1 INTRODUCTION

Imagination is more important than knowledge.

Albert Einstein

1.1 THE QUEST FOR BIPED MOTION

From the 1950s man has dreamed of the day when robots will stand side by side with us, in our image. We now live in an era where the previously well defined dimensions of imagination and reality are beginning to blur at the boundaries. For many years, society has accepted the persona of automata and robots. The January 2001 edition of People Magazine included Robby the Robot (Figure 1.1) as one of the twenty five most intriguing people of the century. While the hardened roboticist may dismiss the science fiction factor as fantasy, it cannot be ignored as a driving force in robotics research. Albert Einstein recognised the power of imagination as a driving force in research. Japan's fascination with androids and the personification of electronic devices has driven the development of products as diverse as miniature PDAs that need to be fed and cared for on a regular basis, to robotic maids that are able to vacuum a room.

Figure 1.1 Robby the Robot from the 1950s movie Forbidden Planet

"We Japanese love new, advanced things", says Minoru Asada, an Osaka University scientist developing soccer-playing robots. "It's more than just owning them. They are our friends, and we want to integrate them into society." (Time, 2000)

More recently, the development of Sony's SDR-3x , Honda's Asimo and Toyota's trumpet playing humanoid (Figure 1.2) demonstrated beyond question, that the Japanese have piloted the development of the humanoid robot or "android" [(Sony, 2000), (Honda, 2003a), (Wolfe, 2004), (AIST,2003)]. Sony market the SDR-3X as an "entertainment robot" as its small size, lack of dexterity and intelligence make it incapable of performing useful service tasks. Realistically, it represents a continuation into the next generation of the extremely popular post war clockwork or battery powered tin toy robot. However, the development of the device has focused engineers, marketers, industrial designers, software developers and psychologists onto the tasks that will one day deliver a realistically priced and capable android. Effectively, they have taken the first steps of the long march that will end with the fulfilment of the science fiction dream. Asimo is of a larger scale and is marketed as a service robot. The increase in size carries an additional level of complexity in terms of engineering, control and actuators. The robot's significant processing power and human-like qualities either satisfy the developers' craving for creation or the market's demand for anthropomorphic devices.

While mechanical walking machines have been proposed, patented and built from the beginning of this century, it is only since the availability of low-cost microcomputers that electronically controlled devices have become viable. The vast majority of walking robots that have been built are modelled on the human form. The geometry presented by an anthropomorphic device and the inherent instability of bipedal locomotion increase both the complexity and cost of the device in terms of construction and control hardware. The construction of robotic biped walking devices is expensive, labour intensive and demanding in terms of programming time. Researchers involved in this field have tended to justify their endeavours in philanthropic rather than economic terms. Such justification is embodied in two propositions that include the study of biped walking machines so that:

Figure 1.2 Honda's Asimo, Kawada's HRP2 and Toyota's trumpet playing humanoid

- Biped devices may replace humans performing hazardous or degrading work (Golliday and Hemami, 1977)
- The study of bipedal control will result in a better understanding of the human gait and lead to devices that will assist with the mobility of people who have lost the use of their legs.[(Todd, 1985), (Kato et al, 1987), (Hemami et al, 1973), (Yamashita, 1993)]

While these propositions may be worthy, the cost of a biped robot compared to that of a wheeled or tracked device inhibits commercialisation of biped robots in the first proposition.

Another justification has been based on the development of robotic-type orthotic devices to aid people with paraplegia. Even if such devices were to be realised, they would be prohibitively expensive to manufacture and maintain, placing them out of reach of all but the most wealthy patient. Further, the requirement for an onboard power supply would render the device bulky, cumbersome, and with the current efficiency of batteries, it would have a very short period of operation. Current research in biomechanics suggests that functional electrical stimulation of nerves and muscles will be significantly more viable in the restoration of locomotion. (Popovic et al, 1999)

Robots such as Honda's anthropomorphic droid have attempted to closely imitate the human form. Takanishi et al. (2005) from Waseda University, where the development of autonomous biped robots began in 1973, suggest the reason for humanoid appearance is that it is a requirement if humans are to work side by side with androids;

> *"By constructing anthropomorphic/humanoid robots that function and behave like a human, we are attempting to develop a design method of a humanoid robot having human friendliness to coexist with humans naturally and symbiotically."*

These robots are research platforms crammed with a range of technologies such as voice and image recognition, as well as gait and balance control systems. Ultimately, this research may lead to a device which would replicate some human characteristics. Sony (2003) justify their biped robot as a proving ground for the demonstration of new technology.;

> *"next generation technology is functional device technology that correspond to the five senses".*

Given a plentiful supply of humans however, the usefulness of such a device would be limited to applications where there is significant hazard and likely risk of injury. Applications may include working in hazardous areas such as bomb disposal, surveillance and the nuclear industry. More conventional arguments would suggest that legged vehicles would traverse irregular terrain inaccessible to conventional wheeled or tracked vehicles [(Raibert, 1986) (Kato et al, 1987)].

The support base of a biped is an order of magnitude smaller than that of any other vehicle. Bipeds also possess the ability to turn in their own space, lift heavy objects by adjustment of posture rather than by increasing their support base and traverse discontinuous surfaces. Here lies the true usefulness of a biped device; its ability to achieve what is beyond the capabilities of contemporary materials handling vehicles and certainly beyond the capabilities of a human.

1.2 EMBODIMENTS OF BIPEDAL MOTION

Biped robot research could be classified as pure research as it does not necessarily satisfy a practical demand. For example, it does not aim to cure a disease, though it claims to investigate a solution to paraplegia. It does not offer to make more efficient an industrial process, but suggests it may make some processes less hazardous to humans. In the case of humanoid biped robots there is no current demand for a device that is less intelligent, less dexterous and less enduring than an able-bodied human. In the instance of an industrial scale biped robot, there is no demand for a device that possesses no capability beyond that of a forklift truck. However, as the industrial environment is currently designed around existing materials handling technology, any device that significantly improved the capability of conventional materials handling plant has the potential to alter that environment. In particular, it is proposed that the development of a biped materials handling platform will not only offer materials handling in confined, uneven terrain where a forklift or other lifting device would be unsuitable, rather it would allow the development of industrial processes that were previously impracticable. Possible situations would be field handling in a military environment, on board a ship or industrial applications in the field such as geological or mining applications. This project endeavours to demonstrate that biped robotic materials handling is viable by the construction and operation of an industrial scale device.

Capable of lifting 500kg	1st Criterion
Able to traverse 500mm discontinuities	2nd Criterion
Robust both physically and electronically	3rd Criterion
Completely self contained	4th Criterion
Able to work for long periods	5th Criterion
Easily maintained	6th Criterion

Table 1.1 Design criteria for an industrial biped

The design of such a device would rely on a set of performance parameters based on the range of tasks it would be expected to perform. Given that no such robot is in existence, these tasks have yet to be defined. However, based on current complex or hazardous materials handling conditions, a set of parameters has been formulated for the first time. For a biped to be industrially viable, it is proposed that it must meet the criteria in Table 1.1.

The following document outlines the design, construction and control of the device that has been built to satisfy these criteria. The result of the integration of the mechanical, electrical, electronic, software and control engineering undertaken in this project is shown in Figure 1.3. Named “Roboshift”, the biped robot stands 2.4 metres tall, weighs 500 kg and is completely self-contained. As such, it is the largest autonomous biped robot to be built. It is the only biped robot which has achieved an industrially viable scale. Table 1.2 outlines the as-built specifications of Roboshift.

The author has presented two research papers on the project. The first was delivered at the 1999 International Symposium on Computational Intelligence in robotics in Monterey, California (Cronin et al, 1999), and the second at the 2004 Australian Automation and Robotics Association in Brisbane, Australia (Cronin et al 2004).

The major contributions made to the field of robotics by this project include;

- A foundation set of design criteria for an industrial scale biped robot have been determined.
- A comprehensive, self contained, full scale prototype of an industrial biped robot has been designed and constructed.
- Roboshift is the first industrial scale robot to be fully self contained, carrying on-board all power, actuation and processing systems required for continuous and extended operation.

INDUSTRIAL BIPED ROBOT SPECIFICATIONS	
Height	2.4 Metres
Width	1.3 Metres
Length	1.2 Metres
Weight	494 Kg
Power	20 Hp LPG Engine (air cooled)
Actuation	Hydraulic (12 Cylinders, 2 Motors)
	3 x 3500psi Gear pumps.
	30l litre reservoir.
	14 Rexroth WRE proportional valves.
	14 x VT10001 PWM Valve Amplifiers
Cooling	3.5 Hp 12V Fan forced oil radiator
DOF	14
Electrical Power	Bosch 12V 60amp Alternator
	2 x 600 W 12VDC to 240VAC Inverters (PC Power)
	3 x 12 Volt Batteries (Instrumentation)
Processors	Pentium III 100MHz (Global Control)
	Pentium III 100MHz (Communications)
	14 x Motorola 68HC11 (local Joint Control)
	1 x Motorola 68HC11 (Artificial Horizon)
	1 x Motorola 68HC11 (Artificial Horizon Compressor)
Sensors	Air driven absolute artificial horizon (Pitch & Roll)
	Flux gate compass (yaw)
	2 x Strain gauge bridges each leg
	14 x Quadrature encoders (one per joint)

Table 1.2 Roboshift specifications

- Roboshift is the first industrial scale biped to demonstrate active balance in the frontal and sagittal planes, and to achieve frontal sway.
- The experiments conducted on the biped robot represent the first credible research into the challenges presented by an industrial scale biped robot in terms of its design, construction, power and control systems.
- The project is the first research to identify compliance as a major issue in the operation and control of an industrial scale biped. It is also the first research to dynamically model a large scale biped robot and to provide solutions to the control of a compliant biped.
- The project has established the requirements of the control system of an industrial biped.

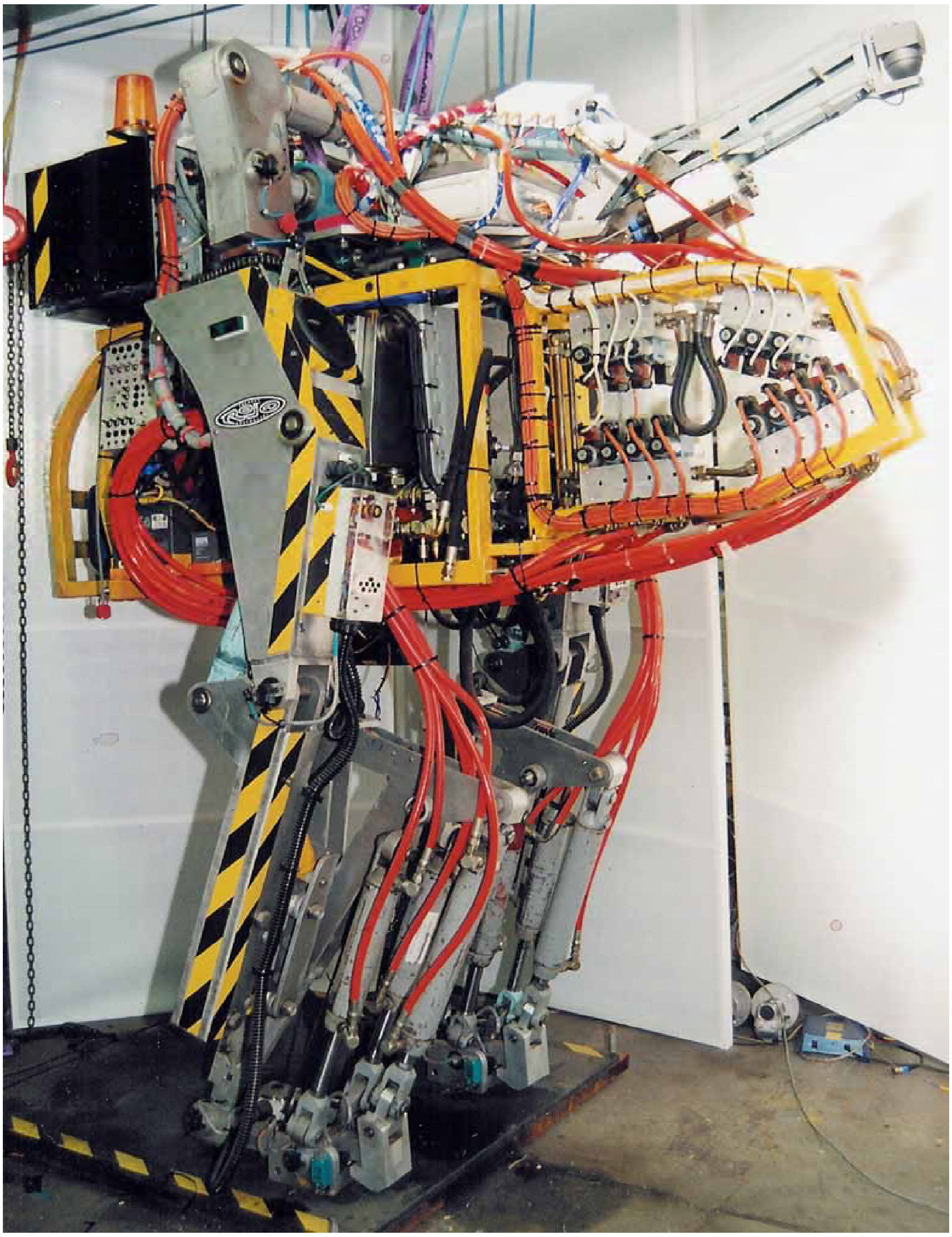


Figure 1.3 Roboshift

1.3 ABOUT THE PROJECT

The project to build an industrial biped robot commenced after the author attended the opening of the movie "Aliens" in which a teleoperated robotic loader was used not only to transfer cargo, but to defeat the alien life form. Impressed with the concept of the loader, research indicated the concept was based on General Electric's Hardiman (Weiss, 2001). Finding no reliable published data on the device, or any similar industrial scale biped, the author attempted to determine why no such research was being attempted.

Originally intending to complete a master's degree on the project of a concept design for such a system, the degree was upgraded to a PhD when it became evident that industry assistance would be available to complete a working prototype. Apart from the generous assistance of his supervisors, the fabrication and welding of the aluminium sections of the robot, the design of the F1 Controller I/O boards and assistance with the communications interrupt routines, the entire project has been completed by the author. This has included:

- Conceptual design of the robot
- Full mechanical design of the robot
- Mechanical assembly of the robot including the fabrication of all non aluminium components
- Design of the electrical system
- Installation of the electrical system
- Design of the control system
- Construction and installation of the control system and transducers
- Design and coding of the control software

1.4 STRUCTURE OF THIS DOCUMENT.

Chapter 2 reviews biped robot research literature. In particular, it explores the following :

- Development of walking robots
- Development of biped robots
- Development of walking robot control systems

The review details the major classes of control systems that have been developed as well as establishing a base for the research in this project. It shows that the majority of biped research has revolved around devices of a scale unsuitable for commercial development. Finally, the discussion concludes with the development of a design specification for an industrial scale biped.

Chapter 3 details the conceptual and mechanical design of the robot including structure and actuators. To enable such a large and complex project to be completed as a PhD, it was necessary to fast track the design process. The use of existing expertise, in combination with the availability of resources, led to a refined solution space using hydraulics as the motive force. Initially, mathematical and kinematic models are used to determine joint trajectories so that the degree of freedom and range of movement is able to be determined for each joint. Further analysis is used to examine the geometry of the actuator/joint combinations. The chapter concludes with photographs of the completed structure which show the body suspended under the hips. This configuration, previously only seen in the science fiction realm, was realised for the first time in this project.

The hydraulic and electrical systems that provide power to the robot are detailed in **Chapter 4**. Based on limb trajectory models, the flow requirements are calculated for each of the hydraulically operated joints. To avoid the potential for hydraulic “crosstalk” as encountered with General Electric’s Hardiman, the robot described in this project uses separate hydraulic systems to operate each of the legs and the hips. Schematics of the hydraulic and electrical systems are included. The electrical system provides high current power for the hydraulic valve amplifiers, the inverters that power the two on board computers and low current power for other on board systems such as processors and transducers.

An overview of the control system hardware, software and modelling is given in **Chapter 5**. The chapter begins with a discussion of robotics and cybernetics. It suggests that the difference between industrial robots and advanced mobile robots is the ability to deal with unexpected information. It discusses the results of the review of previous walking robot control systems and builds on that knowledge base. The control system is hierarchical and distributed using a separate computer to facilitate communications between the sixteen microprocessors on board. By breaking the control task into local and global control, the system mimics that of the human with reactive control occurring at the joints and cerebral processing occurring in the main control computer.

Chapter 6 details the development of the control system electronics including processors, transducers and communications modules. The connection of the major components is detailed in a schematic of the control system hardware.

Chapter 7 explains the kinematic and dynamic models that were used to design the robot mechanically and to design the software that controls it. Graphical output is provided from the AutoCAD Advanced Development System software that was written to display the results of dynamic modelling.

Chapter 8 outlines the structure of the software which controls the various behaviours of the robot. Initially, flowcharts are used to illustrate the hierarchy of the software and the distribution of processing tasks. The software can be broken into three main sections:

- Main control software running on the main control computer
- Communications software running on the communications computer
- Local joint control software running on the Motorola M68HC11s

While other robots have adopted the use of distributed processing, this system is the first to use a dedicated processor to distribute information. This configuration offers the advantage that the communications processing demands on the local joint processors and the main communications PC are reduced by making them invisible to each other. While the joint control and communications software routines are standard for all robot functions, the control software is segmented into three main functions. The first is calibration which homes the robot, calibrating position encoders and proportional valve control. Secondly, the static balancing software uses the robot's vestibular and strain gauge transducers to maintain the centre of gravity of the robot within the reaction polygon of the feet. Finally, the locomotion software initiates frontal sway and controls the forward motion of the robot. This is the dominant software active when the robot has been calibrated and is in an operational mode.

The testing of Roboshift is described in **Chapter 9**. Each of the stages of development was tested to ensure that classes of systems were performing to specification as they were integrated. Initially the local joint control was confirmed by the use of a small wheeled robot that was fitted with the hardware system developed for joint control. A PC was then networked with the joint control microprocessors to confirm and optimise the serial data transfer routines. Once the reliability and the operation of the joint control software had been proved, the software was loaded to the robot where communications were confirmed for the entire system.

With data transfer confirmed, calibration and then motion control was tested for each joint, for two joints simultaneously, and then for the entire system. The testing showed that the system was robust and able to communicate at eight cycles per second. Once the robot was able to be calibrated and moved into a passive balancing condition, the balancing software was then successfully tested.

Chapter 10 examines the outcome of the testing of the robot and reviews the project in terms of the design and the performance of the mechanical, electrical and control systems. Modifications are suggested for the next iteration of the robot including a review of the design of joints and limbs to reduce compliance and vibration in the structure. The choice of transducers is discussed with a recommendation that each degree of freedom is sensed by two independent means.

The performance of the control system hardware and software was surprisingly stable. Both the F1 Controller boards and the two PCs survived a range of mishaps including severe shock and voltage fluctuations. The control software achieved all system specifications proving extraordinarily robust.

Based on the performance of the structure, an initial analysis is conducted into the degree of flex that could be expected in links of an industrial biped.

Chapter 11 continues with the analysis of flex in the structure. A finite element model is created and analysed for a typical link to estimate the stiffness of the structure. A Matlab Simmechanics model is then constructed and analysed to determin the dynamic response of the structure. The model demonstrates the problems created by collocation of sensors and actuators in the control of a flexible structure. the performance of a control strategy using non-collocated sensors is then modelled.

Chapter 12 discusses the major accomplishments and failures of the project. The project's contributions to the research area are outlined including:

- Establishment of design criteria for an industrial biped
- Roboshift is the largest biped robot to demonstrate active balance in the frontal and sagittal planes as well as limited sway in the frontal plane.
- Roboshift is the first biped to incorporate a self contained power system capable of operating the device for extended periods and the first to incorporate an internal combustion engine.
- Roboshift is the first biped robot to be built on an industrial scale so that challenges in terms of structure and control of an industrial biped can be identified. At 2.4 metres in height and 500kg in weight, Roboshift is the heaviest autonomous biped robot yet built.
- Establishment of the requirements for the control system of industrial scale biped robots.

- Identification of compliance as a major issue in the structural design and in the design of the control systems of industrial scale biped robots
- The modelling and analysis of the compliant structure and teh presentation of strategies to deal with compliance by teh use of non collocated sensors.

Finally, areas for future work are detailed including;

- The continuation of frontal balance and locomotion trials.
- The formulation of a dynamic frontal sway model which incorporates compliance in the structure of the robot.
- Comparison between theoretical output of the upgraded dynamic model and experimental data acquired from trials of the robot.
- Continuation of locomotion trials.

2 WALKING ROBOTS

Methinks that the moment my legs begin to move, my thoughts begin to flow.

Henry David Thoreau

This chapter presents the results of the search for literature relevant to the project. A mobile robot can be characterised as the integration of a range of technologies and research combined to construct and to control an autonomous vehicle. Biped robotics research has become a discipline within mobile robotics. However, it cannot be studied in isolation from the engineering and bioengineering disciplines it draws from so heavily. A biped robot is a mechanism, the movements of which are controlled by software processed by microprocessor based electronic hardware. The design of the mechanism is dependent on the definition of movement; the design of the processing platform is dependent on the structure of the controlling software. The definition of movement and mechanism design are dealt with by the mechanical engineering disciplines of design, kinematics and dynamics, and the science discipline of biomechanics. Software and hardware design are disciplines of electronic engineering. In recent years, mechanical engineering has seen the introduction of the discipline of Mechatronics that includes all of the areas described above. This is a strong indication that, in the field of robotics, mechanism design and control design are strongly inter-related.

In the case of a wheeled robot, the mechanical design component of the project is usually less complex than that of a legged robot. For this reason, the majority of research presented on wheeled robots revolves around the issues of sensing and navigation. In the case of multi legged robots, the research tends to focus on gait patterns and the actuation of the legs. In biped robots, where the major control task is not to fall over, the research focuses on the design of the leg system, the stability and dynamics of motion and the architecture of the control system. For a biped robot to walk with a dynamic gait it requires a control system capable of processing sensory data, solving dynamic motion equations and controlling actuators in real time.

The focus of this literature search is broken into three parts.;

1. **The development of walking robots**. Establishing a broad history of legged

robot research allows the identification of technologies that may be relevant to this project in terms of leg actuation, sensors and control system and software architecture. Here, the focus is on the configuration of previous walking robots without in-depth analysis of gait models or control systems.

2. **The development of biped robots**.- It could be argued that, given the high degree of failure to achieve dynamic walking, the value of previous biped research to this project is questionable. However, what is commendable is the contribution to science made by researchers who have tirelessly adapted technology to the task as it has become available. As processing power has decreased in cost and smaller, more powerful microprocessor have become available, these have been absorbed into biped robot control systems. This has also been the case with new developments in control theory. With the increase in processing power and distributed processing, more complex control systems and more sophisticated gait models have been able to be represented in software. Like few other areas of endeavour, the field of biped robotics has insatiably adapted emerging technology from fields as diverse as control theory, avionics, image processing, polymer research and biomechanics.
3. **The development of walking robot control systems**.- Finally, the literature search establishes the current state of the art so that the work in this project may benefit from, and contribute to the current level of knowledge in the field. The last endeavour is more difficult to achieve as the literature search shows that very little research has been conducted into the development of an industrial scale biped. In fact, Honda, the leading researchers in biped robotics, has reduced the size of their latest biped prototype from that of the previous iteration. This section concentrates on the hardware and software used on previous biped robots.

