability while walking [41].

As can be seen in Figure 3.17, the front and rear legs on Strider are each the same length while the middle legs were made slightly smaller in order to reduce the height of the robot, as mentioned previously. Although these leg size differences exist, the strength of the larger legs are the same as the two middle legs. The reasons for making all the legs have the same strength are explained as follows. Firstly, high accelerations were not necessary for this robot and it was easier to use the same strength motors on each leg rather than have the rear legs use stronger motors than the others. Doing this would have caused the body weight to be distributed unevenly across the body. By having the same weights on either side of the body it made the body more symmetrical. The body was also designed so that there were no protruding masses from the body, as is the case with the cockroach. Hence, no legs had to be particularly longer or stronger to hold the body up. Making the workspace of the rear leg overlap that of the middle leg can be a desirable feature. However, this was not implemented on this robot since this research was not involved with the amputations or disfunctions of any particular leg. Therefore, for these reasons, there was no need to make the three pairs of legs have both different sizes and different strengths for this robot.

Again, the robot Boadicea (Section 2.5.9) used different sized front, middle and rear legs in order to approximate the overlapping leg workspaces of the cockroach. This robot also used different strength pneumatic actuators for the different sized legs.

3.3.3 Using Six Legs

One more biological inspiration that can be obtained from insects is the number of legs that they have. One of the first decisions to be made when designing a walking robot is how many legs it should have to be sufficient for its purpose. McGhee et al. [12] found that the stability of a multi-legged walker increases significantly when using four, up to six legs but the stability increases very little when seven or more legs are used.

Many researchers have opted to use four legs in their robot designs but these robots have the problem of not always being statically stable since they can fall over when using certain gaits. Four legged animals, for example, have gaits that include the gallop, trot and the canter. There are actually a large number of different gaits possible using four legs, however, there are only six gaits that exist that keep at least three legs on the ground at a time, making these the most stable gaits for four legged walking. These are called creeping gaits and allow the animal to walk stably for most of a locomotion cycle. According to McGhee et al. [114], only three of these six gaits allow the animal to walk stably at all times. Apart from the type of gait being used, four legged machines must also shift the position of their body at each step in order to maintain their stability [115].

Other robots that have three legs can stand stably but must be dynamically balanced while walking. Robots that have two or one leg must dynamically balance in order to both stand and walk (or hop).

If six legs are used, at least three legs can be kept on the ground at all times while walking. A large number of gaits exist for six legged walking and they will always be statically stable as long as there are three legs on the ground at any time. Therefore, a six legged robot would not require dynamic balancing at any time. For these reasons, six legged walking was chosen for our work.

3.4 The Groove-Slot Mechanism

Most walking robots that were developed use two or more actuators per leg, that is, each leg has two or more DOFs. This gave the legs the ability to lift up and down and swing forward and backward. This is necessary for normal walking since the legs need to move the feet backward while they are on the ground to propel the robot forward and then lift up, move forward and then be placed down again for the next stride. This semicircular cyclic motion can however be achieved using only one DOF.

Previous attempts to use only one DOF had used the four-bar linkage mechanism, described in Section 2.5.3, that produced a semicircular trajectory for the feet of the robots. Some of these robots include MELWALK MARK-III (described in Section 2.5.3), Dante [42] and Dante II [46].

The drive mechanism used for Strider is a unique and simple design that produces a similar semicircular trajectory for each leg. This system, known as the *groove-slot mechanism*, can produce relatively high walking speeds using low RPM (revolutions-per-minute), highly geared motors. The main advantage of the groove-slot mechanism is that no power is required for standing on a horizontal surface and it allows the robot to carry a reasonably large payload.

Raibert and Sutherland [115] were two researchers who believed that legged machines could be built to minimise the vertical fluctuations that naturally occur in animals such as horses. The groove-slot mechanism is one such mechanism that does this.

3.4.1 Mechanical Description

A pictorial breakdown of the groove-slot mechanism is shown in Figure 3.18.

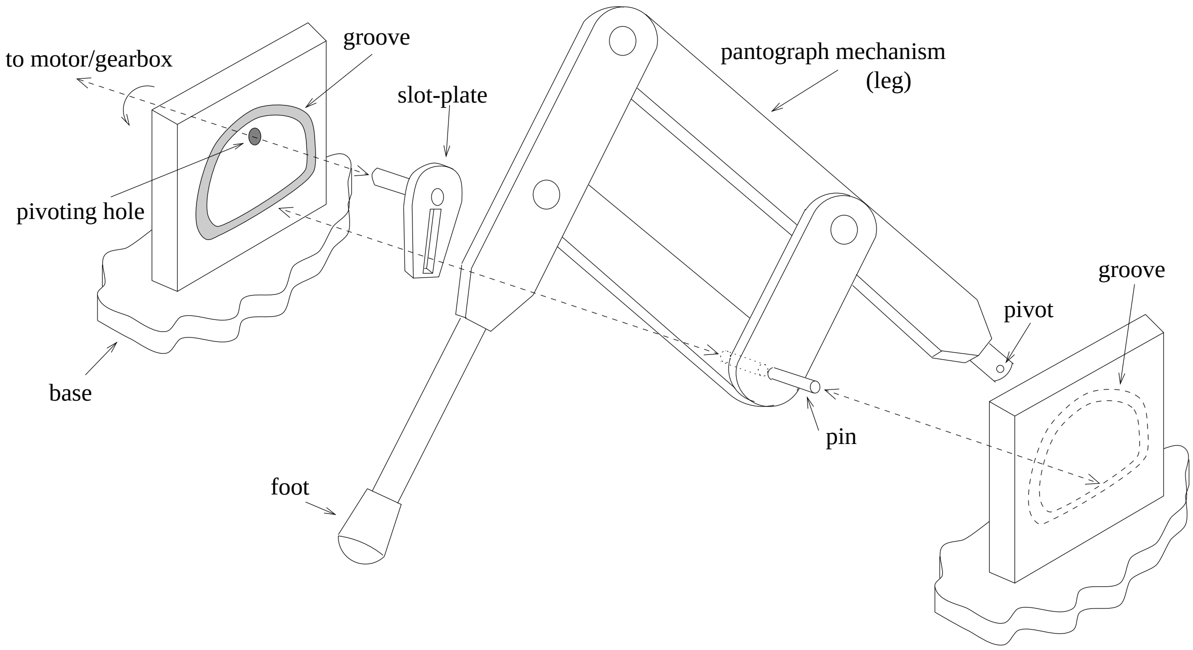


Figure 3.18: The groove-slot mechanism with one leg.

The groove-slot mechanism is comprised primarily of two parts. A pair of plates with semicircular groove sections, where the groove is cut approximately 3/4 into them, form one part. These are the *groove plates*. The semicircular shape has been used since it will allow the robot's foot to move rearward in a straight line while it is on the ground and also allow the foot to be lifted and returned towards the front of the robot for the next stride. The other part is simply a plate situated between the two groove plates that has a slot cut into it and is called the *slot-plate*.

The slot-plate is pivoted through a hole that is situated inside the semicircular groove of one of the groove plates. This is the left-hand groove plate in Figure 3.18. The length of the slot is slightly longer than the maximum radius from the pivot point to the outer edge of the semi-circular groove.

A small rod or pin that is as thick as the groove is fitted through the slot-plate and then into the two groove plates. The semi-circular path in the groove plates can then be traced by the pin by rotating the slot plate about the pivot point. The slot-plate will push the pin along the path of the groove and the pin will therefore trace the semicircular trajectory. Now, by installing the pin into the pantograph leg shown in Figure 3.19 at point Q, the foot of the leg (point P) will follow the groove's trajectory and will be magnified by four times.

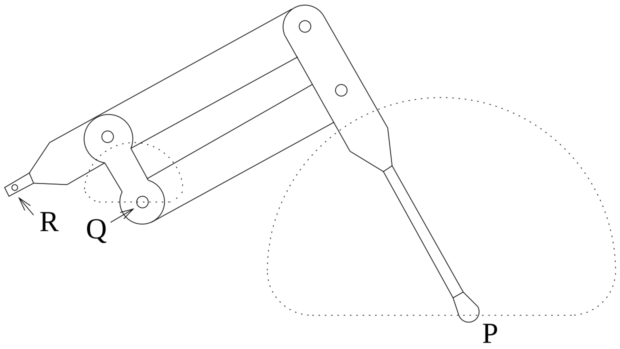


Figure 3.19: Magnifying a trajectory using the pantograph mechanism.
The pantograph mechanism is pivoted at point R. The trajectory at point Q is magnified 4 times at the foot P.

Since the semicircular trajectory is fixed and it allows even traversal along a reasonably flat horizontal plane, it means that it cannot walk over rough terrain using the groove-slot mechanism alone. The legs must have a means of being lifted when small obstacles are in the robot's path. The MELWALK MARK-III robot did this by making the legs vertical and were actuated telescopically as shown in Figure 2.11(c). The vertical leg movement for Strider's legs was achieved using the lead-screw actuator at joint R in Figure 3.19 as described in Section 3.2.6.

3.4.2 The Reasons for the Shape of the Groove

Two terms that are commonly used to describe the motions of a leg are the *retraction* and the *protraction*. The retraction is the process of moving a foot backwards (while it is on the ground) to propel the robot forward. The protraction is the process of lifting and moving a leg from the posterior (rear) to the anterior (front) of the robot for the next retraction.

With reference to Figure 3.20, the groove has a flat, horizontal section that is used to retract the leg to propel the robot forward. This flat section forces both the pin in the groove and hence the leg to move along the flat, horizontal path also. Therefore, the up and down movement of the centre of gravity of the body will be minimised and will also increase the energy efficiency of the walking machine [8].

The large curved section of the groove is used to protract the leg (moves it from the rear to the front). There are two main reasons for choosing the shape of the groove that produces this foot trajectory, as described below.

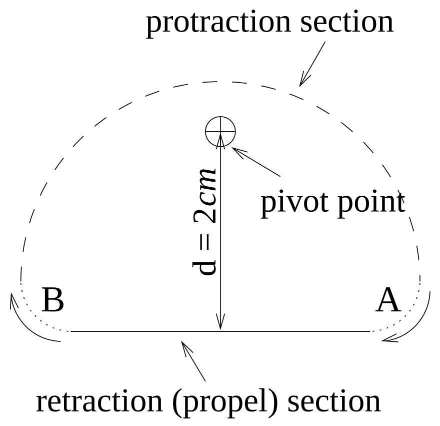


Figure 3.20: The sections of the groove.

Firstly, it was necessary to use a half-circle in the trajectory because of the positioning of the pivot hole. If the hole was made too close to the horizontal (propel) section then the pin would become jammed at either end of the horizontal section. By moving the hole as far away from the horizontal (retraction) section as possible the pin would be less likely to jam. The hole however, had to be within the groove shape so that the rotation of the slot-plate could move the pin along the trajectory. Through experimentation, a distance of d=2cm from the pivot point to the centre of the horizontal section was found to be adequate.

The second reason for the shape of the groove is explained as follows. It involves the two small curved sections shown as dotted arcs in Figure 3.20, labelled ‘A’ and ‘B’. Many walking robots place their feet down before the retraction begins which results in short pauses while walking. The pauses at these leg positions can be avoided to make the walking more coherent or fluent by making use of these two curved sections as described below.

In order to maintain stability while walking using most gaits, two consecutive legs must retract in sequence for a short duration. In other words, when one leg is about to be lifted off the ground and while another leg is about to be placed down, they should both be kept on the ground for a short duration to allow for an even transition from one leg to the other.

A leg that is about to be placed down will follow the curved trajectory labelled ‘A’. The leg will gradually come in contact with the ground and start retracting at the same time. A leg that is about to be lifted will continue retracting until it is lifted by following the curved trajectory labelled ‘B’.

By specially coordinating the legs, the leg being lifted and the leg to be placed down can both be kept on the ground for a short duration and the small curved sections of the groove will allow them to make smooth transitions.

Hence, due to the shape of the groove, since the feet are retracting while they are gradually coming in contact with the ground, we have legged locomotion with the characteristic fluent behaviour of wheeled vehicles.

3.4.3 Standing Without Expending Energy and Payload Limitations

The groove-slot mechanism allows the robot to stand without expending any energy while it is on a horizontal surface. This is a very important feature since many other robots require continuous battery or external power to be applied to at least one actuator to stand at all times.

Hirose et al. [39] also knew of the difficulty of obtaining energy efficiency with legs that are coupled to gravitational forces. This is because both body-support forces and propulsive forces are required by the actuators. One of their robots, KUMO-I [38], consumed much energy to support its own weight. The actuators on such robots expend energy to support the body weight when both accelerating and decelerating. Since Strider's legs are gravitationally decoupled, only the propulsive forces from the actuators are necessary.

Strider's ability to stand without expending energy is explained as follows. When Strider is horizontal and stationary, the pin sitting in the retraction section of the groove will have an upwards force due to the weight of the robot experienced on the legs, that is, the ground reaction force. The pin cannot move vertically in this section and this restriction of movement will therefore allow the robot to stand indefinitely.

This can also be considered an advantage while walking since energy is only needed to push the pins horizontally and hence move the legs, and no extra energy will be used to keep the robot up.

Since the pantograph mechanisms have a 4:1 ratio, the vertical force exerted at joint Q in Figure 3.19 (Section 3.4.1) will be four times larger than that on the robot's feet while standing or walking. The main friction therefore occurs between the pin in each leg and the retraction section of the groove in which it travels through. Graphite powder and grease have been used to reduce this friction. On a larger scale, more elaborate mechanical devices such as a ball bearing system could be used to reduce the friction.

The amount of payload the robot can carry is mostly dependent on the structural strength of the pin, the groove and the strength of the pantograph legs. The amount of friction between the pin and the groove and the torque of the actuators must also be considered. Also, the friction and inertial properties would become a problem when a large payload is being used.

Since the amount of payload is dependent on the structural strength of parts of the robot, the approximate maximum payload could only be determined through experimentation. Previous research compared the performance of walking robots using factors such as the power consumed for locomotion, the mass of the robot, the payload it could carry and the speed and length of the robot. These performance comparisons were based on the energetic cost of motion, or the more common *specific resistance* calculations [30] [39] [8].

Binnard [41] used a different method to compare his robot (Boadicea) with the previous robots. The speed of each robot was normalised by finding the ratio between the speed and length of the robot. Then the ratio between the maximum payload the robot could carry and mass of the robot was determined. The product of these ratios gives the normalised work capability of the robots, given in Equation 3.2.

$$normalised\ work = \frac{speed}{length} \times \frac{payload}{mass} \tag{3.2}$$

The maximum recorded speed that Strider could walk was $17cm/s$. The maximum length of the robot with its legs fully stretched is $63cm$ and its weight is $2.25kg$. The maximum payload the robot could carry was more than its own body weight. The robot was found to

Robot	Length (m)	Mass (kg)	Speed (m/s)	Payload (kg)	Normalised work capability (%)
Ambler [76]	3	2700	0.0058	480	0.0323
PV-II [16]	0.87	10	0.02	2	0.46
Sherpa (Odex) [68]	2	490	0.083	300	2.55
Walking Truck [31]	4	1300	0.9	220	3.91
Genghis [20]	0.39	1.8	0.038	0.8	4.27
ASV [30]	5	3200	3.6	225	5.04
Boadicea [41]	0.5	4.9	0.11	2.3	10.12
Strider	0.63	2.25	0.17	2.7	32.38

Table 3.6: Normalised work capability of various legged robots.

walk very easily with payload a of $2.35kg$ without affecting the robot's speed considerably. However, the maximum payload it could carry before the legs became too unstable was about $2.7kg$. If the legs were stronger, and with less flexibility, it would have been able to carry an even greater weight. Using the above information the work capability can be calculated as shown below.

$$Strider's\ normalised\ work = \frac{17}{63} \times \frac{2.7}{2.25}(\%) = 32.38\%$$

Even when Strider carried $2.7kg$ the motors were still propelling the robot. It was only the weakness of the legs that limited the payload.

Table 3.6 shows the normalised work capability of some other walking robots. Figure 3.21 shows a plot of the payload capacity and the normalised speed of the robots (diagram adapted from [41]). As can be seen the work capability of Strider is higher than any of the previous robots listed. This shows that the design of the groove-slot mechanism can be used for high speed walking and that it allows a robot to carry large payloads.

3.4.4 Determining the Walking Speed

In order to determine Strider's walking speed the length of time that the legs remain on the ground while walking must be known. This must be determined using the dimensions

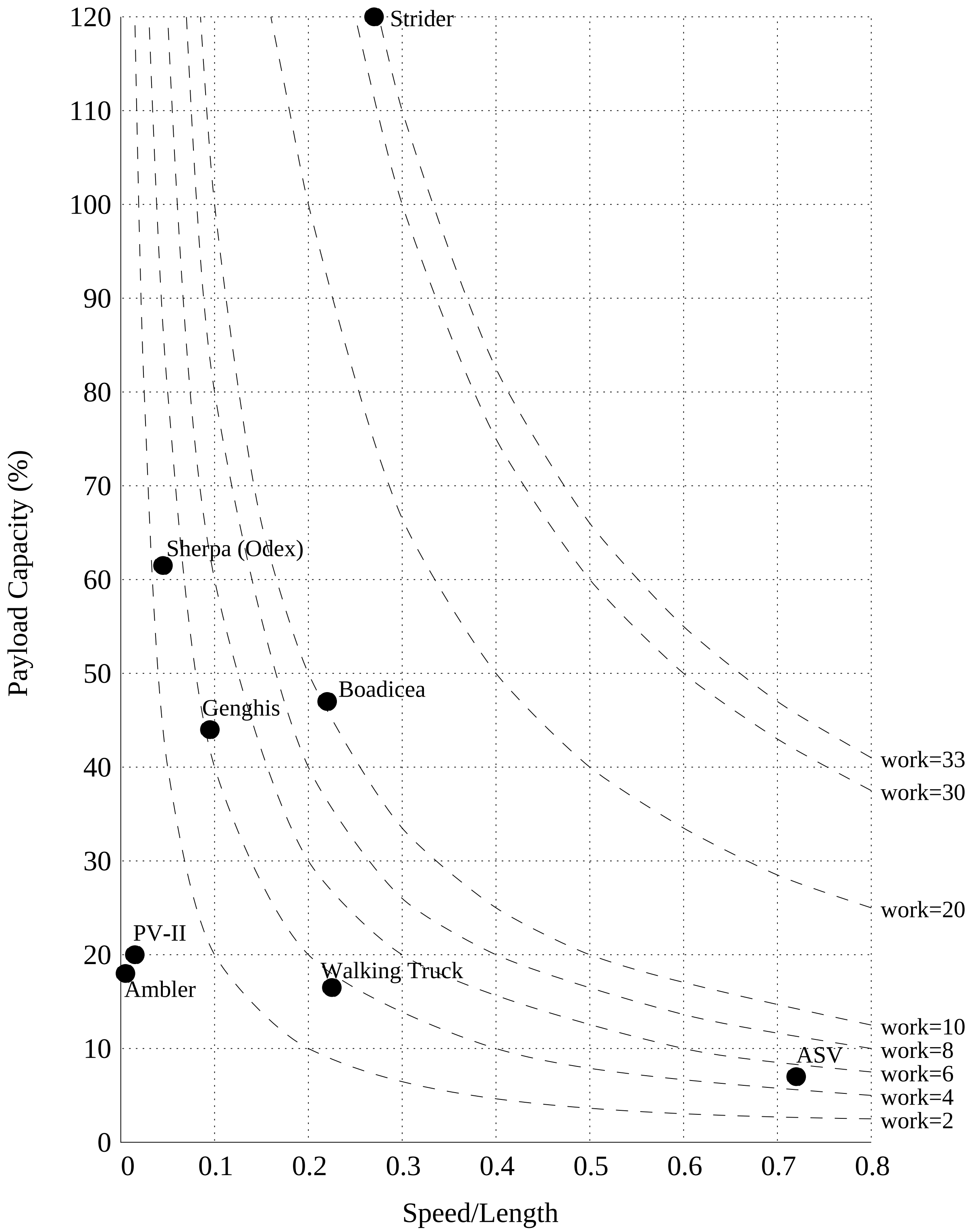


Figure 3.21: The normalised work capability of the legged robots given in Table 3.6. The figures are based on the speed/length ratio and the payload capacity/robot weight ratio.

of the groove given in Figure 3.22.

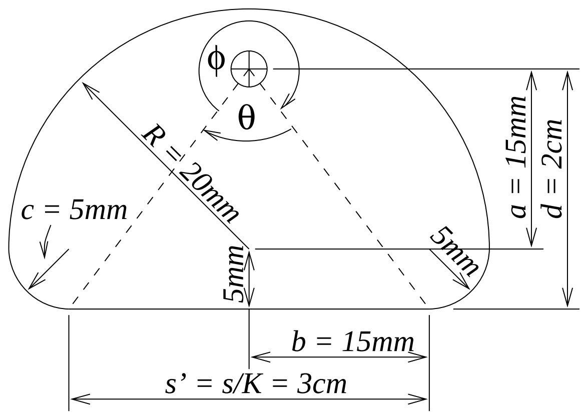


Figure 3.22: The physical dimensions of the groove.

The angle θ and the corresponding angle ϕ relate to the angular position of the slot-plate during the retraction and protraction of a leg, respectively.

The angle θ is about 1/5 of the entire revolution. This means that if the slot-plate is rotating at a constant speed, the leg will spend about 1/5 of the time in the retraction section than it will in the protraction section. As a result, if the robot was walking using a tripod gait where each pair of three legs are 180° out-of-phase, the legs that are retracting must remain on the ground for about five times longer than the legs that are protracting such that the retraction time is the same as the protraction time. This can be done in two ways, as follows.

Let us consider two such legs that are 180° out-of-phase. The rotation speed of the slot-plate can be reduced while one leg is retracting so that it will finish retracting at the same time that the other leg has finished protracting. We can call this Approach A.

The other method (Approach B) would be to maintain the same rotation speed causing a leg to retract almost as fast as it protracts. Consequently, if we consider again two such legs, when one leg has finished retracting, it must stop at the end of the stride and remain in the same position until the other leg has finished protracting. This would cause the robot's body to make abrupt forward movements with pauses in between.

The latter approach was used in most of Strider's programming since it was the easiest to implement. Some attempts have been made, however, to use the former approach.

Normally, the walking speed would be determined based on the speed of retraction. However, since the duration of the protraction using the groove-slot mechanism is longer than the retraction, the walking speed must be determined based on the maximum speed of the protraction. This applies to both Approach A and B, and is calculated as follows. Firstly,

$$\phi = 360 - \theta$$

Using Figure 3.22, θ is given by

$$\theta = 2\arctan(\frac{s'}{2d})$$

or

$$\theta = 2\arctan(\frac{s}{2Kd})$$

where s is the stride length, K is the magnification factor of the pantograph mechanism and d is the vertical distance from the pivot point to the horizontal section of the groove-slot mechanism.

If r_m is the rotation speed of the slot-plate in revolutions per second, then the slot-plate will rotate ϕ° in

$$t = \frac{\phi}{360 r_m} = \frac{1 - \frac{1}{360}\theta}{r_m} \quad seconds$$

As can be seen in Figure 3.22, the horizontal section is s'=3cm long. With a magnification factor of K=4 for the pantograph legs, this will provide a stride length of s=12cm for each leg. The value of s' must also have a scaling factor for the calculations to make it slightly smaller. This is necessary since two legs that are 180° out-of-phase must both retract *together* for at least a short duration, as mentioned previously. This allows the weight of the robot's body to be transferred from one leg to another with a small safety margin in order to maintain stability. This retraction scaling factor will be denoted by k. A typical value for k would be about 0.6.

Therefore, these legs must travel $k \times 12cm$ in t seconds, giving the walking speed v of the robot in Equation 3.3.

$$v = \frac{12kr_m}{1 - \frac{1}{360}\theta} = \frac{12kr_m}{1 - \frac{1}{180}\arctan(\frac{s}{2Kd})}\ cm/s \tag{3.3}$$

Using the dimensions given in Figure 3.22, Strider's walking speed can be calculated using Equation 3.4.

$$v \approx 15kr_m \quad cm/s \tag{3.4}$$

Therefore, this equation would be used to determine Strider's walking speed if Approach B was being used. As an example, using the fastest gait, the tripod gait, a slot-plate rotation speed of $1.6rev/s$ and a retraction scaling factor of 0.6, the resulting walking speed will be about $14.5cm/s$.

Approach A, however, requires the retraction speed to be less than the protraction speed. Therefore, the speed of the retraction of a leg must be determined based on the rotation speed of the slot-plate. The retraction speed of a leg is therefore calculated as follows. A leg will move θ degrees in $\frac{s}{v_r}$ seconds, where v_r is the maximum leg stride speed in cm/s.

$$\frac{\theta}{\frac{s}{v_r}} = \frac{2\arctan(\frac{s}{2Kd})}{\frac{s}{v_r}}$$

This would then correspond to a complete 360° rotation of the slot-plate in

$$\begin{aligned}
\frac{2\arctan(\frac{S}{2Kd})}{\frac{S}{v_r}} &= \frac{360}{x} \\
x &= \frac{180s}{v_r\arctan(\frac{S}{2Kd})} \quad seconds
\end{aligned}$$

Alternatively, this can be expressed as the rotation speed of the slot-plate in revolutions per second.

$$r_m = \frac{v_r\arctan(\frac{S}{2Kd})}{180s} \quad rev/s$$

Now, by transposing we have the retraction speed in terms of the rotation speed of the slot-plate in Equation 3.5.

$$v_r = \frac{180sr_m}{\arctan(\frac{S}{2Kd})} \quad cm/s \tag{3.5}$$

Again, using the dimensions given in Figure 3.22, the retraction speed is given by Equation 3.6.

$$v_r \approx 59r_m \quad cm/s \tag{3.6}$$

Using a slot-plate rotation speed of about $1.6rev/s$ the maximum retraction speed will be about $94cm/s$. However, this calculation gives the maximum retraction speed of a leg only when it is unloaded, that is, when the robot is not standing on the ground. The actual retraction speed (with the robot on the ground) will be slower, mainly because of the friction between the pin and the groove.

Through experimentation the retraction speed while the robot was standing (and walking) was found to be about $30cm/s$. The slot-plate rotation speed had therefore slowed down to about $0.5rev/s$.

Hence, Equation 3.4 can be used to calculate Strider's approximate walking speed and Equation 3.6 can be used to give an estimate of a leg's retraction speed.

3.4.5 Groove-Slot-Pin Kinematics

For every walking robot it is important for the designer to know what possible positions the legs can be in within their workspace in order to determine the leg's kinematic behaviour. These are usually the positions of the feet of the legs and are based on the known joint angles of the actuators [97]. In the case of Strider however, the workspace of each leg is two dimensional. Therefore, the position of the feet is directly proportional to the shape of the groove in the groove-slot mechanism with a scaling factor of four from the pantograph.

The kinematic behaviour of the pin in the groove as the actuator turns the slot-plate was investigated to observe the velocity and acceleration of the pin during the retraction of a leg. As can be seen in Figure 3.23, the angle (or rotary position) of the slot-plate (α) determines the current position of the pin and hence the radius from the pivot point to the edge of the groove. This radius had to be calculated in terms of the angle of the slot-plate, and then the velocity and the acceleration of the pin in the different positions of the groove could be determined with respect to the angle α.

The formulae for the length of the radii is given below. Three sections of the groove

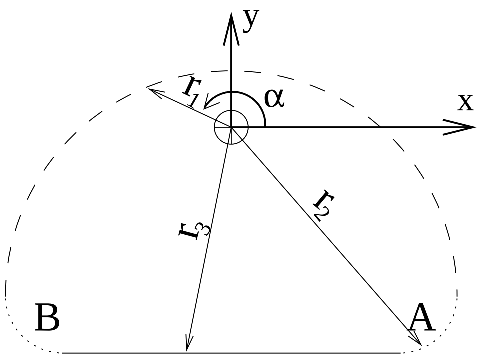


Figure 3.23: Definition of the three different radii used in the groove.

were calculated. With reference to Figure 3.23, Equation 3.7 is the radius length of the protraction section, Equation 3.8 is the radius length of the section labelled 'A', and Equation 3.9 is the radius length of the retraction section. The radius length of the section labelled 'B' will be equivalent to 'A'.

The values for parameters a, b, c *and* R in Equations 3.7 to 3.15 are obtained from Figure 3.22.

$$\begin{aligned} r_1 &= -a\sin(\alpha) + \sqrt{a^2\sin^2(\alpha) - a^2 + R^2} \\ &= -15\sin(\alpha) + \sqrt{225\sin^2(\alpha) + 175} \quad mm \end{aligned} \tag{3.7}$$

$$\begin{aligned} r_2 &= b\cos(\alpha) - a\sin(\alpha) + \\ &\quad \sqrt{a^2\sin^2(\alpha) - 2ab\sin(\alpha)\cos(\alpha) + b^2\cos^2(\alpha) - a^2 - b^2 + c^2} \\ &= 15\cos(\alpha) - 15\sin(\alpha) + \sqrt{-450\sin(\alpha)\cos(\alpha) - 200} \quad mm \end{aligned} \tag{3.8}$$

$$\begin{aligned} r_3 &= \frac{-d}{\sin(\alpha)} \\ &= \frac{-20}{\sin(\alpha)} \quad mm \end{aligned} \tag{3.9}$$

From these formulae, the groove can be reconstructed using polar coordinates as shown in Figure 3.24(a). This diagram can then be remapped onto Cartesian coordinates as shown in Figure 3.24(b).

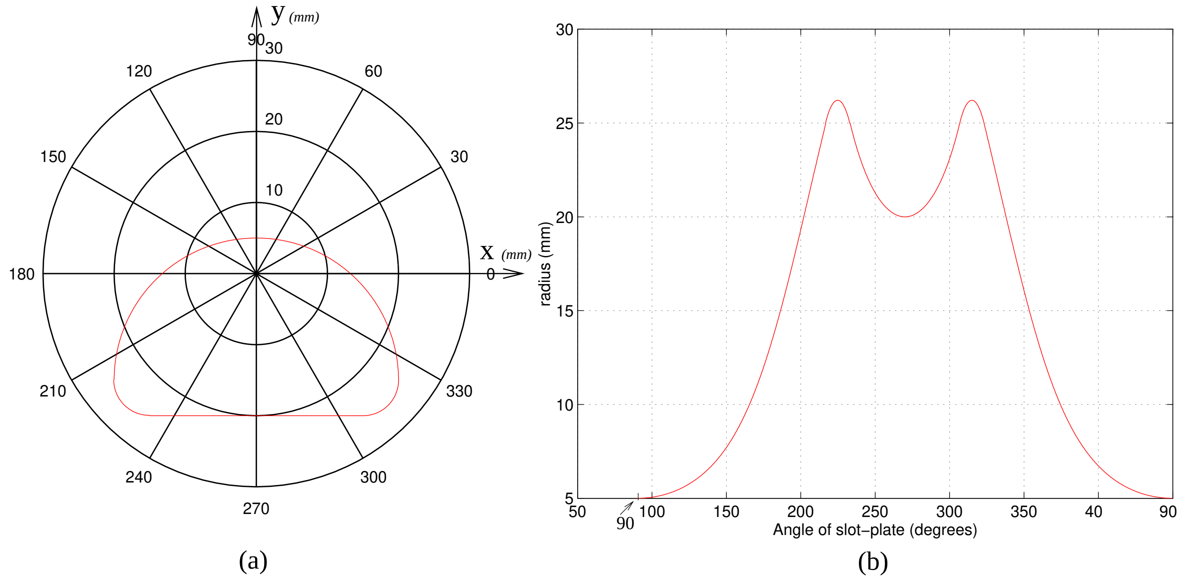


Figure 3.24: A polar and Cartesian view of the groove.
(a) The groove shown on a polar chart. (b) The radius of the groove shown using Cartesian coordinates.

Differentiating the above formulae with respect to the angle α then gives the velocity of each radii in the same three regions of the groove mentioned above.

$$\begin{aligned} v_{r_1} &= -a\cos(\alpha) + \frac{a^2\sin(\alpha)\cos(\alpha)}{\sqrt{a^2\sin^2(\alpha) - a^2 + R^2}} \\ &= -15\cos(\alpha) + \frac{255\sin(\alpha)\cos(\alpha)}{\sqrt{225\sin^2(\alpha) + 175}} \quad mm/degree \qquad (3.10) \\ v_{r_2} &= -b\sin(\alpha) - a\cos(\alpha) + \\ &\quad \frac{ab(1-2\cos^2(\alpha))}{\sqrt{a^2\sin^2(\alpha) - 2ab\sin(\alpha)\cos(\alpha) + b^2\cos^2(\alpha) - a^2 - b^2 + c^2}} \\ &= -15\sin(\alpha) - 15\cos(\alpha) + \frac{225(1-2\cos^2(\alpha))}{\sqrt{-450\sin(\alpha)\cos(\alpha) - 200}} \quad mm/degree \qquad (3.11) \\ v_{r_3} &= \frac{d\cos(\alpha)}{\sin^2(\alpha)} \\ &= \frac{20\cos(\alpha)}{\sin^2(\alpha)} \quad mm/degree \qquad (3.12) \end{aligned}$$

Differentiating Equations 3.10 to 3.12 with respect to the angle α gives the acceleration of each radii in the same three regions of the groove mentioned above.

$$
\begin{aligned}
a_{r_1} &= a\sin(\alpha) - \frac{a^4\sin^2(\alpha)\cos^2(\alpha)}{(\sqrt{a^2\sin^2(\alpha)-a^2+R^2})^3} + \frac{a^2(2\cos^2(\alpha)-1)}{\sqrt{a^2\sin^2(\alpha)-a^2+R^2}} \\
&= 15\sin(\alpha) - \frac{50625\sin^2(\alpha)\cos^2(\alpha)}{(\sqrt{225\sin^2(\alpha)+175})^3} + \\
&\quad \frac{225(2\cos^2(\alpha)-1)}{\sqrt{225\sin^2(\alpha)+175}} \quad mm/degree^2 \qquad (3.13)
\end{aligned}
$$

$$
\begin{aligned}
a_{r_2} &= -b\cos(\alpha) + a\sin(\alpha) - \\
&\quad \frac{(ab(1-2\cos^2(\alpha)))(2ab(1-2\cos^2(\alpha)) + (2a^2-2b^2)\sin(\alpha)\cos(\alpha))}{2(\sqrt{a^2\sin^2(\alpha)-2ab\sin(\alpha)\cos(\alpha)+b^2\cos^2(\alpha)-a^2-b^2+c^2})^3} + \\
&\quad \frac{4ab\sin(\alpha)\cos(\alpha)}{\sqrt{a^2\sin^2(\alpha)-2ab\sin(\alpha)\cos(\alpha)+b^2\cos^2(\alpha)-a^2-b^2+c^2}} \\
&= -15\cos(\alpha) + 15\sin(\alpha) - \frac{(450(1-2\cos^2(\alpha)))^2}{4(\sqrt{-450\sin(\alpha)\cos(\alpha)-200})^3} + \\
&\quad \frac{900\sin(\alpha)\cos(\alpha)}{\sqrt{-450\sin(\alpha)\cos(\alpha)-200}} \quad mm/degree^2 \qquad (3.14)
\end{aligned}
$$

$$
\begin{aligned}
a_{r_3} &= \frac{-2d\cos^2(\alpha)}{\sin^3(\alpha)} - \frac{d}{\sin(\alpha)} \\
&= \frac{-40\cos^2(\alpha)}{\sin^3(\alpha)} - \frac{20}{\sin(\alpha)} \quad mm/degree^2 \qquad (3.15)
\end{aligned}
$$

It would be easier to observe the position, speed and acceleration of the pin in the groove by observing the horizontal and vertical movements separately. Equations 3.7 to 3.15 were therefore separated into the two components and then plotted. Figure 3.25 shows the x and y positions, velocities and accelerations of the pin with respect to the angle of the slot-plate.

Figure 3.25(a) shows that the retraction occurs between about 233° and 307° since the y-position of the pin remains at $-20mm$. Hence, there is only movement in the x-direction. As a result, in Figure 3.25(b) we see that the velocity varies a small amount in the x-direction (red line). This shows that the legs move at slightly different speeds when

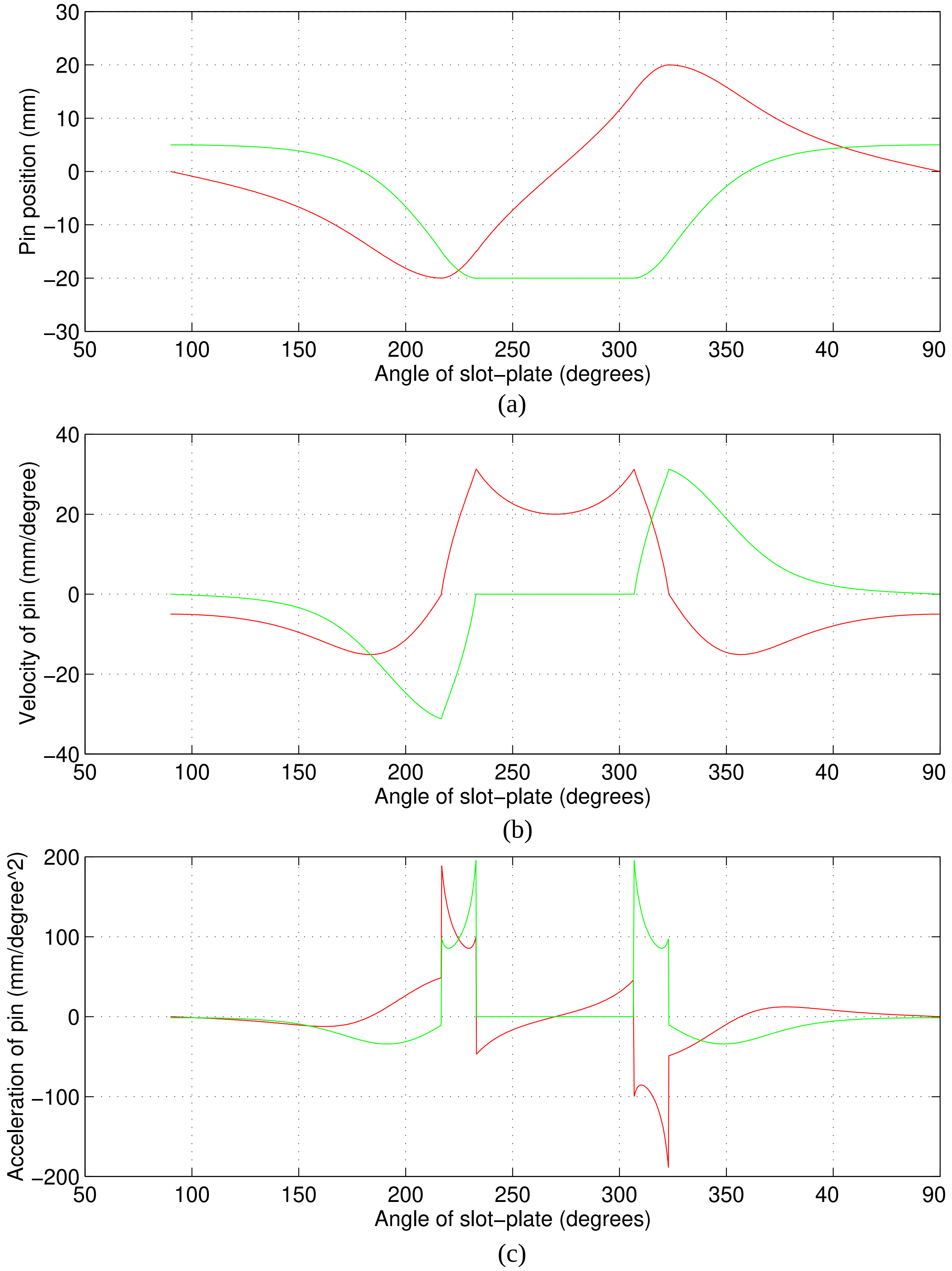


Figure 3.25: The kinematic analysis of the groove.
(a) The x (red line) and y (green line) positions of the pin. (b) The x (red line) and y (green line) velocities of the pin. (c) The x (red line) and y (green line) accelerations of the pin.

their pins are located at different positions along the retraction section of the groove.

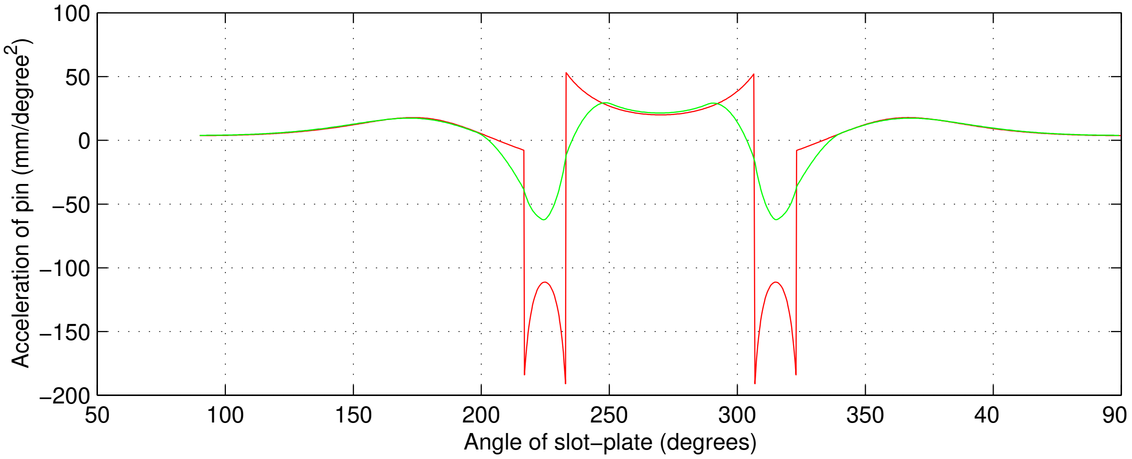
The weight of the leg and the friction in the groove would have a large impact on the velocity of the pin. Hence, the dynamic and inertial properties of the robot tend to make the velocity of the legs more equivalent, even in different leg positions. If any speed differences are present during retraction, it would only create an insignificant amount of foot slippage.

Figure 3.25(c) shows that the acceleration is large in the small curved sections labelled 'A' and 'B' in Figure 3.23. These are between about 217° and 233° for 'B', and about 307° and 323° for 'A'. These accelerations also relate to the high forces that would be produced in these regions. The forces would actually be higher at the end of a protraction since the leg would be falling due to gravity. However, the large accelerations are not very significant since the slot-plate only revolves at about 1-2 revolutions per second.

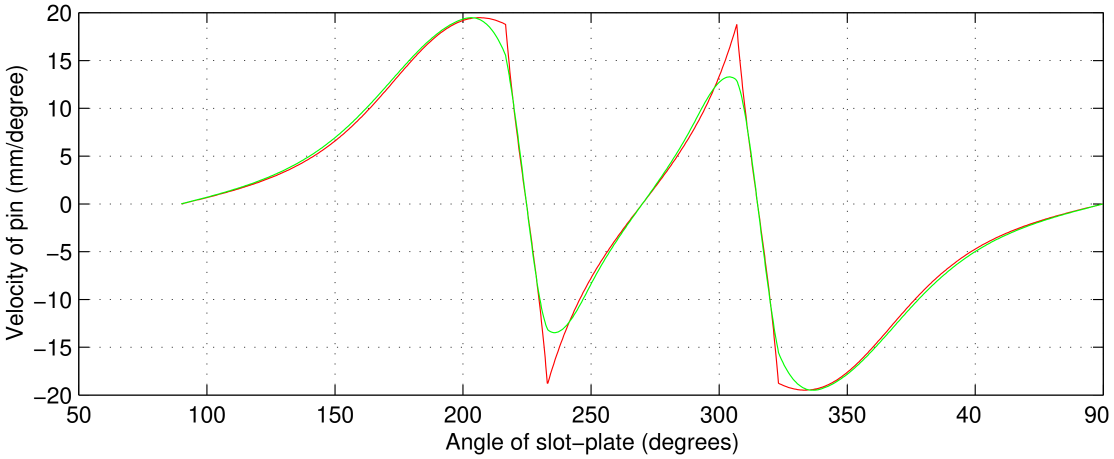
A method to reduce the large accelerations and the discontinuities shown in Figure 3.25(c) is to slightly change the shape of the groove such that a smoother transition occurs between the curved sections of the groove and the straight sections. This can be done by modifying the velocities in the two regions where these large accelerations occur. The modified velocity can then be integrated to obtain a new, slightly modified shape of the groove. This example is presented below.

The red graphs in Figures 3.26(a), (b) and (c) show the original accelerations, velocities and positions of the groove with respect to the angle α, respectively. The large accelerations in sections 'A' and 'B' in the groove (mentioned above) can be reduced by removing the sharp changes in velocity at those points. This was performed by low-pass filtering the velocity.

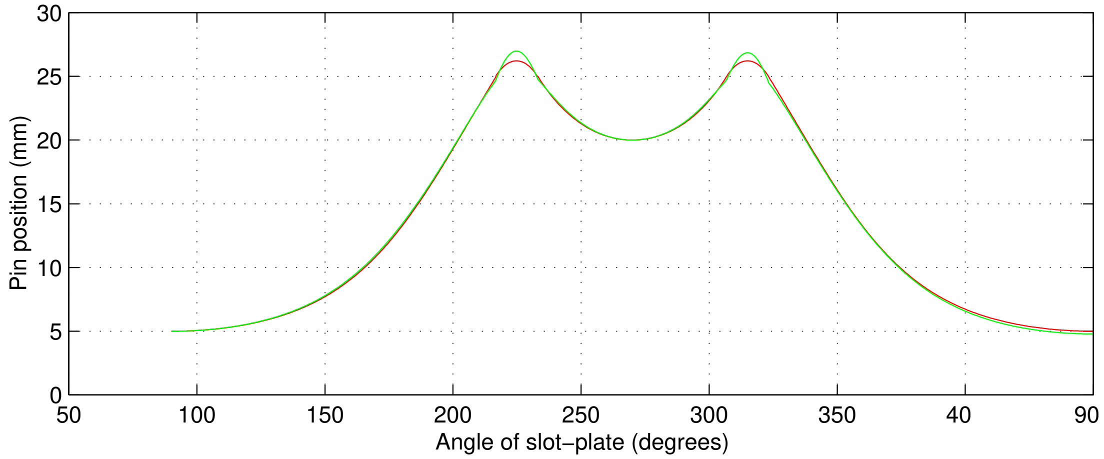
Figure 3.26 shows the original (red) graphs and the new (green) graphs. Figure 3.26(b) shows the green filtered velocity graph. The acceleration is then obtained by differentiating the velocity, as shown in Figure 3.26(a). Here we see that the large accelerations have been reduced and the discontinuities have been removed. By integrating the velocity, the



(a)



(b)



(c)

Figure 3.26: Improving the kinematics of the groove.
The original graphs are given in red. The new (modified) graphs are given in green. (a) The new acceleration is obtained by differentiating the new velocity in (b). (b) The new velocity graph after being low-pass filtered. (c) The new radius (position) graph after integrating the new velocity in (b).

new radius graph is obtained, as shown in Figure 3.26(c).

The resulting shape of the groove can be seen in Figure 3.27. The new shape is only slightly different from the original. The retraction length has been increased slightly and a very small change in the shape of the retraction section is apparent.

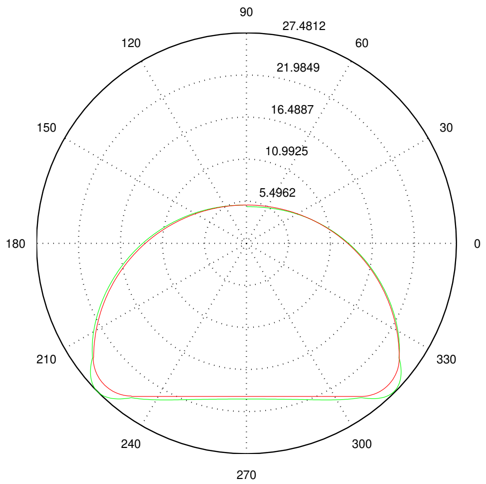


Figure 3.27: The new shape of the groove with reduced accelerations.
The original trajectory is given by the red line.

3.5 Advantages Over the Biological Mechanism

There are several advantages that Strider has over the structural design of the cockroach and other similar biological organisms. These advantages are mainly due to the fact that the robot is purely a mechanical system and can therefore overcome some of the energy-related problems experienced in a living organism.

The main advantage of the groove-slot mechanism is that it allows the robot to stand without expending energy, whereas insects constantly use their muscles to remain standing. Several other advantages of the groove-slot mechanism are mentioned below.

The legs of the *Blaberus Discoidalis* exert vertical forces on the ground of up to 1.5 times its body weight during a stride [11]. This can cause problems for a walking machine if the legs are rigid and no suspension system exists, especially when the legs are first coming in contact with the ground. These forces are mainly due to the changing gravitational potential energy during walking. Since the trajectory in the groove is such that the pin will follow a curve prior to entering the retraction section, most of the downward force exerted by the weight of a falling leg will be absorbed by the groove and the leg will not be pounded into the ground. The weight of the robot will not be experienced until the foot is at the same vertical level as the currently standing legs. This means that when the robot is walking, using the tripod gait, for example, each foot would not apply any greater force than a third of the robot's body weight while walking on a flat surface.

As another example, the centre of mass of the cockroach, while walking, experiences repeated horizontal and vertical accelerations and decelerations. In contrast, Strider would experience very little vertical changes due to the horizontal section of the groove in the groove-slot mechanism. As mentioned above, the shape of the groove produces the characteristic behaviour of a wheel. Therefore, when the robot walks coherently, a similar changing horizontal acceleration can be expected, as was found in the velocity calculations in Section 3.4.5. However, since the vertical motion is generally restricted while the legs are retracting, the gravitational potential energy of the robot's body would be almost constant much like a wheeled vehicle.

One other advantage that Strider has over insects and other living creatures is that using the pantograph mechanism to move the robot reduces the power consumption considerably as compared to using biological muscular systems. This was described previously in Section 2.2.

3.6 Climbing Over Obstacles

The main purpose of a walking robot is to enable it to travel over rough terrain where other types of vehicles have difficulty. Some research has shown that animals usually jump over obstacles rather than climb [99]. However, since most walking robots were not designed to jump, finding methods of climbing is essential, especially since it is the ability to climb over rough terrain that gives walking vehicles an advantage over wheeled vehicles.

Walking over terrain and climbing over rough terrain are two very different activities, as explained by Angle et al. [36]. When animals walk over reasonably level terrain their feet lift only a short distance from the ground. Whereas when they climb over an obstacle their legs need to be lifted higher, or lower depending on the situation.

There are two main methods of traversing rough terrain. Either the shape of the terrain can first be detected using sensing devices and each leg can be lifted appropriately when needed, or every leg can be lifted up to the base of the robot [8]. The latter approach is not very efficient and would cause the robot to walk slower since the legs would be lifted unnecessarily. The former approach is more difficult but more widely accepted.

The robot must be able to react adaptively to unpredictable features in the terrain [116]. Either a visual system can be used to observe the terrain ahead and/or sensors in front of the robot and on the feet can be used to detect the more immediate terrain.

For a legged robot that uses force control on each leg the force information can be used to provide active balancing of the robot's body and to prevent foot slippage, especially when climbing over obstacles. One method of doing this is to monitor the foot forces so that they remain within the friction cone constraints of that robot as described in [117]. A similar method was implemented on the OSU Hexapod (described in Section 2.5.1) [118].

Genghis (described in Section 2.5.6) used "force balancing" behaviours when it walked over obstacles [20]. The robot detected whether an object was high enough to walk over by measuring the force the front legs experience when they are swinging forward and they knock against the object. When a leg is over an object and being placed down, the body should remain in the same position once the leg has made contact with the object, and prevent the robot from tilting over. Genghis' leg servos would detect whether too much force was being used to place a leg down when it had come in contact with an object. The actuator for that leg would then maintain the leg position to stop the robot's body from tilting.

Similarly, Strider has the ability to detect when an object, or the floor, has been touched. As mentioned in Section 3.2.7, the linear potentiometers on each linear actuator have been used to detect when a foot has touched an object. Although this is a crude form of foot sensor, it was sufficient for experimentation.

Another rough terrain walking method implemented on the OSU Hexapod was to first observe the terrain ahead of the robot and then detect the appropriate footholds [119]. An automatic body regulation system was also tested on this robot to reduce the operators burden while walking over rough terrain [63]. The hexapod sensed the terrain using attitude sensors and vector force sensors on each foot [120].

Due to the shape of the groove in the groove-slot mechanism, the vertical distance that the feet of Strider will move will be $10cm$. This is unavoidable since the shape of the groove is fixed, but it can be thought of as an advantage. It means that as the robot walks, the legs should be able to step onto objects that are up to $10cm$ high, relative to the current height of the robot. However, since there is little horizontal movement at the maximum height of the groove, climbing such a height would be difficult, although not impossible.

The lift DOF in Strider's gearboxes was used to raise or lower the leg independently of the fixed semicircular trajectory of the groove. As mentioned in Section 3.2.6, this was done by adding a vertical lead-screw actuator at point R in Figure 3.19 (Section 3.4.1).

As mentioned previously, the legs of Attila (described in Section 2.5.7) were able to lift high above their normal walking level but they couldn't be lowered very much. Therefore, the robot could climb up well but could not climb down easily [14]. The addition of the lead-screw on Strider, however, allows the position of the foot to vary throughout a $9.5cm$ vertical distance. Also, with the addition of the maximum height of the groove, the maximum step height was 19.5cm. This is shown in Figure 3.28. As can be seen, the leg can lift up to 10.5cm above the base of the robot or down to 9cm below the base of the robot. This makes the robot more suitable for climbing both up and down.

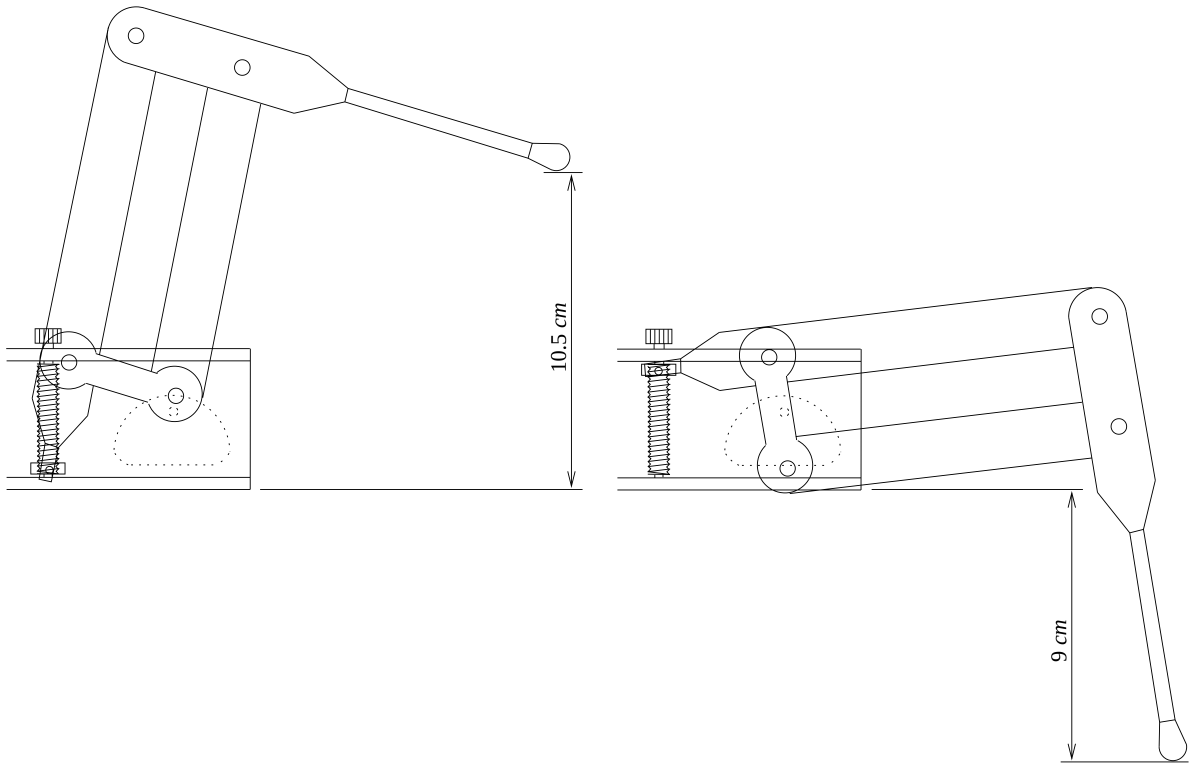


Figure 3.28: The maximum and minimum heights that the legs can reach.

Climbing over an obstacle while walking can be difficult to program for any system that uses a fixed foot trajectory. While a leg is protracting (moving from rear to front), and falling, its foot may land on top of an obstacle. The foot must stop moving downwards and eventually start retracting to move the robot forward. The leg can only retract however, if the pin is in the horizontal section of the groove. The slot-plate therefore needs to turn more until the pin reaches this section. To prevent the foot from being forced into the obstacle and causing the robot to become unstable, the vertical linear actuator must lift the leg while the leg is protracting until the pin is in the horizontal section of the groove. Finally, the foot will again be placed down where the leg will be fully protracted towards the front of the robot, in order to start retracting the leg. This same situation applies to when a leg first notices an inclined slope.

As described in Section 3.2.6, there is a limit to the incline that Strider can walk. This is due to the fact that the motors will act against gravity when the robot is on a slope. The flat section of the groove will no longer be able to support the pin in the pantograph legs and therefore the robot could not stand without expending power.

It is necessary to know the maximum inclination that the robot can climb based on the strength of the motors, the weight of the robot and the number of legs being used to stand. Therefore the maximum torque that the motors can deliver must be known.

In Section 3.2.6, the output torque of the motor/gearbox combination was found to be about $4.0kg \cdot cm$. As can be seen in Figure 3.29, the maximum radial distance from the pivot point of the groove-slot mechanism to the pin in the slot-plate (in the horizontal section of the groove) is $2.5cm$, making an angle of $53.13°$ with the flat section of the groove. This shows that the pin actually gets pushed along the flat section of the groove by a smaller component of the force (w_{min}).

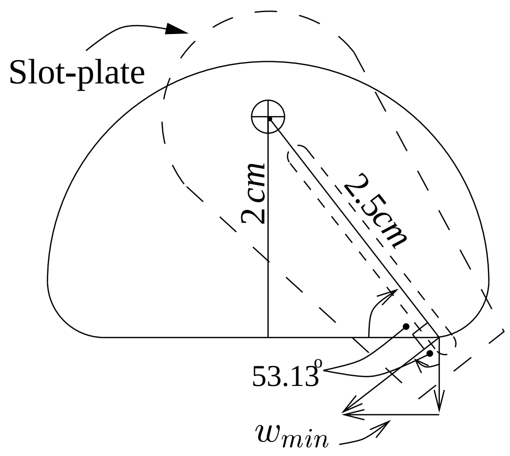


Figure 3.29: Defining the minimum force the motors produce when standing on a slope.

Since the actuator can support $4kg$ at a radius of $1cm$, then at a $2.5cm$ radius it will support a weight of $1.6kg$. Then, from Figure 3.29 the minimum supporting weight (w_{min}) for one actuator will be

Number of legs (n)	3	4	5
Slope angle (θ)	25°	35°	45°

Table 3.7: The maximum possible inclines (θ) that Strider can climb based on the number of supporting legs.

$$
\begin{aligned}
w_{min} &= 1.6\sin(53.13°) \\
w_{min} &= 1.28kg
\end{aligned}
$$

Next, using Figure 3.8 and Equation 3.1 we can determine the weight of the robot acting down the inclined plane. The robot's weight was $2.25kg$ and the magnification factor of the pantograph legs was 4. Therefore, the maximum inclination that Strider can climb can be determined using Equation 3.16.

$$
\begin{aligned}
1.28 \times n &= 4 \times 2.25\sin(\theta) \\
\theta &\approx \arcsin(0.14n) \qquad (3.16)
\end{aligned}
$$

where θ is the inclination angle of the slope and n is the number of supporting legs.

There will be a minimum of three supporting legs and a maximum of five legs on the ground at any time while walking. Therefore, the calculated maximum slope that can be climbed using 3, 4 and 5 supporting legs is given in Table 3.7.

3.7 Making the Robot Turn

Making the robot turn is an obvious necessity for almost any vehicle in order to make it navigate, but was not dealt with to any great extent in this research. The main focus of this study was to obtain a faster (straight-line) walking robot. However, some work had been done to get the robot to turn regardless. Since the legs of Strider were not designed to move in the lateral direction, other methods of turning had to be devised.

Theoretically, if the legs only have movement in the longitudinal direction then there would be no way for the robot to turn. The CWRU Hexapod (described in Section 2.5.8) was also designed in this way and was unable to turn.

Robots such as Genghis (described in Section 2.5.6), that use the sprawled stance were made to turn by reducing the retraction length (stride length) for the three legs on one side of the robot. This allowed the legs on the other side to push the robot in a curve. Some foot slippage does occur but since the robot is small and light weight this is not important.

Since the stride length using the groove-slot mechanism is fixed, another method had to be used. One experiment to make Strider turn was performed by reducing the retraction speed of the legs on one side of the robot. This method failed however, since Strider's feet had too much grip and the legs would only push against one another causing the robot to stand in one place.

Another approach was to change the speed of the legs by changing the stepping sequence of the legs on one side of the body. This method also failed since the robot would only walk forward regardless of the change in pattern.

The next method was to make the legs on one side of the robot stop halfway through its retraction. This was found to twist the body a small amount by bending the legs slightly towards or away from the body. This lateral bending of the legs is similar to the extension movement of a leg as shown in Figure 2.6(a). This type of movement is used in the Adaptive Suspension Vehicle (described in Section 2.5.4).

Strider's legs were flexible enough in the lateral direction to twist the body a small amount for each step while using a tripod gait. The turning radius was found to be about $95cm$.

Making Strider turn was not a goal of this project but these results show that by adding the extension movement to the legs in a larger scale robot of similar design, for example, it will be able to turn.

3.8 Performance Results Using a Tripod Gait

It was found that while using the tripod gait, the two middle legs would experience relatively large forces. In the tripod gait, the front and rear legs on one side of the robot and the middle leg on the other side is used to hold the robot up. These three legs therefore must carry the weight of the body plus the weight of the three lifted legs. The middle leg is under the greatest strain of the three standing legs since about half the total weight will be on that leg. Eltze et al. [40] experienced the same dynamic effects on the TUM walking machine. As a result, one of Strider's weaker small plastic gears in the modified servos of the middle legs had stripped and had to be replaced. The structural strength of the middle legs could have been stronger, and the servos for the middle legs should have contained metal gears.

As Strider walked, the falling legs were not pounded into the ground prior to retraction but rather gradually came in contact with the ground. This was due to the small curved sections of the groove in the groove-slot mechanism.

The vertical potential energy was almost constant but altered very slightly at each 3-pair leg transition of the tripod gait.

The robot was found to consume about 18W of electrical power while walking on level terrain.

Using Equation 3.4, and while walking using a tripod gait, Strider's maximum walking speed was determined. A slot-plate rotation speed of $1.9rev/s$ and a retraction scaling factor of about 0.6 was used. The resulting walking speed was about $17cm/s$. The results show that the robot does have the potential to produce higher walking speeds.

3.9 Summary

This chapter gave a detailed description the mechanical design of Strider and the electronics used to control it.

The description of the mechanics included the materials used in the construction, the reasons for choosing the leg structure, the dimensions of the robot and the mechanical design of the legs and the gearboxes. The robot was constructed mostly of PVC sheeting. The planar pantograph legs were arranged in the longitudinal axis of the robot's body to produce large horizontal leg strokes in order to provide fast walking in a straight line.

The description of the electronics included the choice of motors to be used as the robot's actuators, the position sensors used for the legs and a description of the on-board computer. The motors used were standard hobby servos used in radio-controlled aeroplanes. Each leg used a continuous-turn potentiometer and a linear sliding potentiometer as sensors to measure the position of the leg in the groove-slot mechanism and the vertical linear actuator, respectively.

Section 3.3 of this chapter explained what influences were obtained from biology and what other influences could have been obtained. The main influence used in the design for Strider was obtained from the leg angles of the cockroach. The front legs are angled forwards, the rear legs are angled towards the rear and the middle legs change from pointing forward to rearward. The reason for choosing six legs was also explained.

The groove-slot mechanism was then described in detail. The mechanical design was described and various aspects of it were analysed to explain why the shape of the leg's trajectory was chosen and to determine what the resulting walking speed would be. The kinematics of the mechanism was determined to observe the speed of the leg as it moves along the semicircular trajectory. The biggest advantage of using the groove-slot mechanism is that it allowed the robot to stand without expending energy. The mechanism also allowed the robot to carry a large payload.

The last part of this chapter explained some of the advantages modern-day mechanics has over biological mechanisms. An explanation of how Strider can climb over obstacles and how it can turn was also given.

The performance of the robot was also given which showed that the resulting normalised work capacity was greater than any other robot investigated in this research. Both the walking speed and the payload capacity was greater than other robots of similar size.

Chapter 4

Controlling the Legs of Walking Robots

A control algorithm, that is implemented in hardware or software, that controls the movements and sequencing of the actuators of a robotic system is known as the robot's *control system*. Whether a robot is physically built or only simulated, its actuators will be controlled by the robot control system.

For any particular robot, the robot control system would adjust its actuators to positions that may be predetermined or may be commanded by a user. The control system must make adjustments to its actuators in order to compensate for various dynamic effects that may be produced by relatively fast movements.

For a walking robot, the robot's *locomotion* control system would coordinate the legs to make the robot walk. The control system must decide the best time to place a leg down and where it should be placed for any particular gait, or walking pattern. Different types of gaits can allow the robot to walk at different speeds.

The control system may be distributed. In such cases, smaller local control systems would be used. The subsystems must be able to cooperate with each other and behave suitably to propel the body, and if applicable, to maintain the appropriate posture [116].

It has only been in the more recent years that researchers have looked seriously towards biology to help them design better mechanical robotic systems. However, most of the related research in the past had used biological inspirations for the purpose of gait control, or leg sequencing for walking [41]. Biological control systems were studied because of their robustness and their ability to deal with uncertainty, complexity and strong nonlinearities [121].

Most of the research work in the past involved the coordination of legs. More recent research has included the study of the higher levels of the biological control systems. For example, researchers such as Beer et al. [80] have studied the behavioural strategies that insects use to traverse different kinds of terrain. Cliff [122] suggested that insect behaviour, or more specifically cognition, should be more fundamentally studied in preference to the far more complex mammalian cognition and behaviour.

From the large amount of research in the area of control systems for walking robots, several methods have been studied in detail for possible use in Strider's control system. A description of these control systems is given below.

4.1 Definition of Terms

Various terms have been used in previous research work that describe the morphology and movement of the legs of the investigated systems. These terms are used in this and the following chapters and their definitions are given below. Some of these terms have been obtained from [22].

- *Anterior* is a position that is situated towards the front of the body.
- *Posterior* is a position that is situated towards the rear of the body.
- *Rostral* is a direction that is towards the front of the body.
- *Caudal* is a direction that is towards the rear of the body.

- *Protraction* is the process of lifting and moving a leg from the posterior to the anterior of the body. This is also known as the *swing phase*, *recovery phase* or the *return stroke*.
- *Retraction* is the process of moving a foot backwards from the anterior to the posterior (while it is on the ground) to propel the robot forward. This is also known as the *stance phase*, *support phase* or the *power stroke*.
- *Contralateral* is a position that is situated on directly opposite sides of the body. For example, the contralateral leg of the left-front leg of a cockroach would be the right-front leg.
- *Ipsilateral* is a position that is situated on the same side of the body. For example, the ipsilateral leg of the left-front leg of a cockroach would be the left-middle leg.
- *Anterior Extreme Position* (AEP) is a predefined leg position that places the foot as far to the front as possible.
- *Posterior Extreme Position* (PEP) is a predefined leg position that places the foot as far to the rear possible.

4.2 Previous Biological Research with Insects

The study of walking patterns originated from biology where researchers have observed the walking of various insects and animals. In particular, the study of cockroaches has been popular in the last few decades.

In the early stages of this type of research, mathematicians derived equations to describe some of the walking patterns of insects. These however, did not reveal much about the pattern generators that were later found to control the stepping sequences of insects. In more recent times, researchers have been more inclined to study the gaits of the insects and then deduce the neural circuitry that would be involved [123]. Nevertheless, the earlier approaches were interesting in that they were able to produce the basic walking patterns inherent in cockroaches and other insects.

Some of the notable researchers and a brief summary of their work is given below.

4.2.1 Hughes

Hughes [22] [124] studied the morphology of six-legged insects such as the cockroach and various beetles and investigated their leg patterns while walking.

One of the types of notation used to describe different gaits in this text is based on a system that was used by Hughes [22]. Every leg of the insect was first labelled. Looking from the top of the insect, the three left legs were labelled from front to rear as L1, L2 and L3, while the right-hand legs were labelled R1, R2 and R3, as shown in Figure 4.1.

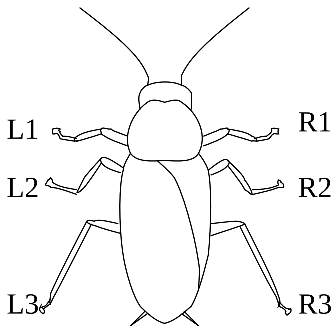


Figure 4.1: The labelling convention for the legs of an insect.

These labels were then used to describe when a protraction of a leg occurred. For example, the walking sequence [L3, L2, L1, R3, R2, R1] represents a gait where each leg is protracted one at a time. While one leg is protracting, the other five legs are retracting. First the left-rear leg (L3) is protracted. Then the left-middle leg (L2) is protracted followed by the left-front leg (L1). The right hand legs are then protracted starting from the right-rear leg (R3), then the right-middle leg (R2) and finally the right-front leg (R1). This sequence of protractions is repeated continuously to produce a periodic gait.

As another example, the sequence [(L3, R1), R2, (L1, R3), L2] represents a gait where pairs of legs are protracting. The left-rear leg, L3, and leg R1, are combined in parentheses. This means that they protract together, followed, in this case, by the protraction of leg R2. Leg L1 and R3 are then protracted together. Finally leg L2 is protracted. The sequence is then repeated.

Another concept obtained from Hughes are his rules of insect walking. He stated two rules that summarized his findings from the many observations of cockroaches and other insects [22].

1. No fore or middle leg is protracted until the leg behind has taken up its supporting position.

2. Each leg alternates with the contralateral limb of the same segment.

The first rule assumes that the legs produce a wave of protractions from the posterior of the body to the anterior. The second rule is stating that any pair of contralateral legs will not protract in-phase.

Legs that protract 180° out-of-phase are most common, although other gaits do exist. For example, in [124] Hughes stated that some insects do exist that contradict the second rule. The *Tropidopola cylindrica*, for example, uses only four of its six legs to walk and at fast speeds uses the sequence [(L1, R1), (L2, R2)]. Although some findings contradict the rules above, in general, the simplest model for walking will follow Hughes' rules.

4.2.2 Delcomyn

Delcomyn [125] realised in the late 1960's that the current research material to date was insufficient for physiological studies of the time. His research with cockroaches (the *Periplaneta Americana*) produced new findings that were very beneficial to his work and could also be of value to future researchers.

The main finding was that the cockroach uses the tripod gait for most of its walking speeds. Any significant changes occurred only at very low speeds (below $5cm/s$).

He also found that the time to perform a protraction of a leg varied as the walking speed varied. This is contrary to Wilson's finding of the stick insect, that the protraction time was constant [23], as explained below.

4.2.3 Full

In more recent years, Full et al. [126] [3] [11] have made many contributions to the study of cockroaches.