Literature outside of these areas will be included, where appropriate, to further explain the development of previous research and the research conducted in this project.

2.1 WALKING ROBOTS

The human body represents the ultimate example of a fully integrated mechanism and control system. Through its five senses, it is able to gain an enormous amount of information, process it on several layers of consciousness and then actuate the motion and control the force of muscles, both centrally and peripherally. But in some situations, where tasks are narrowly defined and repetitive, robots have been able to replace the human by carrying out these tasks more quickly and accurately.

As is widely reported and accepted, the term "robot" was first used by the Bohemian playwright Karl Capek, in his play Rossum's Universal Robots (Capek, 1920). In its cast, the play included creatures called "Robotnics" , a term derived from "robota" which is the Russian word used to described repetitive, labour intensive work. Shahinpoor (Shahinpoor, 1987), defines a robot as;

..a re-programmable multifunctional manipulator designed to move materials, parts, tools, or specialised devices, through variable programmed motions for the perform - ance of a variety of tasks.

This definition describes the industrial robot, which is an extension of the first automated machines introduced to the textile industry during the Industrial Revolution. While the means and complexity of programming have changed, today's industrial robot is simply an intelligently controlled machine, a machine designed to carry out repetitive and laborious tasks as highlighted in Kapek's play.

In parallel with the development of the industrial robot, an area of robotics has existed which has focused around the droid or artificial life form. In 1962, the Britannica World Language Dictionary defined a robot as ;

...a manufactured, mechanical person that performs all hard work.

This definition is based on Isaac Asimov's droids rather than on the industrial robot under development at that time. It was only after the first Unimate was installed in Japan in 1969, that the term "robot" was used to describe re-programmable machines. The droid has become the mobile intelligent agent the development of which has been driven by several stimuli. The first stimulus for research was the romance of science fiction and an inexplicable desire of robot engineers to imitate human and animal behaviour. Examples of such robots are tracked, wheeled or even winged platforms which are fitted with a variety of transducers and at least one microprocessor. Continually scanning their environment, the robots react to inputs with pre-programmed behaviours. These types of mobile robots are most commonly found in mechanical engineering and computer science schools of universities around the world.

The second stimulus for mobile robot research is a requirement for mobile platforms used to convey sensors and surveillance equipment into areas inaccessible or hazardous to humans. Bomb disposal, pipeline inspection and nuclear plant monitoring are common tasks performed by mobile robots. While tele-operated by humans, these robots generally possess control systems capable of accepting both operator and local sensory inputs, which are processed before actuation is enabled. This is especially the case where the possibility exists for interruption of communication with the command console. When this occurs, the robot uses its default behaviour to either continue its mission or attempt to re-establish communications.

The recent expeditions of the Mars Rover are an example where a significant delay exists between command transmission from Earth and feedback from the Mars Rover. As an earth-bound robot operator would not be able to see an obstacle before the Mars Rover came into contact with it, the robot was programmed to navigate its way around the obstacle.

Legged robots are mobile robots or droids which use legs, rather than tracks or wheels, for their mobility. Biped robots are a subset of legged robots that attempt to imitate human locomotion. The Holy Grail of mobile robot engineering is a droid which walks, talks and thinks like a human being. Sias and Zheng (Sias and Zheng 1987) suggests that;

...the ultimate mobile robot is a device that can emulate the agility and autonomous behaviour of the human being...

As seen in the following sections, considerable resources have been invested in anthropomorphic robots and into the development of artificial people and animals.

2.1.1 WHEELS VERSUS LEGS

Classically, research into legged walking machines and robots has been justified by two main arguments. The first suggests that legged vehicles could work on terrain not accessible to tracked or wheeled vehicles. Specifically, legged vehicles can step over uneven or unstable terrain, placing feet only on firm ground. Raibert (1986) highlights the fact that animals can reach a greater area on foot than is accessible to wheeled or tracked vehicles, and proposes that legged vehicles will go places that only animals can now reach. Kato et al (1987) recognised that while wheeled and tracked vehicles operate on a continuous surface, legged vehicles can operate on a discontinuous surface. What Kato fails to highlight is that the continuity of a plane is effectively a function of the diameter of the wheels or the length of a track. Increasing the diameter of a wheel proportionally increases the size of discontinuity that the vehicle is able to traverse.

The real advantage of legged vehicles is that the size of discontinuity they are able to traverse is significantly greater than for a wheeled or tracked vehicle of the same size. By continuously changing shape and centre of gravity, legged vehicles would be far more manoeuvreable than tracked vehicles. Certainly, biped robots would be more adapted to the human environment (labelled the anthroposphere by some researchers). In particular, steps would be more easily traversed by legged vehicles than wheeled or tracked vehicles. In the case of domestic service robots, legged robots would require little or no modification to the existing structure of a house to be able to move freely within it.

A second argument for legged vehicles has been that the development of legged vehicles will assist our understanding of animal and human locomotion. Todd (1984), Raibert et al (1987), Hemani et al (1973), Yamashita and Yamada (1993) all suggest that the development of biped robots will assist with research into orthotic devices. Research by Yamaguchi and Zajac (1996) suggests that the possibility of using controlled functional stimulation of nerves and muscles is more likely to ultimately assist those who have lost the use of lower limbs. Interestingly, their research suggests that crutches or other walking aids would be more than acceptable to those who are wheelchair bound. Therefore, as balance could be achieved using muscle groups of the upper body, open loop control of lower limbs would be possible. Certainly, it seems likely that biped robot control systems could be adapted to control such stimulation.

A third justification for development of legged mobile robots has been their use as a proving ground for artificial intelligence research. As previously highlighted, those involved in robotic research, especially mobile research, have concentrated on the behavioural aspects of the control system. Cybernetic control strategies such as subsumption architecture, fuzzy logic, neural networks and other expert systems attempt to imitate the behaviour of biological control systems. It is natural then, that these systems are demonstrated on platforms which themselves imitate biological forms. Similarly, In a symbiotic relationship, the very complexity of legged locomotion systems has required new methods of control to drive leg actuators.

Figure 2-1. Japanese toy Android

Regardless of the reason or justification, considerable effort has gone into legged vehicle and legged robot research.

2.1.2 LEGGED ROBOTS

Clockwork tin-plate toys were the first examples of walking machines. Generally bipeds, these toys were spring powered and used cranks to actuate single or double link legs. Produced in Japan and Germany between the First and Second World Wars, the devices represent the initial attempt to replicate human motion. Japan continued to mass-produce battery powered toy “robots” after the Second World War (see Figure 2-1).

These toys were based on science fiction characters of the time and contained quite complex arrangements of cams and/or cranks. The relevance of these devices to walking robot research is the evidence they provide of Japan’s fascination with the android or anthropomorphic droid. As discussed in the introduction, this fascination currently drives the most advanced robotic research in Japan if not the world.

Like the mechanisms in these toy robots, early walking machines depended on complex linkages to move the legs. An example of such a machine was A. Rygg’s pedal-powered mechanical horse, patented in 1893 (see Figure 2-2).

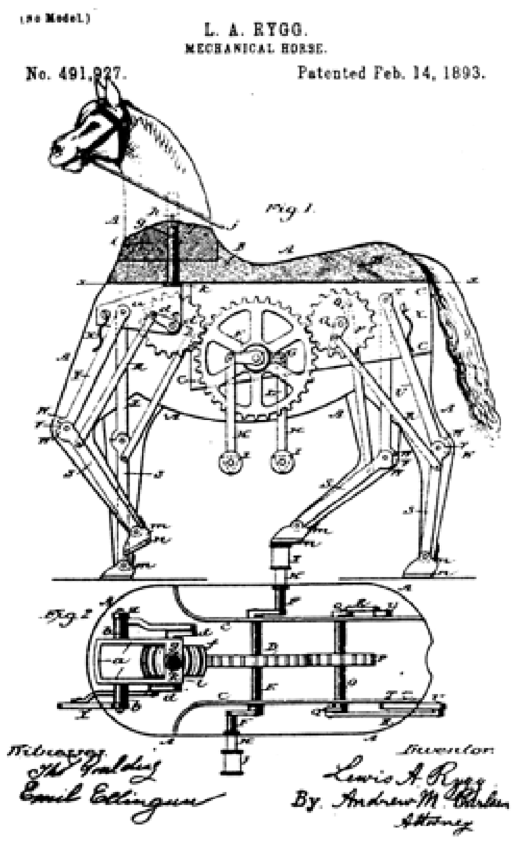


Figure 2-2. Rygg's Mechanical Horse

The further problem encountered by researchers was the method of providing propulsion to the legs. It was only after the advent of the internal combustion engine that legged vehicles became feasible. Like aircraft, they required a compact, relatively lightweight power source compared to steam engines. Without the availability of flexible hydraulic power transmission systems, the legs of early walking vehicles relied on a direct drive train from the power source. The inability to continuously modify the gait of the device left these vehicles with an inability to adapt to varying terrains. As Raibert (1986) highlights, it became apparent that for a walking vehicle to be feasible, adaptable control over individual legs would be required.

The most promising initial research into walking machines was overwhelmingly driven by the requirements of transport and materials handling. Unlike other areas of mobile robotic research, the development of legged vehicles has seen the involvement of large government and private organisations. The first serious attempts at legged vehicle design were initiated by the military, both in England and the USA.

Todd (1984) attributes the first walking machine with independent leg control to A. C. Hutchinson and F. S. Smith in 1940. Hutchinson and Smith built a model of a proposed four-legged 1000-ton armoured walking vehicle with individual hydraulic control of the legs. The model was driven by an operator whose hand and foot movements were transferred by cable to the model. While the model was able to climb over a pile of books, the army was not persuaded to fund further development.

The early 1960's was a volatile time for robotics as teams working in many parts of the world developed new ideas and prototypes. During this period, the USA's Defence Advanced Research Projects Agency (DARPA), through the US Army Tank-Automotive Centres, funded the "Land Locomotion Laboratory", a cooperative venture with the University of Michigan.

As recounted by Todd (1984), in 1962, the laboratory was approached by H. Aurand of General Electric who proposed a bipedal walking machine using force feedback control by a human operator. While models and designs were built and refined, as is often the case with engineering companies, the marketing department, ignoring technical requirements, decided that customer appeal would be better satisfied with a quadruped device.

Raibert (1986) suggests the resulting quadruped walking truck, designed by Ralph Mosher was the first successful walking vehicle. Using human control, in a similar approach to Smith and Hutchinson, the vehicle was developed by General Electric in 1965. Hydraulically driven and weighing 1400 kg, the truck had legs which were controlled by pedals which, in turn, were operated by the driver's hands and feet. This was part of an ongoing experiment in force feedback, and the driver was able to "feel" the vehicle's legs touch the ground. With considerable practice, ultimately the driver was able to manoeuvre the vehicle easily over and around obstacles. This walking truck was, effectively, a mobile robot with a human control system. Although this vehicle successfully demonstrated the principle of independent leg movement, operating it was exceedingly demanding on the operator. Had the laboratory proceeded with a biped, its control movements would obviously have to have been more natural for the operator. Legged robotics was put back many years by the decision to develop a quadruped vehicle.

While various researchers such as Shigley (1957), Liston (1964), Morrison (1968) and Vukobratovik (1973) continued with walking vehicle designs, the problem of controlling the movement of legs prevented further success. As was the case for industrial automation, it was necessary for the human to be replaced with a device that was more reliable and precise. This became possible with the advent of the mini computer. While not as portable or powerful as today's desk-top personal computers, units such as Digital Electronic Corporation's PDP1170 became common objects in mechanical engineering and computer science schools around the world. Access to this equipment provided researchers with the processing power required to solve inverse kinematic equations in real-time.

Robert McGhee (1977), also at the Land Locomotion Laboratory, saw the potential for electronic control of the limbs of walking machines. In 1966 he built a quadruped device based on simple digital control of the legs. Labelled the "Phony Pony" , the quadruped weighed 50kg, used electric motors to drive two degrees of freedom per leg, and used very wide feet for lateral stability.

Encouraged by his experiment with simple digital control, McGhee built a hexapod vehicle in 1977. Each leg possessed three degrees of freedom, each degree of which was operated by an electric motor and reduction gear set. The vehicle was connected to a digital PDP11 computer via an umbilical cord carrying sensory information and control signals. The computer was used to solve the inverse kinematic equations and generate outputs to triac controllers that powered the motors. Without doubt, this was the first successful walking robot.

DARPA continued its development of legged vehicles, funding the development of the Adaptive Suspension Vehicle (ASV) (Johnston, 1985). Another hexapod, this vehicle was built by Kenneth Waldron in 1985 and represents the most realistic attempt at development of a commercial all-terrain walking vehicle to date (see Figure 2-3). This vehicle weighed 2.7 tonnes and was capable of climbing over a two-metre high object. It was originally manoeuvred by an on-board operator who was able to place the vehicle's feet individually, or in an automated mode that cycled legs as groups. Later, the vehicle was operated autonomously, demonstrating a variety of gaits that had been developed for particular terrains. At all times, the control system kept the centre of gravity of the vehicle inside the instantaneous polygon of feet in contact with the ground. Essentially the vehicle was in a stable, supportive mode at all times.

Although it was promising as a transport vehicle for the field, the length and size of the

Figure 2-3. The Adaptive Suspension Vehicle.

ASV excluded it from working in confined spaces. Other hexapods and quadrupeds have been developed on a much smaller scale, however the ASV appears to have eclipsed research into truck-scale walking vehicles. Despite the promise shown by the ASV, it would appear that institutions capable of funding such research are also those that are most resistant to change. It would take a brave general, indeed, to stand before his peers, commanding a battalion of infantry supported by walking vehicles.

One other group of non-biped legged robots, while not practical as transport vehicles, is worthy of mention. These are the insect-like creatures developed by Brooks at MIT, who introduced the concept of layered control systems for mobile robots (Brooks 1986). He showed that by breaking down the tasks of a robot into multiple goals of layered priority, complex control systems could be decomposed into low level and high-level behaviour. He demonstrated, using small multi-legged mobile robots, that a simple low-level algorithm could control individual joint movement, while navigation could be performed at higher levels of control. Further, by rewarding those joint movements (behaviours) that resulted in moving the robot forward, the robot was able to establish a learned gait.

2.2 BIPED ROBOTS

Justification for biped walking machines and biped robotic research has been argued in a similar approach to that for machines with more than two legs. In the case of bipeds, the contention that research will assist with the understanding of human locomotion is more persuasive.

Early biped devices can be separated into two main groups. The first includes walking aids or prostheses designed to assist humans with mobility, while the second group consists of stand-alone walking machines designed to walk independently of humans. As highlighted by the problem definition outlined in earlier sections, it is the second group that is applicable to this project. Prosthesis-type devices will not form a major part of this thesis unless aspects of individual devices are specifically relevant.

As described in the introduction to this text, biped robotic research has flourished since the early 1980s. Almost all of this work has been conducted in institutions attached to or affiliated with universities. In rare cases, large automotive or electronically based institutions such as Honda and General Electric have undertaken biped research. A list of biped robotic vehicles is shown in Table 2-1. Figure 2.4 shows biped robots by mass.

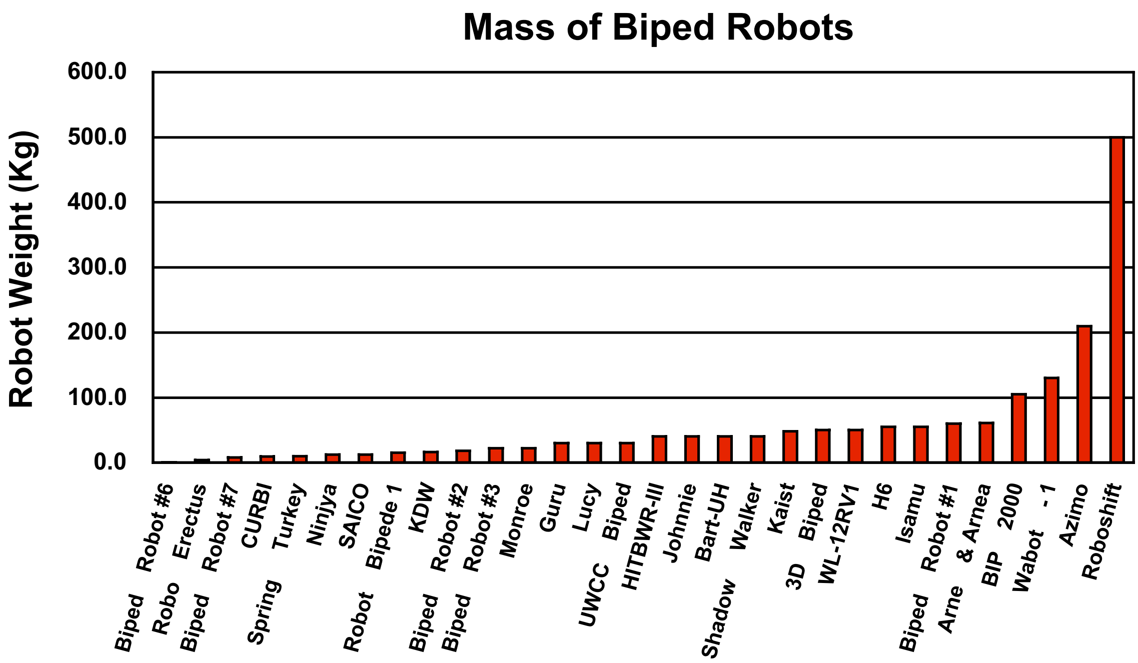


Figure 2.4 Range of biped robot weights

In general,these bipeds can be divided into three main areas of research;

Laboratory biped Robots

Often characterized by proportionally large feet to provide an extended support polygon (similar to that of the Japanese toy bipeds previously discussed), laboratory bipeds provide an apparatus for gait analysis and experimentation. Due to their small size and mass and associated reduction in inertial and dynamic forces, these bipeds are unlikely to be damaged in the event of a fall. As well, the availability of low cost, high power to weight ratio actuators (developed for use in the remote control model market) allow for the rapid prototyping of structures.

While the majority of these structures have been anthropomorphic, several have been based on the avian model. It has been argued by some researchers [(Hugel et al., 2003), MIT, 2005) that the legged system of the bird (the only other bipedal animal) is more stable than that of humans. Unlike the human hind leg, the wide elongated four fingered foot of the bird results in a well supported, redundantly jointed leg comprised of three segments. While the possibility of an avian leg system was considered for this project, human one was chosen. Accordingly, the literature search focuses on anthropomorphic bipeds.

Androids

Androids are immediately identified by their totally anthropomorphic form. These robots are often referred to as “Humanoids” by their constructors, a title which not only describes their appearance but which is used to suggest a measure of human like intelligence. Humanoids can also be easily identified by their characteristic, highly polished plastic, carbon fibre or fiberglass shrouding. This is also an indication of the focus of the projects; these robots are meant to look good. They are predominantly used to display the level of technical competence of the companies that own them. As well the finish of these robots demonstrates the resources available to develop them.

In the case of Honda and Toyota, many years of experience in the design, manufacture and finishing of electromechanical machinery have gone into the design of these robots. Kawada industries not only developed HR2, but developed the servo systems that actuate the robot based on their experience of developing similar systems to control their large scale unmanned helicopters.

While examiners may yearn for a plethora of peer reviewed citations from respectable journals, the state of the art in biped robots is being advanced by large organisations at huge cost. These companies that continually out perform their competitors are unlikely to spill their intellectual property portfolios via conference papers.

Industrial Bipeds.

Currently, there are no industrial bipeds in existence with this project being the first to attempt to develop an industrial scale autonomous biped robot. Therefore it is difficult to determine the characteristics of this class of biped robot. Previous work on manually operated industrial scale exoskeletons and the work completed in this project would suggest that the devices will be predominantly manufactured from steel, will be powered by internal combustion engines and will be hydraulically actuated.

The requirement for safety and reliability and the complexity of the control task will result in the characteristics of the control systems being similar to those found in small commercial airliners.

Figure 2.5 shows the relationship between these families of bipeds robots, and indictates the emphasis of this project which is an industrial biped.