Full found that the energy (per mass-length) used by the cockroach ($0.9\mathrm{Jkg}^{-1}\mathrm{m}^{-1}$) was the same for other species such as ghost crabs, mammals and birds, despite having different body forms, leg numbers and skeletal types [126].

He explained how the horizontal kinetic energy of the cockroach varied in phase with the insect's gravitational potential energy while walking at all speeds using the tripod gait. This is contrary to walking birds or mammals, for instance, where the horizontal kinetic energy and the gravitational potential energy fluctuate out-of-phase, which gave the creatures the advantage of alternately storing and exchanging energy while walking, much like a swinging pendulum. This shows that the walking behaviour of the cockroach was found to be different to that of two and four legged walkers.

Full also stated that the cockroache's highest speeds are up to $1.5m/s$ where it switches from hexapedal running to quadrupedal and bipedal running [3].

One of Full's more important research findings was that of having different mechanical functions of the front, middle and rear legs of a cockroach. While walking, the front legs were found to decelerate the body. The rear legs accelerated the body and the middle legs both accelerated and decelerated the body [11]. It was this finding that inspired the mechanical design of Strider as explained in Section 3.3.1.

4.3 Previous Hexapod Control Systems

Insects have very flexible, robust and adaptive control systems. Various studies have been done over the last few decades in this area and a brief description of the researcher's work is presented in this section.

It was found from biological studies that the locomotion controllers of animals and insects have distributed control systems. There are no central controllers that generate the range of gaits used for walking. The legs each have their own smaller control subsystems that coordinate to produce rhythmic step movements [116]. This allows the local controllers to have less complexity and require less computation. It also allows the overall system to be more flexible and robust [80] [21].

Some of the controllers described below are very algorithmic while others closely resemble the architecture of the biological controllers used in insects such as the cockroach [80].

The control systems described below were studied in this research in order to obtain an overview of the different kinds of methods that are used for the control of walking robots and to decide which method would be most suitable to be used for Strider. Apart from the chosen control system, the other control systems described were not implemented on Strider for reasons explained later in Section 4.4. Regardless of this, some of the results that researchers have found using the other control systems have been provided.

4.3.1 Wilson

Wilson's research [23] provided an improved description of the simplest model for walking than that given by Hughes in Section 4.2.1. Hughes' description provided two rules of walking and Wilson added three more to describe the most common insect gaits.

1. No fore or middle leg is protracted until the leg behind has taken up its supporting position.

2. Each leg alternates with the contralateral limb of the same segment.

3. Protraction time is constant.

4. Frequency varies (retraction time decreases as frequency increases).

5. The intervals between steps of the hind leg and middle leg and between the middle leg and the fore leg are constant, while the interval between the foreleg and hind leg step varies inversely with frequency.

Hence, these five rules provide the simplest walking model for walking in a straight line on a flat surface. In some cases, the walking behaviour of some insects or animals may contradict one or more of the rules. The differences usually occur mainly because of the different morphology found in different species. Contrary to rule three, for example, the protraction time for the cockroach legs actually decrease as the walking speed increases [22], whereas it remains fairly constant in the stick insect [23]. However, by keeping the protraction time for all legs constant, the walking model was able to be kept simple. Therefore, this justifies rule three.

The frequency variations mentioned in rule four relate to changes in the insect's walking speed. As the frequency of protractions increase, the walking speed also increases.

The fifth rule relates to the duration between the protraction of ipsilateral legs. It means that two consecutive ipsilateral legs must retract together for a short (constant) duration so that the body weight can be transferred from one leg to another.

An easier way to observe these rules is by the use of diagrams. Wilson's convention to describe gait patterns is described as follows. Figure 4.2 (adapted from [23]) shows a cockroach and a common insect walking pattern. This is actually a timing diagram of a stepping pattern. The numbers on the left side of the diagram (R3, R2 ... L2, L1) correspond to the leg numbering as shown in the picture of the cockroach to the left, or in Figure 4.1. The black bars represent the protraction of a leg while the dashed lines represent the retractions of a leg.

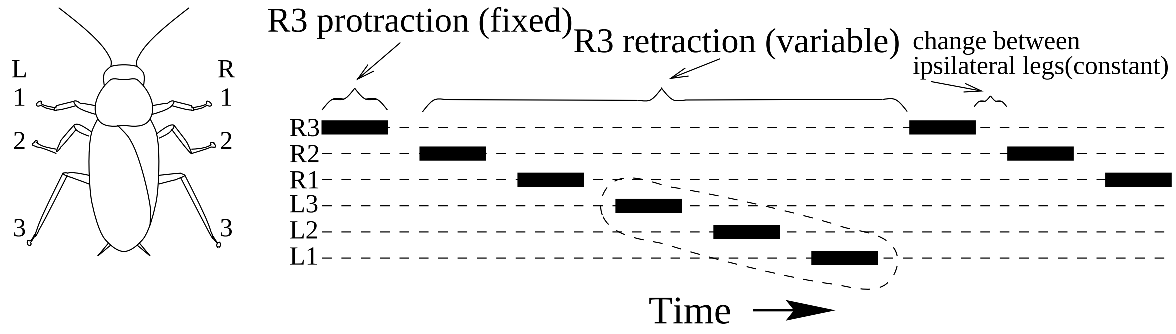


Figure 4.2: Wilson's diagram of a slow-wave gait.

The five rules listed above can be observed in the gait pattern shown in Figure 4.2. The dotted ellipse shows the forward protractions of the three ipsilateral legs according to the rule one. Rule two can also be observed where each pair of legs of the same segment, for example L1 and R1, are in antiphase. The protraction time is given as the length of the black bars and they are shown as being constant, corresponding to rule three. The retraction time is shown to be variable, corresponding to rule four. Finally, the short duration between the protraction of two ipsilateral legs is also shown to be constant, corresponding to rule five.

The descriptions that Wilson provided are only qualitative in that they represent simple walking over a flat horizontal surface [10]. Different walking rules would need to be used for more complex walking over irregular terrain and when changing the walking speed.

In 1966 Wilson also described a simple model for the control of walking based on inhibitory and excitory stimuli between the local control subsystems of adjacent legs [23]. He mentioned that for even a very basic model, the propagation of the leg protractions from the rear to the front occurs when the stepping of leg R3 triggers leg R2, leg R2 then triggers R1, and R1 then triggers R3 to repeat the cycle. This concept was further developed by Graham [33], Cruse [127] and several other researchers, as described below.

4.3.2 Wendler

One of the first models of interleg coordination for a hexapod was proposed by Wendler in the late 1960's [33]. The model consisted of six oscillators that were coupled such that the rear oscillators controlled the middle oscillators and both the rear and middle oscillators controlled the front oscillators. All the oscillators were also controlled by a common input. A diagram of this model is shown in Figure 4.3 (diagram adapted from [33]).

The output of the oscillators produced triangular waveforms. The rising of a wave indicated a protraction of a leg while the falling slope represented the retraction.

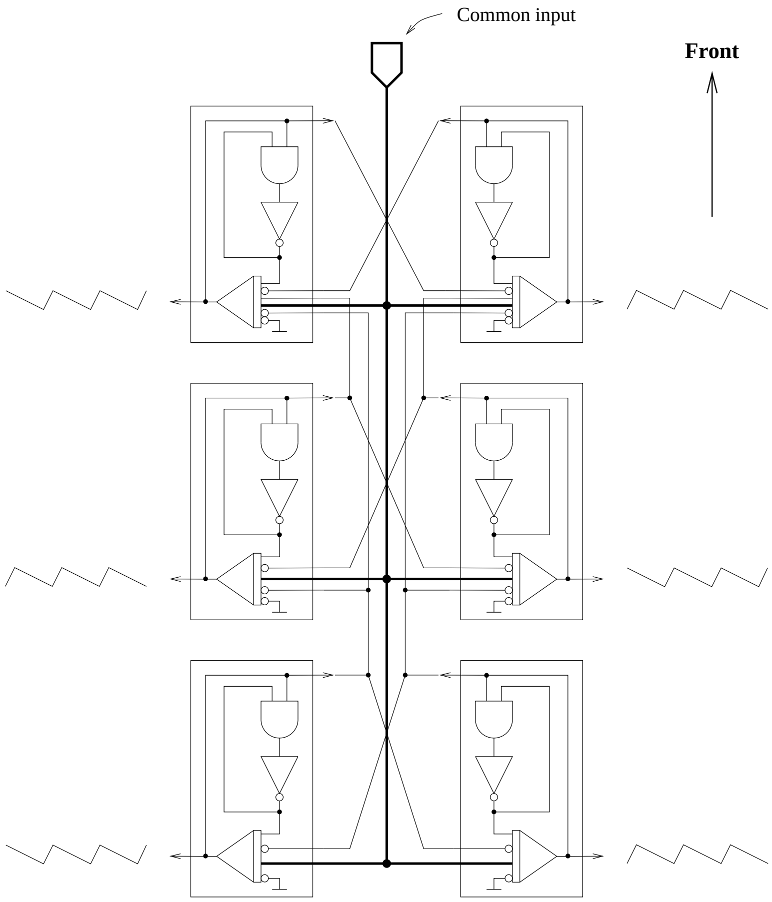


Figure 4.3: Wendler's analogue model for the coordination of six legs.

The model was tested on an analogue computer and produced results that corresponded to Hughes' and Wilson's theories, mentioned above. At low frequencies the model produced consecutive metachronal sequences such as those shown in Figure 4.4(a).

At higher frequencies, the left and right sides merged closer together until the tripod gait was produced, as shown in Figure 4.4(b).

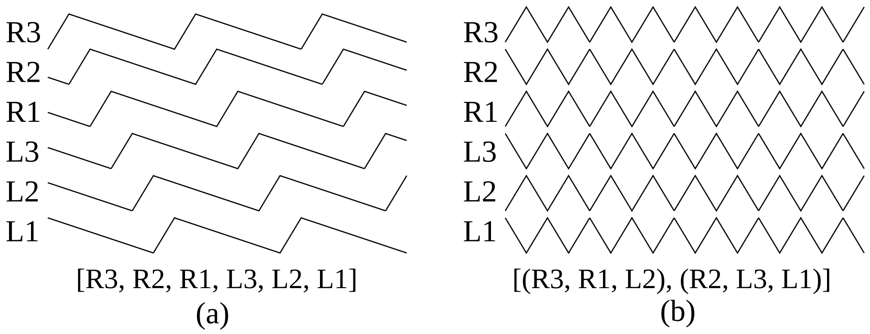


Figure 4.4: Results of Wendler's analogue model.
(a) Low oscillator frequencies produces metachronal waves. (b) Higher frequencies converge to the tripod gait. A rising slope indicates a protraction and a falling slope indicates a retraction of the leg.

Since one common input is used to control the frequency of the six oscillators, the hexapod is able to change its walking speed by varying the input but it would not be able to make the hexapod turn. Separate signals would have to be used to control the frequency of the individual leg controllers such that the left-hand oscillators can be made to oscillate at a different frequency to those on the right. This approach was used by Pearson (described in Section 4.3.3) and Beer (described in Section 4.3.5).

Wendler's analogue model differs from other models derived from Wilson's simple model in that it doesn't use the inhibitory and excitory stimuli between the local control subsystems to produce coordination as described in Section 4.3.1.

4.3.3 Pearson

Keir Pearson et al. [18] studied the locomotion of both animals and insects. They investigated the neural behaviour of the legs of a cockroach and developed a model for individual leg control and the coordination between the legs.

Pearson's model, shown in Figure 4.5 (diagram adapted from [18]), was composed of three sections for each individual leg controller. The first of these sections is known as the *rhythm-generating interneuron*, also known as the *flexor burst generator*. This is simply a sine-wave oscillator that is used to trigger a leg to start a protraction and whose frequency is used to determine the walking speed, hence corresponding with Wilson's fourth rule: "walking frequency varies as retraction time varies".

The frequency, or walking speed, is determined by the strength of the signals that are sent to each of the six flexor burst generators. These signals are obtained from the *central command neurons* in the insect's brain. The greater the strength of the signal, the higher the oscillation frequency of the flexor burst generators, and hence the greater the walking speed.

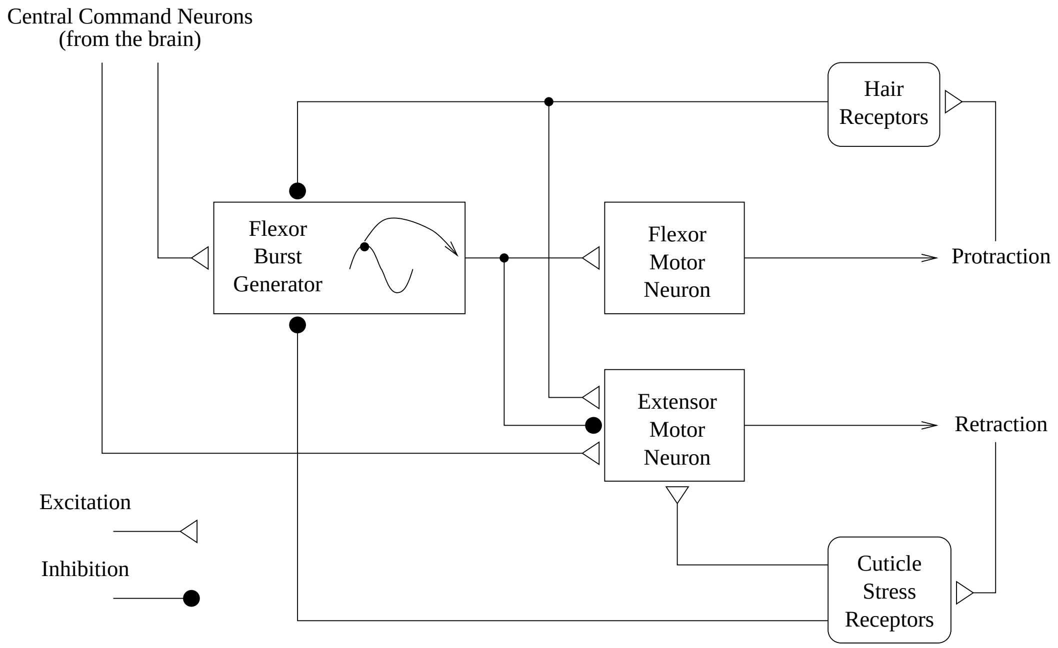


Figure 4.5: Pearson's model of an individual leg controller.
This model produces the rhythmic retraction/protraction movement of a single leg.

The second section consists of two motor neurons – the *flexor motor neuron* and the *extensor motor neuron*. The flexor motor neuron makes the leg lift up and swing forward to produce a protraction. This neuron is triggered at the peak of the sine-wave generated by the flexor burst generator [10]. The duration of the protraction is fixed and is less than the period of the sine-wave, hence corresponding with Wilson's third rule: "protraction time is constant". The extensor motor neuron places the leg down and pushes it backward to produce a retraction. This motor neuron is constantly excited by the central command neurons. When the flexor burst generator excites the flexor motor neuron to make the leg protract it also inhibits the extensor motor neuron to prevent any conflict between the two actions.

The third section is the *sensory receptors*, or biological sensors. The sensory receptors consist of the *cuticle stress receptors* found on the insect's exoskeleton and a group of *hair receptors*. The cuticle stress receptors have two known purposes. Firstly, while a leg is retracting the stress sensors are used to monitor the load experienced on the leg. The signal is sent back to the extensor motor neuron to adjust the force of the leg and to give it a greater push when necessary. Hence, this provides a servomechanism for the leg [10] [128]. The stress receptors are also used to detect that the leg is unloaded when the leg has finished retracting and has reached its PEP. This causes the leg to change from the retraction stance to the protraction swing. The hair receptors are used to detect when the leg has finished the protraction in order for the leg to be placed down at its AEP to start another retraction.

Pearson also determined that the flexor burst generators of adjacent legs mutually inhibit each other, as shown in Figure 4.6 (diagram adapted from [18]). This prevents adjacent legs from stepping together which would cause the insect to become unstable [18], hence corresponding with Hughes' first and second rules: "adjacent ipsilateral legs step in sequence" and "contralateral legs of the same segment protract 180° out-of-phase".

Pearson's locomotion controller was used by Beer et al. [21] (described in Section 4.3.5 below) and was found to work well for a large range of walking patterns.

4.3.4 Cruse

Holk Cruse et al. [127] [129] [130] studied the locomotion and neuronal control of animals, crustaceans and insects. In particular his studies of the stick insect had produced two models relating to the leg movements of the insect. First a model for the control of an

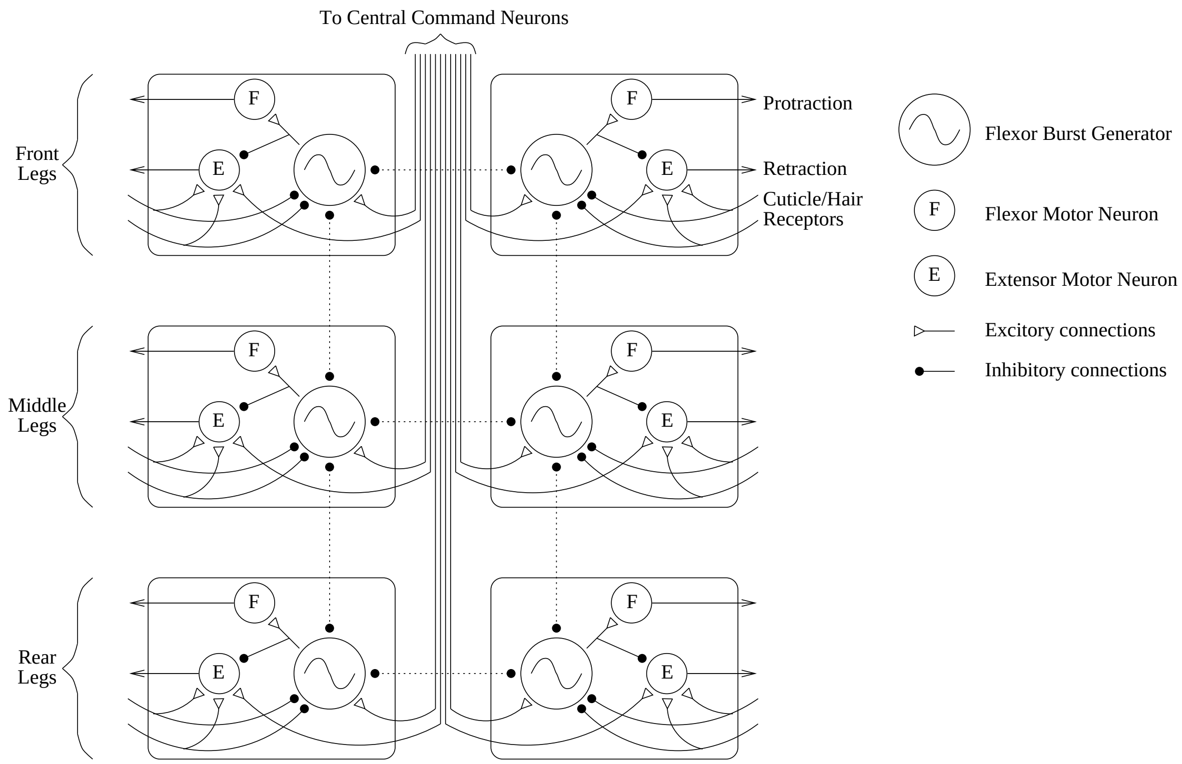


Figure 4.6: Pearson's inter-leg coordination between single leg controllers. The dotted lines show the mutual inhibition between each adjacent flexor burst generator which prevents adjacent legs from protracting at the same time.

individual leg and then a model for the coordination between the legs of a hexapod.

In part of Cruse's earlier work he developed a model for the coordination of the legs of a hexapod [127]. This particular model was different to his newer systems and the other methods described in the previous sections because it was designed to relay information from the front legs to the rear legs rather than rear to front. The model provided stable patterns but did not describe all the properties of the walking insects.

Cruse's newer model for the control of an individual leg is described in detail in [129] and is shown in Figure 4.7 (diagram adapted from [131]). The model was developed based on the leg movement of the stick insect. It allows a single leg to transition from the retraction phase to the protraction phase of the leg and vice versa. The model does not assume to directly control each of the individual muscles (DOF) in the legs of the insect, but rather it assumes that the leg will automatically lift off the ground to begin a protraction, and automatically be placed down to start a retraction.

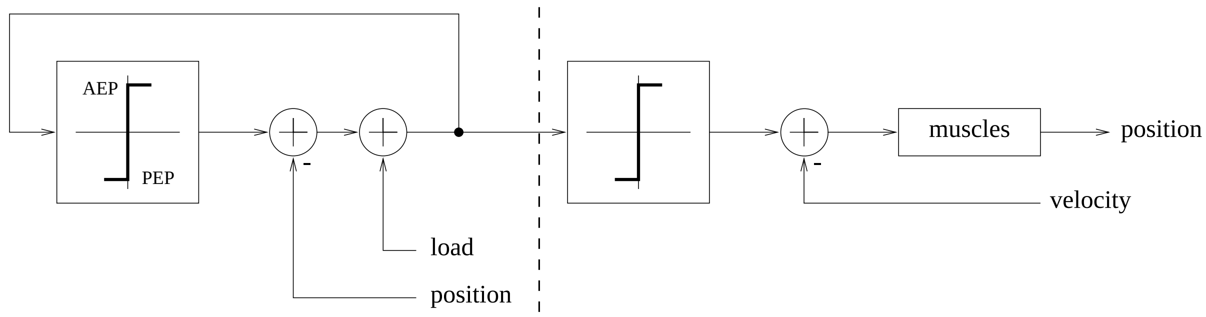


Figure 4.7: Cruse's model for the control of an individual leg.

The left side of the diagram in Figure 4.7 shows a feedback mechanism which is actually a decision circuit that determines whether the leg should protract or retract. The output can be positive or negative indicating that the leg must move towards its AEP or PEP, respectively. Positive positions and velocities are measured when the leg is moving forward (protracting) and negative positions and velocities are measured when the leg is moving rearward (retracting).

The left relay characteristic produces either the AEP or PEP predefined leg positions depending on whether the input value is positive or negative, respectively. The actual leg position is subtracted from these predefined positions to obtain a delta position value.

The vertical load of the leg also plays a role in this decision circuit. As mentioned in Section 4.3.3 above, the motion of a leg will change from the retraction to the protraction firstly when the leg has reached its PEP, the load on the leg must also be small and the adjacent legs must be supporting the body. Therefore, in the model, if the adjacent legs are not supporting the body then the load on the leg would be large. Now, assuming the load value is negative, this will add to the delta position value causing the decision circuit to output a negative value, keeping the leg at its PEP and preventing it from protracting. Once the adjacent legs are supporting the body causing the load on the leg to be reduced sufficiently, the decision circuit will output a positive value and the leg will then protract.

The output of the left decision circuit is then input to the right side of the circuit where it is hard-limited to produce the target positions (AEP or PEP). This section is a velocity-controlling feedback system. A positive output of the decision circuit will produce movement in the anterior direction for a protraction, while a negative output of the decision circuit will produce movement in the posterior direction for a retraction [131] [10] [128].

In order to coordinate six of these individual leg controllers Cruse devised four mechanisms that were used to decide when particular legs should perform particular functions [130]. Of these mechanisms, Ferrell [10] [128] described three as being the primary mechanisms. These are listed below. The fourth mechanism only relates to large forces experienced on the legs of the stick insect such as when walking vertically, and has therefore been omitted.

- Mechanism 1: While a posterior leg is protracting, it will inhibit the protraction of the next anterior ipsilateral leg by adjusting the PEP of the anterior leg to a more posterior position.
- Mechanism 2: When a posterior leg has just started retracting, it will excite both the next anterior ipsilateral leg and the contralateral leg to begin their protraction by adjusting the PEP of those legs to a more anterior position.
- Mechanism 3: While an anterior leg is retracting, it will gradually excite the next posterior ipsilateral leg and the contralateral leg to begin their protraction. The excitation from the anterior leg is weak at first and becomes stronger as it approaches its PEP. This allows the posterior ipsilateral leg and the contralateral leg to protract before the anterior leg has finished retracting.

The influences of these three mechanisms on the six legs of a hexapod are shown in Figure 4.8 (diagram adapted from [128]).

An example of the use of these mechanisms is shown in Figure 4.9 (diagram adapted from [10]). This shows an example of using the three mechanisms described above on leg

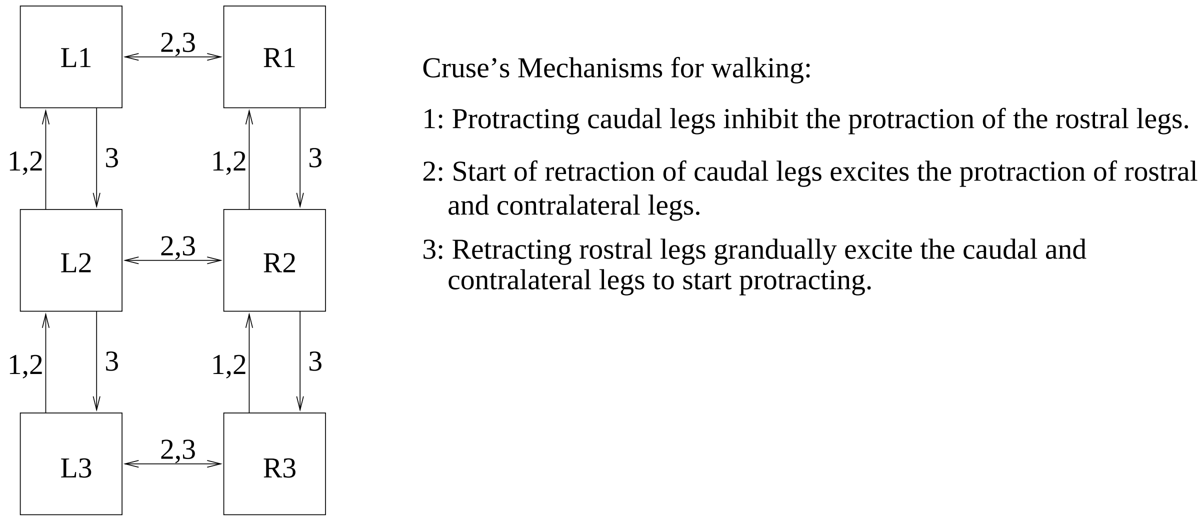


Figure 4.8: Cruse's model for the coordination between individual leg controllers. The three mechanisms described in the text are labelled as 1, 2 and 3 in the diagram. The direction of the influence of each mechanism is indicated between each adjacent leg by the arrows.

L2 and their effect on legs L1 and L3. The mechanisms on leg L2 would also affect leg R2, although this has not been shown. The three influences shown (influence 1, influence 2 and influence 3) correspond to the influence that the three mechanisms have on leg L2.

Figure 4.9 shows that when leg L2 is protracting it inhibits L1 from protracting until L2 has finished protracting, otherwise the hexapod would become unstable and fall over. This corresponds with mechanism 1. Just after leg L2 has started retracting, it excites leg L1 to start protracting. This corresponds with mechanism 2. Finally, while leg L2 is retracting it gradually increases its excitation to leg L3 to begin its protraction. This corresponds with mechanism 3. Thus these three mechanisms have produced a back to front metachronal wave gait.

The combination of mechanisms 1 and 2 corresponds with Hughes' first rule: "adjacent ipsilateral legs step in sequence". The combination of mechanisms 2 and 3 corresponds with Hughes' second rule: "contralateral legs of the same segment protract 180° out-of-phase".

Beer et al. [10] experimented with Cruse's mechanisms for walking and found that

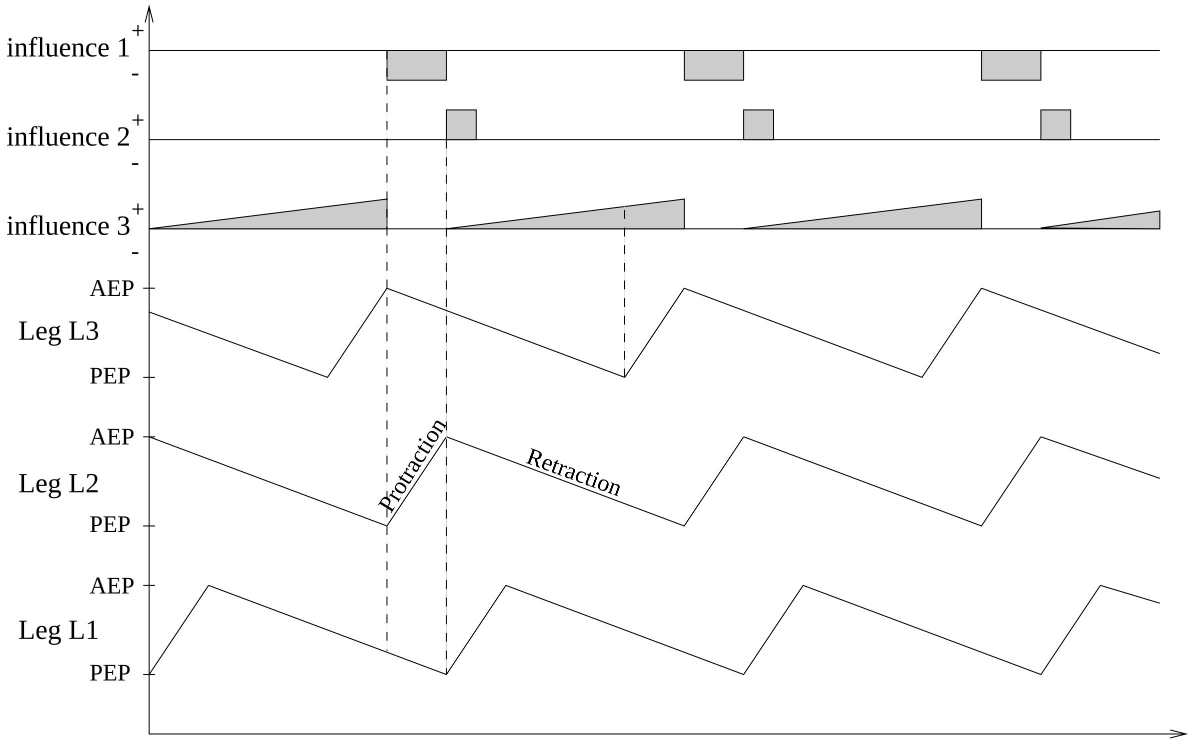


Figure 4.9: An example of leg coordination using Cruse's mechanisms.
The three bottom traces show the leg positions of the three left legs of a hexapod, L3, L2 and L1. The three top traces show the influences that mechanisms 1, 2 and 3 produce for leg L2 and their effect on the ipsilateral legs, L1 and L3. A positive influence is considered to be excitory and a negative influence is considered to be inhibitory.

mechanism 2 mostly promotes a metachronal wave of protractions from the rear legs to the front legs. They also found that mechanism 3 mostly promotes the 180° phasing between contralateral legs of the same segment.

Ferrell et al. [10] used Cruse's mechanisms to control the walking for the robot Attila (Section 2.5.7). They found that Cruse's mechanisms could produce stable coordination between the legs over a wide range of walking speeds as long as the retraction velocity remained the same, that is, when the robot walked in mid-air [10]. They also found that the robot's retraction speed varied when the legs were supporting the body. This caused the walking patterns to shift in and out of phase and sometimes make the robot unstable. Therefore, they modified the individual leg controllers, the original coordination mechanisms and the coordination of the mechanisms between the individual leg controllers. As a result, their modified controller became more robust to inconsistent retraction velocities but had difficulty producing mid-range gaits.

Some of Cruse's later work involved substituting artificial neurons for the algorithms described above for both the oscillatory control of an individual leg and the coordination between legs [116].

4.3.5 Beer

Randall Beer et al. [21] [74] experimented with the control of artificial cockroaches using neural network approaches. They developed an animated computer generated insect called *Periplaneta Computatrix*, named after the American cockroach, the *Periplaneta Americana*. The control system they used for their insect was implemented on a walking robot called the CWRU Hexapod, described in Section 2.5.8.

The locomotion control system that Beer used is shown in Figure 4.10 (diagram adapted from [102]). This controller was primarily based on Pearson's locomotion controller (described in Section 4.3.3 above) but had a few differences. The differences are that Beer used an artificial neuron model whose characteristics were closer to real neurons, and he also used three motor neurons rather than two as Pearson had used [21]. Regardless of these differences, the same biologically based interaction of neurons and appropriate reflexes and sequence generators is equivalent in both systems [46].

As can be seen in the diagram, each of the six local leg controllers have a *pacemaker neuron* which performs the same function as Pearson's flexor burst generators. The *foot motor neuron* keeps the leg down on the ground in a standing position. The *backward swing motor neuron* produces leg movement in the caudal direction. The *forward swing motor neuron* produces leg movement in the rostral direction. The *backward angle sensor* monitors the position of the leg when it is pointing rearward. The *forward angle sensor* monitors the position of the leg when it is pointing forward. Finally, the *command neuron* is used to excite the pacemaker neurons as well as the backward swing motor neurons.

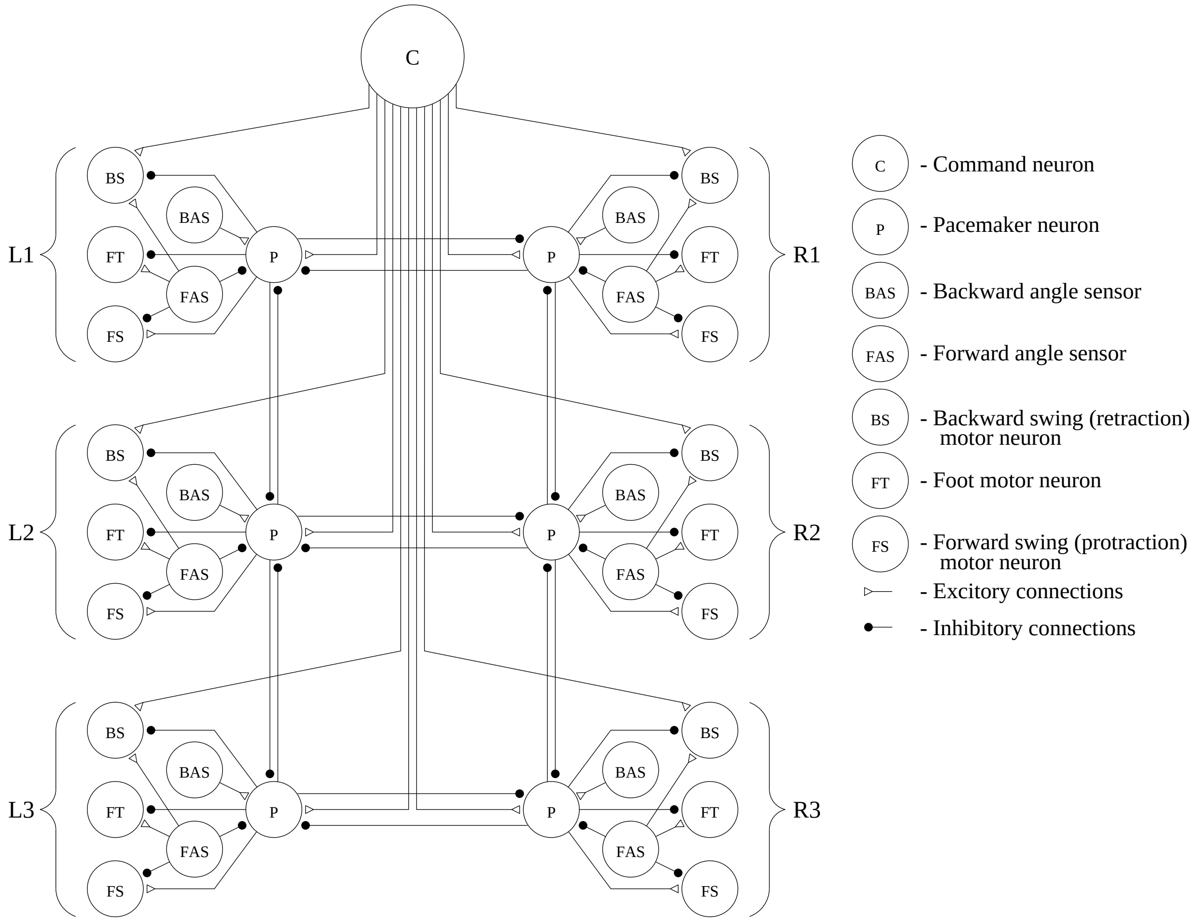


Figure 4.10: Beer's hexapod neural locomotion controller.