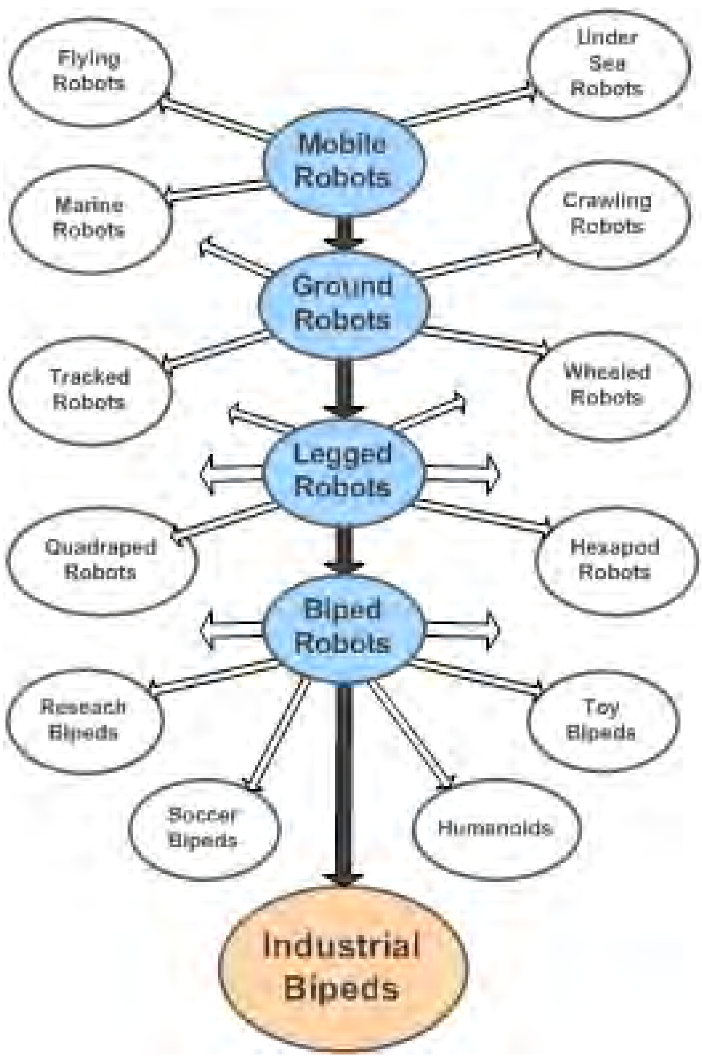


Figure 2.5 Classes of legged robots

Machine Name	Institution	Height	Mass (kg)	DOF	Control Structure	Year	Site
Biped robot #3	UCLA Commotion lab	0.6	*	7	*	1995	www.muster.cs.ucla.edu
Biped Robot #5	Nagoya University	*	*	13	GA & Recurrent Neural Networks	1997	www.hp73.nagaokaut.ac.jp
Biped-Bike	Hori Laboratories	0.8#	*	6	Virtual Inverted Pendulum	1997	
Geekbot	MIT Leg Lab	*	*	6	Hierarchial - state control	1994-1995	www.ai.mit.edu/ projects/leglab/
M2	MIT Leg Lab	*	*	12	*		www.ai.mit.edu/ projects/leglab/
Passive Walker	Uni of Michigan	*	*	*	Dynamic - non powered	1996	
Piernuda	Robtica, Mexico	0.9#	*		*	1996-2000	www.132.248.59.55/ piernuda/piernuda.html
Planar Biped	MIT Leg Lab	*	*	6	Constrained motion planar	1985-1990	www.ai.mit.edu/ projects/leglab/
Smooth Walker	Harvard Robotics Lab	*	*	*	Smooth Walking - Constrained	1996	hrl.harvard.edu
Idaten-II	Osaka University	0.8	*	7	Hierarchial -reactive	1981	www.dyna.ccm.eng. osaka-u.ac.jp
Biped Robot #6	Koube University	0.02	0.67	6	Neuro Oscillator	1994	ziong.cs.kobe-u.ac.jp
Robo Erectus	Singapore Polytechnic	0.5	4	22	central	*	www.robo-erectus.org
Biped Robot #7	Keio University	0.6#	8	6	Impedence Control	1997	www.yamazaki. mech.keio.ac.jp

Estimated from photograph. * No data available

Table 2.1 Survey of biped robot research

Machine Name	Institution	Height	Mass (kg)	DOF	Control Structure	Year	Site
CURBI	Ohio State	0.89	9.16	8	Jacobian Motion control	1995	www.ee.eng.ohio-state.edu
Spring Turkey	MIT Leg Lab	*	10	4	Constrained planar biped	1994-1996	www.ai.mit.edu/ projects/leglab/
Ninjya	Miyazaki University	0.7	12	5	*	1980-1996	*
SAICO	Mexico DF	1.1	12	12	*	1997	*
Robot Bipede 1	LSHT GRAVIR	0.8	15	5	*	1991-1994	*
KDW	Changsha Institute	0.8	16.3	12	Sequential control	1987-1995	*
Biped Robot #2	Kobe University	0.85	18	7	Inverted Pendulum Neural Network	1989	www.ziong.cs.kobe-u.ac.jp
Biped Robot #3	Osaka University	1.1	22	5	Hierarchial - Low order	1986	www.dyna.ccm. eng.osaka-u.ac.jp
Monroe	Tohoku University	1.2	22	6	Hierarchical	2003	www.mechatronics.mech. tohoku.ac.jp/research/biped/
Guroo	Uni of Queensland	1.2	30	23	Neural / Heirarchical	2003	www.csee.uq.edu.au
Lucy	VUB Uni Brussells	1.5	30	8	Hierarchical	1990	www.lucy.vub.ac.be
UWCC Biped	Uni of Wales, Cardiff	1.0	30	6	*	1995	*
HITBWR-III	Harbin Institute of Tech.	1.0	40	12	Gait Control	1988-1995	*
Johnnie	Munich Technical Uni	1.8	40	17	Central	*	www.amm.mw.tumuenchen. de/forschung/zweibeiner/ johnnie_e.html

Estimated from photograph. * No data available

Table 2.1 Survey of biped robot research

Machine Name	Institution	Height	Mass (kg)	DOF	Control Structure	Year	Site
Bart-UH	Hannover University	1.2#	40	6	Central	2000	*
Shadow Walker	Shadow Robot Company	1.4	40	12	Central	1987	www.shadow.org.uk/projects/biped.shtml
Kaist	Korea Advanced Institute	1.2	48	21	Hierarchical	2003	www.Ohzlab.kaist.ac.kr/khr_robot/khr_humanoid.html
3D Biped	MIT Leg Lab	1.4#	50	6#		1989-1995	www.ai.mit.edu/projects/leglab/
WL-12RV1	Waseda University	1.4#	50	8#	*	1996	www.humanoid.waseda.ac.jp
H6	Tokyo University	1.37	55	24	*	2003	www.jsk.t.u-tokyo.ac.jp/research/h6/h6.html
Isamu	Kawada Industries	1.5	55	32	Heirarchical	2003	www.kawada.co.jp/ams/isamu/
Biped Robot #1	University of Kentucky	0.7	60	12	Reduced order dynamic Jacobian	1987	www.crms.engr.uky.edu
Arne & Arnea	New Era, Russia	1.23	61	*	*	1996	www.robotarena.com
BIP 2000	BIP team	1.8	105	15	*	1999	www.inria.fr/rrrt/rt-0243.html
Wabot - 1	Waseda University	1.5#	130	9	Kinematic - Static	1988	www.humanoid.waseda.ac.jp
Asimo	Honda	1.2	210	*	*	1997	www.honda.com.jp
Roboshift	UNSW	2.4	500	14	Hybrid Classic/Hormonal	1994-2004	www.mech.unsw.edu.au/mech/Mechlab/mechatronics.htm

Estimated from photograph. * No data available

Table 2.1 Survey of biped robot research

The concept of a powered exoskeleton, to either assist a human to walk, or increase the materials handling abilities of a worker, was first investigated by Cornell Aeronautical Laboratories (CAL) in the mid 1950s. Using the natural movements of the human to activate and control actuators, the device was essentially to be a motion and force amplifier. CAL built an unpowered prototype, but shelved the project and concentrated on medical robotics.

During the early 1960s, General Electric was developing remotely controlled manipulators or “Telechirs”, the research was driven by the requirement to handle hazardous materials such as radioactive elements required for the growing nuclear power industry. Using force feedback to “feel” the force on the work-piece, an operator used his arms to control the movement of the manipulator.

Employing experience gained in this research, the corporation also began to investigate powered exoskeletons. A similar device to CAL’s man amplifier was designed which used the natural movements of the operator to actuate servo-drives powering the exoskeleton’s joints. This device, the GEC “Hardiman” (see Figure 2-6) was also shelved after the prototype phase (Wiess, 2001).

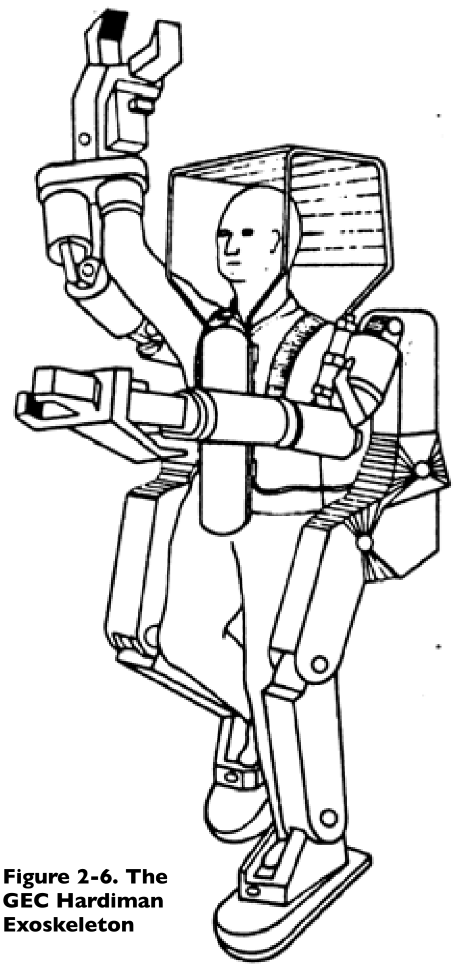


Figure 2-6. The GEC Hardiman Exoskeleton

While neither of these biped exoskeletal devices were successfully built or tested, they highlight two points that are most relevant to this project. The first is that two large corporations, both involved in materials handling and robotics perceived a requirement for an operated bipedal materials handling platform. This suggests that while a market for such a device existed, the technology was not available at the time to realise a working prototype. The defence industry focus of both of these companies suggests that the market for a materials handling biped robot would be military organisations.

The second point highlighted by the exoskeleton research, is that it was the control of the exoskeletons that proved to be the hurdle for development of a fully functional prototype. Todd (1984) discounts the relevance of exoskeletons to biped robotics, as they were not autonomously controlled robots. This seems specious however, as a successful exoskeleton would not be able to rely purely on the human operator for safe operation. The control system of such a device would use human input only as movement commands. It would interpret the commands and control the actuators in such a manner that balance was maintained. Essentially, where a conflict existed between what the operator's movements requested and what could be safely actuated, the control system would have to override the human input. The device would function as an autonomous robot, taking only high-level movement or task commands from the operator. In reality, the controls for a biped materials handling platform would be quite similar to those of a standard forklift truck. One joystick could control the direction and heading of the device, and a second could control the material handling equipment. All functions of gait, balance and joint movement would be autonomously controlled by the supervisory system.

The early 1970's saw the leading edge of biped robotics development shift from America to Japan. In particular, a group at the Waseda University, led by Ichiro Kato (1987), focused heavily on biped robots from the early 1970s. Kato built a number of bipeds including WAP-1, WAP-2 and WAP-3 which were able to walk on uneven surfaces and to turn. In joint research with Hitachi, Kato and Waseda University developed the first full-scale android-like biped in 1973. The device named Wabot-1, not only exhibited anthropomorphic legs but also upper limbs and hands. In addition, the robot was fitted with visual sensors and voice-synthesised communications. The robot remained statically stable by keeping its centre of gravity over one of its large feet at all times. Wabot-1 was hydraulically driven; but the power source was not carried on board.

Later bipeds built by Kato concentrated on simulation of the biped gait without the distraction of other anthropomorphic features such as arms and hands. Kato and Hitachi constructed "Waseda Hitachi Leg-11" (WHL-11) in 1985 (Kato et al 1987). This biped robot, again hydraulically actuated, walked for 40km at The International Science and Technology Exhibition Tsukaba EXPO '85, where it was demonstrated at the Japanese Government Pavilion.

WHL-11 (see Figure 2-7) displayed a quasi-dynamic gait which Kato describes as a gait where “dynamic walking only takes place in the leg changeover period (Kato 1987). The robot was statically stable during the gait cycle except for the stage in the cycle when it transferred weight from one foot to the other. The gait cycle was originally generated by simulation in two parts; the static, single support phase and the dynamic leg changeover phase. This simulation was then used to control the robot in walking trials where the model was modified using the results of repeated tests. Finally, the modified joint trajectory data was loaded into ROM on board the robot. Because the robot did not possess enough memory to load all of the joint data, it was only loaded in point form. During the gait cycle, the control system interpolated between these points to calculate the required joint positions. WHL-11 was the result of twenty years of research at Waseda that is evidence not only of the investment into biped robotics, but also of the complexity of the task.

In 1986, the Japan based Honda Motor Company entered the race to manufacture androids and built eleven biped robots over the next two decades. In similar fashion to the Waseda bipeds, Honda concentrated its early research on the problem of bipedal stability. The first seven prototypes between 1986 and 1993 consisted of a mass supported

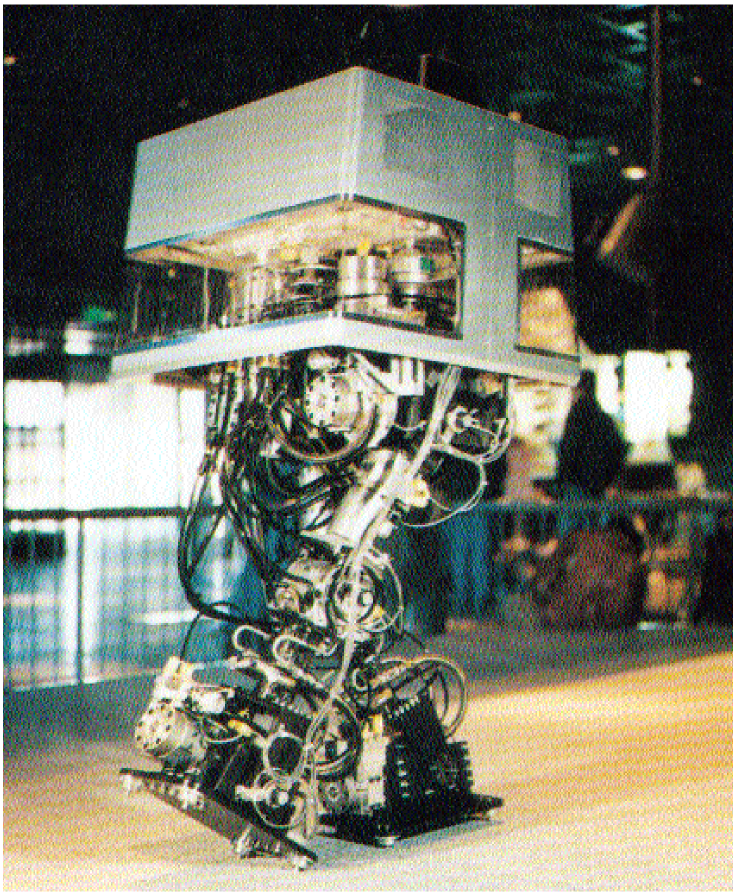


Figure 2.7 Waseda University’s WH 11

by two legs. The fact that a large institution that was the size of Honda took thirteen years to develop a stable biped platform is a further indication of the complexity of the task.

In 1993, Honda released a humanoid robot named P1 (Honda, 2003b) which was the next iteration of their android. The biped included upper arms, hands and a large box which may be taken for a head. P2 (Honda, 2003b) followed in 1996, P3 (Honda, 2003b) in 1997 and the culmination of their endeavours, Asimo (see Figure 2.8) was released in 2000. Asimo is a remarkable technological achievement. The robot is able to walk dynamically at 1.6 km/h, is able to recognise faces and to communicate with people. Honda market the android as a service robot which one day will be able to act as a carer for invalids in the home. Asimo stands approximately 1.4 metres tall which Honda says is the perfect height for helping a person who is bed ridden or is confined to a wheelchair.

It is interesting to note that Honda has decreased the size and mass of its latest androids from P1 (1.92m & 175kg) to Asimo (1.2m & 130kg). The author, based on the research conducted during this project suspects that the effect of internal forces and associated compliance produced by the larger bipeds presented problems for the development of the robot's control system. Accordingly, more rapid and spectacular progress would have been available with the development of a smaller robot. It is speculated by the author

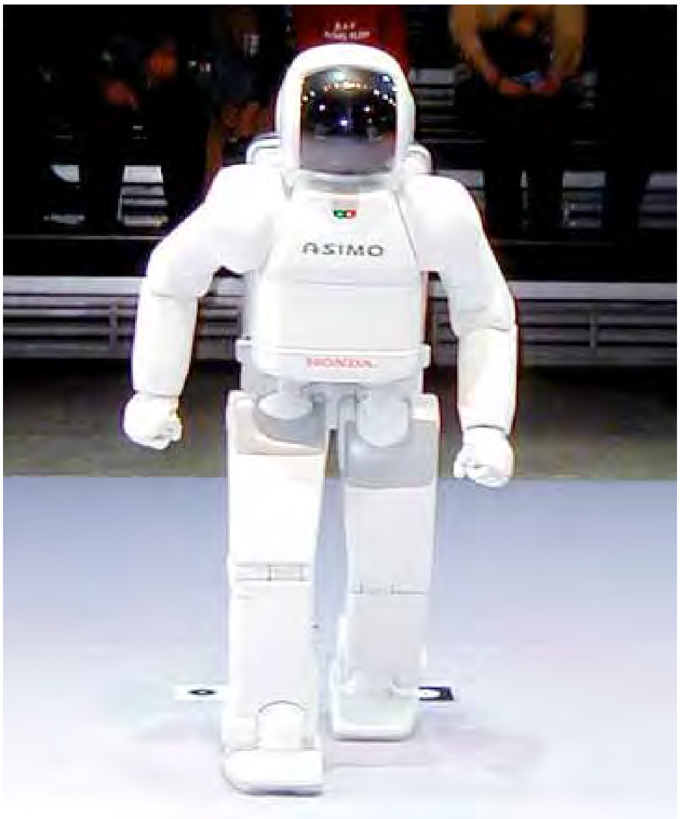


Figure 2.8 Honda's humanoid robot Asimo

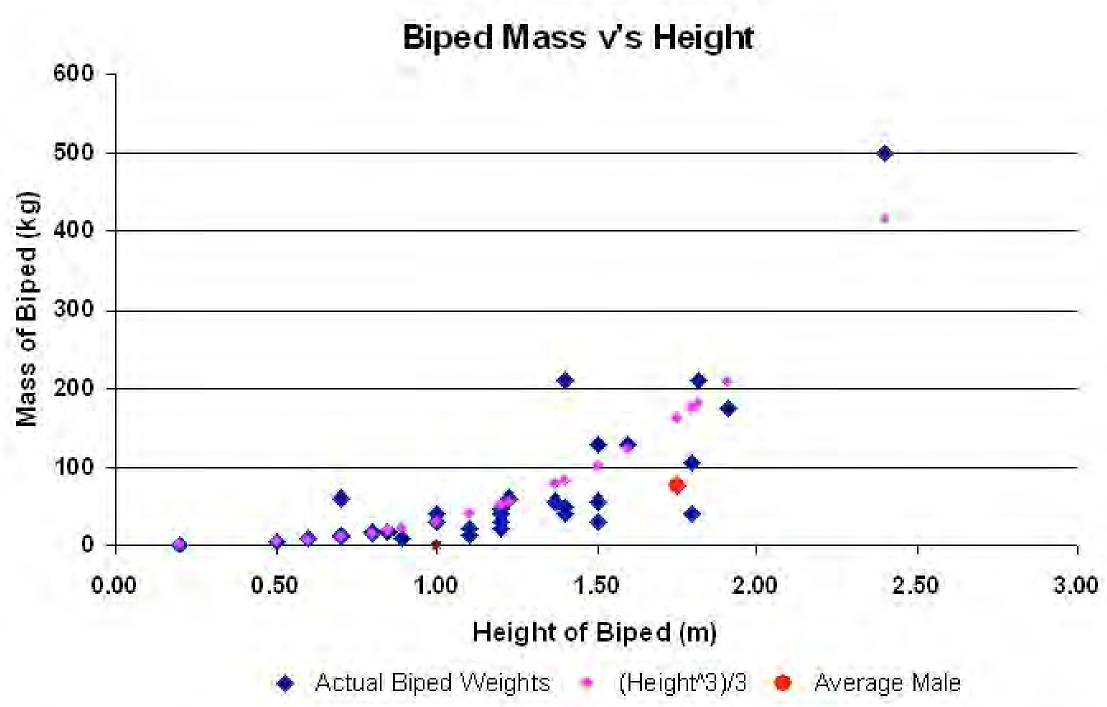


Figure 2.9 Scatter plot of mass v's height of documented biped robots

(technical data is unavailable from Honda), that Honda is currently developing a much larger biped of industrial scale. However, as no other industrial scale devices exist, it would be difficult to predict the size of such a device. Figure 2.9 shows a scatter plot of the mass of reported biped robots versus their height. It can be seen that the data loosely fits a curve which is the cube of the robot's height divided by 3. The significance of this equation is not fully understood. However, it would predict that an industrial biped of the scale exhibited in this project might weigh between 450 and 550 kilograms. It is interesting to note that when the average height and weight of an adult male human are plotted on the same graph, it lies well away from the equation described above, i.e. capability versus weight is better in humans.

As discussed in the introduction, while a service robot would be of use to invalid patients, the cost of the device, and the wide availability of un-skilled labour, excludes the commercial viability of Asimo for such roles. Only an android with greater capability and dexterity than that of a human will be accepted by the market place. For example, in a typical display of the cooperation between large Japanese corporations, Kawasaki has developed a commercial application for the Honda Asimo android. In 2002, Kawasaki fitted an Asimo with protective clothing and then developed teleoperation software so that the android could be used to remotely operate construction equipment (AIST, 2002). The research allowed the robot to mimic the movements of a human operator effectively turning the robot into a “telechir”. In situations such as earthquakes or industrial disasters, there is a requirement for heavy equipment to be used in areas hazardous to humans. For the last decade, with the development of spread spectrum wireless data communications, some construction equipment has been operated remotely via the uses of wireless remote control systems. However, the availability of such equipment at the site of a disaster is unlikely. Kawasaki’s research would enable the Asimo variant named the HRP-1S to be deployed to the disaster area where it would operate standard construction equipment. Therefore, the development of the Asimo variant has added value to construction equipment around the world. By investing in the Kawasaki and Honda technology, once it is available commercially, the operators and owners of these assets would increase the capability and potential market for their equipment. This would constitute the first commercial application of an android, and the state of the art in android development[2].

The basic physical form of the android has been achieved by Honda. In terms of mechanical design, new technologies such as artificial muscles and electroactive polymers (NDEAA, 2003) will be introduced to android structures as they become available. However, it is in the area of control and processing systems where the major advances will continue in this decade.

2.3 CONTROL OF BIPED ROBOTS

A person can walk with a ninety-pound pack on their back, their gait instantly adjusting to the sudden change in balance. People regularly amble along at a decent pace with a stiff knee, or maybe an ankle brace, or perhaps a child hanging onto each leg. Women, regularly walk with dangerously high heels and appear to have no problem adjusting their gait to accommodate the reduction of ankle flexion. Any circus will exhibit the skill of a stilt walker whose shank is extended by several hundred percent, but still manages to walk and to juggle as well. The key to locomotion is control. Try walking after you have been sitting on your legs for half an hour. The lack of blood flow decreases proprioception, limiting feedback to the local control system. Alcohol, drugs, head injuries and strokes all affect the ability of the brain to process information. The

[2] Honda has used Asimo extensively for publicity purposes. Pictures of the Android shaking hands with world leaders has promoted the Honda brand in the same way that the development of Formula 1 racing cars has done so in recent years. Therefore, advertising may have been the first commercial use of an android.

geometry of the biped is far less critical than the control system that coordinates its movement.

The diversity found in the mechanical configuration of biped robots is not reflected in the structure of control systems that have been designed to automate their movement. A range of methodologies has been used for global control. However, the most popular model has been to generate a feed forward trajectory and then to sense deviation from the trajectory as the global control input. The advantage of this method is that the complex dynamic equations governing bipedal motion do not have to be solved in real time. In fact, this research has indicated that the more complex the robot is, the more unlikely it is that the control system will attempt to incorporate and solve the gait dynamics. Almost universally, hierarchical control systems have been used to manage the range of control tasks required to generate biped locomotion. In general, at the highest layer, a main control processor monitors the global status of the robot and generates joint trajectories. At the lowest layer, joint position sensors provide feedback to local processors that control the angle of the joint. Between layers, some form of communication is enabled to pass data from the high-level global control system to the local joint control. While each control system may deviate in some way from the basic structure, the attempt to separate the control tasks is similar.

The technology to build a biped has been available for decades. Hydraulics, Servo motors, sensors and transducers have been readily available since the beginning of the Second World War. Early attempts to build walking robots relied on the human to coordinate the motion of the joints. It is interesting that while the human can readily adapt to changes in geometry, these attempts were unsuccessful, as the brain appeared to be unable to adapt to controlling teleoperated exoskeletons. Development of full size walking machines constitutes a systems integration process. It is the role of the walking robot engineer to bring together all of the available technology required to design, build and control the device. Given that a wide range of motion control hardware is available off the shelf, typically it is the structure and the software development that represent the majority of engineering time consumed during the project. The definitive task of a biped robot control system is to maintain balance while standing and while in locomotion. Dynamic locomotion involves acceleration of the centre of gravity of the robot by manipulation of the resultant reaction vector at the foot/feet in contact with the ground. For this reason the tasks of balance and movement cannot be separated. Walking robot control requires the solution of complex differential and inverse kinematic equations involved with the control of joint motion. Invariably, these equations become non linear and cannot be solved in real time. The almost universal approach of the engineer has been to reduce the amount of data to be processed and to process that data as quickly as possible.