The local leg controllers can also be described using a "dendritic" model of the group of neurons. Figure 4.11 shows an example of expressing the neurons of the local leg controller for leg R1 using this method.

A protraction/retraction cycle is produced by a chain of reflexes, described as follows. First we will assume that a leg is positioned on the ground at its PEP. The pacemaker "bursts" inhibit the foot motor neuron making the leg lift up. The forward swing motor neuron is also excited by the pacemaker which makes the leg swing forward to protract the leg. At the same time, the backward swing motor neuron is inhibited to prevent any conflicts by trying to make the leg swing backward.

Between the pacemaker bursts, and when the forward angle sensor detects that the leg has finished moving forward, the forward angle sensor excites the foot motor neuron and

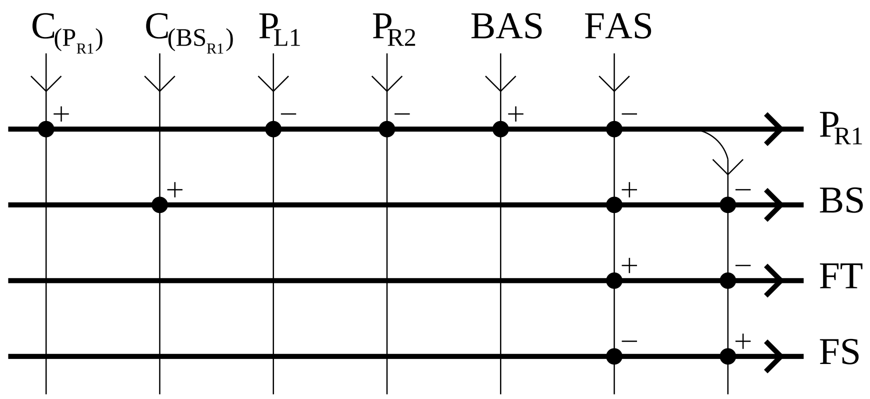


Figure 4.11: A "dendritic" form of the local leg controller for leg R1 in Figure 4.10.

the backward swing motor neuron to place the leg down and push the leg backward for the retraction. The backward swing motor neuron is also excited by the command neuron to push the leg backward. This retracts the legs and propels the insect (or robot) forward. The forward angle sensor also inhibits both the pacemaker neuron and the forward swing motor neuron to prevent them from trying to protract the leg while it is retracting.

When a leg has finished retracting, the backward angle sensor excites the pacemaker neuron to start another protraction. This sequence is then repeated to produce the stepping motion.

As with Pearson's model, Beer's model uses mutual inhibition between the adjacent pacemaker neurons [132]. Also, the frequency of the pacemaker bursts is controlled by the command neuron.

The control system was found to be very robust and was capable of producing a continuous range of gaits from the medium speed gaits up to the tripod gait [80] [10]. The slowest gaits, where each leg protracts in succession, could not be produced using Beer's controller.

4.3.6 Brooks

Rodney Brooks of MIT [133] [19] [20] developed a robot control system in the mid-1980's known as *"subsumption architecture"*. Subsumption architecture was used to control many different mobile robots including several hexapod robots. Brooks' control system produces "artificially intelligent" (AI) behaviour and has many advantages over previous methods.

Traditional approaches to the design of mobile robot control systems had created problems in yielding effective solutions for real-time interactions in unstructured environments. AI programs written for such systems used model-based techniques that involved reasoning over large databases of information. Brooks gave his own views regarding the techniques used to control artificial robotic creatures [133]. He explained that feasible theory still needed to be developed for such systems and explained how the systems should be practically built, while still keeping in mind future developments in this area of robotics.

Brooks et al. plan was to eventually create "artificially intelligent" beings by first building autonomous robots that perform a number of generic task-achieving behaviours and eventually develop the more useful high-level systems [108].

Their approach of developing AI control systems included having no traditional notion of planning, no central representation of the "real world" and they also assumed that creating structured models of parts of the real world was unnecessary. Also, much inspiration could be obtained from biology by observing the behaviours of insects, for example. They also argued that building complete systems in the real world is essential since it eliminates any ambiguity from only simulating the control systems [34], as explained previously in Section 2.6.

In order to demonstrate the effectiveness of subsumption architecture, a small and fast mobile robot was built using a toy car fitted with four infrared sensors [134]. The relatively simple control system allowed the robot to explore an unstructured environment, follow other similar fast moving robots and avoid collisions.

An early version of the subsumption architecture was also used to control another robot fitted with a mechanical arm. The robot was designed to navigate an unstructured environment and then locate and retrieve empty soda cans from either on top of tables or on the floor [135]. In comparison to earlier robots, this robot used very little computing power to achieve its task. Therefore, in general, behaviour control methods require very little computation for autonomous control [136].

As shown in Figure 4.12(a) (diagram adapted from [19]), the traditional method used for a mobile robot control system was to first obtain sensor readings, analyse the readings, make decisions and then produce motor output. In contrast, Brooks' approach was to incrementally build a parallel layered control system where each layer defines a *level of competence* of the overall control system.

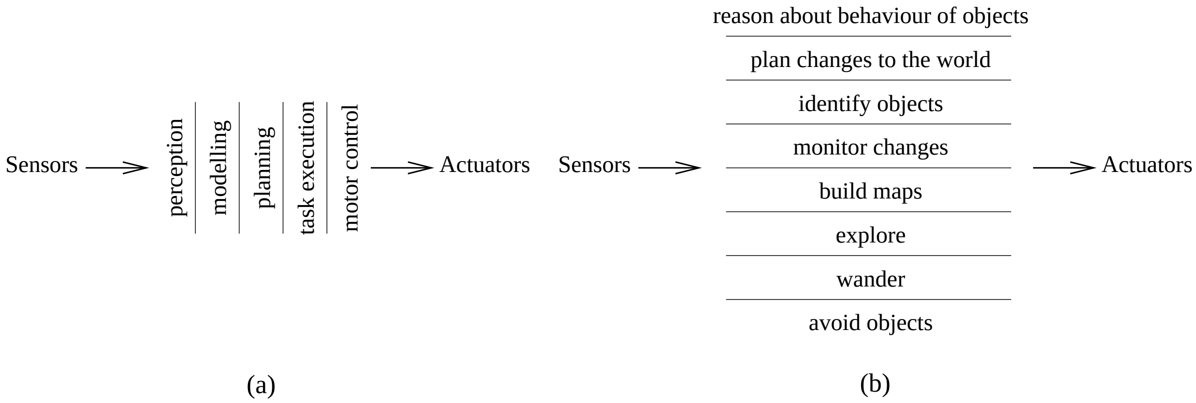


Figure 4.12: The two methods of executing a mobile robot control system.
(a) The traditional decomposition of functional modules of a mobile robot control system.
(b) The decomposition of task-achieving behaviours of a mobile robot control system.

The layers of his control system consist of several carefully designed networks that produce *task-achieving behaviours* [20]. An example of a layered mobile robot control system is shown in Figure 4.12(b). The most basic behaviours are present in the lowest layers of the control system. Higher levels of intelligence are obtained by gradually adding more layers of networks on top of the previous layers. The accretion of new levels gradually evolves the control system by increasing the level of competence of the overall system [134].

The behaviours of each level of competence are evolved by implementing each subsystem as a finite state machine and then arranging them in a manner that will produce the desired interaction between them [106]. These behaviours have also been termed "agents" [116].

This new approach to the general organisation of intelligent systems was argued by several researchers, including Brooks, as being more appropriate for use in dynamic environments [137]. Some researchers believe that designing cognitive architectures, or control systems by hand becomes very difficult as it increases in complexity [138]. This is certainly true but the complexity can be reduced by designing a greater number of smaller control subsystems.

As can be seen in Figure 4.12(b) every layer has direct access to the sensors and the actuators which allows them to directly link perception to action [20]. Subsumption architecture is therefore considered to be "reactive" since it produces direct reactions to sensory inputs [46]. Hence, sensor information is not stored but is rather used to provide immediate actions [73]. Sensor readings may however be stored for the purpose of filtering based on previous samples, for example. Each level runs concurrently and is independent of each other.

The first layer (level 0) will give the robot its lowest level of competence. The next layer (Level 1) will add to the overall level of competence of the system by performing a slightly more intelligent task. Level 1 will execute independently of Level 0 but may use or replace signals from Level 0 and will, in turn, subsume the role of Level 0. Further levels will gradually add to the overall level of competence and each will subsume the role of the lower levels. Hence the name "subsumption architecture".

As mentioned above, the behaviours in each layer are defined using finite state machines that are augmented with registers and internal timers. According to Brooks' specifications, there are essentially four states in each finite state machine. An *output state* will compute a combinatorial function of the registers and direct the result either back to one of the registers or to an output line, and then change to another specified state. A *side effect state* changes the value of one of the internal registers computed as a function of the inputs and any other internal variables. It then changes to a new specified state. A *conditional dispatch state* will branch to one of two other states based on a combinatorial predicate on the inputs and internal registers. An *event dispatch state* is one which monitors the inputs and/or internal timers and can change the value of one of the internal registers or change to another state when an event it true. An event is valid when a combination of certain inputs occurs or when an internal timer expires.

These *augmented finite state machines* (AFSMs) form agents that combine to produce the task-achieving behaviours. The task-achieving behaviours then combine to form levels of competence and the levels of competence produce the subsumption-based controller [10].

Signals from sensors or other AFSMs that are transferred between AFSMs are termed *messages*. Messages are carried between AFSMs using a conceptual type of link between the modules, termed *wires*. The wires in a particular subsumption design are a common number of bits wide. A change of state in an AFSM can occur either when a new message arrives or when triggered by its internal timer.

There are three types of nodes used for wires to interact between AFSMs. These are *inhibitor* nodes, *suppressor* nodes and *defaulting* nodes, and are shown in Figure 4.13. As can be seen each node has an "original" wire labelled 'a' and a "new" side-tapping wire labelled 'b'.

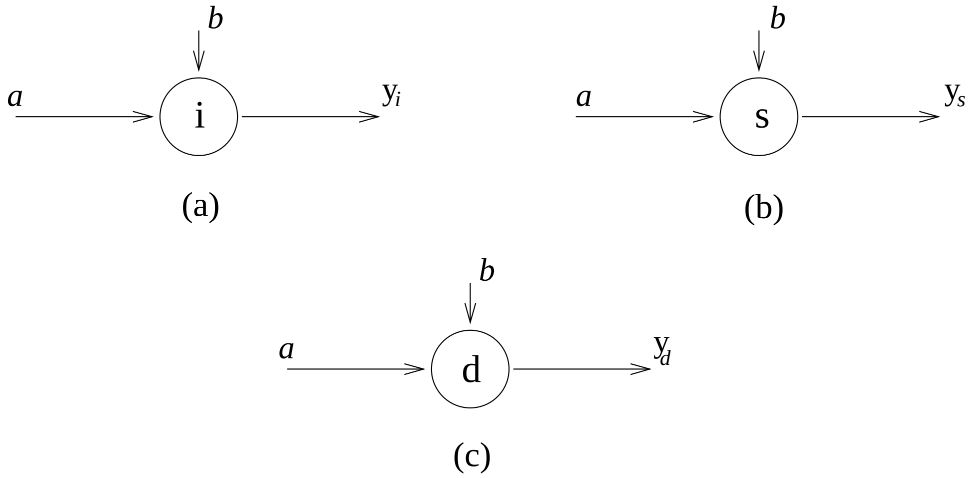


Figure 4.13: The three types of nodes used in a subsumption architecture design. (a) Inhibitor node. (b) Suppressor node. (c) Defaulting node.

With reference to Figure 4.13, the inhibitor node will output the messages on wire 'a' unless a message is present on wire 'b'. In which case the output (y_i) will be zero. The suppressor node will also inhibit the message on wire 'a' if wire 'b' has a message, except that the output (y_s) will be replaced by the message present on wire 'b'. The defaulting node performs the same function as the suppressor node except that the "original" wire (wire 'a') has control over the output (y_d). A more formal description for these nodes is given in Equations 4.1 to 4.3. 'a' and 'b' are either $true$ or $false$ depending on whether they have a message present on them or not, respectively.

$$\mathrm{y}_i = \begin{cases} a & \text{if } b \text{ is } false \\ 0 & \text{if } b \text{ is } true \end{cases} \tag{4.1}$$

$$\mathrm{y}_s = \begin{cases} a & \text{if } b \text{ is } false \\ b & \text{if } b \text{ is } true \end{cases} \tag{4.2}$$

$$\mathrm{y}_d = \begin{cases} b & \text{if } a \text{ is } false \\ a & \text{if } a \text{ is } true \end{cases} \tag{4.3}$$

As mentioned above, the subsumption architecture was used to control the walking of several hexapod robots. The first of these was Genghis, described in Section 2.5.6.

The control system used for Genghis enables a robot with two DOF legs to perform a simple walk using any valid gait, or walking pattern. The two DOF's are organised such that one DOF moves a leg up and down while the other DOF moves the leg forward and backward.

The first two levels of the control system contain a set of behaviours that allow the robot to stand and perform a simple walk, respectively. The first layer (Level 0) is shown in Figure 4.14 and is repeated for each of the six legs.

This part of the control system contains two AFSM modules, the **alpha pos** module

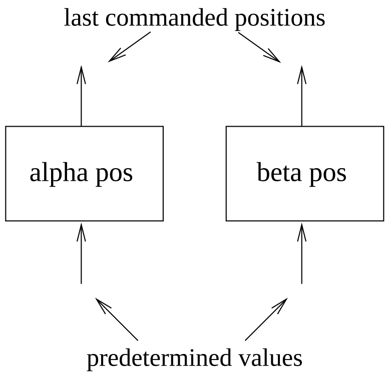


Figure 4.14: Level 0 of the subsumption architecture used to make Genghis stand.

and the **beta pos** module. The input to these modules will determine the position of the forward/backward DOF (alpha motor) and the up/down DOF (beta motor), respectively. The output from these modules are the last commanded positions (or current positions). At reset, a value stored in a register in each of the two separate AFSMs will move the alpha motor and the beta motor to predetermined positions to allow the robot to stand up.

The second layer of Genghis' control system allowed it to perform a simple walk. The two layer control system is shown in Figure 4.15 (diagram adapted from [72]). The boxed section is repeated six times, once for each leg, and there are two global AFSMs, the **alpha balance** AFSM and the **walk** AFSM.

Firstly, the **leg down** module monitors the beta position and outputs a message to the **beta pos** module to keep the leg down in order to keep the robot standing. A global **alpha balance** module is then used to position the alpha DOF of each leg. The alpha positions are such that a zero value will position the leg perpendicular to the longitudinal direction of the robot's body, pointing laterally away from the body. Positive values position the leg forward while negative values position the leg towards the rear. The **alpha balance** module monitors the six alpha positions and ensures that the the sum of new alpha positions are always equal to zero. Hence, if three legs are pointing forward then the other three legs must point rearward.

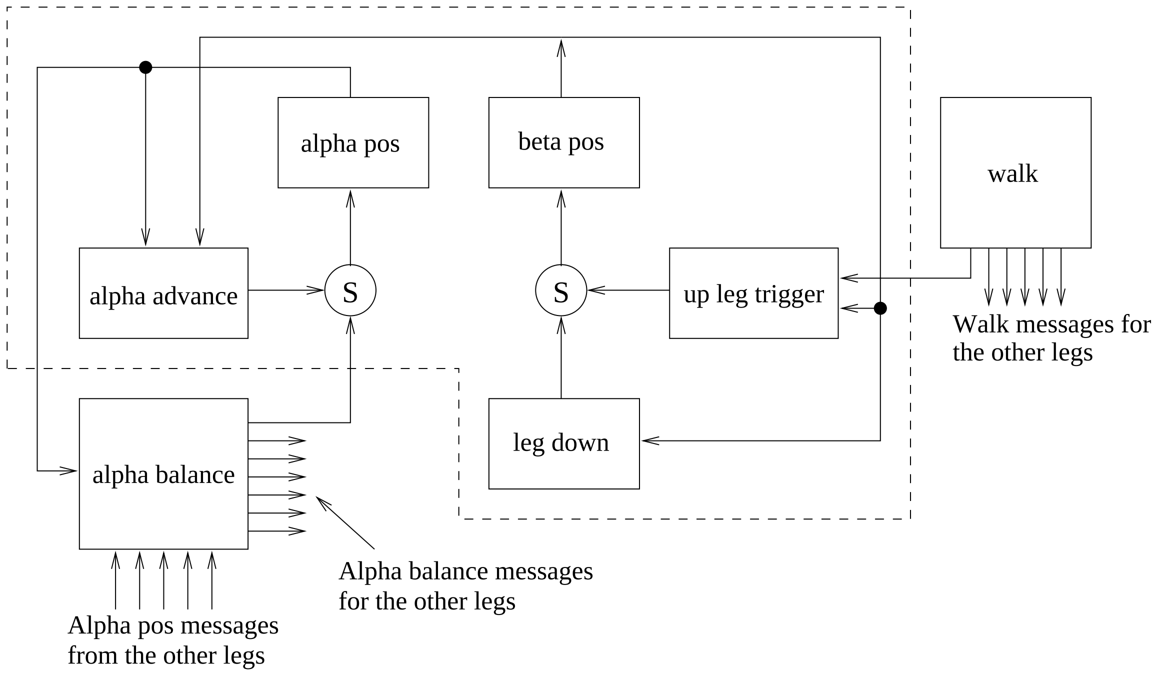


Figure 4.15: Level 0 and 1 of the subsumption architecture used for Genghis. The control system allows Genghis to stand and perform a simple walk. The boxed area is duplicated for each leg.

The **alpha advance** module also monitors the beta position and will make the associated leg swing forward (protract) when the leg has been lifted up by suppressing the signal from the **alpha balance** module. The **walk** module is used to generate various coordinated gait patterns for walking. It sends messages to the six **up leg trigger** modules depending on the current gait that it is generating. When the **up leg trigger** module receives a message from the **walk** module (while the leg is currently down) it will suppress the **leg down** module and output a message to the **beta pos** module to lift the leg up.

The overall sequence is therefore described as follows. For a particular leg, the **walk** module signals the **up leg trigger** module to lift the leg up. This causes the **alpha advance** module to force the leg to protract forward causing the other five legs to move backward a small amount using the **alpha balance** module. This propels the robot forward. Then the **leg down** module places the leg back down in a standing position. The **walk** module will then signal another leg to lift and protract. Hence, the controller allows the legs to move in a sequence or chain of reflexes to produce the necessary retractions and protractions [102]. This therefore produces a periodic walking pattern.

Additional layers were added to the subsumption control system in Figure 4.15 to increase the level of competence of the robot and make it perform in a more intelligent manner. These additional task-achieving behaviours include:

- balancing the robot by measuring the force on the legs as the robot walks, and keeping any particular leg from moving down further if the force becomes too great.
- determining when the legs need to be lifted higher in order to climb high obstacles.
- detecting high obstacles using a feeler (or whisker).
- stabilizing the pitch of the robot when the inclination of the robot becomes too great.
- monitoring six infra-red sensors on top of the robot and making it walk only when a moving infra-red source is detected.
- steering the robot towards the moving infra-red source.

Genghis' controller is only partially distributed since it uses two global AFSMs (**alpha balance** and **walk**) to control the walking. Beer's biologically inspired gait controller (described in Section 4.3.5 above), however, is completely distributed since it uses the interaction of pacemaker neurons, command neurons and other neurons to produce the walking patterns [74]. In an attempt to make Genghis' controller more distributed, Maes and Brooks [139] modified the control system to allow it to learn to coordinate its behaviours. Two types of sensors were added, including a wheel that touched the ground to provide positive feedback when the robot made any forward movement, and ground contact sensors under the body of the robot to provide negative feedback when the robot fell on its belly. Initially the behaviours made the legs move in an uncoordinated manner. The control system allowed each behaviour to determine whether it is correlated to positive feedback and under what conditions it becomes reliable to maximise the positive feedback. The robot gradually learnt to coordinate its behaviours until it successfully walked using a tripod gait. The control system was completely distributed.

Some researchers have felt that subsumption architecture had moved too far away from the traditional methods of artificial intelligence. For example, Thomas M. Mitchell of Carnegie Mellon [140] showed much scepticism when he explained that subsumption architecture is "better suited to building thermostats than intelligent agents". However, Brooks had previously explained that simply because a system cannot perform a particular function does not mean that it shouldn't be investigated. As an example, he explained how it would be "unfair to claim that an elephant has no intelligence worth studying just because it does not play chess" [141].

Brooks' subsumption architecture has proved many times to be far better, easier to implement and more successful than many previous works in artificial intelligence for the control of mobile robots.

4.4 The Control System Used for Strider

Of the locomotion controllers discussed in this chapter, one had to be chosen for the control of Strider.

One aspect that the control systems of Wendler, Pearson, Cruse and Beer share in common is that they all require legs that possess at least two DOFs. This is typically to allow each leg to have one DOF to propel the body and one DOF to lift the leg, which is necessary since the control systems require that the legs are able to be lifted at any time. The legs of the robots must therefore have a *variable* stride length (or a variable retraction time). Such robots are usually difficult to control while the body is being propelled since many DOFs need to be coordinated [8]. Fewer DOFs would be easier to control.

The groove-slot mechanism used in Strider decouples the body propelling DOF from the leg lifting DOF, making use of only one DOF per leg in order to walk. Hence, the stride length is *fixed*. Therefore, the above mentioned control systems would not be as suitable as a system that controls only one DOF per leg to walk. According to Kaneko et al. [8], such a control system would be simpler in design than the other above mentioned control systems.

Regardless of the fact that Strider uses one DOF per leg to walk, if the leg movement is limited to only horizontal movement using one DOF and the vertical lift actuator (described in Section 3.2.6) is used to lift the leg, then the above mentioned control systems could be used to control Strider's walking.

One of the disadvantages of the control systems mentioned above is that they have only been able to produce metachronal wave gaits. Moreover, the systems can usually only produce a subset of these gaits. The range of metachronal wave gaits are described in Chapter 5. The only control system that does not require a variable stride length and is capable of producing any sort of gait is Brooks' subsumption architecture.

The example given above of the control system used for the robot Genghis required two DOFs per leg. The alpha motor and the beta motor were individually controlled to produce a stepping motion. Since subsumption architecture is very modular in design it is reasonably easy to implement a new control system for our purposes. Brooks layered approach could be used to develop a control system for robots that use one DOF per leg. Therefore, subsumption architecture was the chosen method to be used to control the mechanics of Strider.

4.4.1 A Word About the Implementation of Subsumption Architecture

All the AFSM modules of a subsumption design should theoretically run concurrently and asynchronously. Since the entire control system had to execute on a single processor on-board the robot, the parallelism had to be emulated in software.

Brooks also used this type of approach when he implemented the subsumption architecture on his robots. To emulate the parallelism would not be necessary however, if actual (individual) finite state machines were being used which contained timers, hence preserving the original architecture design.

The original AFSM design consisted of a standard finite state machine which was augmented with timers and registers. In the control system used for Strider the timers were left out as they were not required. Also, the wires that carried data between the AFSM modules are normally a common number of bits wide. In our implementation the wires are not restricted to any bit-length. Therefore, the control system used for Strider is a variation of the original subsumption architecture.

Each AFSM was implemented as a separate function, written in the C programming language. Each of these functions were called within a large loop which cycles through the functions hundreds of times a second. The control system can read the sensors and control the motors at a very high rate. Executing the subroutines many times a second helps to emulate the concurrency of the parallel structure of subsumption architecture.

The many subsumption modules that are described in the following sections are described using flowcharts in Appendix C.

4.4.2 Servo-Controlling the Motors

Part of designing a control system that can be used to generate walking patterns is to design the lower-level control subsystems. These subsystems will be used to control the six motors that control the positions of the six legs. We will call the motors that drive the slot-plate in the groove-slot mechanisms, the *drive motors*.

One method commonly employed in motor control is to control not only the position of the motor but also the speed at which the motor turns. A velocity feedback loop to control the position allows for smoother trajectories with less chance of overshooting the desired position. Ferrell [10] had implemented such a system on the robot Attila (Section 2.5.7). A velocity feedback controller was initially tried on Strider also. The algorithm detected when the leg was either moving too fast or too slow and had adjusted the PWM signal to the motors accordingly. However, the frictional forces were sometimes difficult to overcome and as a result the change in the voltage on the motors did not produce a sufficient response time for the velocity to be accurately controlled. Therefore, a different approach was required. A first order position control system was implemented that moved the slot-plate to given positions using only position feedback, as described below. This system worked adequately and therefore a velocity feedback loop was not implemented.

The legs of Strider had to function such that they could be moved to a desired position in the semicircular trajectory of the groove. The low-level control system had to move the legs to their desired positions and maintain them by monitoring any change in the leg positions, thus creating a servo-mechanism. This forms the lowest level of the overall control system and is shown in Figure 4.16. This diagram is a functional block diagram that is based on the subsumption architecture where each block (labelled **position**, **hold position**, and so on), represent the AFSMs. The arrows between them are the wires that carry data.

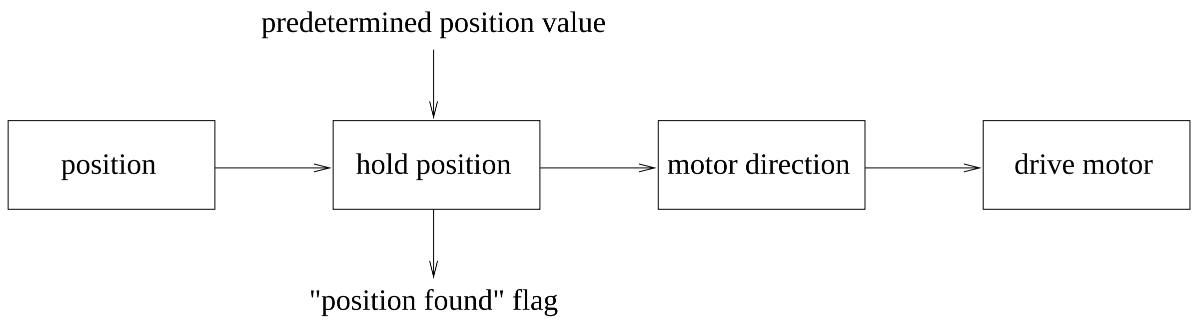


Figure 4.16: The first layer (Level 0) of the control system used for Strider.
This part of the control system is used to control the position of the individual legs.

The **position** module periodically reads the current position of the slot-plate of a particular leg. The actual position of the legs is read from the corresponding voltage present on the continuous-turn potentiometers that are connected to the slot-plate in the groove-slot mechanism. The voltage is converted to a digital value using the ADC and then read by the microprocessor.

The **hold position** module accepts a predetermined position value (from the **position** module) and compares this to the actual leg position from the **position** module. It will determine whether the drive motor needs to move clockwise or counter-clockwise, or not at all. If the actual position is within the region of the predetermined value, then the module will output a "position found" flag that can be used by higher levels of the control system.

The **motor direction** module produces the appropriate signals for the drive motor to either remain stationary or turn clockwise or counter-clockwise, depending on the current result of the **hold position** module. Finally, the **drive motor** module directly controls the direction of the motor by applying the appropriate voltage polarity to it.

The second layer of this control system will adjust the speed setting of the drive motor that controls a particular leg. This layer uses signals from the previous layer and hence subsumes the previous layer. The first two layers are shown in Figure 4.17. The control system shown in Figure 4.17 therefore shows the complete **drive servo** that is used for each of the six drive motors.

The **change speed** module reads the current leg position from the **position** module and will output, for example, a high motor speed signal when the leg is protracting and a slower motor speed signal when the leg is retracting. The **adjust speed** module will detect when the desired position has been found by monitoring the "position found" flag and will use a different motor speed setting to maintain the desired position. It does this by suppressing the output message of the **change speed** module and replacing it with a predetermined speed setting from the **adjust speed** module. The **motor speed** module directly changes the motor's rotation speed by adjusting the mark-space ratio of the PWM signal being applied to them according to the speed signal that is input to the

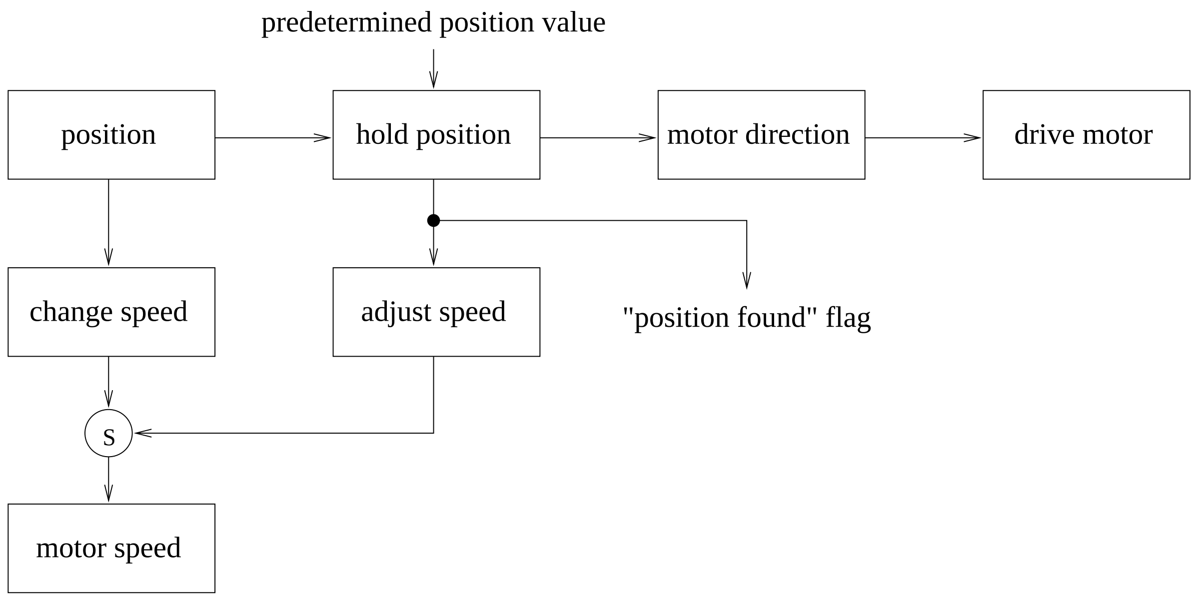


Figure 4.17: The **drive servo** used on each leg of Strider.
The **drive servo** consists of the first and second layers (Levels 0 and 1) of the control system used for Strider. It is used to servo-control the position and the speed of the individual legs.

module.

Using these two levels of the control system to servo-control the drive motors, the higher layers of the control system need only supply the desired position for a leg to move to. The leg will move to its new position at a particular speed and will be kept at the new position until the desired position changes.

4.4.3 Generating Gait Patterns

Now that the complete drive servos have been designed, only a few more modules are necessary to produce any periodic gait. The behaviours that are added form the third layer (level 2) of the control system.

The actual sensor readings from the drive motors range from 0 to 255. Inside the continuous-turn potentiometers there is a small gap (about 20°) between the ends of the track. This gap was positioned in the upper region of the groove trajectory as shown in Figure 4.18. Since the positioning of the gap will be slightly different for each leg, the leg positions must be calibrated by defining a common position for all the legs. This position will be the centre of the (horizontal) stride section of the groove of each leg. The actual sensor reading from each leg will be offset by a certain amount such that the centre of the stride length will be zero. The stride positions will therefore have positive and negative values ranging from about -30 to $+30$. These will be called the stride *delta values*, as shown in Figure 4.18.

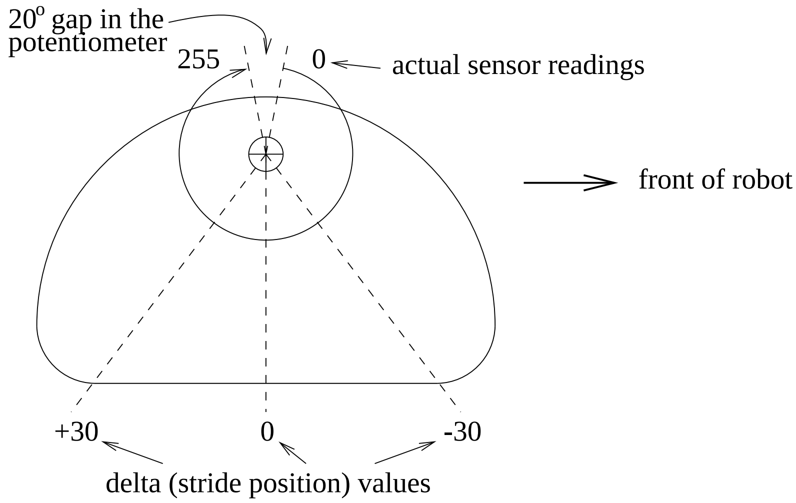


Figure 4.18: The positions of the sensor readings in the groove.
The diagram shows the original sensor positions and the redefined delta position values in the stride section of the groove.

When the control system was implemented on the robot the actual delta values used ranged from -34 to $+34$. These two positions are located just before the retraction section and just after it, on the two small curved sections of the groove. This allows the leg to be lifted slightly off the ground just prior to retraction, and just after. For the purpose of this discussion we will use the range $[-30\ +30]$ for the extreme positions of the stride length.

As can be seen, the positive offsets are directed towards the rear of the robot and the negative offsets are directed towards the front. Therefore, the delta values must be incremented in order to propel the robot forward. This can be accomplished using the **increment** module shown in Figure 4.19.

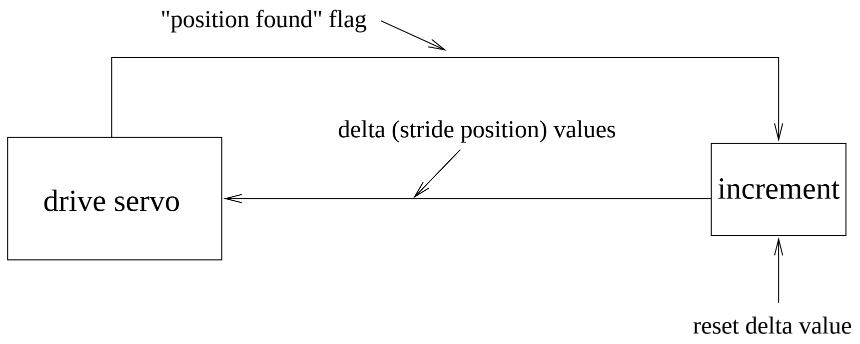


Figure 4.19: Advancing the position of a leg.
The current position of a leg that is set by the **drive servo** module (shown in Figure 4.17) is incremented by the **increment** module every time a "position found" flag is detected.

This module will produce a behaviour that will monitor the "position found" flag from the **drive servo** module (Figure 4.17) and will increment the leg position every time the last commanded position has been found. The **increment** module therefore increments from -30 to $+30$. This will allow the drive motor to turn in stages and advance the leg positions. The other input to the **increment** module is used to reset the delta position value to prevent it from incrementing too far.

If we assume that the initial leg position is at the AEP, then the **increment** module will increment the leg position to retract the leg until it reaches its PEP. At this point the leg would have finished its retraction and must begin its protraction. This is accomplished using the **protract** module shown in Figure 4.20.