Generally, tasks are dealt with at several levels, to reduce the processing load by distributing the control functions. One would speculate that this was particularly the case with early walking machine development, where processing power was limited. However, the first robotic[1] walking machines used a single "mainframe" computer to control all aspects of locomotion. GE's walking quadruped truck was controlled by a human operator tele-operating the vehicle's legs by manipulating levers and pedals. While not a mainframe as such, the operator acted as total control system, taking visual and sensory data, then controlling the hydraulic valves to coordinate the machine's motion. Ideally, if GE had been able to replace the human operator with a digital control system capable of comparable levels of control, the vehicle may have been a great success. Perhaps, today, digital control is achieving similar levels of control to that which can be offered by a human operator.

Waldron's Adaptive suspension vehicle, a hexapod with multiple statically balanced gaits (Johnston, 1985) used a single mainframe computer to replace the human operator, becoming the first successful digitally controlled walking vehicle. Kato et al (1974) developed a hydraulically controlled biped in 1980. The Wabot-1 is universally accepted as the first biped to walk with a quasi-dynamic gait. During the gait cycle of the robot, there were periods between stance phases where the robot effectively "fell" dynamically from one leg to the next. While Wabot-1 used a single computer to control the motion of the robot, a software scheduler was used to switch processes within the control system. Effectively, the control software was multi-tasked, breaking elements of control into discrete programs that were processed in a sequential manner. Though the processing of data was not distributed, the strategy was certainly an attempt at a segmented control system. The "software scheduler" recorded requests from input/output devices, referring

[1] The definition of a robot is source for continual argument. It is outside the scope of this project to fundamentally define it. Some would argue that a numerically controlled machine, running punched tape or operating from cams would constitute a robot. Others would suggest that an industrial robot is nothing more than a numerically controlled machine. Karl Kopec who first used the term would suggest that it represents zombie like, repetitive behaviour, certainly not an intelligently controlled machine. For the purposes of this project, the word robot will be taken to mean a microprocessor-controlled machine.

to a lookup table to determine in what preference the requests were processed. Given that WABOT1 was fitted with optical sensors as well as voice recognition and speech synthesis systems, the amount of data to be processed was considerable for the processing power available. The use of the scheduler constituted a hierarchical level of control where the scheduler became the supervisory processor, determining the priority of data to be processed. During the early 1980s smaller and more powerful microprocessor became more widely available. At the same time an explosion of computer science research led to the development and widespread industrial use of layered control systems. The developers of biped robots, essentially systems integrators, incorporated these technologies in their research.

Wagner et al (1988) used transputers and the OCCAM parallel processing language to distribute the control tasks to separate processors that shared memory via a data bus. At the joint level, foot sensors and shaft encoders provided feedback to those transputers dedicated to local control.

Monroe (Kumagai, 2000), a 1.2m, 22kg biped built by the Mechatronics Department of the Tohoku University also uses a hierarchical control system consisting of two 486 and one 386 computers. Global feed forward trajectories based on empirical human data, and orientation data are processed by one 486 processor, while local feedback joint control is processed by the other 486 and 386 processors. Communication is via shared memory. What makes this hierarchical control system unique is that the same family of processor has been used for all levels of the hierarchy. Most commonly, hierarchical systems use processors capable of being programmed in a high level language for global control where more complex mathematical and data processing functions are required in the programming language. At a lower level, simpler processors only call for basic mathematical functions to perform PID type control.

In 1986, Zheng et al (1986) developed a hierarchical control system to automate the motion of a biped robot. By using four joint processors to facilitate local feedback control of joints, a central computer was released to coordinate global control. Of interest was the project’s strategy to use digital I/O to communicate across layers of the control system, rather than serial communications or shared memory. Zheng used eight channels of bi-directional eight bit parallel I/O to transfer position commands between the central computer and the joint processors. A further four bit channel was used to control the data transfer. A similar system was investigated for the transfer of data in this project, however, once constructed, the system can not be expanded without the addition of further I/O ports. In the case of the F1 controller boards which were selected for local joint control, no further I/O ports could be fitted.

Zheng suggests that if the period taken to complete a single iteration of the main control system loop is denoted as T, then 1/T gives the frequency or resolved motion rate (RMR) for the control system. He further suggests that the RMR for the control system of a biped should be ten times the natural frequency of the robot. Biped robots are frequently modelled as inverted pendulums [(Kitamura et al 1990), Hemami (1977) Hemami et al (1973)] which require restoring torque to remain stable. However, as will be discussed in Chapter 9 of this document, the natural frequency of the inverted pendulum system will then be a function of the gain of the control system controlling the restoring torque.

Research that involves simulation of biped robot dynamics often leads to graphical output of joint torques during the gait cycle. It is interesting to note that all previous biped robots have used shaft encoders to provide feedback from the joints. It is suggested that if torque control as opposed to position or velocity control had been used in biped robotics, the control would either have been open loop, or via the use of servo amplifiers. Such amplifiers would not only sense the current in the motor, but must also have been able to sense the change in friction characteristics as the load on the joint varied during the gait cycle.

An exception to the above is the BIP 2000 biped robot developed by INRIA (Azevedo 2000). The fifteen degree of freedom robot stands 1.8 metres tall and weighs 105kg. Brushless DC motors are used to move the biped’s joints via reduction drives or screw–crank systems. The BIP team use an external Unix workstation running a generic robot control system to dynamically model the robot’s motion before downloading joint trajectories or “robot tasks” to an on board VME processor. During motion, the robot senses which foot is in contact with the ground and then controls the torque of the joint actuators based on the error from the predetermined trajectory, the position of the gravitational vector (sensed from foot force sensors) and predetermined friction coefficients based on previous data. The group have achieved a high level of success, with the robot able to balance and to walk while constrained in the frontal plane. The use of dynamically accurate joint trajectories represents a major factor in the efficiency of biped control systems.

The majority of biped robot control systems attempt to reduce control processing by the use of pre-generated joint trajectories. Often, as would be expected, these are modifications of the trajectories of the human leg joints during normal gait. The control system then monitors the performance of the robot against these trajectories, applying restoring forces when actual values depart from the bounds of expected values. In the case of Baltes, the only feedback to the control system is the angular velocity of the torso in the frontal and sagittal plane. These values are monitored to ensure they are within predetermined limits. Additional extension or flexion (over pre-generated trajectory values) of joints is then used to stablise the gait.

A number of methods have been used to generate joint trajectories. Shimoyama et al (1985) used simulated trajectories that were stored in the main control processor. These were based on human locomotion data and then sent to the local joint processors sequentially. Using dynamic models, the control system calculated modifications to the feed forward actuator torques to maintain balance and to force the actual trajectories to converge with simulated data. In the case of the biped robot BIPER-4 the error was allowed to accumulate during the initial swing phase, but was corrected by the positioning of the swing foot as it landed. Wagner et al (1988) also used a stored set of joint trajectories that had been generated through the use of optimised (reduced order) dynamic motion equations. Rather than use separate processors to achieve hierarchical control, Wagner incorporated a multitasking operating system to parallel process the global and local motion control tasks. To minimise error from the predetermined trajectory, a knowledge-based system adapted control parameters based on historical values. Of course, the control system relied on a sufficiently accurate simulation to ensure that the biped stayed upright for long enough to generate valid historical data.

Several researchers [(Batlle et al., 1999), (Baltes et al., 2004)] have attempted to reduce the complexity of the control task by reducing not only the number of inputs and outputs in the system (by reducing the number of degrees of freedom) but by reducing the number of feedback variables. As highlighted by One novel approach to the complexities of the multiple degrees of freedom of the biped leg system was to articulate the foot with passive compliant actuators. Batlle also eliminated the requirement for hip abduction by providing the body with a counterweight that was able to be moved in the frontal plane in order to generate frontal sway for the swing phase. This configuration results in only two degrees of freedom for each leg; knee extension and hip extension. While unable to produce a dynamic gait, their robot was able to walk with a ten second period.

Wollherr et al. (2003) recognize that the constraints of a foot or feet in contact with the ground and controlled torso motion result in unique solutions to hip and knee kinematics. Recursive multi-body algorithms are then use to evaluate reduced body dynamics without actually extracting them. This reduced order processing can be conducted in real-time allowing the control to model pre-calculated trajectories in selected directions to reduce stability deviation.

In a similar method, Vanderborght et al. (2004) use pre-generated trajectories to stabilize the pneumatically actuated biped “Lucy”. Initially the natural motion of the torso is determined. Polynomial knee and hip trajectories are then generated kinematically from this motion. The control system then uses ankle actuators to superimpose restorative torque over the predetermined hip and knee torque to ensure the torso motion adheres to the pre-generated path. Vermeulen et al. (2204) explains that, as with other bipeds, the control systems, batteries and motive force are contained within the torso of the biped “Lucy”, making it the heaviest link of the robot. By allowing the torso to maintain a “natural” motion energy requirements are minimised. This highlights the strong link between the structure of the robot and the design of the control system. As highlighted by Vaughan et al. (2004), it is also desirable to reduce the moment of inertia of limbs by controlling the maximum weight of the links. In particular, they suggest, as in the case of the human, the foot should restricted to weigh less than the shank, the shank should weigh less than the thigh, etc. By reducing the inertia of the extended limb, power requirements to drive the limb are also minimised. Carl et al. (2005) suggest the most critical criteria in the design of a biped is to maintain the centre of mass of the robot at the pelvis. They argue that a lower COG would require larger oscillations of the trunk to maintain balance in the sagittal plane.

Isik and Meystel (1988) suggested that a hierarchical structure based on resolution relevance for a wheeled mobile robot would reduce reaction time by concentrating processing on areas most relevant to the navigation of the robot. General areas were scanned in low resolution and then subsections of interest were rescanned in a higher resolution. This strategy allowed image processing to be concentrated on those areas most relevant to the navigation of the robot. Given that the human lower limb system contains fourteen principle degrees of freedom (DOF), a similar strategy would concentrate processor time on the control of those degrees that are most directly linked to the control of the stability of the robot at any given time. For example, during single leg support, the motion of the joints in the support leg exert considerably more control over the centre of gravity of the robot than those of the swing leg. By using either a set trajectory for the joint positions of the swing leg, or a linear approximation as suggested by Lee and Mansour (1984), central processing would then be concentrated on the ankle knee and hip joints of the support leg. Effectively, this would reduce a 14 degree of freedom system to a six DOF system.

The team developing the Shadow Biped (Shadow 2003) have used some interesting strategies to control their robot. They use a series of "hand generated" rules to control the valves that inflate and deflate the pneumatic actuators of the robot. No trajectories or dynamic algorithms are used to control the positions of the joints. A series of fuzzy sets determines the outputs to the valves based on a series of inputs. The membership functions of the sets are then hand modified based on observation of the robot's reaction to external forces. The Shadow team have been able to balance the robot using this strategy. They have also been able to control the robot to take two steps prior to falling. The suggestion is that by continually modifying the fuzzy controller sets, the robot will achieve continuous biped locomotion.

The drawback of such a control strategy is the reliance of the control system on practical data as opposed to a dynamic model of the robot. While the hand generated reactions may provide finer control than a linearised dynamic model, the control envelope is confined to the range of inputs that have been experienced during trials. In the event that the robot is subjected to an external force larger than previously experienced, the reaction to the force may be unpredictable.

The Shadow Group acknowledge this drawback and suggest that the use of a neural network may be used to control the robot. A neural network offers the opportunity to expose the robot's control system to a greater range of inputs and to develop a much greater range of output behaviours than would be possible by hand. However, the disadvantage of neural networks is that the network must be given a series of inputs and outputs to learn to generate control behaviours. As highlighted by the Shadow Group, these relationships must either be derived from accurate dynamic models (in which case there is no requirement for non linear control), or developed from continuous experimentation. In the latter case, as a random element is required, and as initial trials would be with an uneducated network, the result would be continuous falling or unpredictable behaviour which would be guaranteed to destroy the robot, in the case of Roboshift. Those who have developed neural networks which control bipeds in a simulation do not realise that each unsuccessful trial that took two minutes on a computer screen, may have resulted in days of repairs in the laboratory.

An area of humanoid robotics where the technology has advanced in recent years is that of soccer playing robots participating in the Human Soccer Robot League. The small size of the robots enables the use of off the shelf technology such as servo drives from the remote control model market. The development is heavily focused toward the vision processing and decision making abilities of the robots as they attempt to kick small balls past each other. Again, the feet of these robots are disproportionally large providing an extremely stable base. Some robots such as "Clyon" (Senior & Tosunoglu, 2005), with no facility for hip abduction, are still able to statically shift the centre of gravity of the robot completely over one foot while it rotates around the ankle in swing phase. With the relative simplicity and low cost of the structure and actuators, the developers are able to concentrate on software development which has produced novel and efficient biped robot control strategies.

Zhou et al. (2003) reduces the demands of three dimensional dynamics by decoupling the frontal and sagittal planes. Using a neural fuzzy system two FRL agents search frontal and sagittal state spaces to speed up learning. The advantages of a fuzzy system lend themselves to the non-linear multi input and output control of a biped robot. The disadvantage of a fuzzy system lies in the unpredictability of the response to inputs not previously encountered. While not critical in a small robot, this may cause disastrous results in an industrial scale biped weighing several hundred kilograms.

The Institute of Applied Mechanics at the Munich Technical University (TUM) have developed a 16 degree of freedom biped named Johnnie (TUM, 2003). The humanoid robot is self contained except for power supply which is provided by an umbilical cable. The biped uses a hierarchical control system with three levels of control. The highest layer computes the joint trajectories which are based on an optimised gait pattern developed from dynamic modelling. The second layer monitors basic dynamic characteristics of the system superimposing dynamic adjustments to the feed forward joint trajectories. The lowest layer control the individual joint motors using PID control and a friction compensation algorithm. The robot has achieved dynamic locomotion while walking on a conveyor belt. The control system used in this project raises two interesting issues.

The first question that arises in the TUM project is that, given that the joint trajectories were developed from dynamic modelling, why is it then necessary to use a second layer of control to maintain dynamic stability? The most likely answer is that the dynamic model used to generate joint trajectories was not sufficiently accurate to account for compliance in the system or non-linear characteristics of the drive system. However, by processing the majority of dynamic analysis externally, the control system is able to focus on a reduced order model during locomotion. Essentially, this strategy increases the computational efficiency of the control system while maintaining a pseudo dynamic model.

Given the wide availability of powerful, low-cost microprocessor that are easily able to be networked, there is no limit to the number of models that could be used to control a biped in real time. For example, one processor might contain a reduced order dynamic model, another may contain a neural network based on historical data, yet another may contain an inverted pendulum model etc. The final control output may be some form of weighted average of the outputs of all models in the control system. Taken to the extreme, a final processor may use fuzzy sets to compute the outputs based on the membership of the outputs of the previous models. If nothing else, this proposition strongly suggests the use of an expandable control structure.

The second question raised by the TUM project is the lack of an onboard power supply. Given the success of the project, it would appear to be a simple task, and a minor modification to the dynamic model, to mount the power supply on board the robot. Based on the experience gained in this project, it is suggested that the additional weight of batteries would increase the non-linear dynamic characteristics of the robot beyond the capacity of the control system.

Another group to make use of extensive dynamic modelling is the Mobile Robots Group at the University of Queensland, Australia. They use the DynaMechs package to model their 1.2m tall, 38kg, and 23DOF humanoid named GuRoo (Roberts et al, 2003). They have achieved an extremely high level of correlation between simulated and measured data. The robot's hierarchical control system consists of a Compaq Ipaq as the main processor for global control and five Texas Instruments DSP boards each controlling three local joint motors. The robot's control software is modelled and optimised using the DynaMechs package prior to downloading to the robot. The group have achieved balance using local control but are yet to achieve global motion control.

Some researchers such as KAIST (Kim and Oh 2002) have embraced the concept of the zero moment point (ZMP). This is a point on the ground, about which the sum of all moments produced by forces in the robot (including gravity) equates to zero. In static balance this point must be kept between the toe and heel in the sagittal plane and between the feet in the frontal plane. The application of ZMP control in bipeds can be achieved at two levels of hierarchical control. At the lower level, fine motor adjustments of ankle and foot actuators move the point of actuation of ground reaction forces providing an offset torque to balance minor unbalanced forces within the biped structure. At a higher level, movement of larger masses at a greater distance from the ground, such as the hips, provide larger torques to offset accelerations produced by external forces. Again, ZMP control can be used to control the error of the system from predefined open loop or loosely coupled trajectories.

During the late 1980s and early 1990s, development of biped robots proliferated. Key institutions in Japan such as The Tokyo, Nagoya, Osaka, and Kobe Universities, as well as American groups such as the Harvard Robotics Lab, the MIT Leg Lab and Ohio University all began to develop biped projects which will be discussed in the following sections. This acceleration in the development of the android over the last 20 years has been astounding. In recent years humanoid robots have appeared all over the globe. Amazingly, though it took Honda over 20 years and eleven prototypes to develop their humanoid, groups with no previous history of android development are announcing humanoids with similar capabilities to Asimo. For example, New Era, a St Petersburg company in Russia (New Era 2003), have developed two 1.23m, 61kg humanoids that can supposedly recognise and follow people while avoiding obstacles. Further pushing back the frontiers of android research, the company claims that one robot ARNE is male, the other ARNEA, is female. The author of this document was relieved to learn that;

> *..there are no obvious physical differences*
> *between male and female, apart from their colour…..*

The Kibertron Humanoid Robot Project (Kibertron 2004) also appears to be progressing well. Their 1.67m, 90kg, 92 DOF humanoid is still in the design stages, however research has progressed to the stage where the group has determined that by using self-education;

> *..extremely complicated and intelligent units, which do not*
> *need very large computing power are very effective and efficient….*

The control strategy of this group is to build an android with more degrees of freedom than any biped to date, and then to use simpler processors to control it. It appears we have come a long way in the last 20 years from Kato whose successful philosophy was to keep the mechanics simple and throw every bit of the latest processing capacity at the motion problem!

2.4 DESIGN CRITERIA OF AN INDUSTRIAL BIPED

Having investigated the history and the state of the art in biped robotics, it is clear that there is little or no research being conducted specifically in the field of industrial scale bipeds. Accordingly, no benchmark performance or operational specification was available for the design or capabilities of such a device. While this categorised the research presented in this project as unique, it also present a requirement for the formulation of a set of design criteria for the device. The following sections outline the characteristics that have been developed for the design of the biped robot presented in this project.

Naturally, much biped research can be applied to all bipeds regardless of scale. However, research presented later in this document will show that the scale of an industrial biped presents unique challenges in the design and control of such a device. During dynamic walk, or during testing of an automated device possessing fourteen hydraulic actuators, large dynamic forces are generated. These forces are unique to biped robots and are not experienced by industrial robots or wheeled or tracked mobile robots. Further, transducers such as shaft encoders and orientation sensors used in mobile or industrial robotic applications have not been designed for shock loadings that may be experienced in biped applications. When unexpected behaviour occurs, these forces may cause damage to the structure. This is evidenced in the literature. For example, M2 is a 3D biped robot developed by the MIT Leg Lab (2001) In their description of the device, MIT state that one of the design goals of the robot is the ability to be

readily used to perform experiments without breaking .

The Shadow robot company report that initial experiments with their biped, the Shadow biped (Shadow 2003), suffered from repeated mechanical failure with an MTBF of less than two minutes. In the case of an industrial scale biped, where most failures require welding to repair, such breakages considerably frustrate the testing process.

Choong et al. (2003) suggest that a basic set of specifications for a biped robot would include a requirement that it be robust and reliable and that it should be easily maintained. Certainly these are common requirements of all industrial plant.

Therefore the first two design requirements of this project shall be;

- **that the industrial biped robot is physically robust** (Design criterion #1)
- **wherever possible, off the shelf components should be incorporated so that repairs can be expedited.** (Design criterion #2)

A final major item that was excluded from the analysis of leg deflection was the additional weight of a payload. Any industrial or domestic biped robot must be able to lift substantial objects to be useful. Australia Occupational Health and Safety legislation prescribes that 25kg is the maximum unaided lift to be attempted by employees. One industry where the incidence of manual handling or overexertion injuries is high is the health industry. The US Department of Labor and the Bureau of Labor Statistics has reported that the frequency of lost time injuries due to overexertion is at the rate 474 per 10,000 workers. The South Australian Workcover Office reports that the average cost of an overexertion injury is in the order of $8,000. This industry, according to Honda’s publicity, is the target market for Asimo.

These statistics offer two insights. Firstly, the cost of injuries per 10,000 workers is approximately $3,000,000. Even if the cost of an Asimo was reduced to $300,000 by mass production, and it was assumed that one Asimo would replace up to 3 workers, the implementation of the robots would only reduce injuries by 3%. As a service robot in the health care industry, the device is commercially unviable. Secondly, if it is assumed that the regulated 25kg lift is considered as safe weight, workers must regularly be required to lift a substantially greater mass to cause such a high frequency of injuries. It is suggested that a safe working load of at least 40kg would be required of any robot working in the industry.

In the case of an industrial biped, the effect of payload would be considerably greater. Ideally, an industrial biped would sustain a payload of 1000kg. However, based on the analysis of Figure 2.10, such a load would increase the leg deflection of the to the order of 100mm. This value of error would prove difficult for the control system to manage. In the event that the control system was able to function with this magnitude of position error, an error of 100mm at an end effector would render the device useless for military applications such as the loading of bombs to aircraft.

To determine a realistic capacity for the prototype designed and constructed in this project, a payload of one 500lb bomb was selected. Therefore the third design criterion is;

- **A working capacity of 250kg.** (Design criterion #3)

The use of the device for military materials handling applications suggests that the biped would be used in the field, in environments unsuitable for conventual materials handling equipment. As previously discussed, while completing the review of literature for this project, no references were found in respect to the performance parameters of an industrial scale materials handling biped robot. The author then attempted to approach major manufacturers of materials handling equipment to canvass opinions on the subject. Unfortunately, the sheer size of these organisations rendered them incapable of providing access to the senior engineers responsible for research and development in these areas. The major piece of equipment used by industry and the military to handle material in off road situations is the all-terrain forklift. Surprisingly, these vehicles (which the author has operated extensively during the course of employment) can only manage quite small discontinuities given the size and bulk of the vehicles. For example, the forklift shown in Figure 2.10 has a capacity of over 2000kg yet it only has a ground clearance of 304mm. This height is only slightly higher than a standard stair riser. Not only should an industrial biped be able to climb similar stairs to humans (provided the stairs are able to bear the weight), but it should also be able to climb or step over larger

Figure 2.10 All terrain forklift

discontinuities. Therefore, another design criterion is set as;

- **Capable of traversing a 500mm discontinuity.** (Design Criterion #3)

The final design criteria, which would be expected of any industrial vehicle, are;

- **Able to work for long periods.** (Design Criterion #4)
- **Completely self contained.** (Design Criterion #5)

2.5 CONCLUSION

Based on the literature review conducted for this project, no industrial scale materials handling robot has been previously designed or built. Therefore, the research conducted in this project constitutes the first serious attempt to build and to control such a device.

While smaller humanoid biped robots have been successfully demonstrated, the potential working load of the devices make them unsuitable for the applications for which they are proposed. It is also suggested that even if the cost of the devices was reduced to $300,000, they would not be commercially viable. As quoted by Lytle (BBC 2003), a gentleman visiting a recent robot exhibition in Japan was impressed by Honda's ASIMO:

I don't know how useful a robot like ASIMO is, but I wouldn't mind having one at home for the kids.

3 MECHANICAL DESIGN OF ROBOSHIFT

A good scientist is a person with original ideas. A good engineer is a person who makes a design that works with as few original ideas as possible.