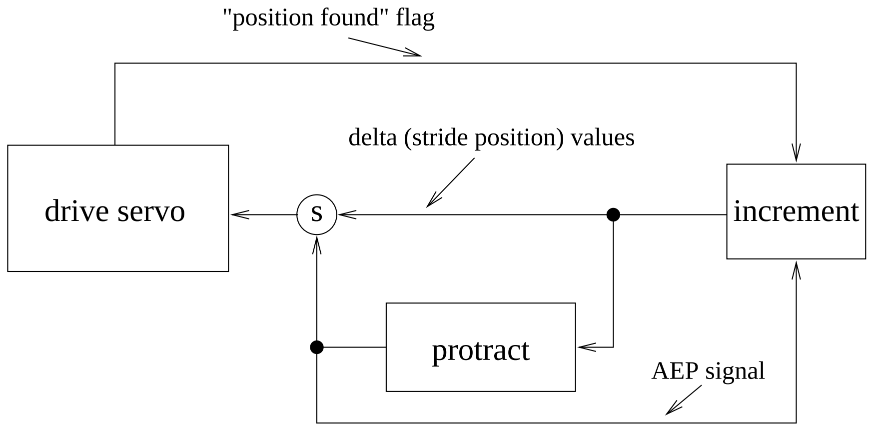


Figure 4.20: Strider's complete individual leg controller.
The **protract** module allows a leg to protract from its PEP to its AEP.

The **protract** module detects when the leg must protract by monitoring the delta values. When the leg has reached its PEP the **protract** module will suppress the current delta value and replace it with a special signal to return the leg to its AEP by following the semicircular trajectory of the groove in the groove-slot mechanism. We will call this signal the "AEP signal". At the same time, the AEP signal resets the **increment** module in order to start another retraction.

Up to this point each leg can retract and protract with an associated speed, set by the drive servos. This then completes the individual leg controller that is used to separately control each leg.

One more behaviour must now be added to synchronise the six legs. By initialising the six leg positions to predefined locations and then starting the individual leg controllers, the legs would not remain synchronised due to each leg having different amounts of frictional forces in the groove-slot mechanisms. Therefore, one more *global* module must be added to ensure the legs are always synchronised. This is the **all found** module shown in Figure 4.21. The shaded modules are the individual leg controllers that are duplicated for each leg. Only one **all found** module is used in the whole control system.

The **all found** module simply monitors the "position found" flag from each of the six **drive servo** modules and will inhibit the new delta values from the **increment** modules until all the previously commanded positions are found. This will sufficiently synchronise all the legs and allow the robot to walk using any periodic gait, depending on the initial leg positions.

An example of a simple walking sequence is shown in Figure 4.22. Here we see six photos of the right-hand lateral view of Strider. Using Hughes' convention, this walking sequence is described by [(R3, L1), (R2, L3), (R1, L2)]. Figure 4.22(a) shows the initial position of the legs. The rear leg (leg R3) is at its PEP (delta value = +30), the middle leg (leg R2) is in the centre of its stride (delta value = 0) and the front leg (leg R1) is at its AEP (delta value = −30).

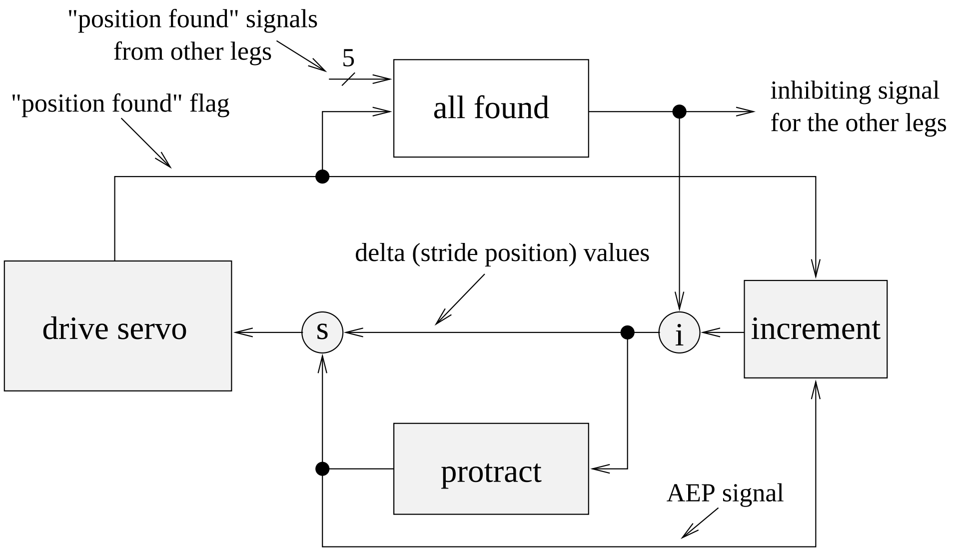
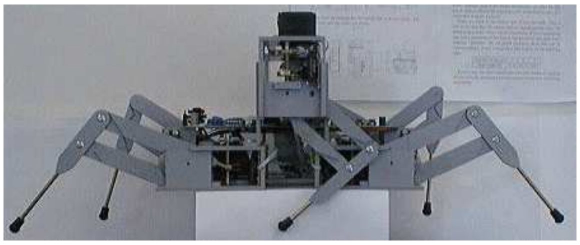


Figure 4.21: Levels 0, 1 and 2 of the control system used for Strider.
This is the first, second and third layers of the control system used to generate any particular periodic walking sequence. The contents of the **drive servo** module is shown in Figure 4.17. The shaded modules are duplicated for each leg.

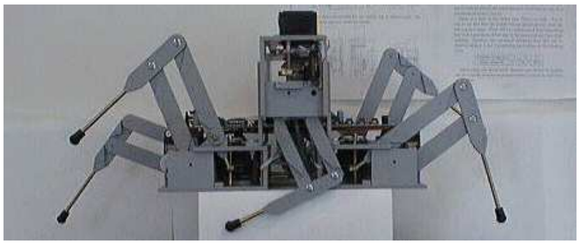
The next commanded leg positions are given below the photos. These positions are obtained from the corresponding **increment** modules. Since leg R3 is at its PEP, it is just about to protract, therefore the corresponding **protract** module will suppress the new delta value from the **increment** module and replace it with the AEP signal as its next commanded position (delta value = -30). The leg is shown protracting in Figure 4.22(b). The new delta value for leg R2 will be +30 which will move it to its PEP. The new delta value for leg R1 will be 0. These new positions are shown in Figure 4.22(c).

The next commanded positions will protract leg R2 and then leg R1. The next commanded positions given in Figure 4.22(e) will return the robot back to the initial positions of Figure 4.22(a). The control system therefore produces a continuous cycle of events to make the robot walk.

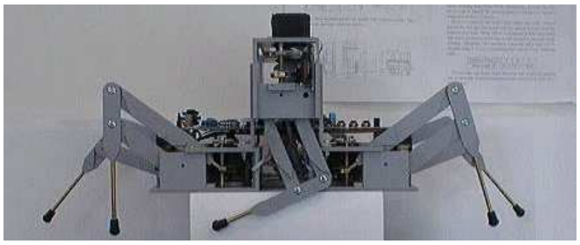
Any other periodic gait can be generated using this control system depending on the initial position of the legs. As another example, the tripod gait, given by [(R3, R1, L2), (L3, L2, R2)], can be obtained by initialising the six legs as follows. The delta values for legs R3, R1 and L2 will be initialised to +30 and legs L3, L1 and R2 will be initialised to



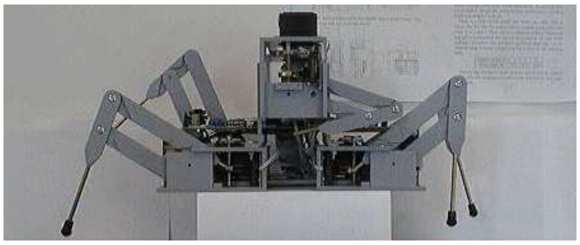
(a) Next commanded positions: R3=AEP, R2=+30, R1=0



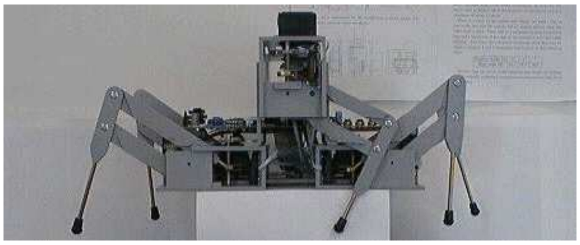
(b)



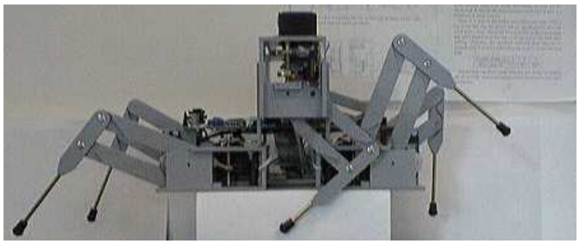
(c) Next commanded positions: R3=0, R2=AEP, R1=+30



(d)



(e) Next commanded positions: R3=+30, R2=0, R1=AEP



(f)

Figure 4.22: An example of moving the legs using the subsumption control system. The front of the robot is to the right. (a) The initial leg positions for the gait [(R3, L1), (R2, L3), (R1, L2)]. (b) Leg R3 is swinging forward and legs R1 and R2 are retracting. (c) Leg R3 has protracted. (d) Leg R2 is swinging forward and legs R1 and R3 are retracting. (e) Leg R2 has protracted. (f) Leg R1 is swinging forward and legs R2 and R3 are retracting.

0. This will cause legs R3, R1 and L2 to protract together while legs L3, L1 and R2 are retracting and vice versa.

A more detailed discussion on the generation of gait patterns is given in Chapter 5.

4.4.4 Controlling the Lift Motors for Climbing

When Strider walks using the groove-slot mechanism the legs produce a fixed stepping trajectory attributed to the shape of the groove. The trajectory allows the robot to walk over flat, reasonably level terrain. If however a small obstacle is in the robot's path, such as an object or a small ditch in the ground, then the leg mechanism should be able to lift or lower the legs capably in order to overcome the obstacle, as shown in Figure 4.23. The structural leg design of Strider allows this by making use of vertically positioned actuators.

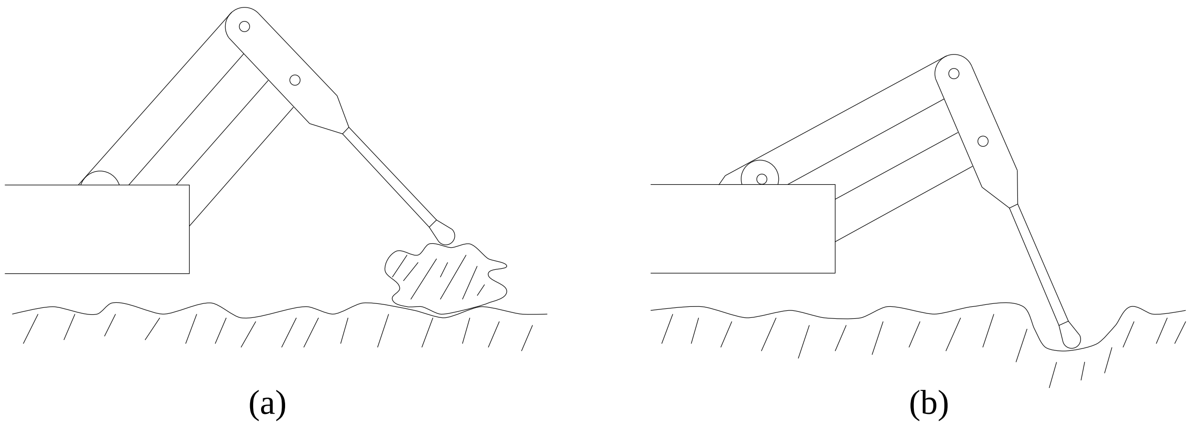


Figure 4.23: Overcoming small obstacles in the path of the robot.
(a) Stepping over a small obstacle. (b) Stepping through a small ditch in the ground.

As mentioned previously in Section 3.2.6, the vertical lift actuators use a lead-screw mechanism. This was also shown in Figure 3.28. The vertical position of these actuators is measured using the linear slider potentiometers connected to the actuators. The variable voltage from the potentiometers was converted to a digital value in the range 0 to 255 that was then read by the microprocessor in the same way as the drive motors.

The control system used for the lift motors was the same as the control system used for the drive motors and is called the **lift servo**, shown in Figure 4.24.

The **increment/decrement** module accepts a "desired" position value and will either increment or decrement the current position until the new position is found. The **all found** module performs the same function as that used for the drive motors. It will wait until the last commanded positions are all found before allowing the lift motors to advance. This allows the legs to be synchronised when all the legs are lifting or lowering the robot's body.

Therefore, the mechanical design and the control mechanism with which to perform leg lifting is available for walking over small objects and through small ditches in the ground.

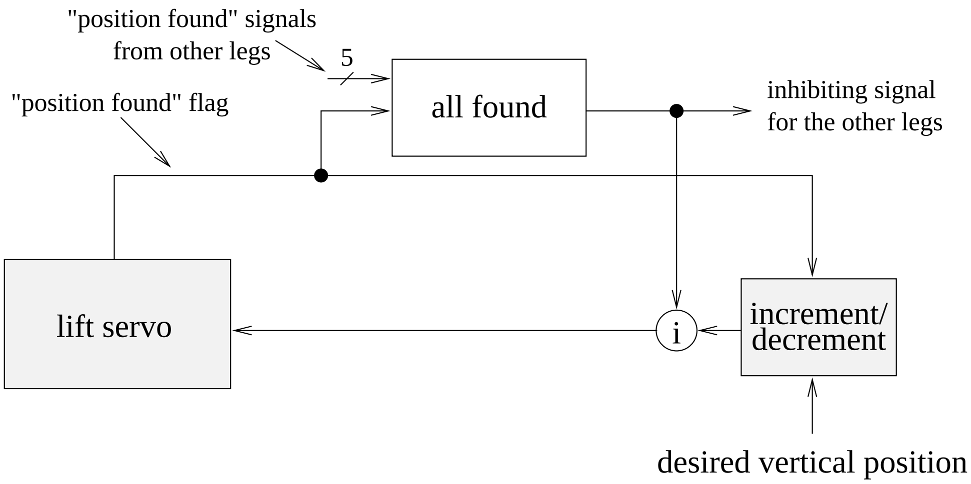


Figure 4.24: The subsumption control system for the lift motors.
The shaded modules are duplicated for each leg.

The robot only requires the necessary sensors to detect the obstacles. The control system can then receive an indication of the height (or depth) of the obstacle to determine the necessary vertical position of a leg, or legs.

4.4.5 Detecting Obstacles

Some future capabilities that can be added to Strider at a later stage would be to include obstacle avoidance. This research has provided a possible solution to obstacle avoidance using Strider, as described below. This was not dealt with to any great extent in this research and it was not actually implemented on the robot.

Two methods can be used to detect most obstacles in the path of the robot. Firstly, sensors that detect obstacles in front of the robot can be used. One such mechanism is to use a type of “feeler” in front of the robot as shown in Figure 4.25. The feeler is spring-loaded to keep it touching the ground. It would be able to detect small objects by lifting the feeler over the object as shown in Figure 4.25(a). Also, it could detect ditches in the ground using the spring-loaded mechanism shown in Figure 4.25(b). This method is analagous to a blind person using a walking stick. If this system was used then the control system would resemble Figure 4.26. This would be another layer of the overall control system that would run concurrently with the lower levels of the control system.

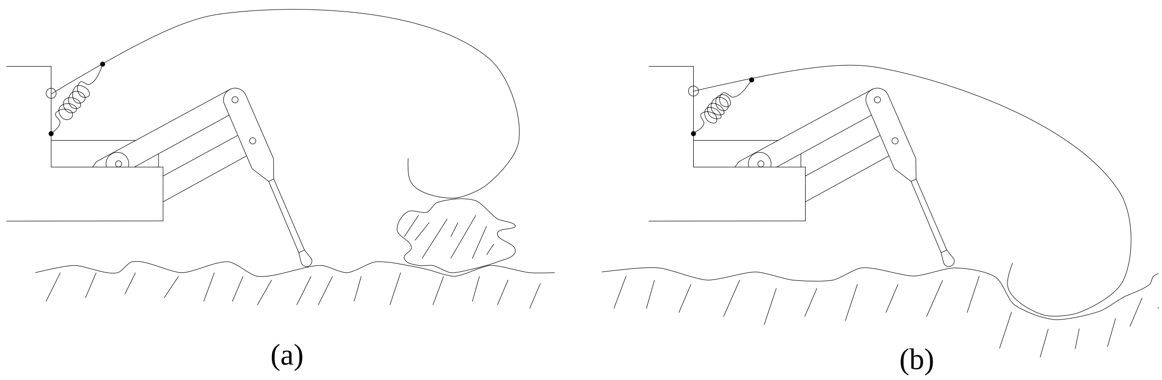


Figure 4.25: Detecting small obstacles in the path of the robot.
(a) The spring-loaded feeler drags over a small object. (b) The feeler drags below the level terrain to detect a small ditch.

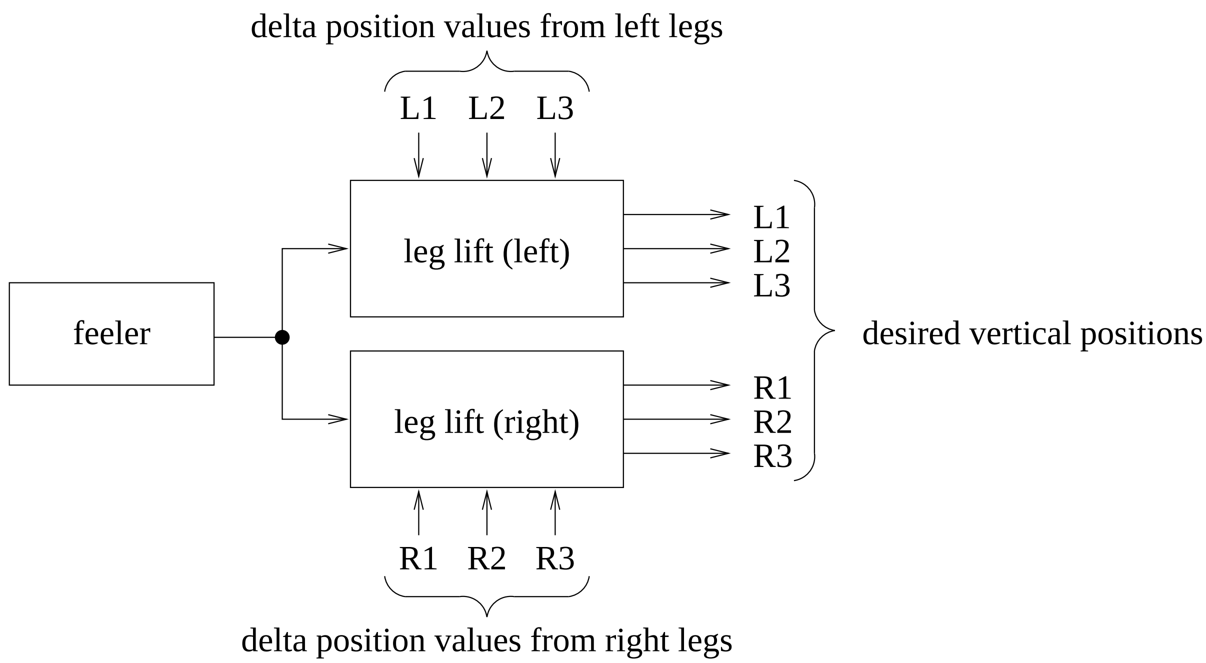


Figure 4.26: The subsumption control layer for using a feeler on the front of the robot.

The **feeler** module would periodically read the sensor on the feeler. The sensor could be a rotary potentiometer providing an analog voltage that varies according to the changes in the terrain. The **leg lift (left)** module and the **leg lift (right)** module monitor the delta position values of the left and right legs from the single leg controllers used for the drive motors (as shown in Figure 4.20). These two modules will then signal the appropriate **increment/decrement** module (as shown in Figure 4.24) to lift or lower the appropriate legs when necessary. Since the two latter modules were not implemented in this work their flow-charts have not been included in the Appendix.

The above-mentioned approach could not be used to detect walls. This is because if the feeler pressed against a wall, it would squash the feeler and make the robot think that a small object was in its path. Another method would have to be used. One solution would be to use ultrasonic or infrared rangefinders to detect walls in front of the feelers.

Another method to detect small obstacles in the robot's path is to use sensors on the feet of the legs to detect when the legs touch something. In Section 3.2.7 a type of foot contact sensor was described that allowed Strider to detect when a foot touches the ground. This type of sensor is essential when walking over rough terrain so that the legs know when they have touched either the ground or a solid object. This method is analagous to a blind person using the force feedback from their feet to evaluate the terrain they are about to walk on. The relatively simple control system used for the foot contact sensors is shown in Figure 4.27.

Figure 4.27: The control system layer for detecting and signalling when a foot has touched either the ground or an object.

The **v.position** module periodically reads the current position of the vertical actuator of a particular leg in the same way as the **position** module in Figure 4.16. This module will also be present in the **lift servo** module in Figure 4.24.

The **foot switch** module monitors the current position of the vertical actuator and will activate the "touch" flag when the difference in the vertical position exceeds a threshold.

The two modules described above are duplicated for each leg.

Various other types of sensors can also be used. The more types of sensors that are used to detect the terrain, the better the robot can evaluate the type of terrain it is walking on. The robot Attila, for example, used many different types of sensors and could make many intelligent decisions based on the sometimes noisy data that the sensors provided [10]. An even more advanced solution would be to use one, or even two cameras to identify the various types of terrain and obstacles in the robot's path.

As mentioned previously, the groove-slot mechanism used in Strider was designed for reasonably flat terrain, although the vertical actuators in the robot's leg design can allow it to overcome small obstacles in its path. Stepping over a small object, for example, can be achieved. If the robot is to climb *over* an obstacle however, the groove-slot mechanism would be very difficult to use due to it having a fixed semicircular trajectory. As a result, Strider's design does not allow it to climb over obstacles very easily.

If Strider's leg movement was limited to only the horizontal movement in the groove-slot mechanism and the vertical lift actuator was used to produce vertical leg movement, then the robot may be able to climb over obstacles. This however, was not one of the goals of our project.

4.5 Summary

This chapter described the methods recently used by researchers to control and coordinate the many DOFs present in a walking robot, including the control system used for the control of Strider. Previous research in entomology is presented since some of the researcher's concepts are used in modern-day control systems for walking robots.

The most common hexapod control systems were described in order to gain an understanding of the researcher's previous work. Of all the control systems investigated, the chosen control system used for Strider was Brook's subsumption architecture.

A detailed description of Strider's control system was then presented. The method used to servo-control the motors for the individual leg controllers was presented as well as the method used to coordinate the six individual leg controllers.

Strider's control system was designed for any robot that uses one DOF per leg to walk and it allowed Strider to walk using any valid periodic walking pattern. The control system that would allow the robot to detect and climb over obstacles was also presented.

Chapter 5

Coordinating the Legs for Walking

The subsumption architecture-based robot control system used for Strider allows it to walk in a straight line using any stable gait. The legs must first be initialised to predefined positions and then the control system will continually retract and protract the robot's legs in the same sequence. The robot can then walk in a straight line over reasonably level terrain.

The CWRU Hexapod (described in Section 2.5.8) is similar to Strider in that the designers had to develop methods of sequencing its leg movements in order to maintain static stability (stop it from falling over) at a variety of walking speeds during straight-line locomotion across flat horizontal surfaces [74]. The control system used for this robot is described in Section 4.3.5 and could only produce walking patterns from the medium speed gaits up to the tripod gait [80]. This was one of the reasons why this control system was not used for Strider.

All the possible gaits that exist can be classed as two different types: *periodic* and *non-periodic*. There are actually an infinite number of possible gaits that are considered stable as will be explained below. Strider was programmed to walk using several of these periodic gaits. A brief description of the non-periodic gaits is also given.

Since Strider was not designed for turning (as explained in Section 3.7), this chapter will only consider gaits that are used for straight line walking.

The notation and conventions used to describe the gaits in this chapter are the same as those used in Chapter 4.

5.1 Periodic Gaits

A periodic gait, as the name suggests, periodically repeats its walking pattern for every cycle of placing six legs on the ground in a particular sequence. The gait descriptions below are always considered to be used on *perfect terrain*, where no obstacles exist in the pathway. Periodic gaits should be used on this type of terrain [9]. Non-periodic gaits would most likely be used for climbing over obstacles. This explains why walking and climbing are considered to be two different events [36].

Wilson's rules given in Section 4.3.1 were obtained mostly by observing the walking patterns of cockroaches walking on graph paper, as shown in Figure 5.1. As mentioned previously, by following these rules a walking robot can produce a large range of stable periodic gaits. These particular gaits are known as the range of *wave gaits* and are considered to provide the optimum stability margin for hexapods [9]. Some of these wave gaits are shown in Figure 5.2.

At low walking speeds, insects usually adopt the *metachronal wave gait* shown in Figure 5.2(a). The dotted ellipses show the consecutive rear-to-front protractions of the right-hand and then the left-hand legs. For this particular gait, ipsilateral legs have phase differences of 1/6 of a cycle and contralateral legs are separated by half a cycle [123]. The stepping cycle therefore repeats after six separate steps, one for each leg.

In Figure 5.2(b), the retraction time is reduced causing the rear-to-front protractions to occur at shorter intervals. The vertical ellipses show that pairs of legs protract together. By reducing the retraction time further the walking pattern will gradually converge to the tripod gait in Figure 5.2(e). Here we see the fastest walking pattern where three legs

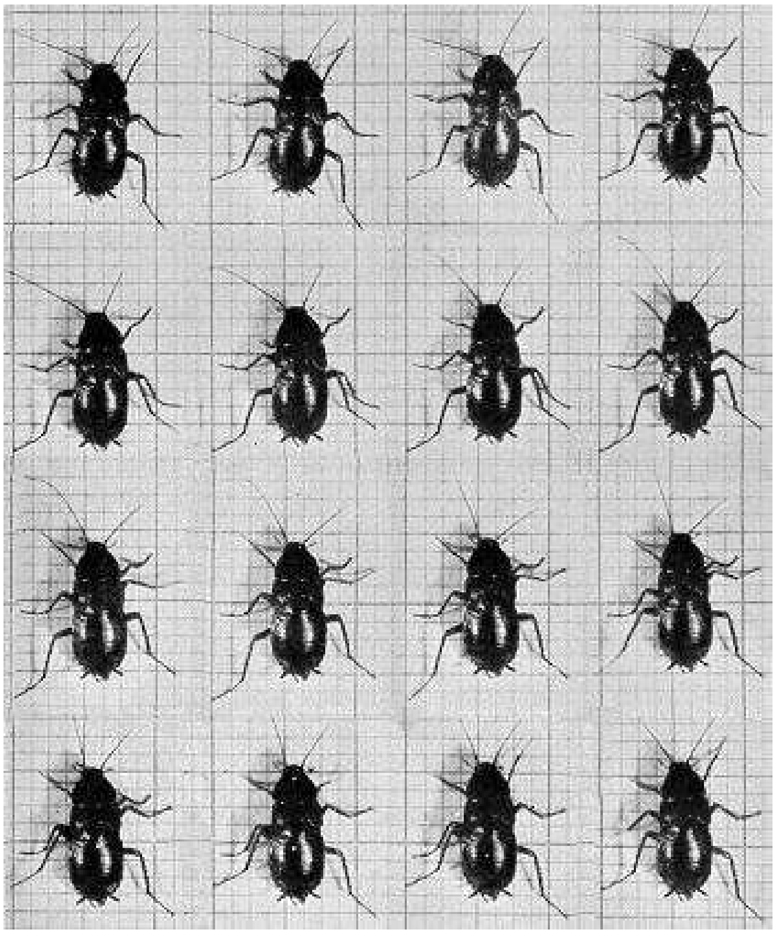


Figure 5.1: An example of how researchers observe the gait of insects. The cockroach is walking using the gait: [R3, (L1, R2), L3, (R1, L2)].

protract at a time. Delcomyn [125] found that cockroaches and most other insects use the tripod gait for walking speeds of $5cm/s$ to $80cm/s$. It is only at the lower speeds that the slower wave gaits are used [3].

In fact, by varying the retraction time from that used in the slow-wave gait of Figure 5.2(a) to that of the tripod gait in Figure 5.2(e), an infinite number of wave gaits can be obtained.

The relative phase angles between the protractions of the legs can be defined using Figure 5.3 (diagram adapted from [13]). Here we see a top view of a hexapod with the relative phase angles indicated on each leg. The angles have been normalised such that the phase interval between 0 and 1 is equivalent to the interval between 0° and 360° for

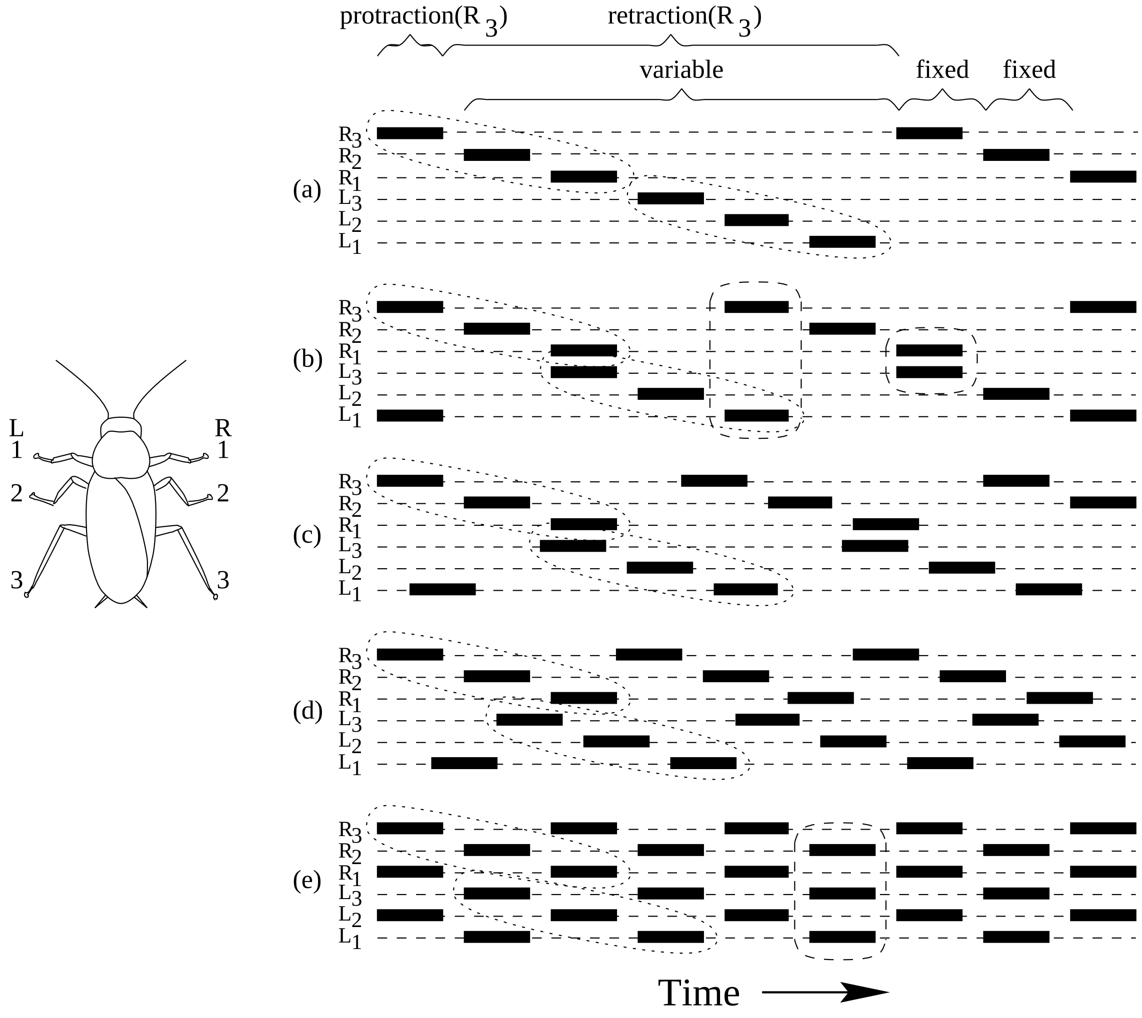


Figure 5.2: The range of periodic wave gaits.
(a) The slow-wave gait: [R3, R2, R1, L3, L2, L1]. (b) A medium speed gait: [(R3, L1), R2, (R1, L3), L2]. (c) and (d) Reducing retraction time increases walking speed. (e) The tripod gait: [(R3, R1, L2), (R2, L3, L1)].

one complete walking cycle, that is, $0 \leq \phi \leq 1$. Leg L1 is taken as a reference and will therefore have a phase angle of 0 (and 1). The next ipsilateral leg (leg L2) is phase shifted by the angle β. The value of β will define the type of wave gait that is produced. β can vary over the interval $1/2 \leq \beta < 1$. The leg L3 will also be shifted by 2β (or $2\beta - 1$). The right-hand legs are 1/2 cycle out-of-phase with the left-hand legs.

As an example, the slow-wave gait in Figure 5.4(a) is produced when $\beta = 5/6$. The corresponding phase angles are calculated from the diagram in Figure 5.3 as follows.

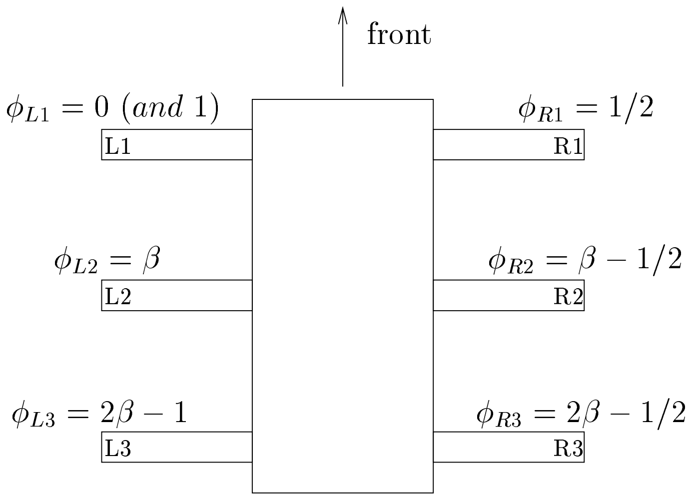


Figure 5.3: The phase differences between the legs for the range of wave gaits. The phase angles are normalised such that a complete cycle is over the interval $0 \leq \phi \leq 1$.

$$\phi_{L1} = 0\ (and\ 1) \tag{5.1}$$

$$\phi_{L2} = \beta = 5/6 \tag{5.2}$$

$$\phi_{L3} = 2 \times \beta - 1 = 2/3 \tag{5.3}$$

$$\phi_{R1} = 1/2 \tag{5.4}$$

$$\phi_{R2} = \beta - 1/2 = 1/3 \tag{5.5}$$

$$\phi_{R3} = 2 \times \beta - 1/2 = 1/6 \tag{5.6}$$

For $\beta = 3/4$, the medium-speed gait in Figure 5.4(b) is produced. The phase angles are given as follows.

$$\phi_{L1} = \phi_{R3} = 0\ (and\ 1) \tag{5.7}$$

$$\phi_{L3} = \phi_{R1} = 1/2 \tag{5.8}$$

$$\phi_{L2} = \beta = 3/4 \tag{5.9}$$

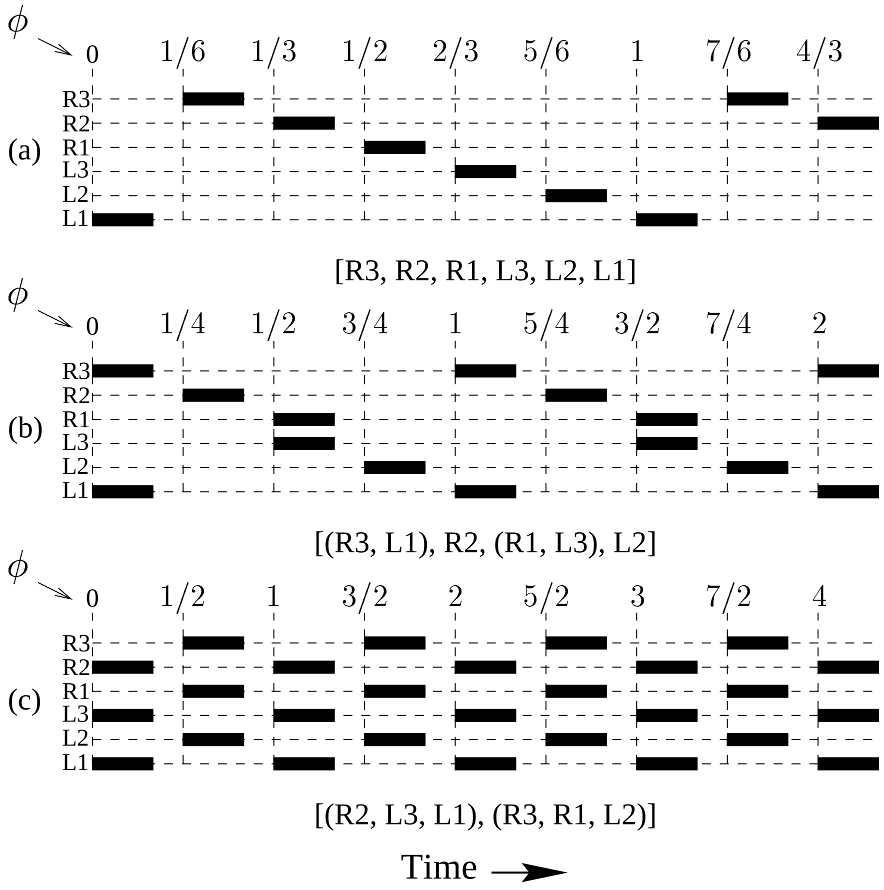


Figure 5.4: The wave gaits produced using different values for β.
(a) $\beta = 5/6$, (b) $\beta = 3/4$ and (c) $\beta = 1/2$.

$$\phi_{R2} \quad = \quad 5/4 \ (or\ 1/4) \tag{5.10}$$

For $\beta = 1/2$, the following phase angles are produced.

$$\phi_{L1} \quad = \quad \phi_{L3} = \phi_{R2} = 0 \ (and\ 1) \tag{5.11}$$

$$\phi_{L2} \quad = \quad \phi_{R1} = \phi_{R3} = 1/2 \tag{5.12}$$

This corresponds to the tripod gait in Figure 5.4(c). The resulting gaits are in accordance with Wilson's rules for straight line walking.

Some examples of other periodic gaits are shown in Figure 5.5. These gaits are not part of the range of wave gaits although they are valid periodic gaits that can be used to make a robot walk in a straight line on level terrain. The difference with these particular gaits is that they are not in accordance with Wilson's (or Hughes') second rule of straight line walking: "contralateral legs of the same segment protract 180° out-of-phase". As can be seen, the circled protractions of the contralateral legs, R3 and L3, do not protract 180° out-of-phase. Similar gaits have also been found in some insects.

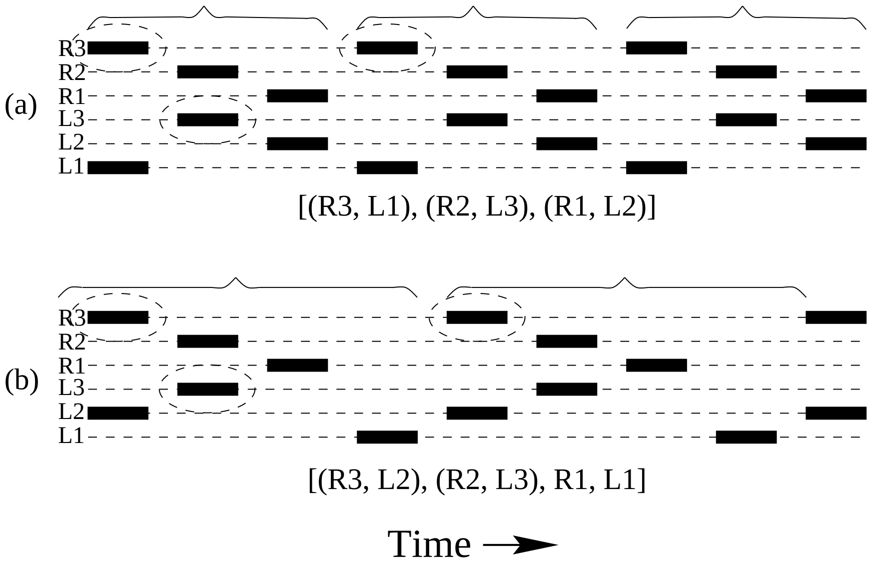


Figure 5.5: Some examples of other periodic gaits.
The braces indicate one cycle of each gait.

5.2 Non-Periodic Gaits

Any gait that does not repeat a given sequence is known as a non-periodic gait. The legs do not protract at set intervals but are instead lifted and placed down when they need to be. These gaits are usually used for rough terrain walking or climbing over obstacles.

For non-periodic gaits to be useful, the feet of the robots should have contact and/or pressure sensors. These will allow the shape of the terrain to be detected so that the appropriate footholds can be made [106].

Being non-periodic, the duration of the retraction and/or protraction of the legs are not fixed and may vary. Also, the location of the foot placement may change for each step during walking. Therefore, these gaits cannot be represented using Wilson's timing diagrams or Hughes' stepping sequence convention. They may however be described using two-dimensional foot placement diagrams showing the top view of the robot and terrain. Three-dimensional drawings of the terrain could also be used showing the foot placement.

Two types of non-periodic gait are briefly described below. One other type of non-periodic gait is a gait that changes from one periodic pattern to another, or a *dynamically changing gait* [9]. This type of gait is explained below in Section 5.3.

5.2.1 The Free Gait

A gait that does not follow a fixed sequence of lifting and placing of legs, and that can place the legs in any local position is known as a *free gate* [37]. The legs are not constrained to be placed down in any particular position and can therefore traverse the terrain with more agility. This type of gait is analagous to a person stepping from stone to stone to get to the other side of a small creek.

The free gait is generally the most complex form of walking for several reasons. Firstly, more information about the terrain is needed to determine the desired feet positions. The robot's control system must ensure that the new support polygon of the robot's feet will be able to stably support the body. The trajectory for any particular leg must be determined in advance of any movement. Also, the terrain should not contain obstacles that are too large for the robot to climb over [142].

The legs of the ASV (described in Section 2.5.4), were able to swing away from the body and a free gait was implemented on it. Video cameras were positioned under the body and directed towards the foot of each leg. The images were used to observe the terrain and then the control system would determine the most appropriate positions to place the feet.

Pal et al. [143] used a graph search method to determine the state of the legs, that is, the leg positions of a virtual walking robot as it walks through an irregular terrain. The walking was restricted to forward linear movement but was successfully able to negotiate the terrain.

The free gait requires that the robot's legs have three-dimensional movement such that they can move laterally away from the body. Since Strider does not have this feature, it cannot perform a free gait.

5.2.2 Follow-the-Leader Gaits

A walking pattern where the same foot locations are used for each ipsilateral leg is known as a *follow-the-leader gait*. The ipsilateral legs will protract from the front leg to the rear leg rather than produce the rear-to-front protractions that are characteristic of the wave gaits, described above.

For a hexapod, the front two footholds are first determined, perhaps by a human operator. These two footholds must be in valid locations that are suitable to hold the weight of the robot. After this the following two ipsilateral legs will be placed in the same vicinity of the foothold in front [9]. It does this by placing the middle legs where the front legs previously were, and the rear legs where the middle legs previously were as the robot is walking. Therefore, as long as the front legs have been located in valid positions, the follow-the-leader gait will ensure that the following feet will also be located in valid positions on the terrain.

This type of gait has previously been implemented on several walking robots including the ASV [9].

It should be noted however that the follow-the-leader gait can be discontinuous (non-periodic) or continuous (periodic). The continuous follow-the-leader gait generates continuous body motion and can reach higher walking speeds [9].

5.3 Dynamic Gait Changing for Strider

There are essentially two ways that a walking vehicle can change its walking speed. One way is to maintain the same periodic gait and only change the speed of the actuators (or muscles). The other way is to keep the speed of the actuators the same and change the gait pattern.

Both of these methods are actually used in insects since the cockroach, for instance, uses the tripod gait at most speeds [125], but uses the slower range of wave gaits at lower speeds. This means that at most speeds the cockroach changes the speed of its muscle contractions to change its walking speed.

Kaneko et al. [8] stated that a walking machine that uses only one DOF per leg to walk (such as MELWALK MARK-III (described in Section 2.5.3) or Strider), and consequently has a fixed stride length is limited to having only one possible gait. The work presented below contradicts Kaneko's statement by showing a possible method of dynamically changing from one known periodic gait to another, and hence change the robot's walking speed. This method is also described in [144].

5.3.1 Changing From One Gait to Another

Some hexapod control systems that were developed by researchers such as Beer [21] and Wendler (Graham) [33] (described in Chapter 4) use rhythmic oscillators in their design. They are able to change between gaits by changing the frequency of oscillation of their central pattern generators. These control systems however, are restricted to robots that have two or more DOFs per leg, since these robots change from one gait to another by modifying the AEP and PEP of certain legs such that the legs can be lifted or placed down in any position along the stride length. This allows the retraction time and the protraction time to be variable, although the protraction time is typically kept constant according to Wilson's third rule of walking: "protraction time is constant".

Due to the design of the groove-slot mechanism, the stride length of the legs of Strider is fixed. This means that the legs can only be lifted and placed down at the extreme front and rear positions of the stride length. Therefore, the methods used to change between gaits described above cannot be used. A method of changing between gaits was required that could make use of the existing subsumption architecture-based control system previously implemented, shown in Figure 4.21.

Since the stride length is fixed the only other solution is to keep the retraction time the same as it previously was and only modify the protraction time. The method involves keeping a protracting leg lifted until it can be placed down on the ground at the same time that another leg has just finished protracting, and hence synchronise the legs. Therefore, the protraction time for that leg would be extended. In Wilson's timing diagrams of walking patterns, this would be shown as an extension of the length of the black bars.

Extending the protraction time does not strictly go against Wilson's third rule of walking ("protraction time is constant") since the protraction time would be kept constant while walking a periodic gait and would only be modified (extended) when changing from one periodic gait to another.

To change from one gait to another requires knowing which legs need their protraction extended and with which legs they need to be synchronised. Once these have been determined the data can be stored in a table to be read by the control system. It is important however, to ensure that when one protracting leg is being delayed, that one of the ipsilateral legs (a leg that is directly next to and on the same side) is not protracting also. This would cause the robot to become unstable and fall over.

This system was implemented by adding two more subsumption modules to the existing periodic gait generator in Figure 4.21. The new control system is shown in Figure 5.6 and is described below.

The **extend protraction** and **sequencer** modules constitute another layer in the control system that subsumes the role of the previous layers. The **extend protraction** module is duplicated for each leg and a single **sequencer** module sequences all the legs.

The flowcharts for these two new subsumption modules are given in Appendix C.

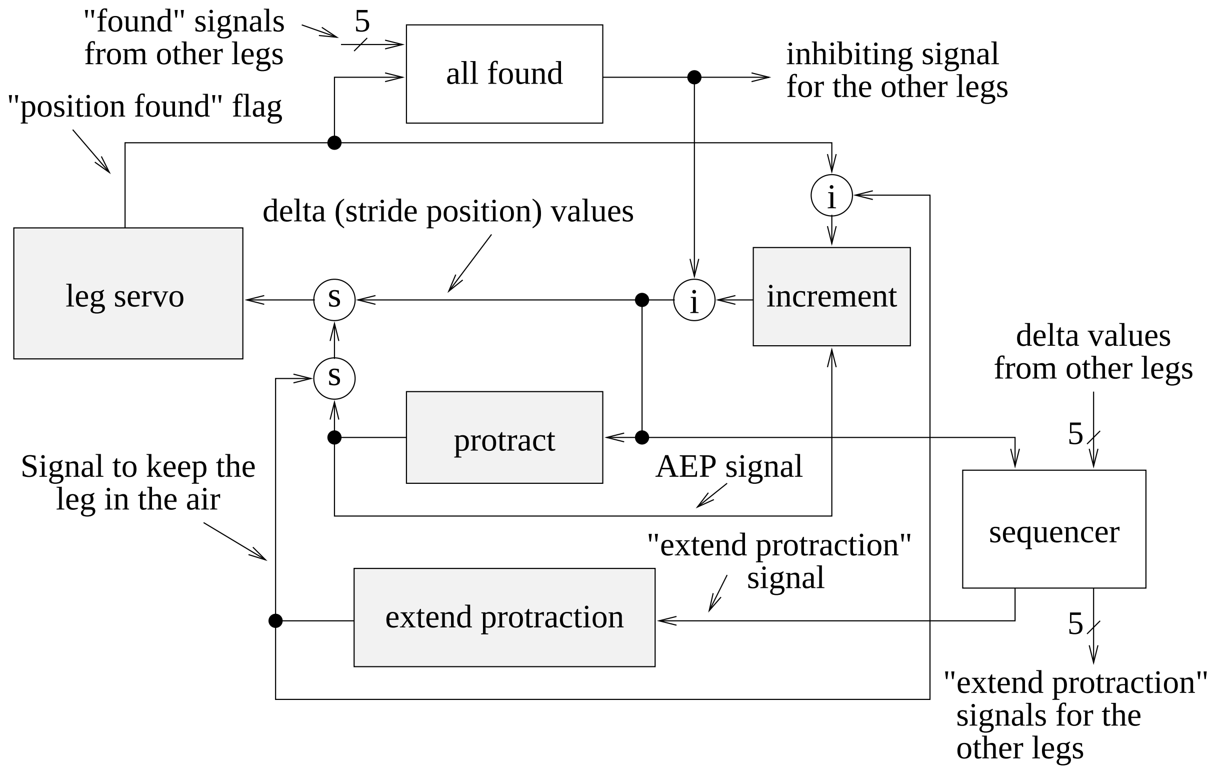


Figure 5.6: The complete control system used for Strider.
This (gait changing) subsumption architecture based control system allows Strider to walk at different speeds. The shaded modules are duplicated for each leg.

The **sequencer** module reads the delta values for each leg and signals the appropriate **extend protraction** modules (predetermined in a table) to extend the protraction of those legs.

The **extend protraction** module keeps a leg off the ground, and hence extends the protraction of the leg by suppressing the signal from the **protract** module and replacing it with a delta position value that would keep the leg in the air. The “found” flag is also inhibited by this signal to prevent the delta value from being incremented.

The input signals to the **extend protraction** modules must eventually be removed by the **sequencer** module in order to place the legs down (and start retracting) at the same time as those legs that they are to be synchronised with. The legs to be synchronised with must also be predetermined in a table, as mentioned above.

Although Strider uses only one DOF per leg for walking, and the method of changing gaits described was designed for this type of robot, it can still be adapted for use in other robots with higher DOF legs by maintaining a fixed stride length for each of their legs.

The examples below demonstrate how the control system would extend the protraction of certain legs in order to change the gait and hence the walking speed of the robot.

5.3.2 Increasing Speed from a Slow-Wave Gait

The following examples describe how Strider can be made to change its gait from a slow-wave to a tripod gait with several intermediate gaits.

The initial slow-wave gait is shown in Figure 5.7(a). In order to increase the walking speed such that the robot uses the gait shown in Figure 5.7(c), the protraction of leg L1 must be extended. This leg must finish protracting and then start retracting at the same time that leg R2 starts retracting in order to be synchronised with it.

This can best be explained by observing the changing gait shown in Figure 5.7(b). Here we can see that by extending the protraction of L1 (the shaded bar), that this lifted leg will not interfere with any ipsilateral leg (L3 or L2) since they are both retracting. That is, L3 and L2 are on the ground holding the robot up. Leg L1 is then placed down at the same time that leg R2 is placed down.

When the robot continues walking, the previous duration that was originally used to protract leg L1 is removed. Therefore, the retraction time for every leg will reduce by one protraction time length since we no longer need to wait for the protraction of leg L1 to end.

One way to do this is to increase the increment of the retraction position (delta position value) more than before. Another way is to increment the same amount as before assuming that less time will be used to retract the legs.

Hence, the robot will be walking faster using the gait in Figure 5.7(c) since only four

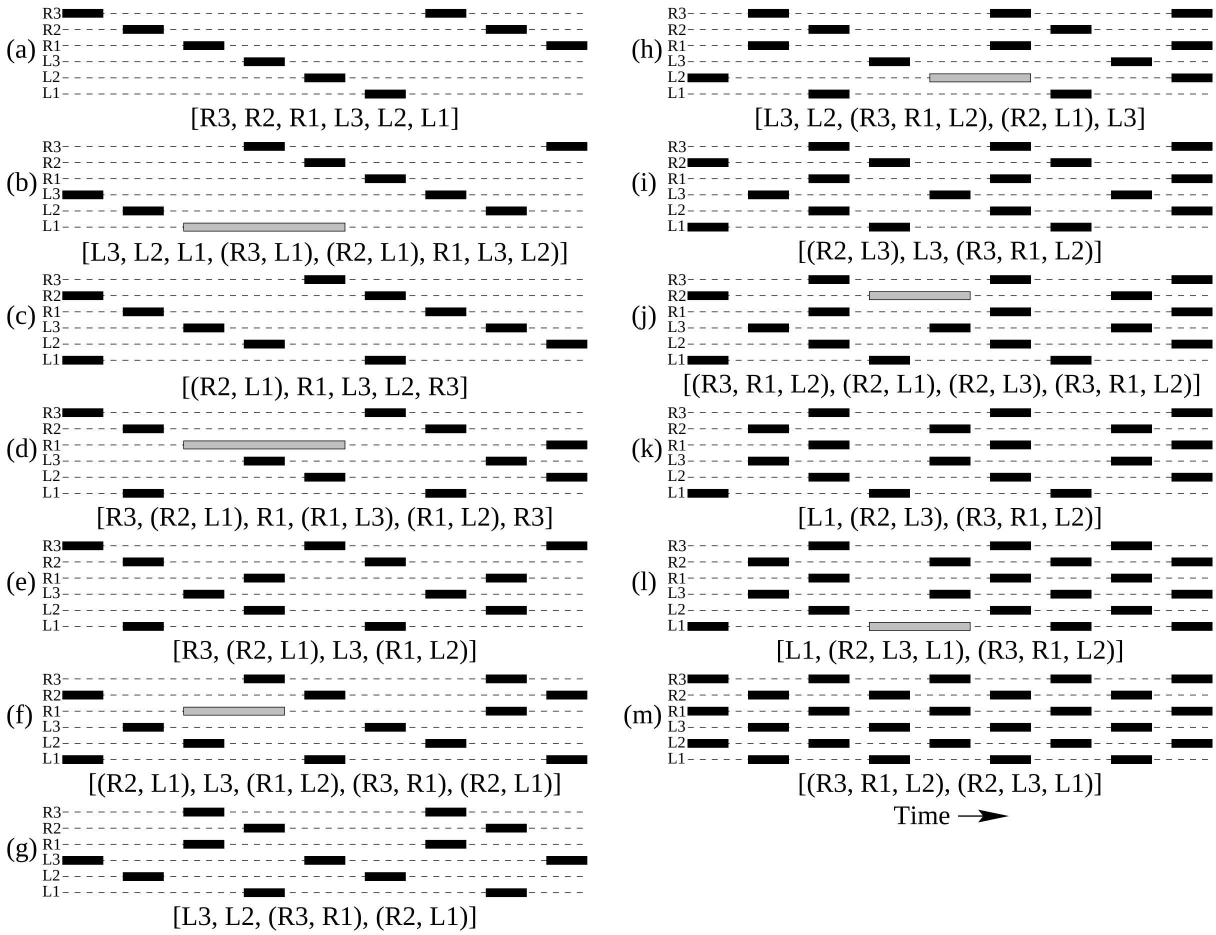


Figure 5.7: An example of slowly increasing Strider's walking speed. Changing from the slow-wave gait in (a), via the changing gaits of (b), (d), (f), (h), (j) and (l) to the corresponding periodic gaits in (c), (e), (g), (i) and (k), respectively, to the tripod gait in (m).

legs will protract in sequence and two legs will protract together.

This same method is then repeated for leg R1 in Figure 5.7(d). The leg's protraction is extended and it is then synchronised with leg L2 to produce the gait in Figure 5.7(e). Here we can see that two pairs of legs are now protracting together and the other two are protracting in sequence. The retraction time for each leg is reduced again by one protraction time length and hence the walking speed is increasing.

Again, this same method is repeated in Figure 5.7(f) by extending the protraction of leg R1 and synchronising it with leg R3. We can now see in Figure 5.7(g) that two pairs of legs are again protracting together but in a different pattern to Figure 5.7(e). Therefore, the walking speed would not have increased. This step was necessary for it to change to the next gait.

Figure 5.7(h) shows the protraction of leg L2 being extended and then being synchronised with legs R3 and R1. Now three legs are protracting together, a pair of legs are protracting together and one other leg (leg L1) is protracting separately, as shown in Figure 5.7(i).

The gait produced in Figure 5.7(k) is a different pattern to that of Figure 5.7(i) although it produces the same walking speed.

Finally, Figure 5.7(l) shows the protraction of leg L1 being extended and then being synchronised with legs R2 and L3. This produces the fastest walking speed (the tripod gait) shown in Figure 5.7(m).

A maximum of seven different periodic gaits are shown in Figures 5.7(a), (c), (e), (g), (i), (k) and (m). These correspond to five different walking speeds since Figures 5.7(e) and (g) are the same speed and Figures 5.7(i) and (k) are also the same speed.

The above example extended the protraction of one leg at a time to increase the walking speed. However, the change in walking speed can be increased by extending the protraction of two legs at a time, as described below.

The slow-wave gait is again shown in Figure 5.8(a). In order to increase the walking speed such that the robot uses the medium speed gait shown in Figure 5.8(c), the protraction of the legs L1 and R1 must be extended. These legs must finish protracting and then start retracting at the same time that legs R2 and L2 start retracting, respectively, in order to be synchronised with them.

When the robot continues walking, the previous duration that was originally used to protract legs L1 and R1 is removed, reducing the retraction time by two protraction time lengths. Hence, the robot will be walking faster using the medium speed gait in Figure 5.8(c).

Now, for changing from the medium walking gait in Figure 5.8(c) to the tripod gait

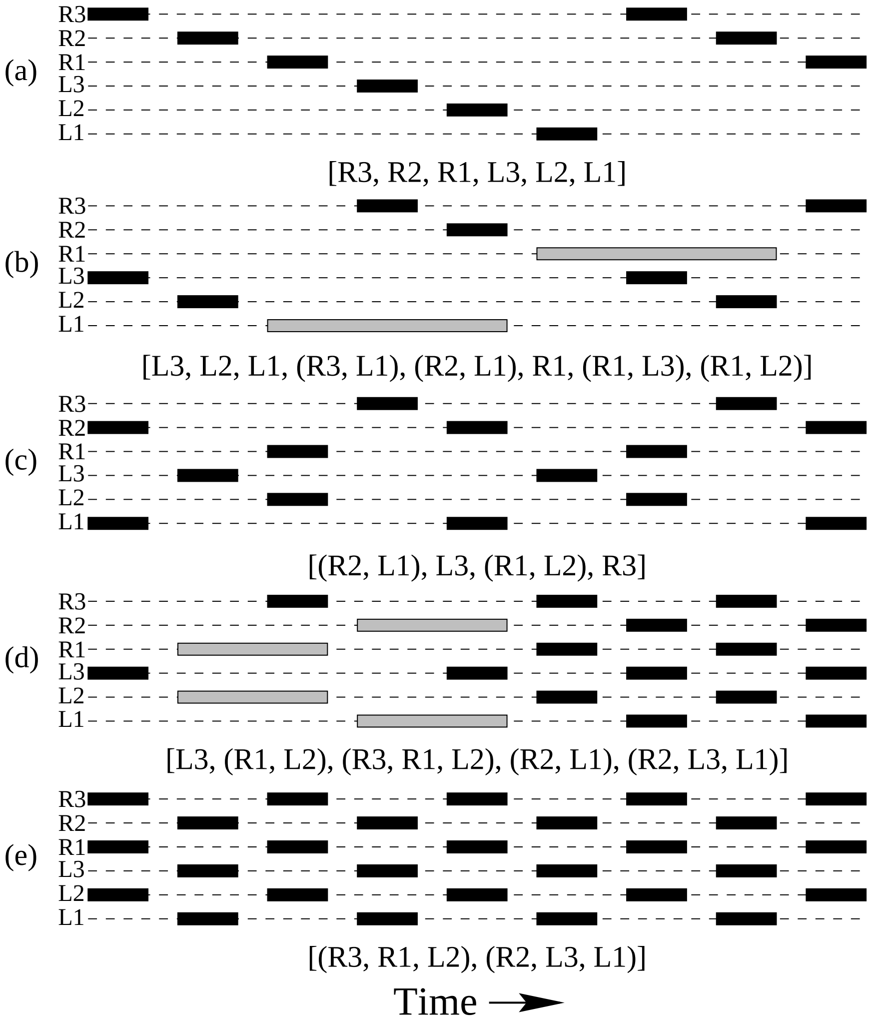


Figure 5.8: An example of increasing Strider's walking speed with a higher acceleration. Changing from the slow-wave gait in (a), via (b) to a medium speed gait in (c), then via (d) to the tripod gait in (e).

in Figure 5.8(e), the protraction of a pair of legs need to be extended and synchronised with a third leg. In this example, the protraction of legs R1 and L2 are extended and synchronised with leg R3 in the same way as before. Then, R2 and L1 are synchronised with L3. Again the retraction time is reduced causing the robot to walk faster using the tripod gait.

If we again start from the slow-wave gait and the protraction of different legs are extended and synchronised with other legs then a vast range of gaits can be produced. Although the gaits produce different patterns, the resulting walking speeds will be equal to one of the five possible walking speeds that were described above.

The changing gaits shown above have been tested on Strider. The robot successfully changed its walking speed from a slow-wave gait to a fast tripod gait which dynamically increased its walking speed.

5.3.3 Increasing Speed from a Modified Slow-Wave Gait

A *modified slow-wave gait* is shown in Figure 5.9(a). It is different from the slow-wave gait shown in Figure 5.8(a) because the protractions for legs L2 and R2 have been swapped around. According to Hughes, this gait is used by typical insects at most speeds [124]. Using this gait has the advantage of changing directly to a fast tripod gait as will be described below.

As with the previous examples, to change from the modified slow-wave gait in Figure 5.9(a) to that in Figure 5.9(c) certain legs must have their protraction extended and then be synchronised with another leg. In this case legs R3 and L3 must be extended and synchronised with legs L2 and R2 respectively, to obtain the medium speed gait in Figure 5.9(c). The tripod gait is then obtained by extending leg pairs (R3, L2) and synchronising them with leg R1 and then extending (R2, L3) and synchronising them with leg L1. Notice that the same number of speed changes occurs as the previous example in Figure 5.8.

If we wanted instead to change speed directly from the slow-wave gait to the tripod gait, then we can do this by extending the protraction of two legs at a time as shown in Figure 5.10. Here we see that the protraction of legs R3 and L2 are first extended and synchronised with leg R1. The protraction of legs L3 and R2 are then extended and synchronised with leg L1. This causes the gait to change directly to the tripod gait.

It should be noted that there are are many different combinations in changing from one gait to another. However, the method remains the same.

The changing gaits shown in Figures 5.9 and 5.10 have been tested on Strider. The

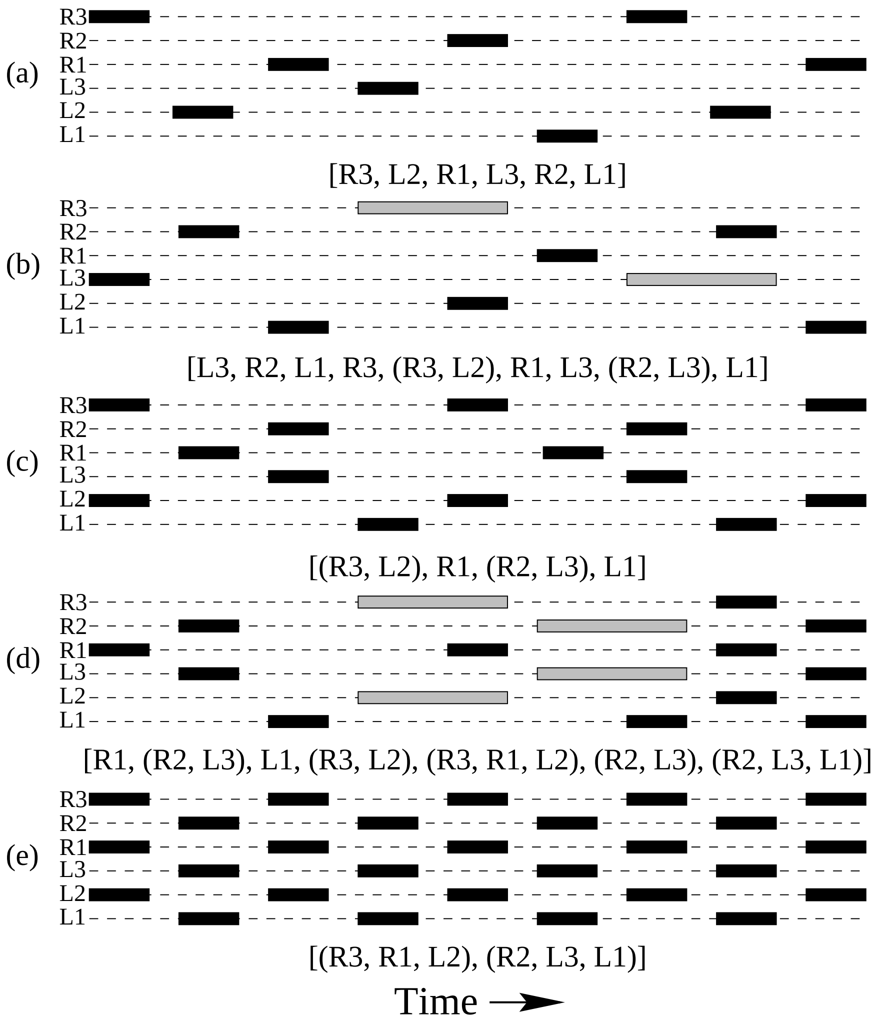


Figure 5.9: Increasing the walking speed from a modified slow-wave gait. Changing from a modified slow-wave gait (a), via (b) to a medium speed gait (c), then via (d) to a tripod gait (e).

robot successfully changed its walking speed from a slow-wave gait up to a fast tripod gait which dynamically increased its walking speed using the two methods described.

5.3.4 Decreasing Speed from a Tripod Gait

In order to decrease the robot's speed, the protraction of some legs again need to be extended. However, in this case, when the legs end their protraction they do not get synchronised with any other leg whose protraction has also ended. Instead, the aim is to extend the retraction of the currently standing legs. This can be done by allowing

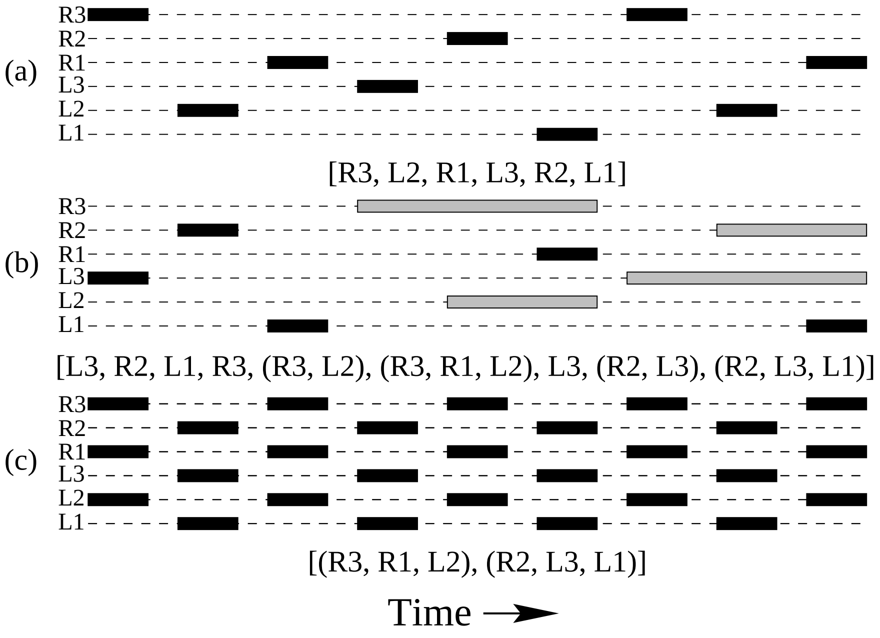


Figure 5.10: Increasing Strider's walking speed with the highest acceleration. Changing directly from a modified slow-wave gait (a), via (b) to a tripod gait (c).

the **sequencer** module in Figure 5.6 to wait for several stride (delta) increments until a single protraction duration has passed and then start retracting the leg. This method is depicted in Figure 5.11.

As can be seen in Figure 5.11(b), the protraction of legs R1 and L2 are first extended. During this extension the retraction time of legs R2, L3 and L1 are extended (the dotted lines) which causes the robot's speed to reduce. Leg R3 is left unchanged. The protraction of legs R2 and L1 are then extended while the retraction time of legs R3, R1 and L2 are extended to reduce the robot's speed to that of the medium speed gait in Figure 5.11(c). The same method is again used to change from (c) to (e). Here, the protraction of L1 is first extended, followed by that of leg R1. The resulting gait is the modified slow-wave gait used in Section 5.3.3.

Figure 5.11 shows only one combination of changing the gait pattern. In fact quite a few different combinations are possible.

The changing gaits shown in Figure 5.11 have been tested on Strider. The robot successfully changed its walking speed from a fast tripod gait to the modified slow-wave

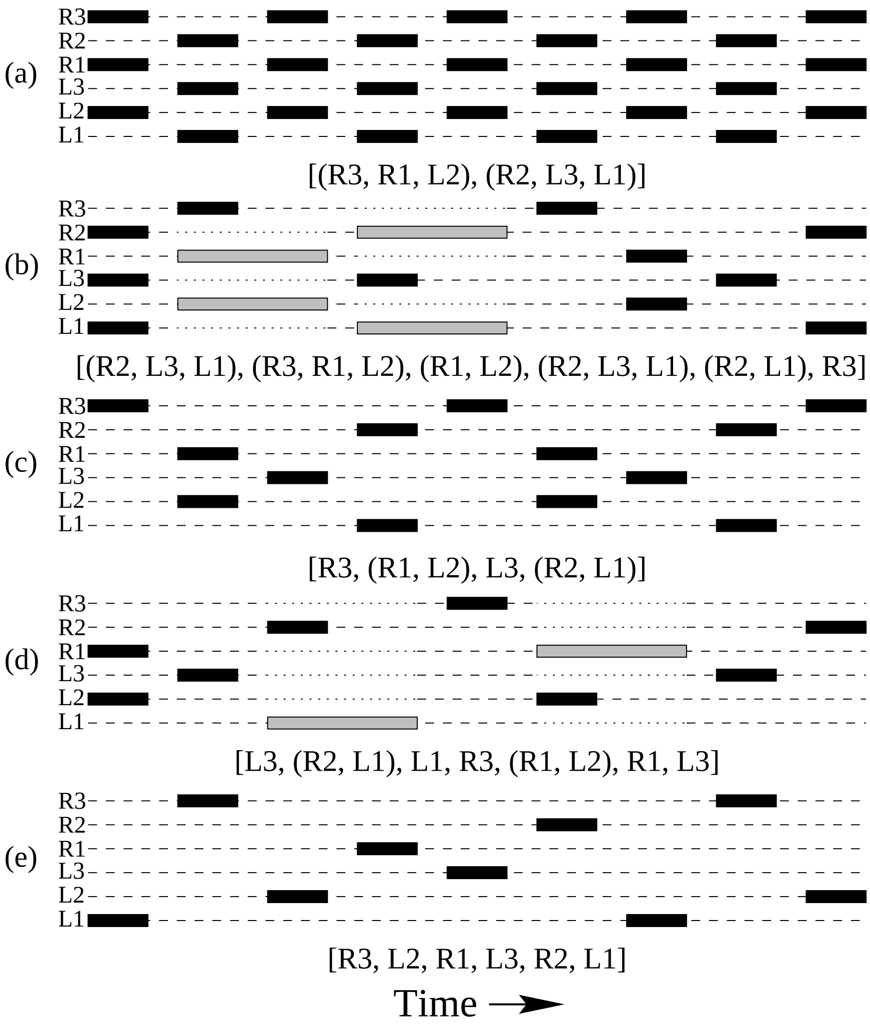


Figure 5.11: An example of decreasing Strider's walking speed.
Changing from a tripod gait (a), via (b) to a medium speed gait (c), then via (d) to a modified slow-wave gait (e).