- Freeman Dyson

It is remarkable that when a mechanical device is modelled on a biological form, or when a machine attempts to imitate the actions of an animal, the geometry takes on a biological appearance. The following sections detail the evolution of the mechanical design of Roboshift concluding with photographs of the completed machine.

3.1 DESIGN PHILOSOPHY

Further to the conclusions drawn from Chapter 2, this project endeavours to demonstrate that an industrial scale biped robotic materials handling device is viable. The performance specification for the device has been defined in Chapter 2 and is repeated in Table 3.1.

• Robust both physically and electronically	(1st Criterion)
• Easily maintained	(2nd Criterion)
• Capable of lifting 250kg	(3rd Criterion)
• Able to work for long periods	(4th Criterion)
• Able to traverse 500mm discontinuities	(5th Criterion)
• Completely self contained	(6th Criterion)

Table 3.1 Roboshift design criteria

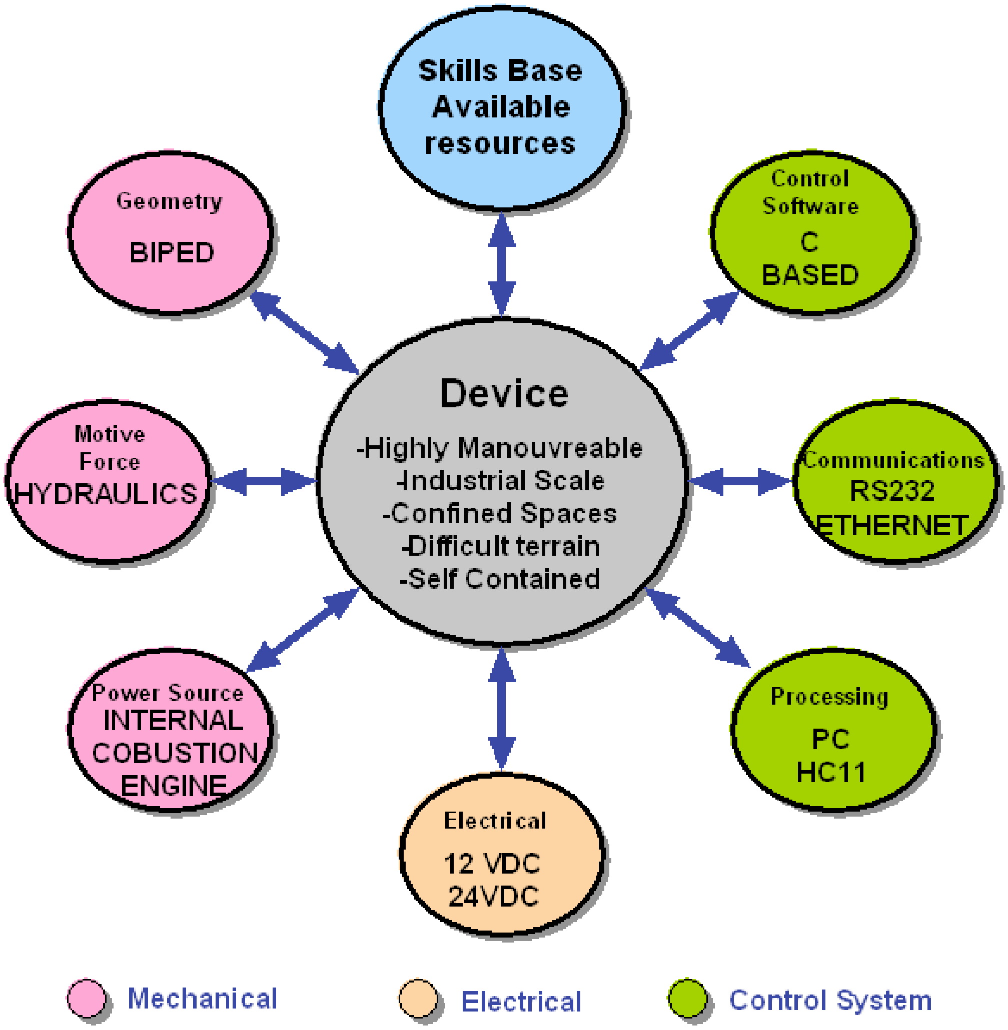
Given the scale and complex nature of the design, construction and testing of a device of this scale, it was necessary to "Fast-Track" the project. Given the available resources, the knowledge base of those involved, and the timescale available, the following decisions were made very early in the project:

- The device would be an anthropomorphic Biped
- The Software would be C based
- Communications would be RS232
- Power source would be an Internal Combustion Engine

- Motive force would be Hydraulics
- Power would be 12 Volt
- Control Hardware would be PC and Motorola HC11 Based

Figure 3.1 shows a semantic net of the initial decision making process.

Figure 3.1 Device configuration decision matrix



The drawback of fast-tracking the initial design was the possibility that an error of judgement made early in the project would lead to more serious problems later on. However, the amount of research required for full confidence in each aspect of the initial decision and design process would result in the project never being realised. As will be discussed in Chapter 12, with the benefit of hindsight, there are aspects of the robot's design that could be improved. However, the majority of these issues would only have come to light after testing of the robot and it is unlikely that any amount of analysis would have prevented the difficulties that were encountered. Any complex robotic project relying on limited funding continues to work with the original prototype where, if funds were available, two or three iterations would be built prior to the final prototype. For this reason, significant resources are expended attempting to maximise the return on existing designs.

In terms of the mechanical configuration, the overriding design philosophy was to imitate the human lower limb structure as closely as possible. Where it was not possible to follow the human structure exactly, then analysis and modelling would be used to confirm that divergence from the model did not affect the integrity of the philosophy. For the robot to be able to walk, it was believed that if the robot:

- Possessed all of the degrees of freedom of the human lower legs and hips
- Was constructed with joints that exhibited a similar range of movement to that of the human
- Could be controlled with sufficient speed and accuracy

The philosophy was based on the facts that:

1. Humans are able to walk with knee injuries, foot injuries, hip and ankle injuries, a child hanging onto one leg or both legs, their own weight on their shoulders or any number of pathological or structural modifications.
2. The wide range and variants of the basic biped structure displayed in the designs of other biped researchers indicate that while the design of leg systems may be appropriate for the project, their exact configuration is not critical.
3. The range of gaits used by the human including skipping, running, jogging and even hopping, suggest that the human lower limb system has not been optimised for any particular gait. Rather, the control system is so completely adaptable that it adjusts joint trajectories to optimise any of the modes of locomotion based on the existing leg system.

Therefore, given the above philosophy, it is proposed that it is the ability of the control system to manipulate the joints of the legs that is more critical to locomotion than the actual structure of the leg system.

3.2 MECHANICAL CONFIGURATION

The following sections outline the design processes that led to the final configuration of Roboshift. As shown in Figure 3.1, the decision to build a biped robot immediately determined the basic geometry of the device. The use of hydraulic actuation and an internal combustion engine as the power source also determined many characteristics of the mechanical design. While not having as substantial an impact, the choice of transducers, mounting of sensors, requirement for 12 VDC power and the mounting of hydraulic valves also imposed constraints on the mechanical design.

3.2.1 BASIC STRUCTURE

Since 1965, attempts have been made to realise a bipedal walking materials handling robot. Previous attempts have been based on force multiplying exoskeletons such as the General Electric Hardiman, previously discussed in Chapter 2. This was a teleoperated device with the operator strapped into the exoskeleton using his/her limbs to control the robot's motion. Given the available technology, this project was adventurous and may have proceeded had it been commenced even ten years later when more compact micro processing became available. Information on the Hardiman is limited; however reports suggest that the device was uncontrollable. Current research into exoskeletons is being conducted at the University of California, Berkeley, where a motorised exoskeleton is being developed (New Scientist, 2004). The research has attracted DARPA funding which reinforces the suggestion that the most appropriate use and commercial market for such devices will be the defence industry.

Regardless of the size or configuration of an exoskeleton, any device must be significantly larger and heavier than the human to which it is strapped. The centre of gravity of the device, as well as the centres of percussion of the joints must shift from those of the operator. As well, to avoid accidental operation of actuators, a positive force would be required from the operator to initiate control. When these characteristics are combined, the operator would become both mentally and physically fatigued in a short period as he or she fought to positively control their own limbs in unnatural trajectories, while applying continuous force. As discussed in Chapter 2, this also appeared to be the case with the Mosher's walking truck. For this reason, any kind of imitative or limb tracking teleoperation was rejected. Therefore, the decision was made to use a fly-by-wire control system where the commands of the operator would be interpreted by the control system to move the robot in a given direction, or to lift an object. The control

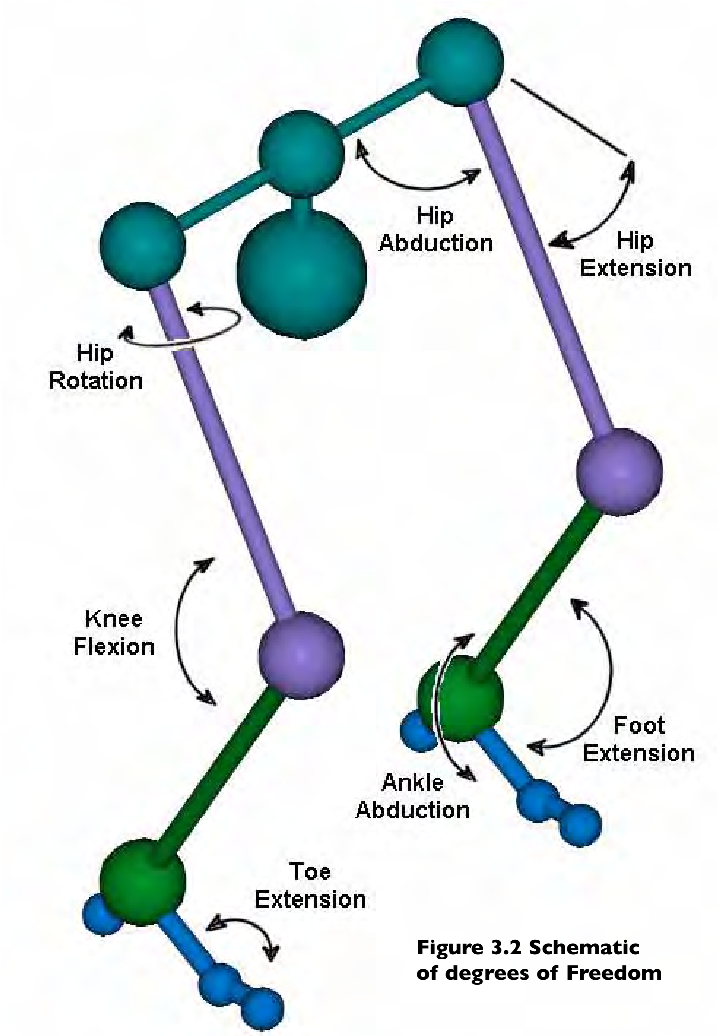


Figure 3.2 Schematic of degrees of Freedom

system would then translate these commands into joint movements. Whether the operator was on board the device, or was operating the robot remotely made little difference to the control system.

To increase the mobility and stability of the robot without increasing its size, the decision was made to attach the hips to the shoulder of the body as shown in Figure 3.2. Thus, for the same size, its stride length was increased twofold. As well, the moment of inertia of the robot's upper body about the foot would be increased along with the period of oscillation and the time available for the control system to react. A mathematical model was developed to confirm the feasibility of such a configuration (see chapter 4).

To satisfy the first design criterion (see Table 3.1) the ability to transport 250kg, the biped had to be able to balance as a human does. Balancing of the robot requires fine motor adjustments to the feet allowing stable motion on non-uniform surfaces. This led to the development of a fully anthropomorphic robotic foot and ankle. No biped device to date has incorporated a foot that consists of a separate toe, ball and heel. To provide the required force locally to each joint, in as compact a manner as possible, it was decided that all joints would be hydraulically driven. The advantage hydraulic power presents over electric servo-motors is a higher power to weight ratio of the actuator which can be mounted separately from the power source.

For the robot to be physically robust and easily serviceable, it was decided to construct the major members from Aluminium, using roller bearings at each joint and to use off-the-shelf hydraulic actuators and valves. The effects of these overall design paradigms and the evolution of the design will be discussed in the following sections.

3.2.2 CONFIGURATION OF JOINTS

The overall design philosophy for the robot was the premise that if the device possessed similar degrees of freedom to those of the human, it should be able to walk. The human joints and type of joint that required replication are shown in Table 3.2:

Joint	Limbs joined	Type of joint
Metatarso phalangeal joint	Toe and forefoot	Ball and socket
Tarso-metatarsal	Midfoot and forefoot	Hinge
Ankle and subtalar	Midfoot and leg	Perpendicular Hinges
Knee and patello-femoral	Leg and thigh	Double Hinge
Hip	Thigh and Pelvis	Ball and Socket

Table 3.2 Human lower limb joint movement

By use of tendons, ligaments, muscles and bones, humans and animals possess fine control of highly articulated joints. Significant research has been conducted into the imitation of these biological systems and the control of them by the use of electromyographic signals. Groups such as the Department of Mechanical Systems Engineering at the Tokyo University of Agriculture and Technology, the Department of Computer science, Institute for Control and Robotics, University of Karlsruhe, Germany and the Institut Automatisierungstechnik at the University of Bremen have developed artificial hands for installation on service robots. These manipulators are designed to increase the service capacity of robots by allowing a greater degree of dexterity and the ability to operate in the human environment where artefacts and machinery have been designed to be used and operated by the human hand. Such end effectors are promising for this purpose, however they are of little significance to this project as an industrial scale robot will be used in an environment where items have been designed for manipulation by equipment such as forklifts and cranes. For example heavy objects are fitted with lifting lugs or strapped to pallets rather than being fitted with handles.

Electroactive Polymer Actuators (EPAs) or artificial muscles show enormous potential for the imitation of the muscular function both in the construction of artificial anthropomorphic systems (Androids etc) and for the replacement or implantation of human limbs or organs such as the heart. In terms of advanced android research, the future may see the development of an anthropomorphic robot using this technology. When combined with the technology developed to imitate the human hand, it may be possible to closely reproduce human joints using artificial materials. Realistically, using such expertise to construct and control the joints of an industrial biped is beyond the scope and resources of this project. Rather, the challenge of the design of the joints of the robot was to reproduce the joint movement using available industrial hardware.

Based on the available joint movement data and models [(Fischer & Braune, 1987), (Hartrum, 1973)] it was determined that fourteen degrees of freedom were critical to the replication of the movement of the human lower limbs. In the human, joints such as the hip joint exhibit up to three degrees of freedom. To simplify design, fabrication and control, these joints were deconstructed to a combination of single degree of freedom systems. In the case of the hip joint, the motion has been broken into two hinge and one rotational degree of freedom. The schematic of the degrees of freedom required by the robot can be seen in Figure 3.2, found earlier in this chapter, where the seven distinct movements available to each leg are illustrated. The human joints and the types of joints that were used to simulate those of the human lower limb are listed together with included limbs in Table 3.3.

Limbs joined	Movement	Type of joint
Toe and forefoot	Plantar flexion/extension	Hinge
Midfoot and lower leg	Ankle flexion/extension Subtalor abduction/aduction	Hinge Axial rotation
Leg and thigh	Leg extension/flexion	Hinge
Thigh and pelvis	Thigh extension/flexion Thigh abduction/adduction Thigh rotation	Hinge Hinge Axial rotation

Table 3.3 Simulation of human lower limb joints

3.2.3 RANGE OF MOVEMENT

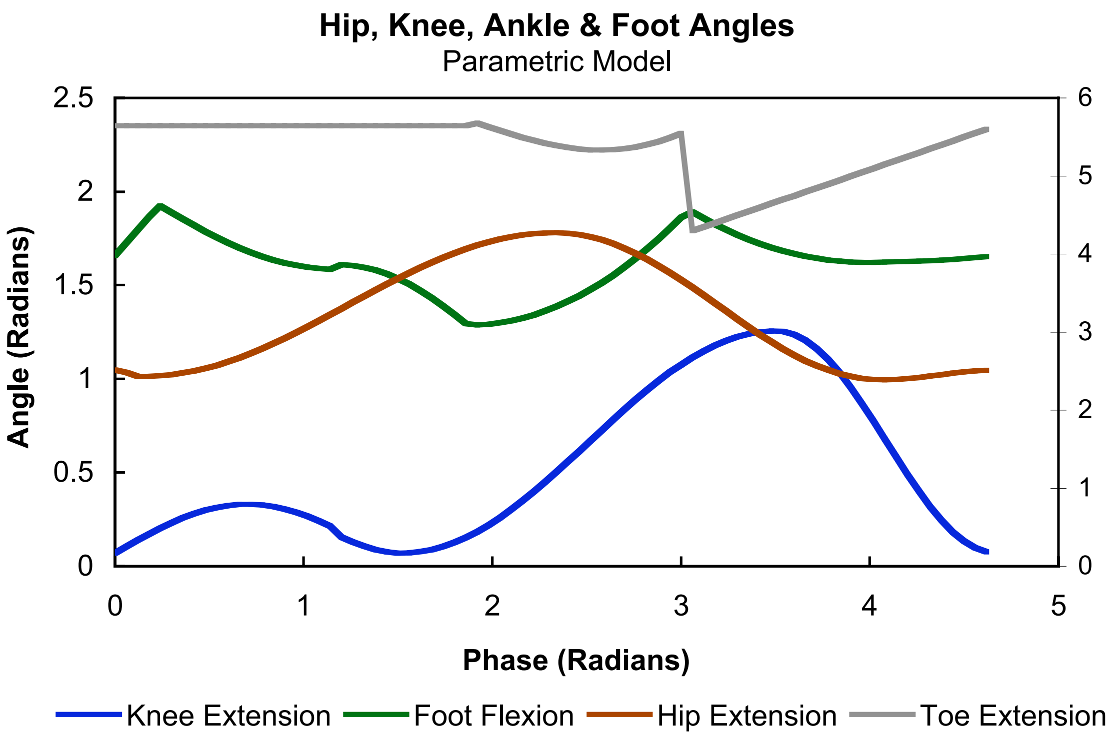
Maintaining the design philosophy that the robot should exhibit the same range of movement of the human lower limb, data of joint trajectory angles was plotted to determine the maximum joint trajectories. The primary joint movements responsible for bipedal locomotion in the sagittal plane are:

- Hip extension
- Knee extension
- Foot flexion.

Toe flexion, hip abduction and ankle abduction serve to stabilise the trajectory during the single support or swing phase. Additionally, hip abduction and ankle abduction allow the transfer of weight in the frontal plane during the initiation of locomotion and during double support phase.

To determine the range of movement required for the hip extension, knee extension and ankle flexion, a range of data from the examination of human movement was required. Braune and Fischer (1987) used time lapse photography to highlight joint trajectories through a range of standard, loaded and pathological locomotion cycles. As this data was acquired from individuals, even the standard locomotion data could be assumed to display individual characteristics of the subject's gait. In 1973, Hartrum (1973) used Fourier Transforms to generate a parametric model from Braune and Fischer's data. While this model smoothed the data it was found to be discontinuous at the boundaries of the phases of locomotion where the minor terms of the Fourier series had been ignored. While not sufficient for use in the generation of joint trajectories for control of the robot, it was decided to use data generated from the use of the model for mechanical design purposes. However, as Hartrum's model did not include the metatarsals, the model was modified for this project to include a simplified foot joint and toes (see analysis in Chapter 4). As no data was available for the trajectory of the toes during swing phase, it was assumed that they would return to the pre heel-strike position in a linear motion from lift off. This phase of the toe motion was not modelled and appears discontinuous in the plotted ranges. Joint trajectory curves plotted from Braune's data and from the modified Hartrum model are shown in Figure 3.3 (a) and (b).

(a)



(b)

Figure 3.3 Hip, knee, ankle and foot angles (a) interpolated from Braume (b) from the modified Hartrum model

Angle	Minimum	Maximum	Determined by;
Hip Extension	0.994857	1.780196	Modelling
Hip Abduction	-03.492	0.5238	Estimation
Hip rotation	-1.0	1.0	Estimation
Knee Extension	0.0698	1.256119	Modelling
Ankle Flexion	1.287423	1.922746	Modelling
Ankle Abduction	-1.0	1.0	Estimation
Toe Flexion	1.153757	2.531241	Modelling

Table 3.4 Human lower limb joint movement

Table 3.4 records the joint angles from the analysis of human locomotion. As indicated, the primary driving angle ranges were modelled whereas the minor angle ranges were estimated based on Braune and Fischer's data. These minor angle ranges were later confirmed during kinematic and dynamic modelling (see Chapter 4).

The angles above were viewed as the minimum required for locomotion. It could be expected that an industrial scale biped would require a range of gaits for lifting large objects, moving on unlevel ground or negotiating discontinuities. Therefore it should be expected that the required range of joint motion would be greater than that which could be seen in normal, level locomotion. The initial aim of the project was to produce a biped capable of locomotion on level terrain. However, where the joint could accommodate a greater range of movement this was incorporated into the design. Ideally, joint motion would be designed to reduce the risk of damage from interference between limbs. For the robot to exhibit the same degrees of freedom found in the human lower limbs, this method of inbuilt safety was not possible. The robot relies on software to determine the range of movement permitted during active motion.

3.2.4 MECHANICAL DESIGN FOR ASPECTS OF CONTROL SYSTEM

In terms of mechanical design, the requirements of the control system for the design of the structure are:

- The location and adaptation of transducers
- The location and connection of actuators
- The location and mounting of power and electrical systems

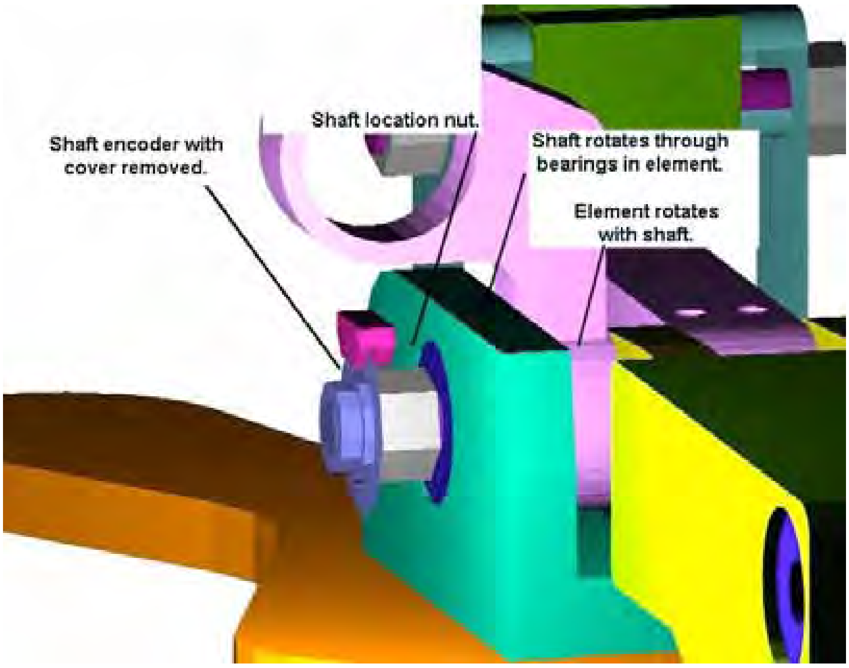


Figure 3.4 Mounting of shaft encoder

3.2.4.1 TRANSDUCERS

Having decided to use digital shaft encoders to provide the level of accuracy and repeatability required for joint control, the selection of encoder was considered. Industrial digital shaft encoders include their own bearings, seals and shafts and are typically housed in containers sealed to IP67 or greater. Most importantly they incorporate an input shaft that is then connected to the machine shaft via a flexible coupling which allows for any misalignment in the connection. Unfortunately such encoders are expensive, prohibiting their use in this project. To achieve a high level of accuracy for a realistic price, Hewlett Packard HEDS 5540 encoders were used. In most cases, these encoders are located on extensions of the joint hinge shaft. As shown in Figure 3.4, a machined stud is threaded into the end of the joint hinge shaft which protrudes through the nut which locates the shaft. The shaft encoder then measures the rotation of one joint member relative to the other.