(single-stepping) gait which dynamically decreased its walking speed.

The above examples therefore allow a walking robot that uses one DOF per leg to walk to change from one gait to another and hence change its walking speed. As mentioned previously, other robots that use two or more DOFs per leg to walk can also use the method described by simply maintaining a constant stride length. More flexibility in the design could also be produced if both the above method and the previously described methods that use variable stride lengths are combined.

5.4 Summary

This chapter described how walking robots coordinate their legs to walk in a straight line using stable gaits. Both periodic and non-periodic gaits are described with more emphasis on the former. The mathematics used to describe periodic gaits was shown for the range wave gaits.

The next part of this chapter described a method that enabled Strider to change from one periodic gait to another in order to change it's walking speed. The subsumption architecture-based control system that was used for Strider in Chapter 4 was modified to allow it to dynamically change its walking speed. The method was designed for robots that use one DOF per leg to walk but it could also be used for robots that use legs with higher DOFs.

Strider was successfully capable of increasing its walking speed from a slow-wave gait up to a tripod gait in one, two or five walking speed stages. It was also able to decrease its walking speed from a tripod gait to a single stepping gait using two speed stages.

Chapter 6

Conclusions and Future Considerations

In this concluding chapter we summarise the results obtained from the research that was carried out. Various aspects of the design of Strider are addressed including its mechanics, electronics, the way it was controlled and the types of walking patterns it could perform. Following this a discussion about the future of walking robots is given.

6.1 Review of Results and Contributions

As described in Section 1.3, the main contributions that this research has provided in the area of walking robots relate to the mechanical design, the control of legged robots that use one DOF per leg to walk, and the way such a robot can dynamically change from one periodic gait to another.

In relation to the amount of time that was spent in the production of Strider, the mechanical part of Strider took about three months to design and build. The design and manufacture of the on-board computer and other electronics took several months. The robot was walking within ten months of its initial planning.

6.1.1 Strider's Mechanical Design

There are essentially two main contributions that this research has provided in the area of the mechanical design of walking robots. The structural leg configuration constitutes one contribution in that it was biologically inspired. The second contribution is the design of the groove-slot mechanism that was specially designed for Strider.

Section 3.3 described three inspirations that were obtained from biology in order to design the mechanical leg structure for Strider. These included the leg angles, the leg sizes and the number of legs used.

The leg angles of the robot (from a lateral view) were positioned in the same directions as those of the cockroach. The front legs were angled towards the front of the body, the rear legs were angled towards the rear. The middle legs changed from pointing forwards to rearwards in a complete stride. This allowed the front legs to decelerate the insect's body while walking, the rear legs to accelerate the body and the middle legs to both decelerate and accelerate the body [11]. According to Full et al. [11], by having the legs positioned this way they will push against each other and the horizontal accelerating and decelerating ground reaction forces that are generated would reduce the overall force production.

Each of the legs are essentially a pantograph mechanism with a 4:1 magnification. The two-dimensional movement of the legs are in the longitudinal plane of the robot. By having the legs positioned in the longitudinal direction, that is, in the direction of the robot's travel, the leg configuration is best suited for fast walking in a straight line.

The legs do not swing away from the body and therefore the robot is not designed to turn, although turning was possible as explained in Section 3.7. Since the legs had some lateral flexibility, it was possible to twist the body while the legs were on the ground using a tripod gait. This was sufficient to make the robot turn with a radius of about $95cm$.

Section 3.3.2 described how the different leg sizes of the cockroach can be useful in the design of a walking robot. Although there would be advantages to having different leg sizes, it was explained that it was not necessary for this particular work. Nevertheless, the leg sizes were chosen such that the middle legs were smaller than the front and rear legs. This was necessary only to reduce the height of the robot.

When the structure of Strider was being designed it was decided to use six legs like insects, such as the cockroach. Since at least three legs are assumed to support the body at all times, the robot would never fall over when it is standing or walking using a valid gait. During testing there were actually several times that Strider did fall down. One instance was when one leg needed to be placed down to support the body, at which time the adjacent legs would lift up. If the supporting leg did not manage to be positioned in the horizontal section of the groove in the groove-slot mechanism then the leg could not support the body and the robot would fall down. Another instance where the robot would fall down occurred when a particular leg was already in the horizontal section of the groove. Sometimes when the leg moved to its PEP (at the end of the horizontal section of the groove), the leg would over-shoot the position due to the robot's inertial effects where it could no longer support the weight of the body. The leg would start to move up the curved part of the groove and the robot would fall down. Through experimentation the optimum positions and actuation speeds were found where the legs did not overshoot and cause the robot to fall down.

As mentioned above, the second main contribution in the mechanical part of the robot is the design of the groove-slot mechanism, described in detail in Section 3.4. The groove-slot mechanism allows the legs to follow a semicircular trajectory in the longitudinal direction of the robot's body when being propelled by a single DOF. The semicircular motion provides the necessary lifting, lowering and propulsion for each of the legs. A separate DOF (a linear actuator) is used to lift a leg vertically for rough terrain walking. The mechanism is relatively simple in design and is reasonably easy to construct.

The groove-slot mechanism can make the robot produce relatively high walking speeds using low RPM, highly geared motors by combining it with a pantograph mechanism leg which magnifies the semicircular trajectory to produce longer strides. The greatest advantage of the groove-slot mechanism is that it allows the robot to stand without expending any energy and it also allows the robot to carry a very large payload compared to any of the other walking robots that were researched.

6.1.2 Strider's Control System

The control system (or the control algorithm) that was used to determine the position of Strider's actuators as well as to coordinate the six legs for walking was based on a method developed by Rodney Brooks of MIT in the mid-1980's known as subsumption architecture [19].

The subsumption architecture for Strider consisted of several layers of carefully designed networks that were meant to be executed concurrently. The parallel processing had to be simulated since only one processor was being used. Each layer contained a set of task-achieving behaviours to produce levels of competence to control the robot. Low-level behaviours such as servo-controlling the set of actuators would therefore run concurrently with the higher levels that coordinated the legs of the robot.

The first two layers of the control system were used to servo-control the actuators and consisted of several behaviours. This is known as the **drive servo** and can be seen in Figure 4.17. The first layer (Level 0) of the **drive servo** was used to control the position of the single DOF used to drive the groove-slot mechanism of each individual leg. A predetermined position is given to the layer and the control system will adjust the leg position until the desired position is found. The second layer of the **drive servo** is used to change the speed of the actuators. This level runs concurrently with the first layer.

The third layer of the control system was used to generate any particular periodic walking sequence and consisted of three behaviours. This layer also runs concurrently and together with the first two layers mentioned above and can be seen in Figure 4.21.

The first behaviour was used to increment the current leg position so that it can advance. The second behaviour monitors the leg position to make the leg protract when the leg has reached the end of its stride. The addition of these two behaviours completes the individual leg controller shown in Figure 4.20. The third behaviour ensures that the sequence of leg movements (retractions and protractions) are coordinated such that the robot could walk using any valid periodic gait without falling over.

Up to this stage the robot was able to successfully walk using the wave gaits shown in Figure 5.2 and the other gaits shown in Figure 5.5.

The addition of one more layer to the control system allowed Strider to dynamically change from one periodic gait to another. Previous robots would change from one gait to another by modifying the stride length of particular legs. However, since Strider has a fixed stride length the only way it could change gaits was to extend the time that the legs remain lifted off the ground, that is, the protraction needed to be extended.

The fourth layer of Strider's control system contained two new behaviours. The complete control system is shown in Figure 5.6. One of the new behaviours would keep a particular leg from being placed down when it was signalled to do so by the sequencing agent (the other new behaviour).

The four layer subsumption architecture control system was tested on the robot and was able to perform the changing gaits shown in Figures 5.7, 5.8, 5.9, 5.10 and 5.11. These examples show that Strider is capable of both increasing and decreasing its walking speed.

The control system was originally designed for robots that use only one DOF per leg to walk. However, the method can be used for other hexapod robots that have two or more DOFs per leg by maintaining a fixed stride length.

6.1.3 Walking Speed and Payload Limitations

As mentioned previously, the main factors that contributed to producing a faster walking robot were the chosen leg structure and the combination of the groove-slot mechanism and the pantograph legs.

The leg structure was designed such that the first axis of the leg (the main leg movement) was in the longitudinal axis of the robot. Therefore, any quick leg movements could directly propel the robot in a straight line. In comparison, other robots that use the arthropod stance shown in Figure 2.6(b) have their first axis in the vertical. As the legs swing backward to propel the robot, both forward and lateral movement is produced making it less efficient.

The groove-slot mechanism produces the semicircular trajectory where the horizontal section is $3cm$ long. When this is combined with the pantograph leg which has a 4:1 magnification factor the resulting stride length is $12cm$. Therefore, the slot-plate in the groove-slot mechanism only needs to turn at about $2rev/s$ for the robot to be walking relatively fast.

The walking speed varies depending on the type of gait the robot is using. The fastest walking pattern is the tripod gait where three legs are used in succession. Using this gait, the fastest walking speed that Strider could walk was $17cm/s$. When this was measured, the weight of the robot was $2.25kg$ and it was carrying no payload. When this walking speed is normalised with the maximum length of the robot ($63cm$) and compared to other walking robots previously built, it was found that Strider's walking speed was better than other walking robots of similar size. The ASV (described in Section 2.5.4) had the greatest normalised walking speed as shown in Figure 3.21.

Figure 3.21 also shows the normalised payload capacity that Strider could carry with respect to the robot's weight. The maximum payload that was tested on Strider was $2.7kg$. The robot was walking using a slow-wave gait where only one leg protracted at a time, therefore allowing five legs to be on the ground at any time for maximum support. Since the original weight of the robot was $2.25kg$ this means that Strider was carrying more that its own body weight. According to Figure 3.21, other robots have only been able to carry up to about half their body weight. It was the design of the groove-slot mechanism that allowed Strider to carry such a large payload as explained in Section 3.4.3. It was only the weakness of Strider's legs that prevented it from walking while carrying an even greater payload.

The product of the normalised walking speed and the normalised payload capacity gives an indication of the robot's work capability which can be used to compare the performance of the robot with any other walking robot. As can be seen in Figure 3.21, the work capability of Strider was found to be 32.38%. This is about three times higher than the robot Boadicea (described in Section 2.5.9) which had the second highest work capability of 10.12%.

6.2 Conclusion

This research has provided an in-depth investigation into the mechanical design and control of legged robots. Descriptions of the mechanics, electronics, simulation and control that have been commonly used for walking robots was given.

The mechanical designs used for many walking robots from the past have been investigated and presented. The various types of actuation devices that are commonly used in robotics were described as well as some of the unconventional devices. An overview of the methods used to simulate walking robots using computer graphics was also given.

The most common methods of controlling legged robots were investigated in this research. Much of the descriptions described in this work of the walking patterns used for these robots were obtained from biological research of six-legged insects.

A detailed discussion on the design and construction of the robot Strider was given with an emphasis on the inspirations that were obtained from biology. The inspirations were obtained from the physical biological structure of the cockroach such as the *Periplaneta Americana* or the *Blaberus Discoidalis*.

The design of the groove-slot mechanism was described. It was this mechanism that allowed Strider to walk on level terrain using only one DOF per leg. The robot could use a separate DOF to lift or lower its legs for climbing or walking on rough terrain.

The design and implementation of the subsumption architecture-based robot control system that was developed for Strider was also described in detail. Strider's control system enabled it to walk using any valid periodic gait while making use of only one DOF per leg. It also had the ability to change from one periodic gait to another and hence dynamically change its walking speed, again using only one DOF per leg.

Although the many walking robots that have been investigated in this research were impressive, the walking speed of most of them was relatively slow and the amount of payload they could carry was also fairly low. One of the main purposes of this research was to improve on both of these factors. The mechanical design of Strider's leg structure and the design of the groove-slot mechanism has shown that is has the ability to produce relatively high walking speeds. The design of the groove-slot mechanism has also shown that it can support a large payload, hence making it more superior in these respects than any of the other robots researched in this work.

6.3 A Future for Land Striders

Although there have been many new developments in the area of walking machines, many of the goals that researchers had hoped to reach have still yet to be achieved. The ability to create a legged vehicle that has the agility, dexterousness, robustness and flexibility of a small animal, such as a cat, is still far from being perfected.

It is difficult to estimate how much the designs for walking machines will improve in the future since it is highly dependent on the technologies produced in industry that are used to construct, actuate and control them.

This section provides an overview of what could be expected in the future developments of walking robots. Some of the advances in the various areas described in this section relate not only to walking robots but also to robotics as a whole.

6.3.1 Improving the Mechanical Designs

The mechanical design of walking robots can be improved by their structural design and the materials used to construct them. Some guildlines are given below that may help the future developments.

The materials used to construct robots in the past consisted of aluminium, certain other metals, plastics and various types of rubber. Strider, for instance was made mostly using PVC sheets. Some of the more modern robots make use of materials that have been developed in more recent years. Some of these materials include carbon-fibre composites, Teflon and special resin plastics or rubbers.

Polymer technology has much to offer the field of mechanical engineering. There are literally thousands of different polymers that can be created having different properties relating to temperature, elasticity, hardness, resilience, friction, transparency and colour. Polymers can be used for many parts of robots from the chassis construction to a protective covering. This protective covering, or skin, would be advantageous for a walking robot that would work in areas where the environment may be hazardous. The feet of the robot Attila (described in Section 2.5.7), for example, has exposed springs on them that can get caught on obstacles [14]. By covering these sections by a protective polymer skin, the mechanisms can be protected.

Future developments of polymers and other materials will enable designers to produce mobile robots that are mechanically lighter, stronger and perhaps protect the robot to make it more robust. The lighter the structure of the robot, the less energy that is wasted by the actuators that move it. The actuators must be able to freely move the structure and the structure must be strong enough such that the actuators will not damage it.

The actuation devices themselves are important to a designer. In an ideal situation, actuators would be able to produce large forces with respect to their size and weight.

Also, they would ideally have accurate high and low speed operation, high efficiency, easy controlablity, would be easy to integrate into mechanical systems, would be very robust, require little or no maintenance and have a long life. At present there are no actuation devices that fit all of these criterion.

In 1978, Hirose et al. [38] stated that it was unlikely that small powerful and effective actuators would be available in the near future. Since then there have been several good attempts at producing such actuators, as described in Section 2.4. The polymer hydrogel actuators that are still in the development stage (described in Section 2.4.4), show great promise for the future. Muscle Wires (described in Section 2.4.3) will also most likely be used more often in robotics once researchers determine the best ways of handling them, both physically and electrically.

The most common actuators currently used in robotics are the electric motors and hydraulic and pneumatic actuators. These actuation devices will most likely continue to be the most common for quite some time.

Another very important physical item used in robots are their sensing devices. Some ideas are described below that are possible ways that sensors may be used for mobile robots in future designs.

There are two ways that a walking machine can adapt to its terrain. One way is to use vision or proximity sensors to preview the terrain ahead. Another way is to walk "blindly" and let the robot's legs detect the irregularities in the terrain [120]. The use of cameras probably provides the ideal solution to obtaining information about an environment. Vision provides an enormous amount of information that can be used for navigation, object recognition, distance measurement, identification of hazardous areas, and so on. Many developments have been carried out already on vision processing and will continue until an efficient method is developed that will extract as much information from the camera images as possible to be useful for mobile robots.

Since it has proven to be very difficult to use vision systems to detect the shape and structure of terrain in the past, many researchers are experimenting with simpler sensors that can obtain the necessary information [31].

Arthropods and crustaceans use sense organs and deformation sensors in their exoskeletal material to detect leg movement, leg stress and external contact [145]. The insects are very agile which is mostly due to having a large variety of sensory information by sense organs in the legs [146]. This is one of the reasons why many different types of sensors were used in the robot Attila (described in Section 2.5.7). Using many different types of sensors increases the robustness of the robot since the same information about the environment can be obtained using several different sensors at the same time. It would therefore be beneficial to use this approach for future walking robots that need to obtain a lot of information about its environment.

One of the advantages of using sensors that are positioned on the legs of a robot is that when the legs move through space they can obtain a huge amount of information about the terrain [32]. They do this by using tactile sensors or knocking against objects in the robot's path to detect the height of the objects, the hardness of objects, and so on.

When designing an agile walking machine, an important task is deciding what types of sensors to use, how many to use and where to put them [146]. Some of the types of sensors that are currently being used in robot legs and will continue to be used include force sensors, joint angle sensors, motor velocity sensors, foot range sensors and ground contact sensors. Some of the types of sensors that can be used in the body of a mobile robot include inclinometers, long-range infrared sensors, CCD cameras, gyroscopes and accelerometers [32].

There are actually far more sensors available in industry that detect different parts of the environment. There is no doubt that these sensors will be improved in the future and different types of sensors will also be developed. These advances will help researchers to develop far more impressive walking robots.

In the past researchers have felt that the difficulty in producing useful legged robots for the future would be due to both the mechanics and the control of many DOFs [38] [147]. As we have shown in Chapter 4, many ways of coordinating the legs exist. The greatest difficulty still lies in the mechanical design. A good mechanically robust platform has yet to be designed.

One of the ultimate goals of producing walking machines in the future is to develop fast movement that perhaps exceeds that of most biological organisms. This is very difficult to do using current technology. For a vehicle to "run", for example, its mechanical design would differ greatly than for a machine that was designed for only walking. This is due to the fact that running is characterised by travel at high speeds by periodic ballistic flights where all the legs would leave the ground [47]. The mechanical designs of such machines would have to be able to handle such extreme dynamic properties as well as be able to last a long time. The use of springs as described in Section 2.3 by Alexander [43], would be well suited for this type of application.

The advantage legged vehicles have over wheeled vehicles is their ability to adapt to the terrain they are traversing. The legs of the robot can be positioned appropriately when sudden changes in terrain height are encountered so that the robot can climb over the obstacles. The overall height of the robot or its legs provides a rough indication of the maximum height of an obstacle that can be overcome, that is, assuming that the robot walks over the terrain and doesn't jump to overcome relatively high obstacles. Therefore, any leg configuration for future robots should be designed with sufficient vertical movement to overcome any high obstacles relative to its size so that it can adapt to the terrain it is designed to walk on. The legs also should be mechanically flexible enough to manoeuvre them into various positions. This requires a minimum of three DOFs in each leg to make the robot "fully terrain adaptive" [30].

Mechanical robustness is a major issue since the robot can experience a lot of physical interaction within its environment. If a robot's leg encounters a knock, bump or scrape against another object it should be mechanically reliable enough not to be damaged in any way. Many previous walking robot designs did not have a high mechanical robustness. A smooth, flexible outer skin over the mechanical endo-skeleton (as described previously) would probably be best suited to help solve this problem. The robot would be more physically reliable and robust with an outer covering than without.

Some researchers in Japan [148] have decided to take a far more radical approach to solving the problem of having a robust mechanical platform. Rather than use a mechanically engineered platform of a hexapod they decided it could be advantageous to use the existing biological mechanisms. They have built tiny microcontrollers to fit on the back of real cockroaches, moths and other insects and inserted stimulating probes into their nervous system. They were then able to control the direction and speed that the cockroaches walk. This also solves the problem of developing complex control systems to coordinate the legs. Nevertheless, an insect would be incapable of performing many of the tasks that a walking robot could be used for, such as land excavation, where a large robot would be better than using many small artificially controlled insects.

One other thing that can be pointed out in the mechanical design of walking robots is the limitation that designers have due to the actuation devices that are used. Actuators range in size, shape and weight and can therefore restrict a designer from creating a particular leg design. As actuation devices are improved in the future, the designers will be able to produce better mechanical designs for their walking robots.

6.3.2 Improving the Control Systems

Any new control systems for walking robots that are developed in the future will most likely be influenced by the previously developed control systems described in Chapter 4. Some guildlines are given below that may help the future developments.

The controller must be able to accommodate various sorts of terrain by controlling all the actuators of the robot simultaneously. It must be robust to allow for various errors or failures. Also, the controller must adapt to various terrain by first detecting the type of terrain and performing the appropriate behaviours accordingly.

An intelligent control system should be able to try different ways to avoid or get out of difficult situations where the robot may become mechanically hindered [32].

According to Ferrell [10], a controller must be able to scale well so that peripheral items such as sensors, actuators and processes can be added without causing computational bottlenecks. She also believed that the controller must be modular so that new peripherals could be readily integrated into it. The controller must be flexible and adaptive to be able to effectively locomote the robot over a variety of terrains. The controller must also be robust such that it will still operate if certain failures occur, such as mechanical failure or obtaining bad sensor readings.

By using many different sensors to detect the shape of the terrain the level of computation can be reduced. The use of sensors in this way makes the control system more flexible [36].

The robustness of a control system is important so that it will still be able to operate if the controller finds that a problem has occurred, such as when a leg fails to operate. Beer's distributed neural network controller (described in Section 4.3.5), for example, was found to be very robust to sensor, actuator and subcontroller failures [149].

The control system must be adaptable to the terrain it walks on. Rather than use position control methods, researchers have found that force control is far more important [150]. The legs would move to particular positions and use force feedback from force sensors to adapt to the terrain.

The study of insects and animals has helped researchers a great deal to develop control systems. For example, Pearson [18] explained that Serrington and Brown found that rhythmic stepping movements of the hind legs of cats and dogs could still be produced several weeks after their spinal cord had been severed. This shows that higher levels of the nervous system (from the brain) do not produce the oscillatory movement of the legs. Rather the rhythmic movements are produced by the interaction of local controllers within each leg. Also, Shik, Severin and Orlovskii (in [18]) discovered that a cat whose higher nervous levels were disconnected from the rest of its brain could be made to walk, trot and gallop on a treadmill by applying a stimulus to the locomotor region of its existing brain. This again shows that coordination of the lower local leg controllers produces a wide variety of gaits. Beer's gait controller (shown in Figure 4.10) is based on these biological principles. Therefore, this shows that inspirations from biology can help to develop the control systems for walking robots. There is no doubt that biology will play a vital role in the development of future control systems.

6.3.3 The Ultimate Goal for Walking Machines

The current developments of walking robots shows great promise for the future. In time, both fully autonomous and semi-autonomous, fast moving legged vehicles will be available. Some will be walking on distant planets collecting information for scientists (such as the Ambler [151]) while others will be here on earth carrying people and cargo across very rugged terrain.

One such example of a walking machine that will be developed further in the future is the walking chair for the disabled [152]. Another great advance for the future may include developing extremely small walking machines, whether they be less than 15cm long, 1cm long or even in the micro or nanometre range. Shimoyama et al. [153] are developing such microrobots by constructing external skeletons of rigid plates made of polysilicon that are cut from silicon wafers. The micro-sized robots are to use polyimide to produce elastic joints.

Realisticly, the ultimate goals that we are trying to achieve will not be realised for several decades. The mechanics has to be improved, as well as the actuation devices, the control systems, the power sources, and so on.

One of the possible future uses for legged machines is for land excavation. As mentioned previously, one large robot used for excavation purposes can perform better and probably do more work than using many small robots. In order to use the current excavation machines that use wheels the land usually has to be leveled out in sections to prevent the vehicle from falling over. Also, a lot of mud accumulates on the wheels which usually makes a big mess. By using legs on such a machine, no special pathways are required because it would be able to stand on very uneven terrain. Also, since less contact is made with the ground, there would be less mud on the feet to make a mess. An artists impression of such a vehicle that uses the same structure as Strider is shown in Figure 6.1.

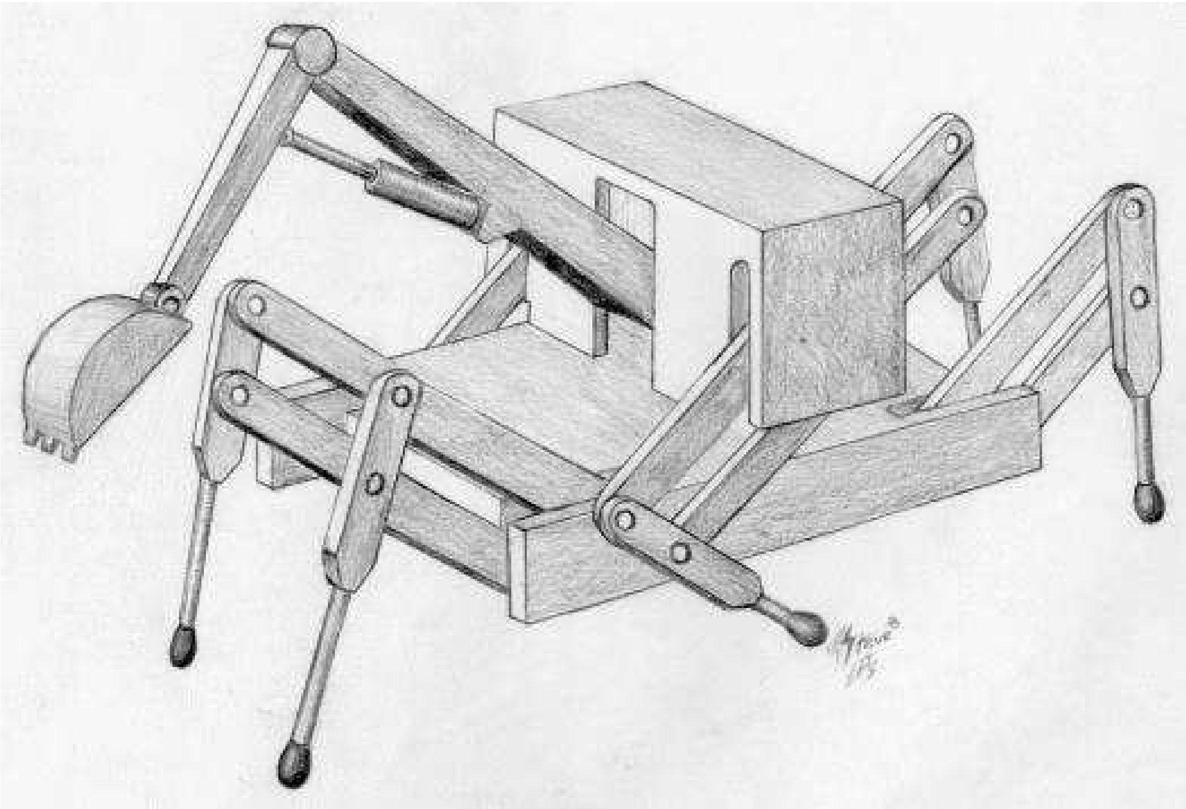


Figure 6.1: An artists impression of a walking machine used for land excavation.

The many applications that were mentioned in Section 2.1 will surely be realised in the future. The technology is already available to produce reasonable walking robots. In time, researchers will be able to use far more impressive resources due to technological advances to develop walking vehicles that will be virtually ideal.

Appendix A

The On-Board Computer

A.1 The Memory Map

The entire memory map used for Strider's on-board computer is shown in Figure A.1. Five sections between the memory locations $\texttt{000000}_{16}$ and $\texttt{FFFFFF}_{16}$ were chosen for different parts of the computer to operate. These sections are itemised and described below.

- $\texttt{000000}_{16}$ to $\texttt{007FFF}_{16}$ are the memory locations for the EPROM. The EPROM holds the monitor program that is executed when the microprocessor is first turned on. It initialises the microprocessor ports and the other memory locations described below.

- $\texttt{010000}_{16}$ to $\texttt{01000A}_{16}$ are the memory locations for the two ADCs. Only six address locations are used including $\texttt{010000}_{16}$, $\texttt{010002}_{16}$, $\texttt{010004}_{16}$, $\texttt{010006}_{16}$, $\texttt{010008}_{16}$ and $\texttt{01000A}_{16}$. Word locations are used since the eight data lines of one ADC are connected to the high-byte of the microprocessor and the eight data lines of other ADC are connected to the low-byte. Therefore, by reading word locations, the full 16-bit words are read which reads both ADCs at the same time.

- $\texttt{080000}_{16}$ to $\texttt{100000}_{16}$ are the memory locations for the external RAM. Up to 512kB

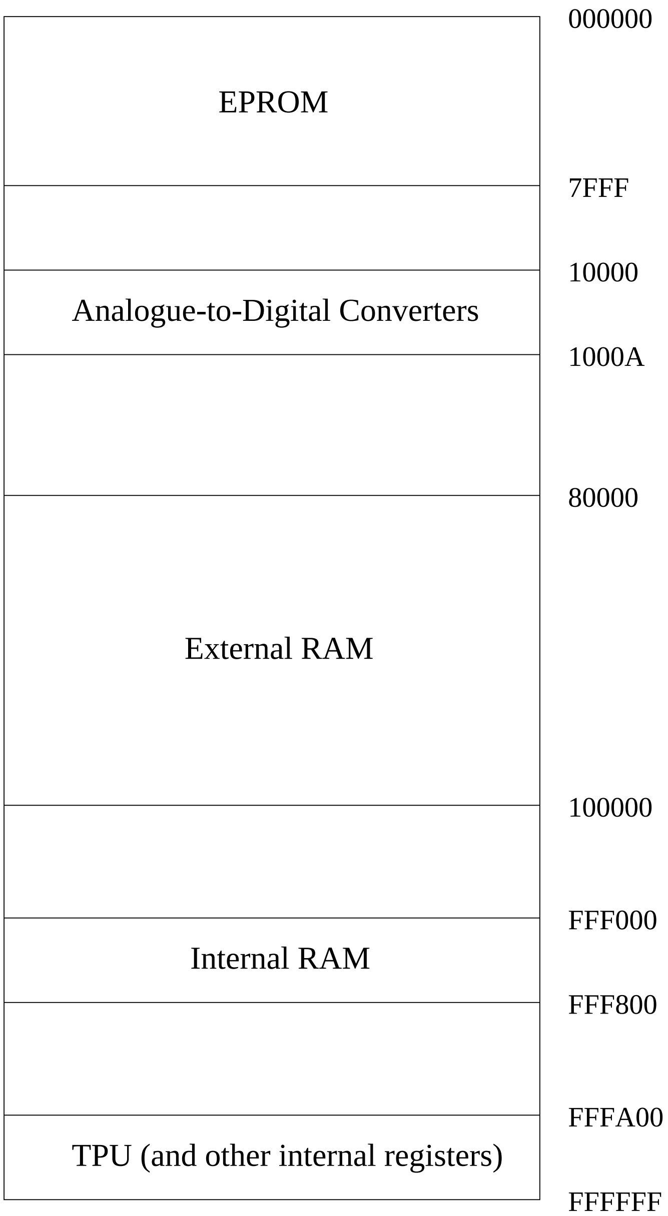


Figure A.1: The memory map used for Strider's on-board computer.

can be accessed for program and data storage.

- $\texttt{FFF000}_{16}$ to $\texttt{FFF800}_{16}$ are the memory locations for the microprocessor's internal 2kB of RAM. This RAM was used by the monitor program in the EPROM to store constants and variables. It was also used to for the system stack.

- $\texttt{FFFA00}_{16}$ to $\texttt{FFFFFF}_{16}$ are the memory locations for the Timer Processor Unit's internal registers in the microprocessor.

A.2 The Circuit Board Layout

The circuit used for the on-board computer for Strider was described in Section 3.2.8. The actual printed circuit board (PCB) was shown in Figure 3.14. The component layout of the top-side of this PCB is shown in Figure A.2. The location of various main ICs and connectors are indicated in the diagram.

The PCB layout was created using the EEDesigner circuit design package.

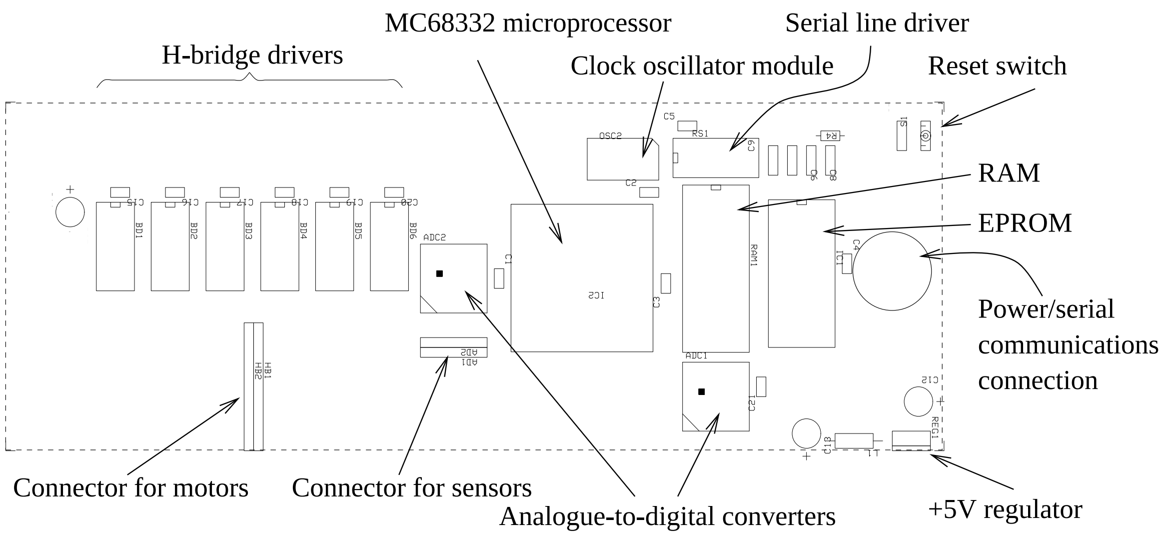


Figure A.2: The circuit board component layout for Strider's on-board computer.

A.3 The Schematic Diagram

The block diagram of the circuit for Strider's on-board computer was shown in Figure 3.13. The complete schematic diagram for this circuit is shown in Figure A.3. The MC68332CFC16 microprocessor is shown in the centre of the diagram. The six duel h-bridge drivers are shown on the left of the microprocessor. The connector to the twelve motors is shown on the top left of the diagram. The EPROM and RAM ICs are on the right of the microprocessor. The two ADCs and the connector to the sensors are shown on the far right of the diagram. Finally, the voltage regulator and the serial line driver is shown on the bottom left of the diagram.

The circuit diagram was created using the EEDesigner circuit design package.

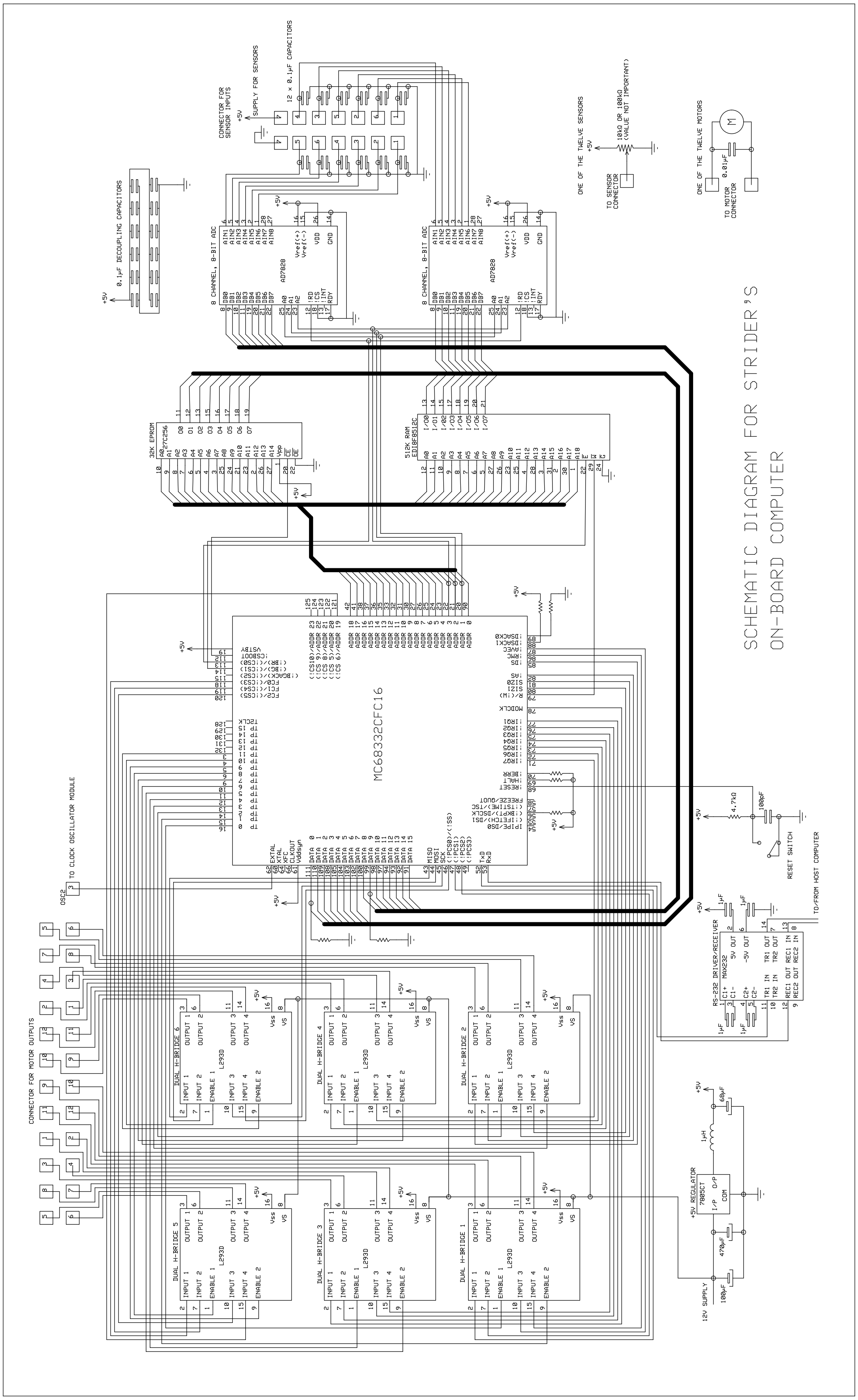


Figure A.3: The schematic diagram of Strider's on-board computer.

Appendix B

The Drive Mechanisms

As described in Section 3.2.5, the drive mechanisms (or gearboxes) are the physical structures used to house the servo motors, the groove-slot mechanism, the vertical lift gears and to connect the legs to the chassis.

The two front and two rear drive mechanisms all use the same PVC pieces in their construction. The PVC pieces of two of the mechanisms are simply the mirror image of the other two. The diagram used for the front, right-hand drive mechanism (or the rear, left-hand drive mechanism) is shown in Figure B.1.

The two middle drive mechanisms also use the same PVC pieces in their construction and are again pieced together as mirror images of each other. The diagram used for the middle, right-hand drive mechanism is shown in Figure B.2.

In Figures B.1 and B.2, the '+' signs represent screws that are fitted into the page. The '×' signs represent screws that are fitted out of the page. The '∗' signs represent screws that are fitted both inwards and outwards of the page. The short length dotted lines represent screws that are in the same plane as the paper.

The drawings used to create the drive mechanisms were drawn using a two-dimensional drawing package known as XFig.

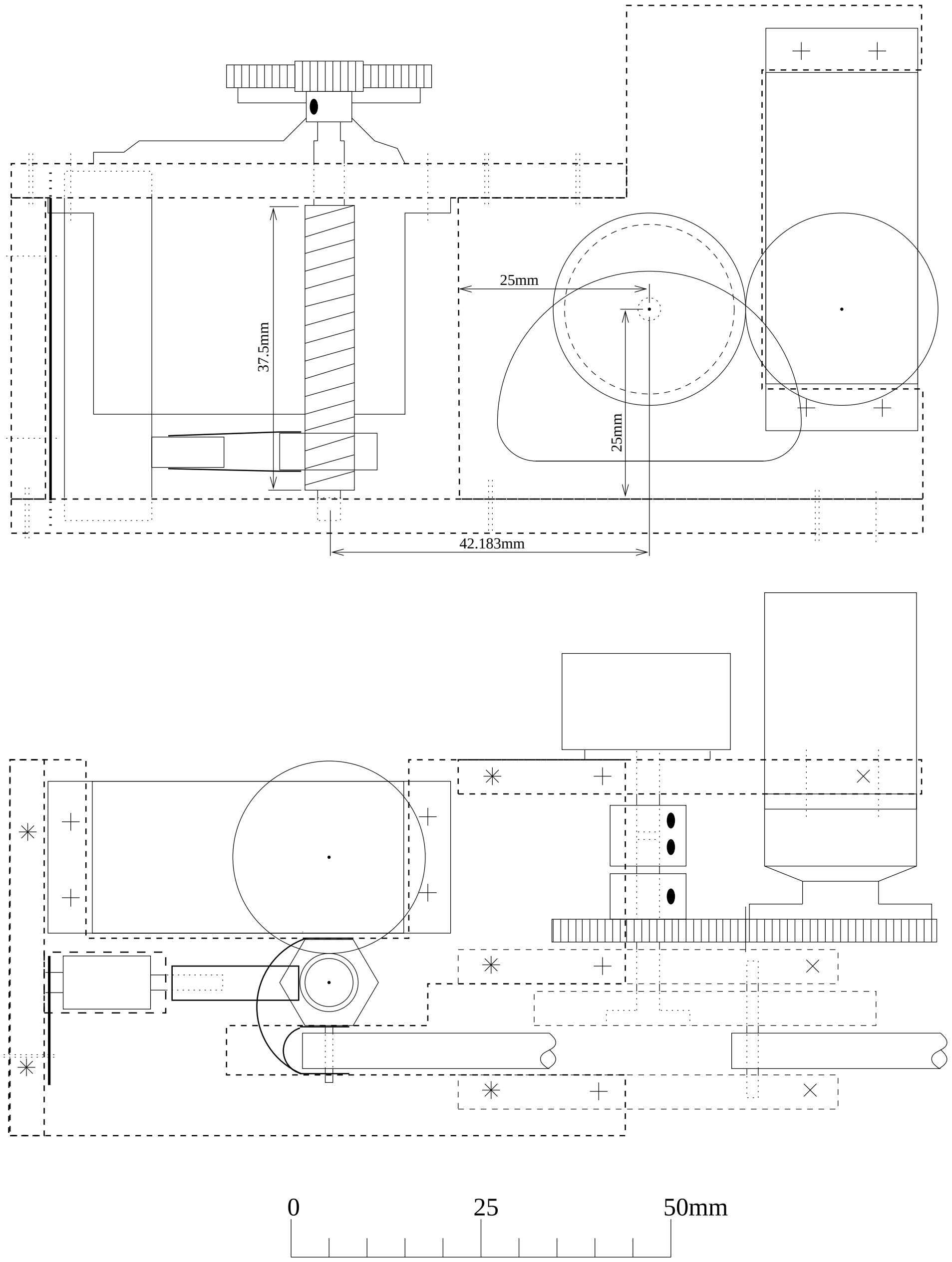


Figure B.1: The front, right-hand drive mechanism.
Top: side view. Bottom: top view

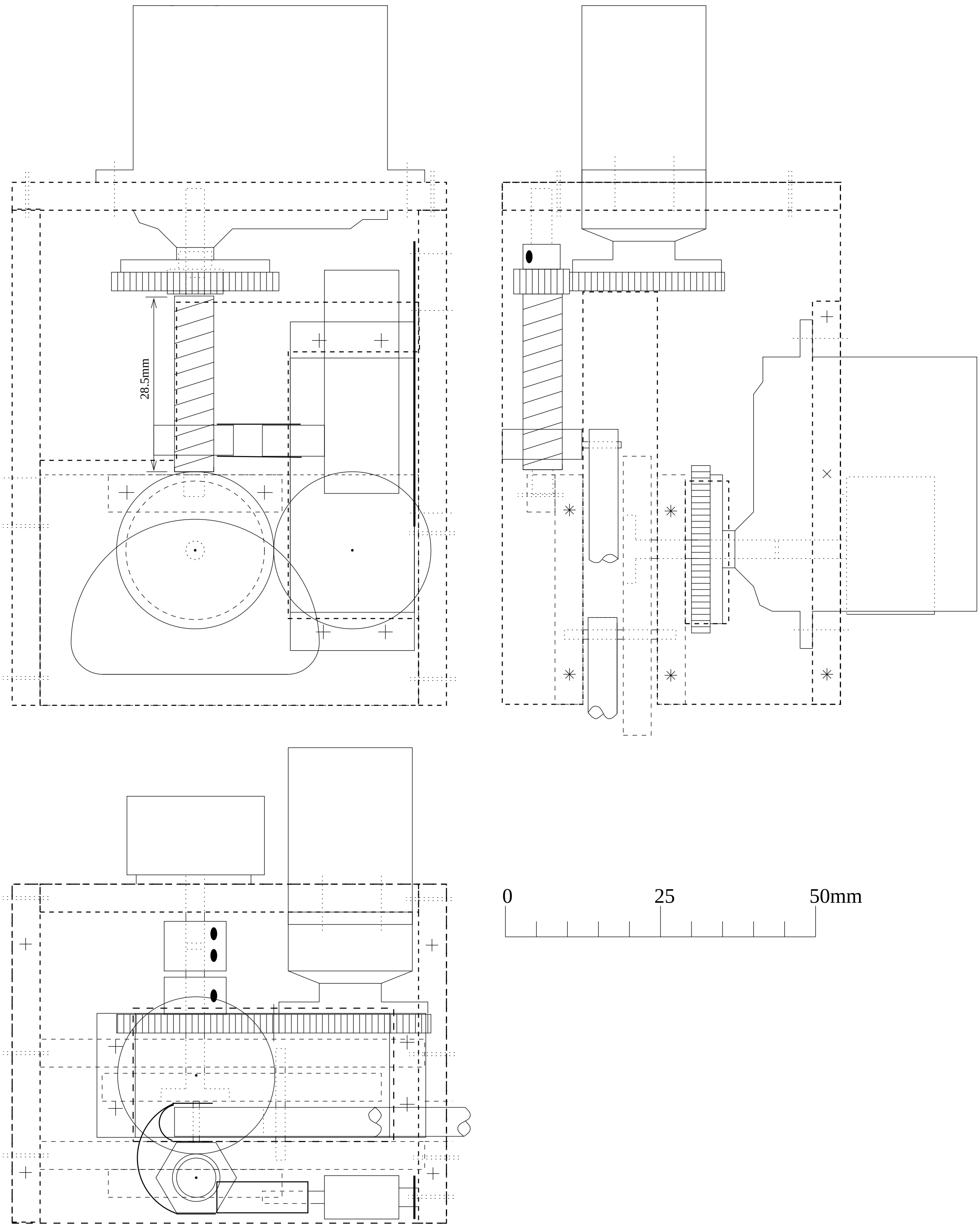


Figure B.2: The middle, right-hand drive mechanism.
Top-left: side view. Top-right: front view. Bottom: top view.

Appendix C

The Flowcharts for Strider's Control System

The flowcharts for each of the modules of the subsumption architecture used for the control of Strider is presented below. The **position**, **hold position**, **motor direction**, **drive motor**, **change speed**, **adjust speed** and **motor speed** modules are shown in Figure 4.17. The **increment**, **protract** and **all found** modules are shown in Figure 4.21. The **increment/decrement** module is shown in Figure 4.24. The **increment** module in Figure 4.24 performs the same function as the **increment** module in Figure 4.21. The **feeler** module is shown in Figure 4.26. The flowcharts for the **leg lift (left)** and **leg lift (right)** modules in Figure 4.26 were not included since they were not implemented in this work. The **v.position** and **foot switch** modules are shown in Figure 4.27. The **sequencer** and **extend protraction** modules are shown in Figure 5.6.

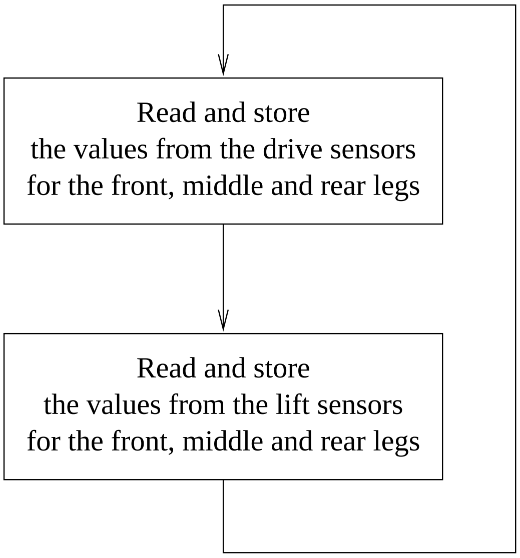


Figure C.1: The **position** module.

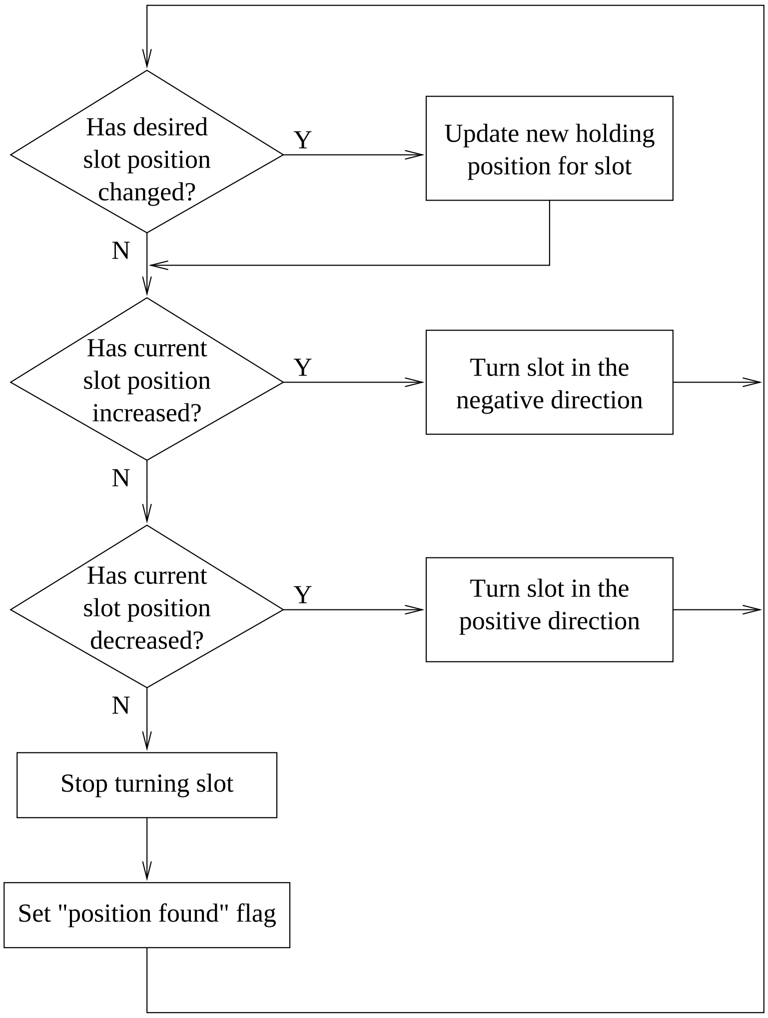


Figure C.2: The **hold position** module.

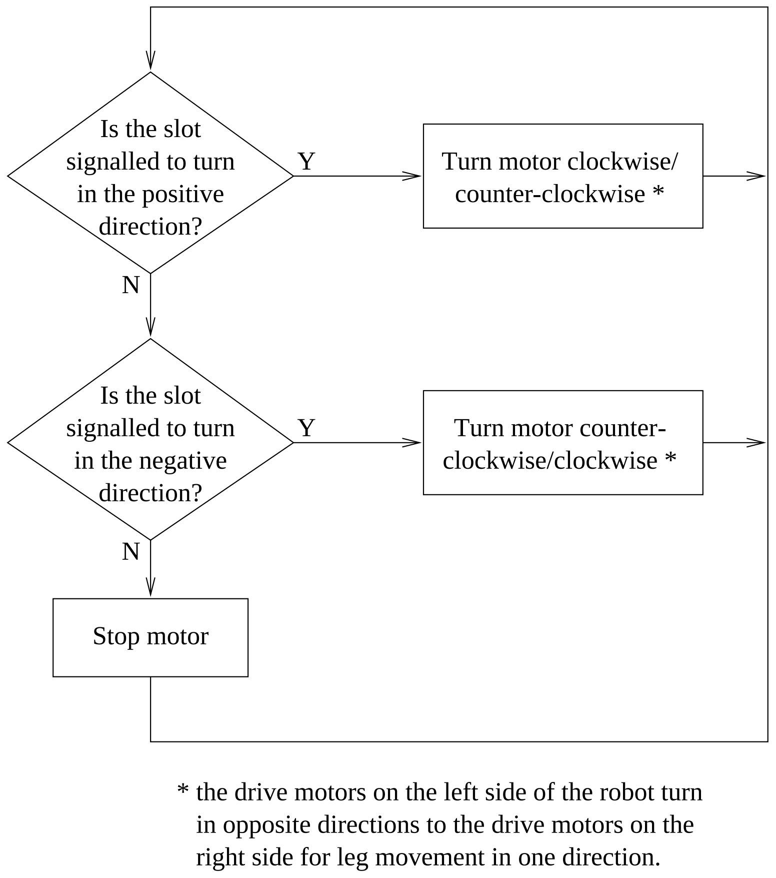


Figure C.3: The **motor direction** module.

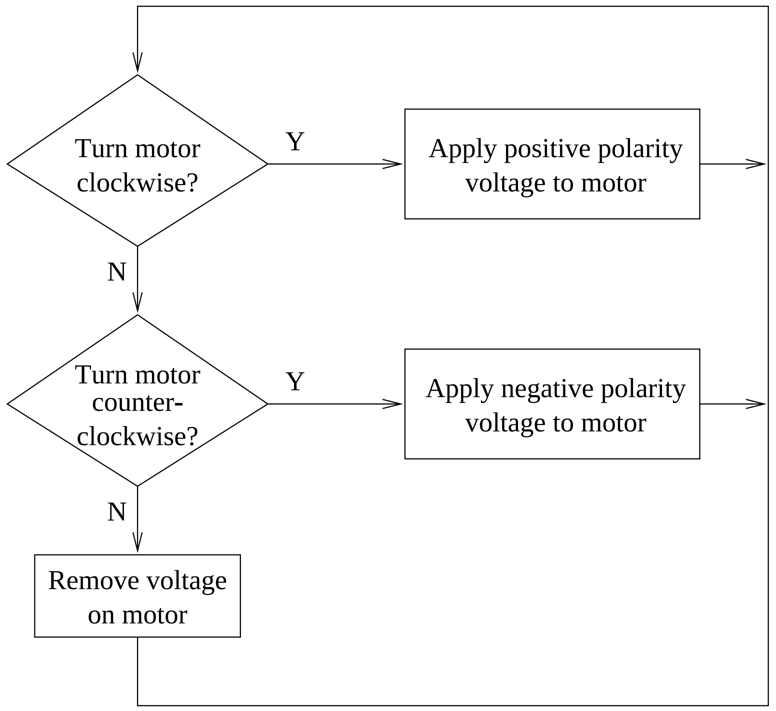


Figure C.4: The **drive motor** module.

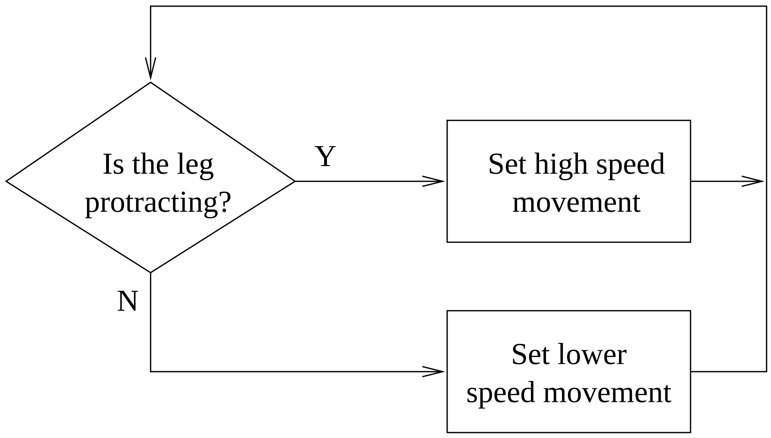


Figure C.5: The **change speed** module.

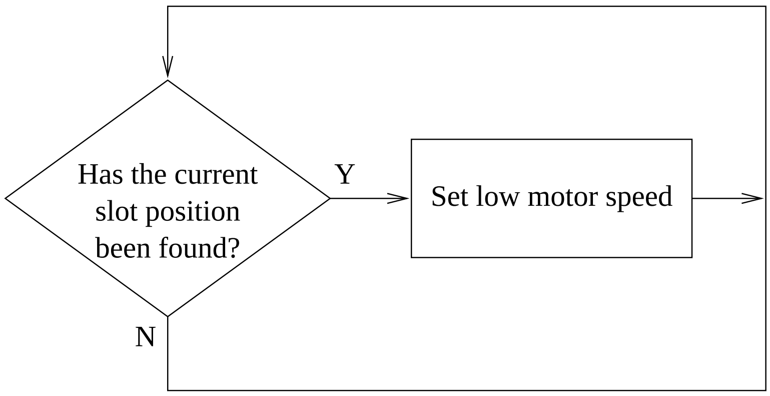


Figure C.6: The **adjust speed** module.

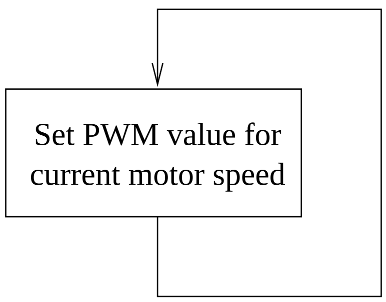


Figure C.7: The **motor speed** module.

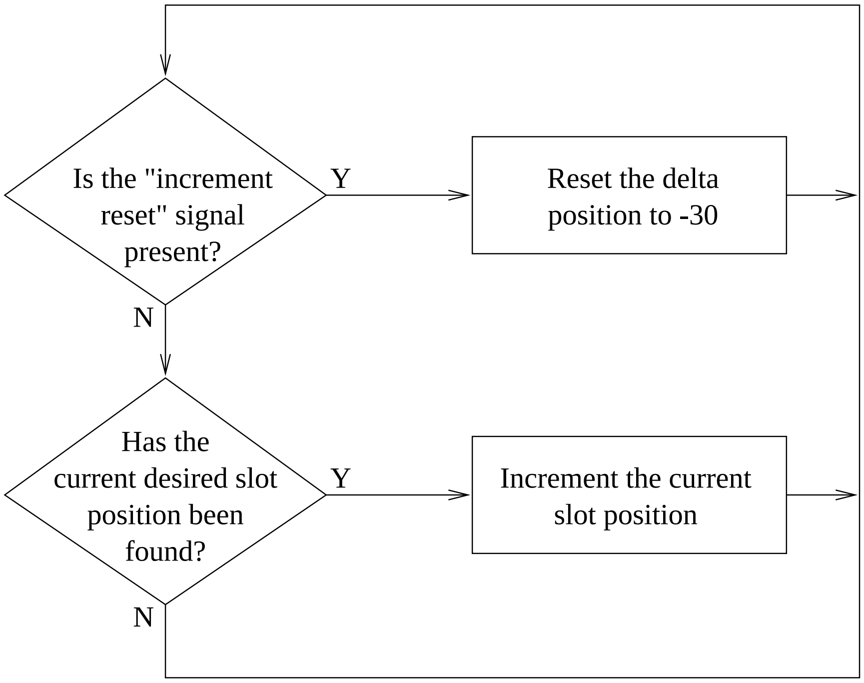


Figure C.8: The **increment** module.

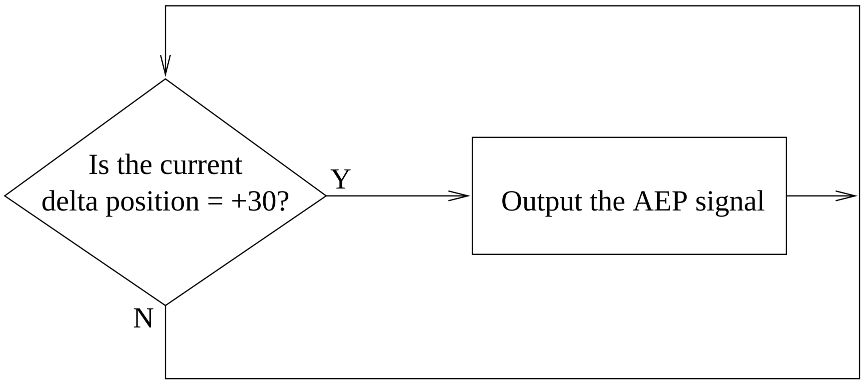


Figure C.9: The **protract** module.

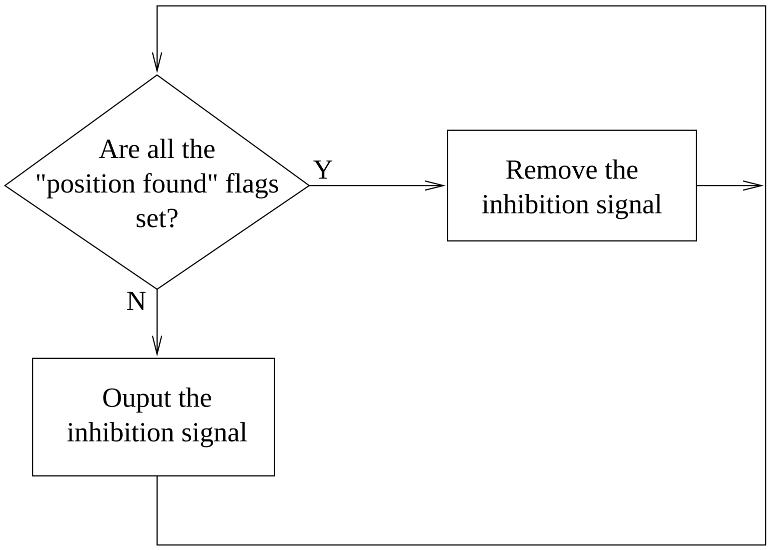


Figure C.10: The **all found** module.

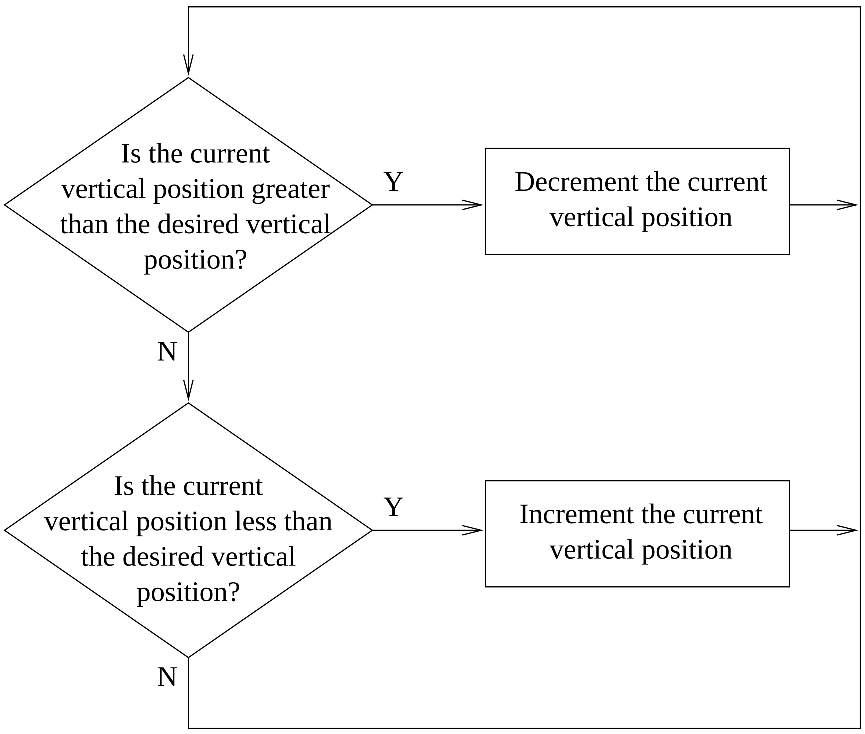


Figure C.11: The **increment/decrement** module.

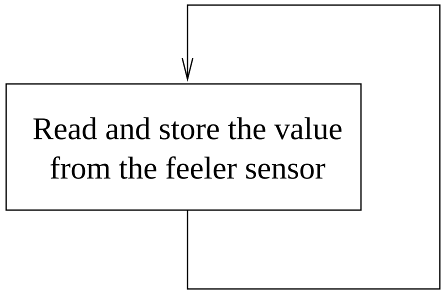


Figure C.12: The **feeler** module.

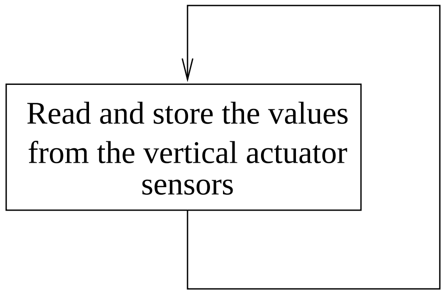


Figure C.13: The **v.position** module.

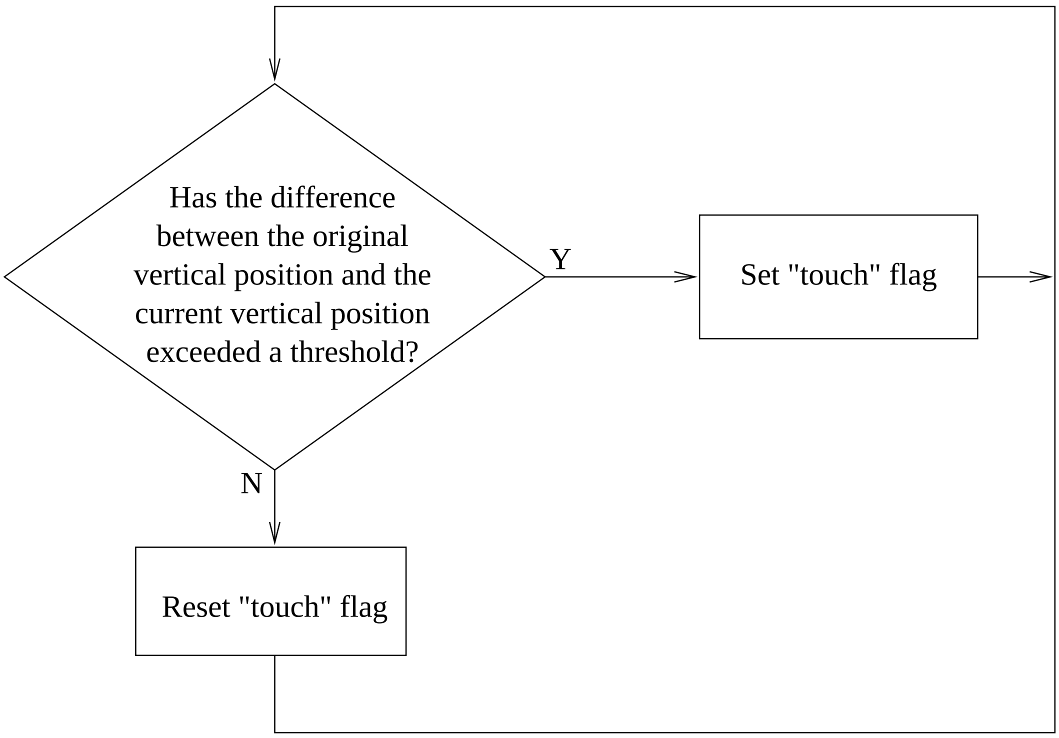


Figure C.14: The **foot switch** module.

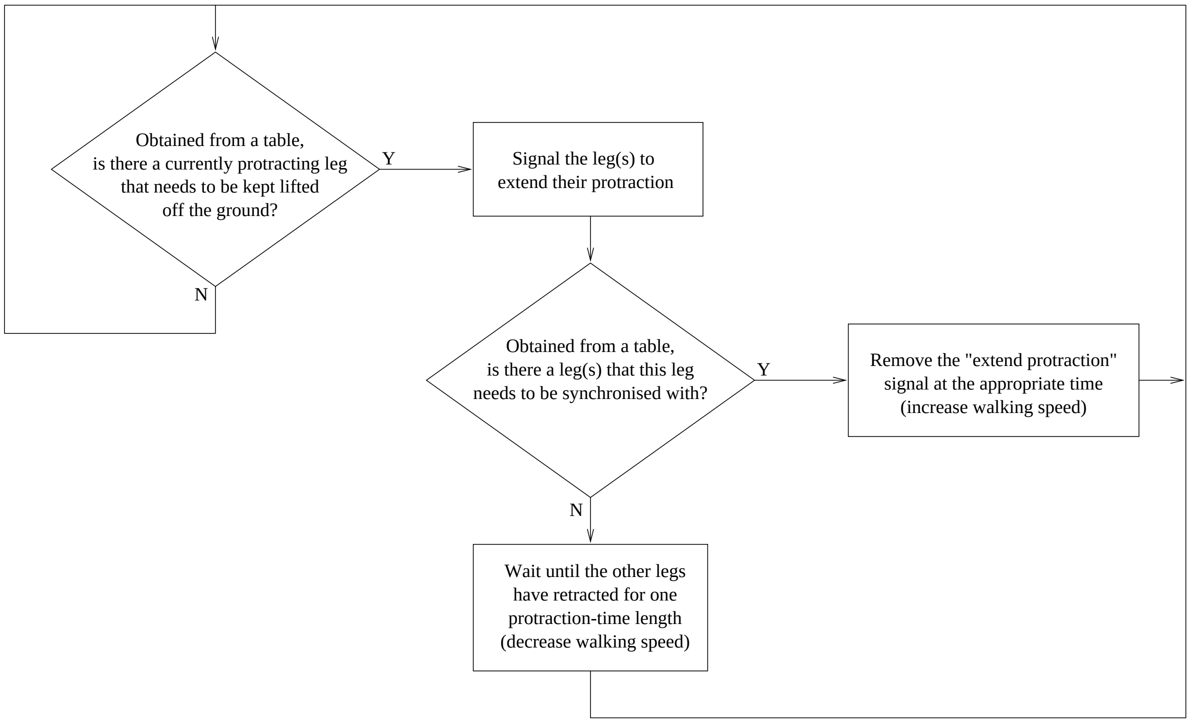


Figure C.15: The **sequencer** module.

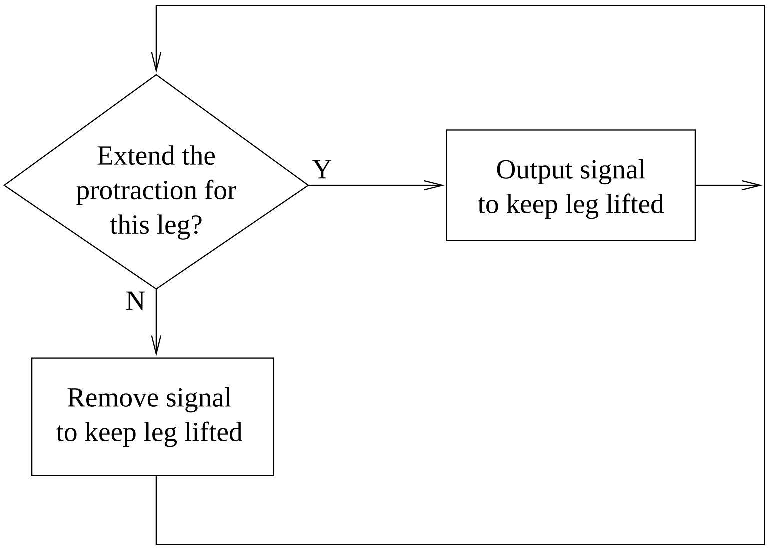


Figure C.16: The **extend protraction** module.

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