As the encoders are not connected via flexible couplings, the alignment of the shaft encoder on the shaft is critical. For this reason, bearings were used in all joints to reduce any "slack" in the location of the shafts. In the case of the hip extension shafts which support the full load of the robot, excessive flex was found at the joint. This led to misalignment of the shaft encoder and a resulting loss of data. To overcome this situation, the shaft encoders were mounted remotely, and then connected using timing

Figure 3.5 Hip extension shaft encoders

belts and pulleys (see Figure 3.5). An additional advantage of this configuration was that the rotation angle of the hip extension shafts was multiplied by the use of different sized timing pulleys which allowed a greater resolution of the hip extension angle. Generally, the shaft encoders are mounted on the outside of the robot to minimise damage from limb to limb contact. Where this has not been possible, they have been mounted in recessed areas.

3.2.4.2 ACTUATORS

In keeping with the philosophy that only readily available, “off the shelf” components are used in the project wherever possible, the decision was made to use Vickers Hydro-Line hydraulic cylinders and Vickers B1-Series hydraulic gear motors to actuate the robot. The use of hydraulic cylinders requires greater space for actuation in the vicinity of the joint than would be the case with servomotors. As the cylinders are linear actuators, only the tangential component of force relative to the centre of rotation of the joint is available to produce torque. In some cases the angle between the member and the cylinder is small, thus the radial component i.e. the sine of the angle between the axis of the limb and the axis of the cylinder, must be relatively high to provide the required torque in the joint. This is typically the case in joints such as the knee as shown in

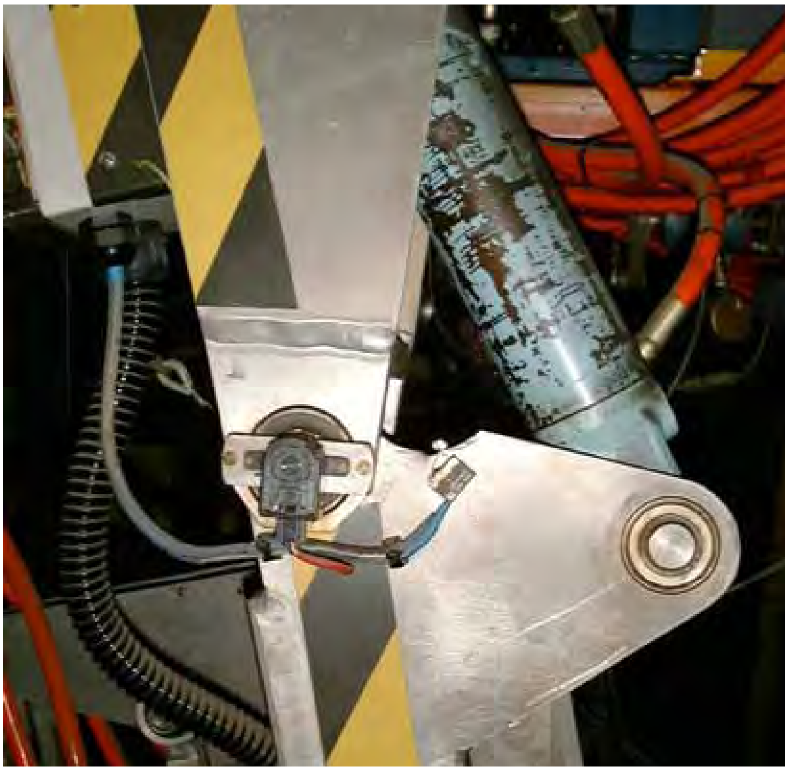


Figure 3.6 Knee extension cylinder

Figure 3.6. The joint must therefore be designed to withstand the forces produced by the actuator in addition to the forces produced by the dynamics of the robot. This design must include stronger sections around actuator connection points. As the axis of the cylinder changes as the joint moves, the motion of the cylinders relative to the joint must be accounted for when designing the joints of the robot. The details of these design issues will be illustrated during the discussion of the design of each joint.

3.2.4.3 POWER AND ELECTRICAL SYSTEMS.

Generally, the design process commenced with the modelling of the required movement of the robot. From these models the limb and actuator design was developed. Power and electrical devices were then incorporated into the structure so that the centre of gravity of the robot was generally maintained coincident with the hip extension axis. Devices were placed in positions where they were accessible when required for maintenance and would not interfere with the movement of the joints.

Typically, power, control and electrical components are contained within modules that are mounted to the robot's frame. The internal combustion engine, alternator, hydraulic pumps and batteries are housed within the engine module which is manufactured of tubular steel. While the overall dimensions of this module were derived from the design process, the placement and mounting of components within the module were determined by investigation. The installation of electrical and control wiring and hydraulic and pneumatic piping was also determined by investigation of the completed structure.

3.3 DETAILED MECHANICAL DESIGN

The following sections detail the evolution of the design of the individual components that make up the robot. The design was driven by a combination of:

1. The prime design paradigm; that if the robot had the same basic form of the human lower limbs, and same degrees of freedom, it would be able to walk
2. The five design criteria as listed in Table 3.1
3. The requirements of the control system, actuators and power and electrical systems

3.3.1 FEET

Effectively end effectors; the feet of the robot are the only components that are in contact with the outside world during locomotion. Ground reaction and gravity are the only external forces available to maintain the equilibrium of the robot. For these reasons it is critical that the feet are able to move in such a manner as to develop the required forces and torques to maintain the robot's stability. In the human large muscle groups such as the gastrocnemii (calf muscles - plantar flexors), tibialus anterior, extensis hallucis longis, flexor digitorum longus and perenius tertius (anterior plantar extensors) and flexor hallucis longus control the motion of the foot and toes via tendons such as the tendo Achilles and the tendon of the flexor hallucis longus in the case of the toes. Located in the lower leg, remote from the foot and toes, these powerful muscles transfer their force via the tendons which run over grooves in bones. This configuration, common in animals, allows the joint to be compact and allows for a greater range of movement than would be possible if it were encumbered by large muscles located at the joint.

As discussed above, significant research is being conducted into the design of anthropomorphic systems that use artificial muscles and tendons to reduce the size of the structure required for the control of dextrous effectors. While various types of linkages were considered for the control of the foot, the precision required to eliminate any slack in the control of the joint, or stretch in control cables was deemed to be beyond the capability of the project. Given the forces involved, and the size of control actuators required, it was decided to control each degree of freedom by direct actuation. The subsequent challenge in the mechanical design of the robot was to determine the structural arrangement for the mounting of actuators. This process was common to all joints. As the foot/ankle configuration was the most complex, concentrating several degrees of actuation in a single region, the design issues will be discussed in the following paragraphs. Other joints found in the robot were designed with similar analysis, however the design of these joints will not be detailed to the same extent.

Figure 3.7 shows various concepts that were investigated to incorporate the mechanical linkages required to move the toe and foot and the abduction of the foot. The design of the foot was conducted as an iterative process with the overriding design philosophy being to model the human lower limb. Various combinations of actuators and foot components were analysed to determine their ability to replicate the freedom of movement of the ankle and foot. One of the challenges presented in the design of the joint was to incorporate the ability to control the toes independently of the foot. Ideally the toe angle would remain constant regardless of the angle of the foot. To achieve this, the control mechanism for the toe would either have to be completely contained within the foot and toe, or the control software would have to maintain the angle of the toe relative

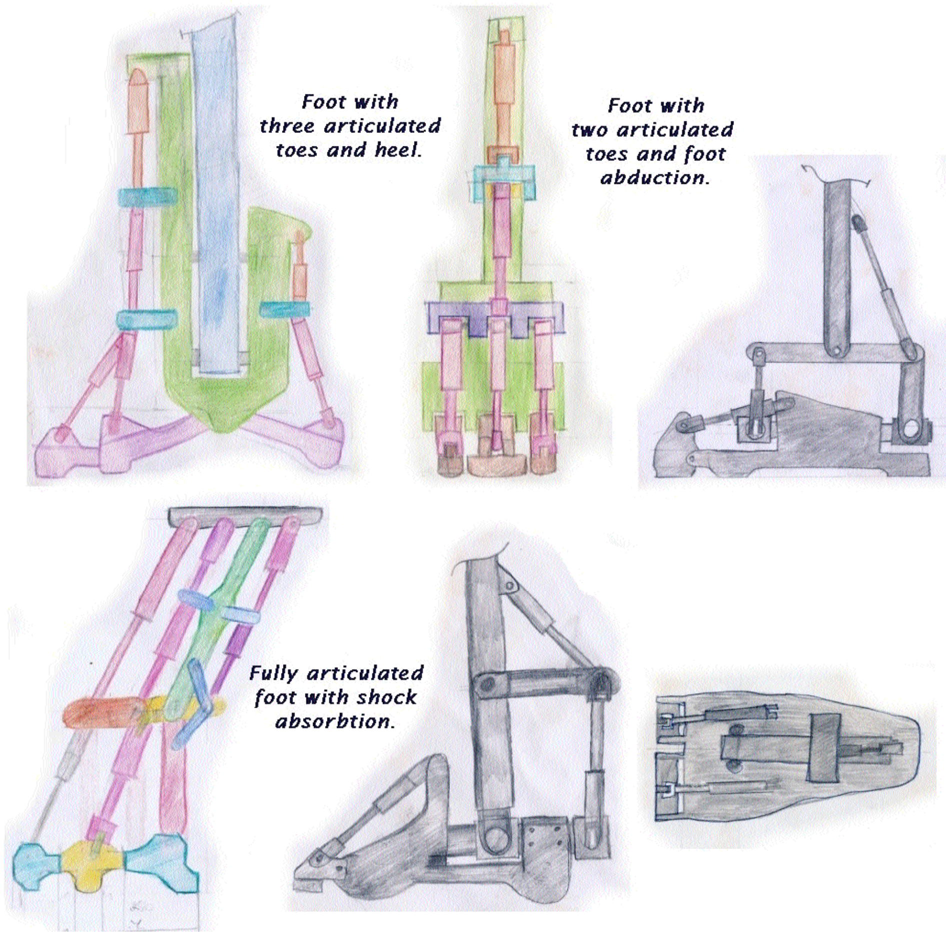


Figure 3.7 Various concepts for foot design

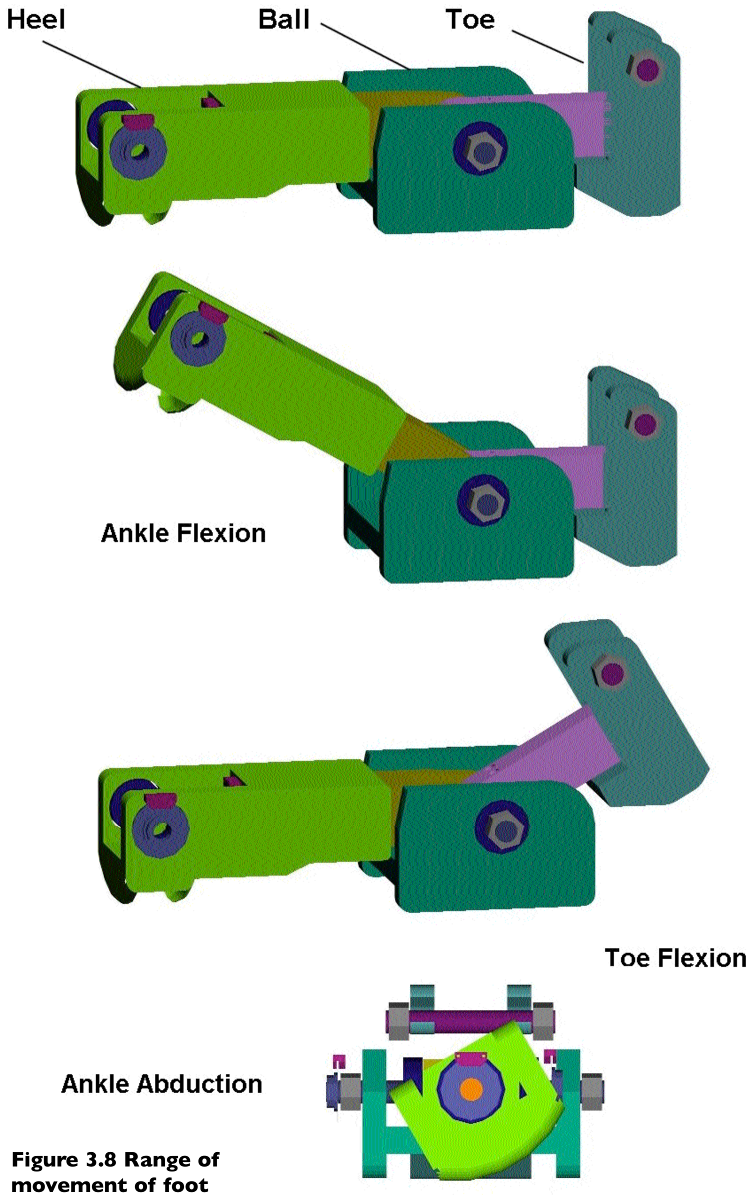


Figure 3.8 Range of movement of foot

to that of the foot. Similarly, the control of the foot relative to that of the ankle would require the foot control to be completely incorporated into the ankle, or for software to maintain the angle of the foot relative to that of the ankle. Figure 3.8 shows the basic foot structure and its degrees of freedom. A range of toe configurations were investigated including three, two and single toed feet. The ability to move toes independently allows for stabilisation of the foot in the frontal plane. It was decided that this control would be achieved through foot abduction or roll and that a single toe would be used to stabilise the foot in the sagittal plane. The analysis showed that it would be extremely difficult to mount any actuator between two joints on the foot. This led to the decision to incorporate the foot and ankle into a combined structure that attached to the lower leg. The foot itself was designed as a three component device with a heel, ball and toe. To simplify the

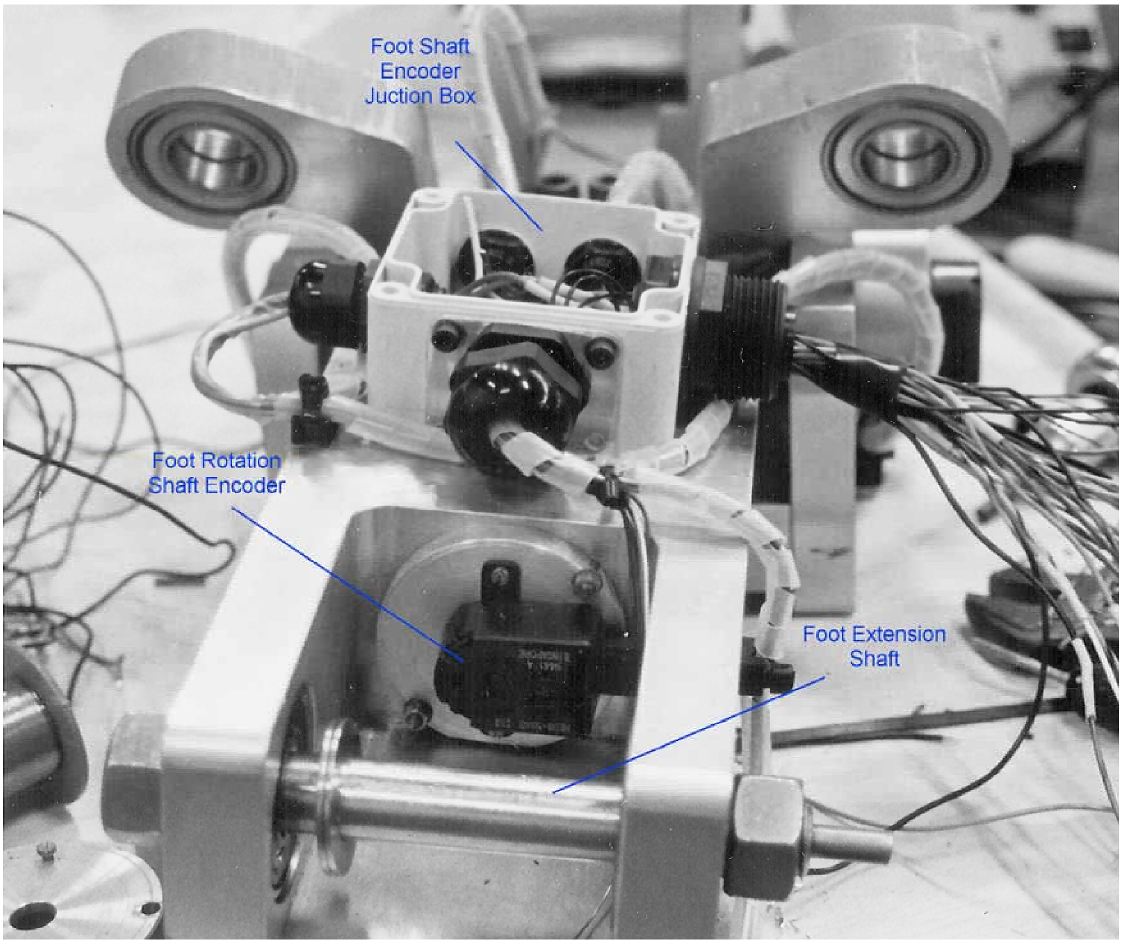


Figure 3.9 (a) Rear view of Roboshift's foot

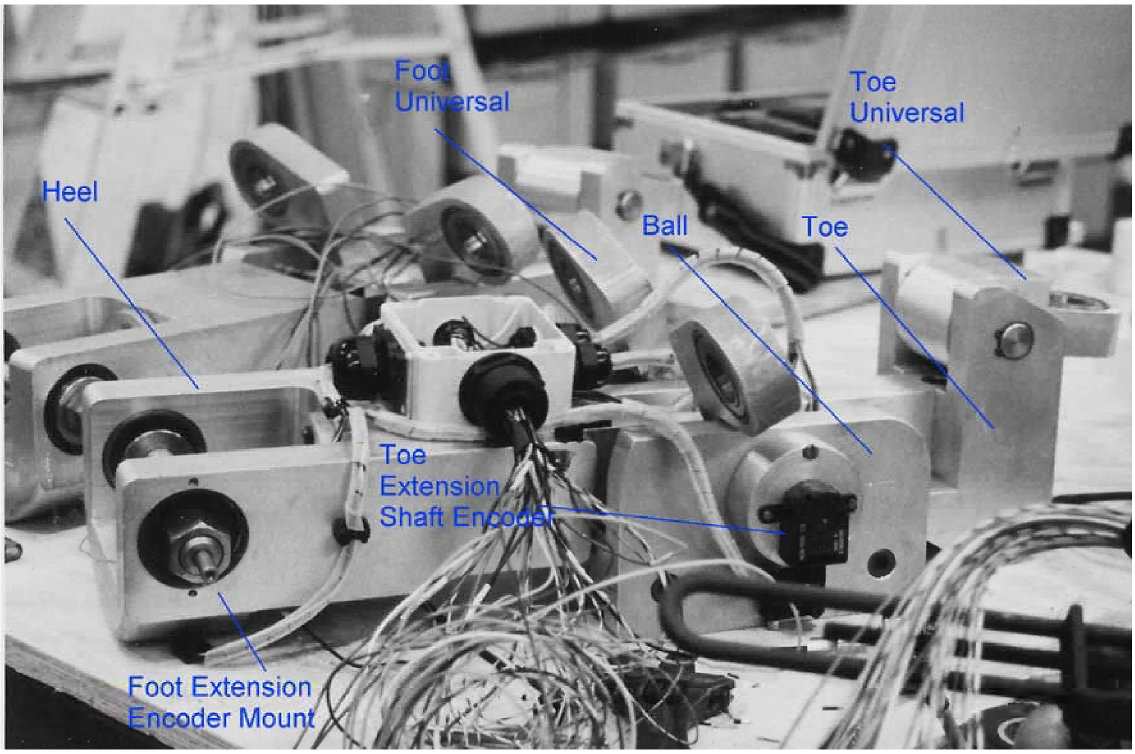


Figure 3.9 (b) Side view of Roboshift's foot

ankle, the rear of the heel has been radiused to allow for ankle abduction without the requirement for a separate joint. Photographs of Roboshift's feet can be seen in the photographs of Figures 3.9 (a) and (b).

Having made the decision to actuate the joints directly, the total length and stroke of the hydraulic cylinders was determined from algebraic analysis. Figure 3.10 shows the range of movement required by the foot. For small angles about the vertical, it can be seen that:

$$X_{MIN} = X - L \cdot Sin(\Theta) \qquad (1)$$

$$X_{MAX} = X + L \cdot Sin(\alpha) \qquad (2)$$

Given the length of a hydraulic cylinder in the closed position is equal to the fixed length of end components plus the stroke length;

$$X_{MIN} = L_{Fixedcomponents} + S$$

The length of the extended cylinder is equal to that of the fixed cylinder plus the stroke length:

$$X_{MAX} = X_{MIN} + S$$

Then:

$$X_{MAX} - X_{MIN} = S = X + L \cdot Sin(\alpha) - X + L \cdot Sin(\Theta) \qquad (2) - (1)$$

$$\therefore S_{troke} = L\left[Sin(\alpha) + Sin(\Theta)\right]$$

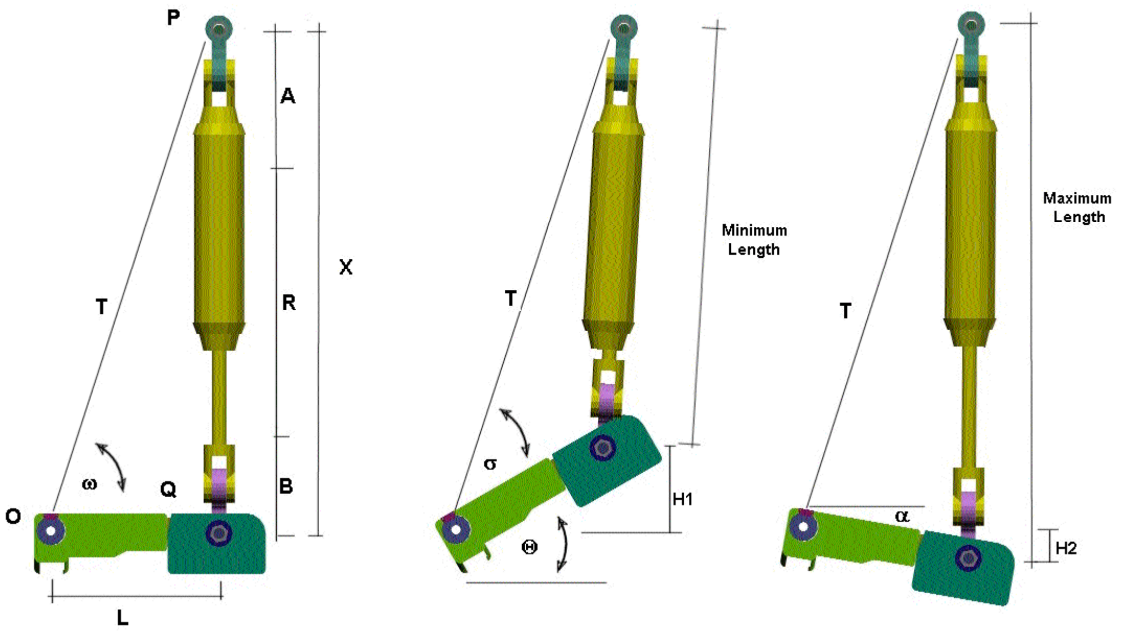


Figure 3.10 Range of movement of foot

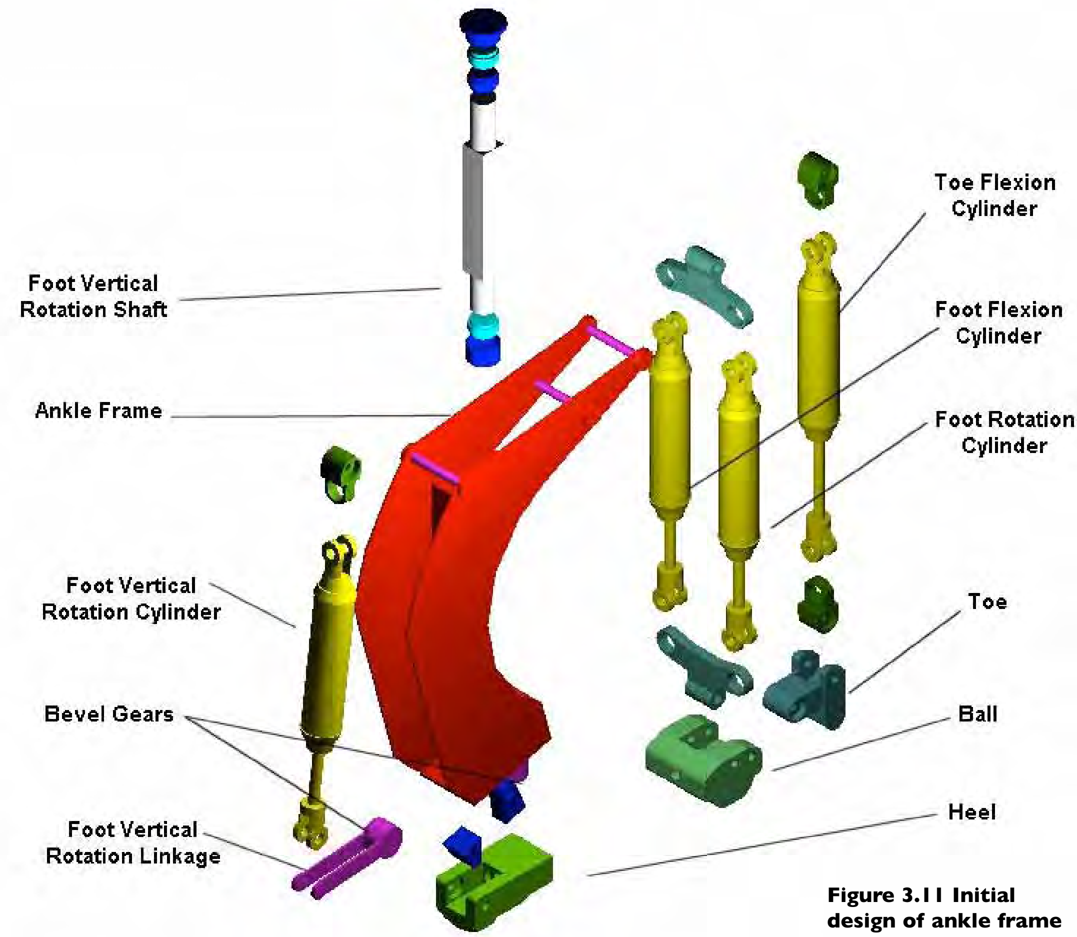


Figure 3.11 Initial design of ankle frame

Having determined the stroke required of the hydraulic cylinders, the length of the cylinder and the position of the mounting point of the top of the cylinder can be determined. As the foot cylinders would be counteracting the full ground reactions of the robot, the mounting structure was required to be extremely strong. However, as the structure would be attached to the end of the lower leg its mass would have a significant effect on the mass moment of inertia of the leg. For this reason various configurations of space frames were considered to minimise the weight. In the frontal plane the feet are positioned under the body as is the case in the human. However, the thighs of the robot were to be positioned on either side of the body. Such an arrangement required a transition of the lower leg towards the centre of the robot. As the entire robot's weight would be taken by the lower leg, a significant moment would be produced due to the horizontal translation of the vertical load. Again, the space frame configuration lends itself to the application of these loads. Initial solutions (see Figure 3.11) included a rotation of the ankle in the vertical plane. While not a degree of freedom found in the human lower limbs, it was thought that this movement would allow more efficient turns. This initial design was based around a welded box section frame with mounts for bearings and the hydraulic cylinder clevis pins. As the foot would be capable of both extension and abduction, the cylinders would rotate in two planes. Universal joints, incorporating roller bearings, were included in the design of the cylinder attachment points to allow this motion and to minimise any slack in the joint. Using solid modelling utilities in AutoCAD, the model was moved to the extremes of motion of the cylinders to determine if there was any interference in the joints and that the mechanics of the joint allowed the degree of freedom required of the foot segments. This analysis showed that the two mounts for the foot rotation and the foot extension cylinders would have to be split as the cylinders subtended different angles in the sagittal plane when the foot was both extended and abducted. Additionally, further consideration determined that turning could be facilitated by hip rotation, eliminating the requirement for foot rotation about a vertical axis.

A number of other design issues, such as the method of attachment to the lower leg led to a redesign of the frame. The final configuration of the foot/ankle assembly is found in Figure 3.12. There is no question that the design could have been further refined. Perhaps

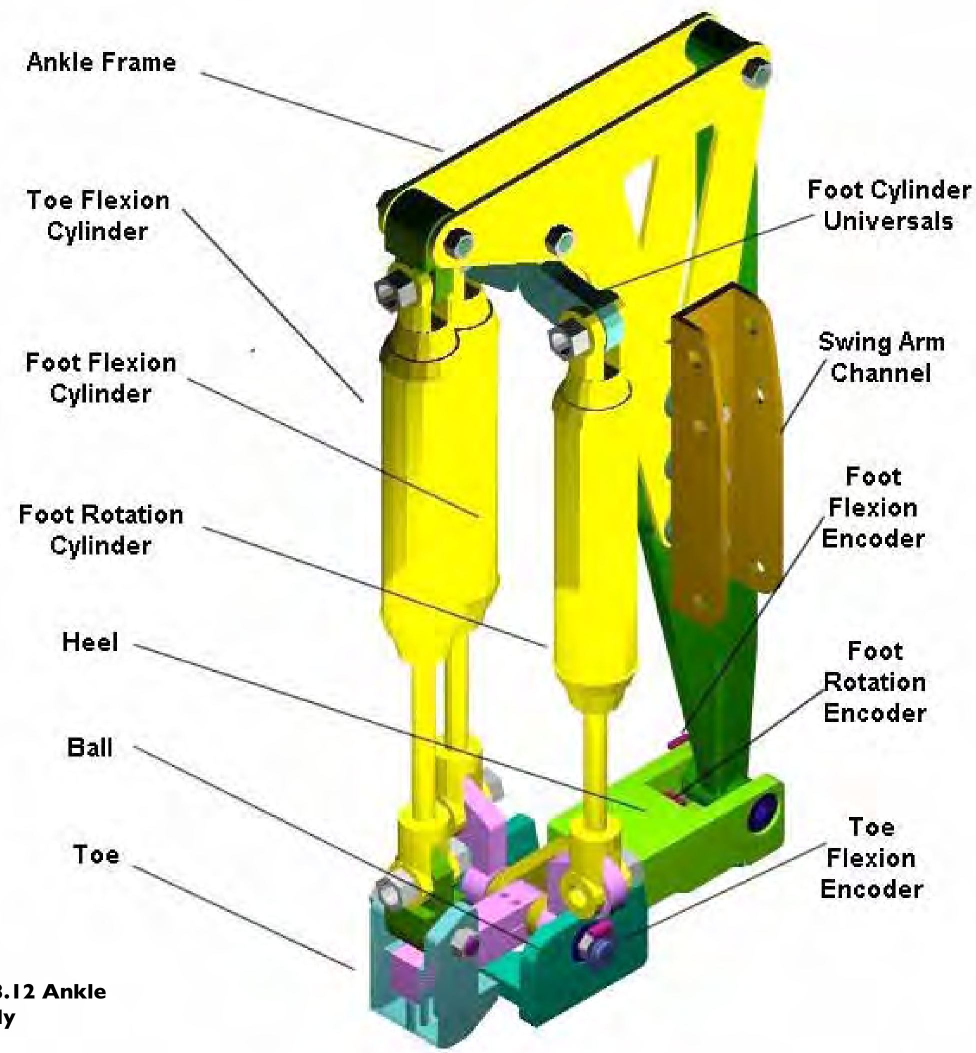


Figure 3.12 Ankle assembly

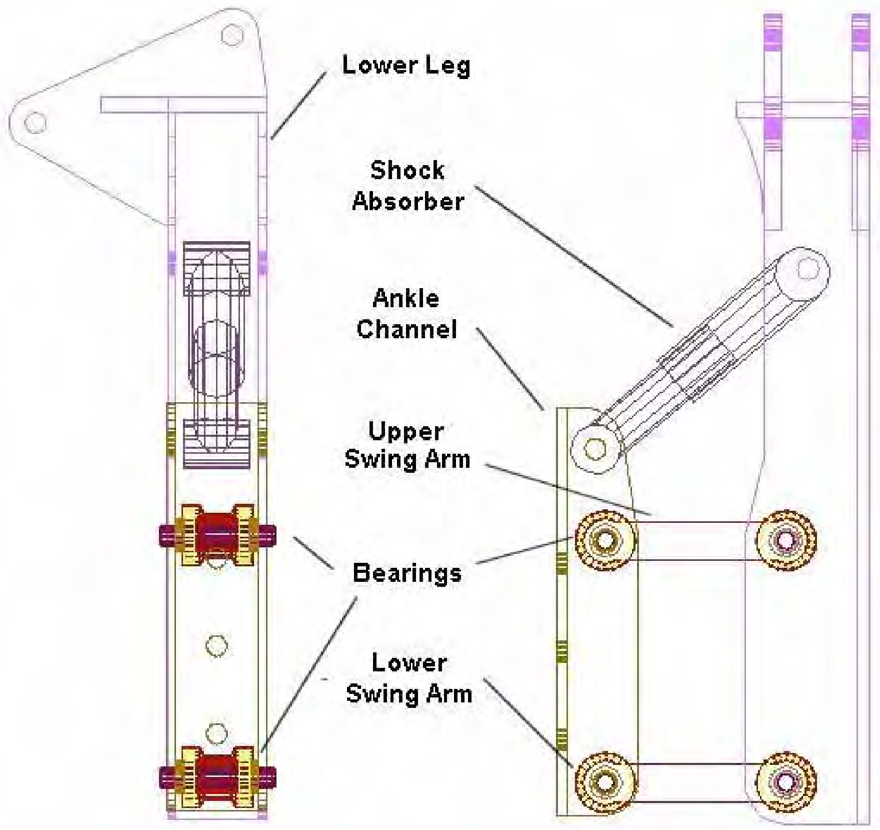


Figure 3.13 Ankle/ lower leg swing arm connection

the major drawback of attempting a large and complex project without a substantial budget is the limited number of iterations available during the design process. While technology such as solid modelling is available, it is only through the construction of prototypes that the design process can be completely optimised

3.3.2 KNEES, LOWER AND UPPER LEGS.

Having completed the design of the ankle, the next section to be created was the lower leg and transverse attachment to the ankle. Again, various configurations were considered before a parallel swing arm arrangement was selected. This design offered the additional advantage of allowing for accurate indication of the load on the feet by measurement of the bending strain in one of the swing arms. It was anticipated that significant shock loads could be generated at the ankle structure contacting the ground at heel strike. To minimise the risk of damage, automotive, pneumatic type shock absorbers were incorporated into the joint with the ability to control spring force via adjustment of air pressure. It was essential that the swing arms would be sufficiently rigid to transfer the moment of the lower leg in the sagittal plane. Each of the ends of the swing arms were fitted into substantial channel sections using ball bearings and stainless steel shafts to ensure that there was no slack in the joint and that the motion would be absolutely parallel. Figure 3.13 shows the parallel swing-arm arrangement which can also be seen in the photograph of Figure 3.14.

Figure 3.14 Swing arm arrangement

The knee of the robot was designed as a straight hinge joint directly driven by a hydraulic cylinder. The joint is formed by a hinge pin running through two roller bearings contained within a housing located at the lower end of the thigh and the top end of the lower leg. Two grub screws located within the cheeks at the top of the lower leg hold the hinge pin laterally and also ensure that it rotates with the lower leg. The knee angle shaft encoder is mounted on the thigh and measures the rotation of the hinge pin. The hydraulic cylinder driving the knee is located within the thigh which was fabricated as a box section structure.

The human hip consists of a ball joint where the femur is able to rotate freely in the socket about three axes, one of which is about the axis of the femur itself. By translating the point of rotation along the axis of the femur, it was possible to limit the hip itself to two degrees of freedom. The thigh (Figure 3.15) is connected to the hip by a 40mm stainless steel shaft which runs down into the thigh through two thrust bearings

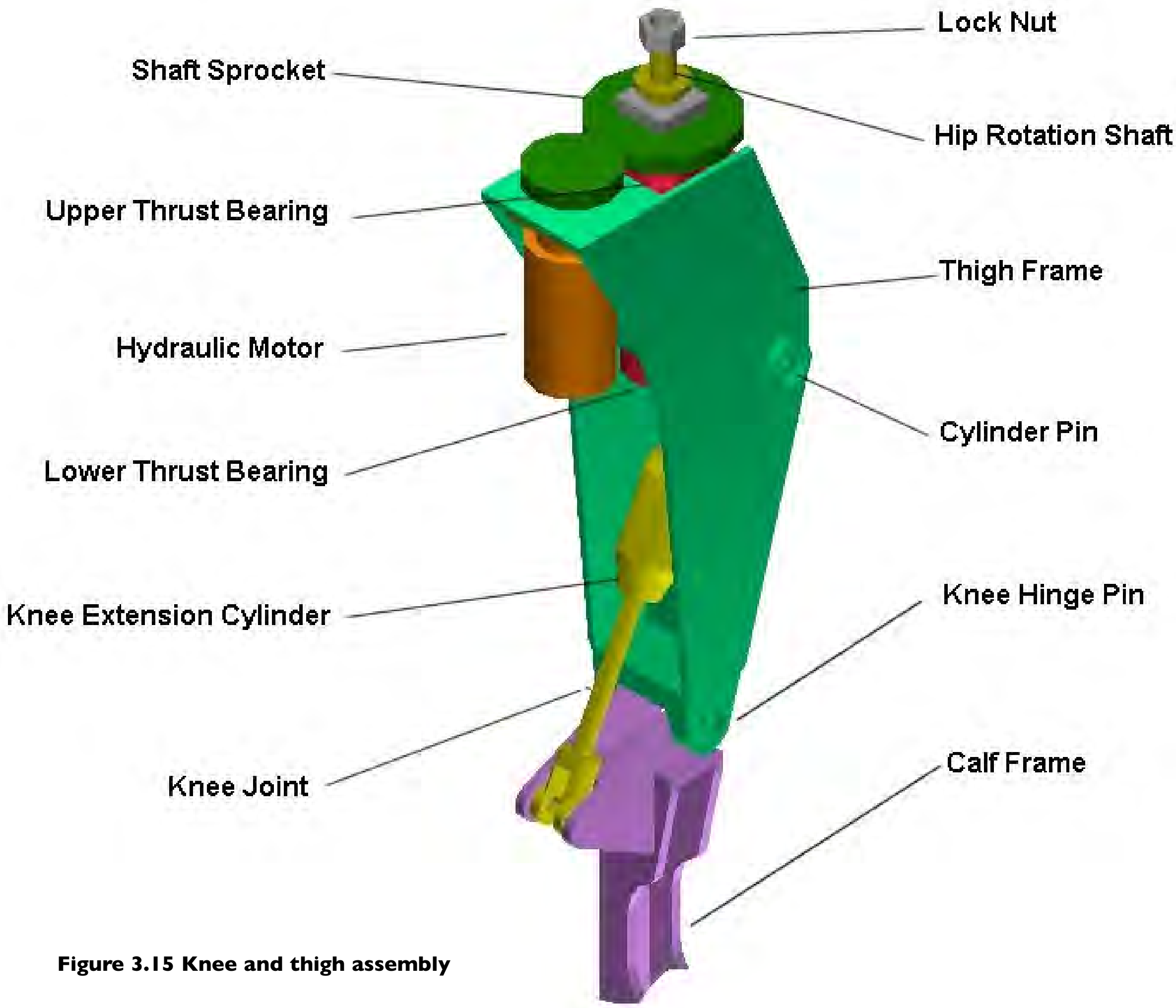


Figure 3.15 Knee and thigh assembly

which support the weight of the robot. These thrust bearings are mounted in opposite directions so that the leg is also supported during swing phase. A hydraulic motor is mounted to the back of the thigh which rotates the thigh around the shaft. This is achieved via a small sprocket on the motor which drives a larger sprocket on the hip rotation shaft (Figure 3.16). The shaft itself is fixed into the base of the hip section and does not rotate. The hydraulic motors are slot mounted allowing for tension adjustment of the chain. Unlike the hydraulic cylinders used to control other degrees of freedom, the motor will allow slip with the controlling valve in the closed position.

3.3.3 HIP

Again, a number of configurations were considered for the hip. The final arrangement is capable of both hip abduction and hip extension with both axes driven by hydraulic cylinders. The hip extension shaft is located by two Plummer block bearings mounted on the suspension plate of the robot. A torque arm is integral to one end of the shaft to which the hip extension actuating cylinder is connected. Extension and contraction of the

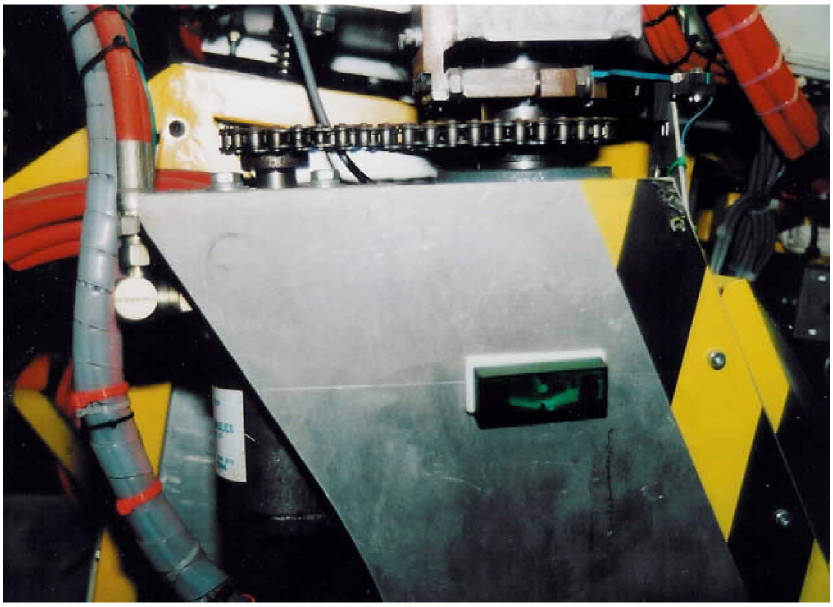


Figure 3.16 Hip rotation mechanism

cylinder rotates the shaft. Mounted on the other end of the cylinder is a boss fitted with a shaft about which the hip is free to abduct, controlled by the hip abduction cylinder mounted above the hip extension shaft. Figure 3.17 shows the layout of the joint. Two grub screws are fitted to the boss which hold the shaft stationary while the hip rotates about it. A shaft encoder mounted on the front cheek plate of the hip measures the movement of the hip relative to the boss, thus giving the hip abduction angle.

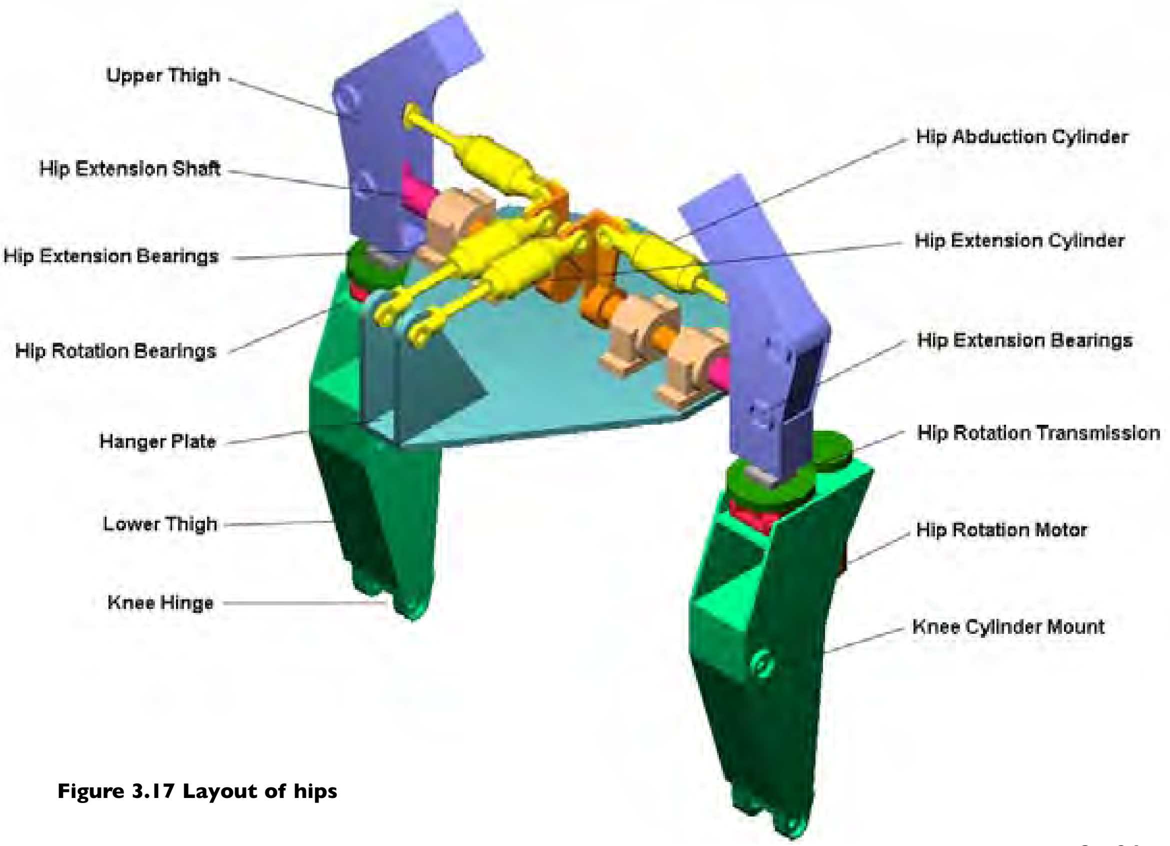


Figure 3.17 Layout of hips

3.3.4 BODY

While General Electric's Hardiman exoskeleton can be considered the first attempt at a biped materials handling platform, it was not strictly a robot as it relied on the human operator's own control abilities to manoeuvre it. As discussed previously, the device was controlled by the movement of the pilot's limbs directly operating hydraulic valves. Ultimately, the control of the device proved too difficult to coordinate and the project was scrapped. Perhaps, if the project were to be recommenced today, it would be possible to insert a level of digital control between the operator and the hydraulic valves. Effectively the control would become "fly by wire" with the operator indicating their intentions to the control system which would then calculate joint trajectories to achieve the required motion while maintaining stability. The control system would prioritise the control tasks, with balance and safety systems having the highest priority, and with the operator's requests being the lowest priority. Such a system would no longer require the operator to coordinate the movement of the Robot's legs, rather the operator would simply indicate via a joystick that the robot should move in a given direction. Once this level of automation had been achieved, there would no longer be a requirement for the operator to be on board the device. Given a communications link with sufficient bandwidth for stereoscopic vision and control data, it would be possible for the operator to be located anywhere in the world. Perhaps, ultimately, the device would become completely autonomous. Effectively, the ultimate conclusion from such discussions is that industrial scale exoskeletons would require such a level of control to convert the operator's intentions to movement of the device, that there would be no requirement for the operator to be on board.

Initial designs of Roboshift displayed accommodation for an operator (see Figure 3.18). However, after analysing power and control system requirements, it was determined that there was no longer space available for an on board operator. Of course there may be some applications where it would be advantageous to have the operator on board, however there would be no requirement for the device to be built as an exoskeleton. It is anticipated that once biped materials handling robots become commercially viable, specialisation of components will significantly reduce the space requirements of the onboard systems allowing for accommodation of an operator.

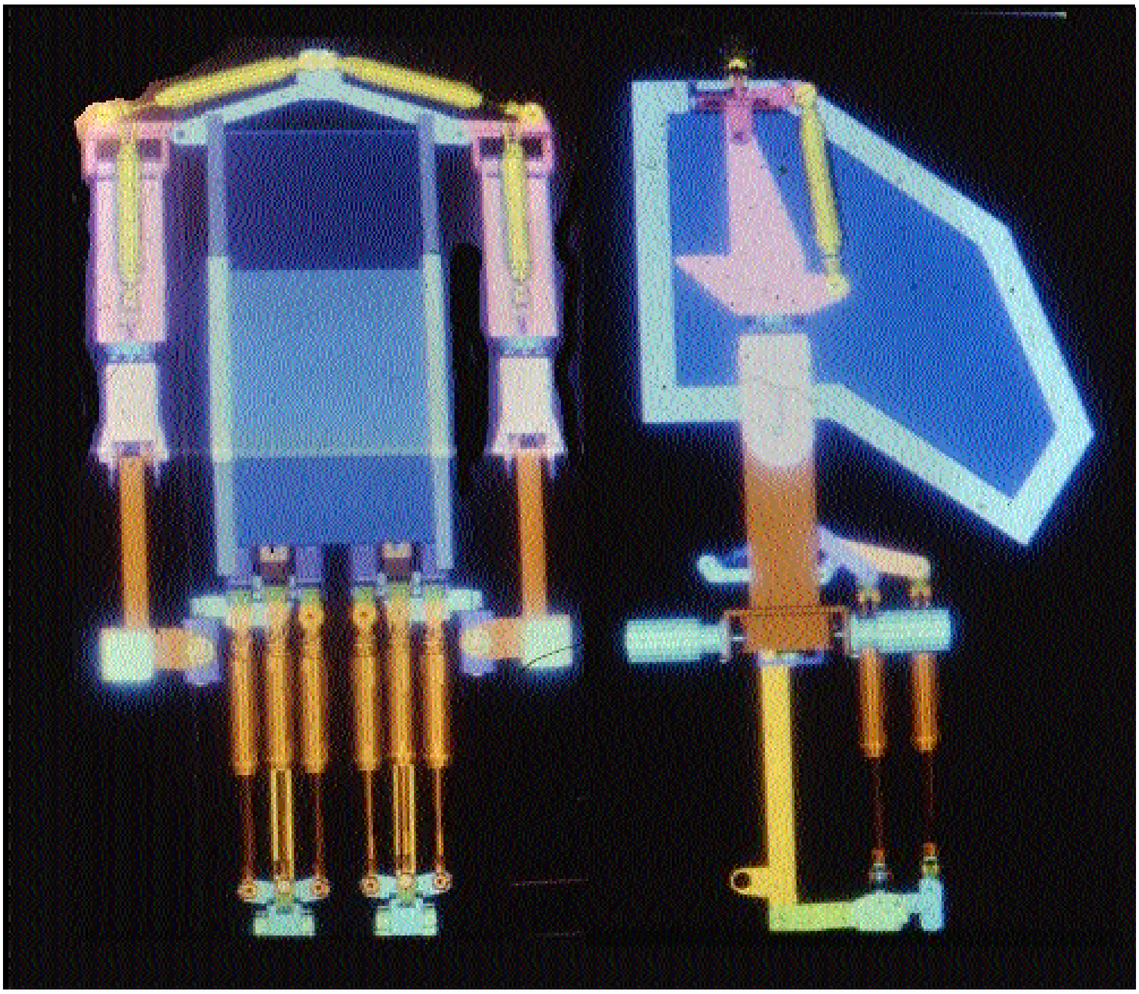


Figure 3.18 Initial design of Roboshift showing operator cabin

3.3.5 CONSTRUCTION

As Roboshift is a prototype of an industrial scale device it is to be expected that some components or systems would require repair or replacement during or after initial trials. Such failure could arise from an incorrect design decision during the initial fast tracked design process, or from electrical or mechanical failure. To minimise unavailability, the primary strategy for the construction of the robot was to ensure that disassembly and the replacement of parts would be as efficient as possible.

For the major box sections such as lower and upper thighs, hips and ankle space frames emphasis was placed on dimensional and spatial accuracy. To achieve a high degree of precision between left and right hand members, drawings were prepared from the solid models of components used to design the robot. These were then downloaded to a numerically controlled water cutting machine which then cut the frame panels. The panels were then fabricated into frames using TIG welding to “stitch” the panels together. Once the stitched fabrications had been checked for accuracy, they were them MIG welded after being heated to ensure penetration. Where additional strength was required around bearing mounts or where hinge pins were located, machined components were welded to the frames. Power and control system hardware making up the "body" of the robot have been arranged in modular form under the hips in such a manner as to maintain the centre of gravity of the body under the hips. These modules are discussed in the following chapter.

Once all of the aluminium body parts had been fabricated, they were assembled together with the hydraulic actuators to form the basic structure shown in Figure 3.19. The photographs clearly show the hydraulic actuators and the bearings that coincide with the degrees of freedom of the joints. The instrumentation console can be seen hanging below the hips in the initial configuration where hydraulic power and main control processing were externally located. Once initial testing was completed, the hydraulic power pack was fitted under the hips with the instrumentation console mounted above and aft of it.

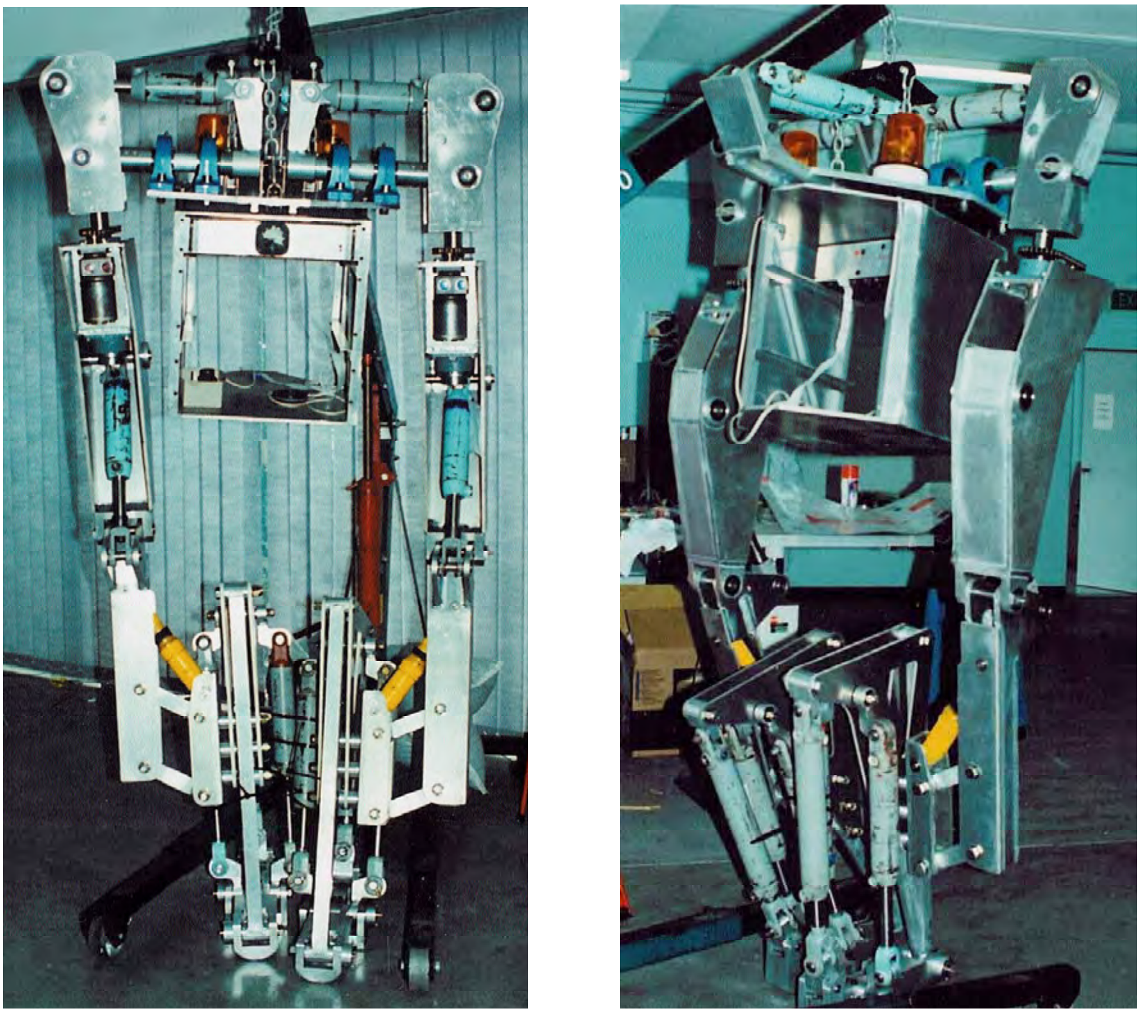


Figure 3.19 Mechanical structure of Roboshift

4 POWER AND ELECTRICAL DESIGN

I am an old man now, and when I die and go to Heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics and the other is the turbulent motion of fluids. And about the former I am rather more optimistic.

- Sir Horace Lamb

The world is full of mobile systems relying on self contained power units to provide motive force and electrical power. The car, for example contains an internal combustion engine which provides drive and also powers the alternator to provide electrical power and a hydraulic pump to provide hydraulic flow to drive the power steering. Cranes, garbage trucks, excavators and forklifts all use internal combustion engines to provide electrical and hydraulic power. In very few cases do any of these systems rely on real-time control for the actuation of their systems. In the case of a forklift truck, the sizing of the hydraulic pump is dependent on the weight to be lifted and the speed at which it is to be raised. The desired speed is a function of the required productivity of the vehicle, the size of the engine and the viable cost of materials of the forklift. Whether the pallet takes four seconds to reach the desired height or four and a half seconds to reach the desired height is not critical to the operation of the device. The manufacturer makes a financial decision based on market research to determine the acceptable speed of lift in order to minimise the cost of the hydraulic pump and engine of the device.

In the case of a biped robot, it is critical that the motion of the joints is able to be controlled in real-time if the robot is to actively balance. Achievement of this constraint is dependent on a control system capable of processing the required information in the required time, and an actuation system capable of moving the joints with the required velocity. As discussed in the previous chapter, a hydraulic system was chosen as the motive force in this project for the following reasons:

- The skill set of those involved in the project
- The capability to deliver required force
- The available resources
- The fact that the Wabot (Kato, 1987)) was hydraulically driven and was able to walk with a quasi static gait

This chapter details the design of the hydraulic and electrical power systems to achieve the motion required for locomotion. In section 4.1.1, the required hydraulic flows are calculated based on the expected motion of the robot and the size of actuators. Pump configuration is then discussed in section 4.1.2 as is the problem of hydraulic crossflow. A schematic of the hydraulic system is provided showing the three separate pressure systems used to drive each leg and the hips. The section concludes with a photograph of the power pack as built. Electrical systems are described in section 4.2 culminating in a schematic of the system and the sizing of the alternator. This information then allows the internal combustion engine to be sized and the final configuration of the power pack is realised.

4.1 HYDRAULIC DESIGN

To determine the required capacity of the hydraulic power pack it was necessary to establish the peak flows required by the hydraulic components during the gait cycle. As previously discussed, kinematic models were used to determine the range of movement required by the joints. These models were then used to calculate the peak joint velocities and the corresponding hydraulic component flows.

4.1.1 FLOW CALCULATION

The chart shown in Figure 4.1 displays the joint trajectory angles for a single human gait cycle. Once again it was assumed, during the design phase of the project, that if the geometry of the robot was similar to that of the human lower limb system, and could be controlled, the robot would be capable of biped locomotion. It was therefore assumed that the gait cycle would be somewhat similar to that of the human. For this reason the human

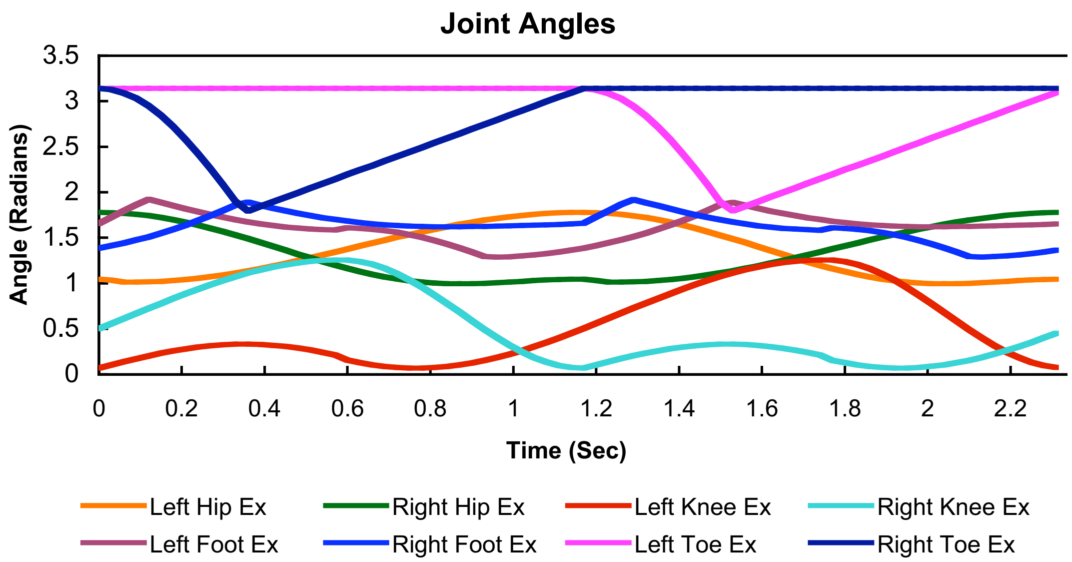


Figure 4.1 Joint angles over single gait cycle

gait cycle was used as the basis for the calculation of hydraulic flow required for locomotion. A target velocity of 1.4 metres per second or 5km/h was used to calculate hydraulic flow. At this velocity the gait cycle would be completed in approximately 2.5 seconds.

The following analysis was conducted to determine the hydraulic flow required for each joint:

- The cylinder length was calculated as a function of joint angle
- The cylinder length was numerically differentiated from one iteration to the next to determine the cylinder velocity
- If the velocity was positive, it was multiplied by the cylinder end area to determine the flow. If the velocity was negative, it was multiplied by the rod end area (the cylinder area less the area of the rod) to determine the flow

The results of the analysis shown in Figure 4.2 indicate that the maximum flow occurs in the toe cylinders. On first inspection it may appear unexpected that movement of the toe would require a high capacity of oil. However, with no toe movement relative to the foot, the toe cylinder must move proportionally with the foot to maintain the toe angle. Given that the toe is located further from the ankle than the foot, the velocity required to maintain the toe angle is higher than that required to move the foot itself. When this demand is combined with the demand required for actual toe movement relative to the foot, the flow spike can be seen as shown in Figure 4.2 after 1.2 seconds.

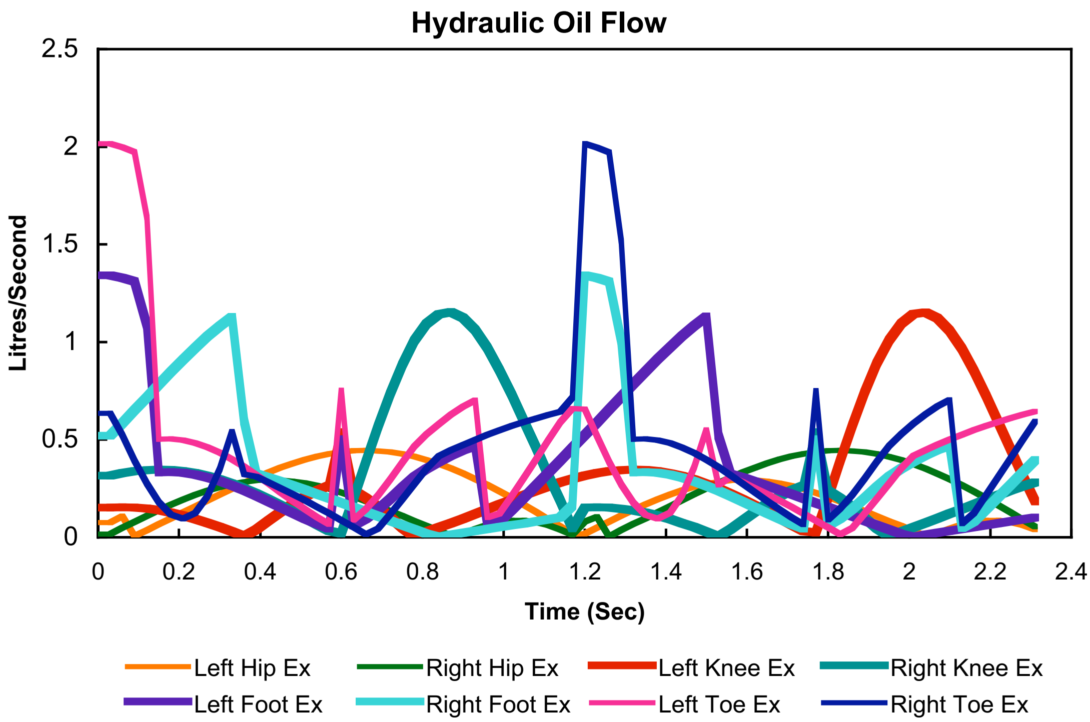


Figure 4.2 Total flow requirements for single gait cycle

Accumulators are used in hydraulic circuits to temporarily store hydraulic fluid under pressure so that it can be released during periods of high demand. By acting much as capacitors in electrical circuits, the accumulators reduce the maximum flow requirements of the hydraulic pump by storing oil during periods of lower demand. To determine the appropriate size of the accumulator, the individual flow requirements were summed to produce the total flow requirement seen in Figure 4.3. The spike can be seen again in Figure 4.3 after 1.2 seconds, however it has been amplified as the foot cylinder flow has now been added to that of the toe. This spike occurs immediately after heel strike as the foot and toe quickly extend to the ground. The flow analysis was achieved by manipulating the flow and accumulator variables on a spreadsheet. Values for pump flow rate and the size of the accumulator were determined. The blue line in Figure 4.3 shows the oil stored in the accumulator during the gait cycle given a pump capacity of 2.6 litres/second and an accumulator capacity of 1 litre. As discussed, this analysis was based on the motion of the human lower limbs during normal gait. By varying the gait, it may have been possible to reduce the spikes seen in the foot and toe cylinders. However, without substantial analysis such a deviation from the strategy to maintain human like characteristics was not considered. Having established the flow required, the method of distribution of oil was then considered.

4.1.2 HYDRAULIC CIRCUIT DESIGN

In typical industrial hydraulic applications the motion of actuators is well defined. Systems are designed so that ample flow is available for each axis of motion in order that the operation of one actuator does not affect the supply of oil to the other. This effect, known as crosstalk, can make the control of hydraulic actuators difficult and

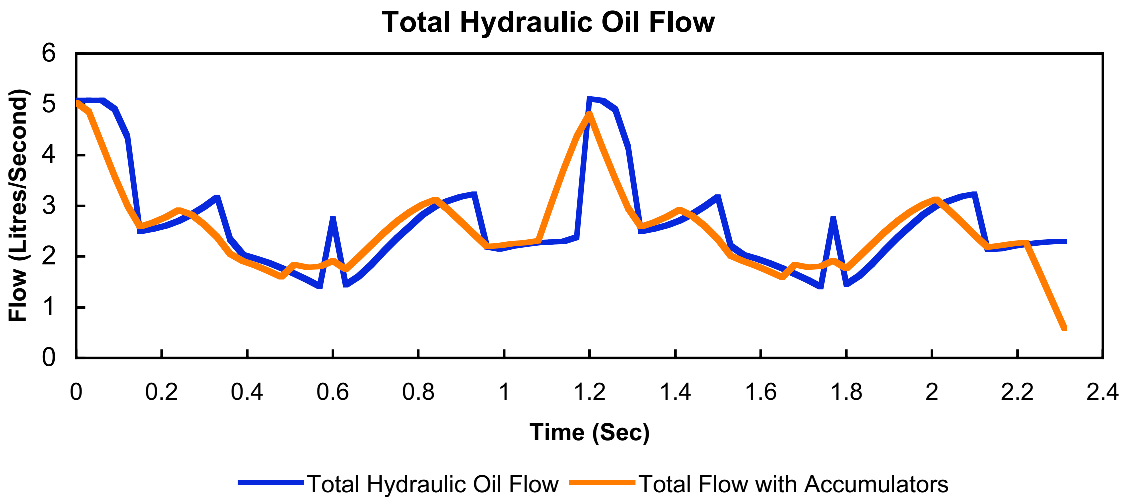


Figure 4.3 Total hydraulic flow

unpredictable. As an example of this in robot design, unqualified accounts such as reported by Wiess (2001) would indicate that General Electric's Hardiman suffered from severe hydraulic crosstalk.

The robot, as heavy as a car, would have enabled a person to lift a refrigerator as though it were a bag of potatoes. However, the machine's inventors could only get one arm of the device to work. And attempts to operate both legs at once would lead to "violent and uncontrollable motion," according to an old report on the project.

Hydraulic crosstalk can be explained in terms of domestic water pressure. It is not uncommon for the water pressure in the shower of a house to be affected by a washing machine or someone using the kitchen sink. However, as the street supply is at a higher pressure and higher flow, turning a shower on in one house does not affect the shower pressure in the house next door. Similarly, hydraulic cross flow can be dealt with by ensuring that the pressure on the supply side of the controlling valves is always substantially greater than that required by the actuators. A second method to deal with cross flow is to provide independent supplies for actuators. In the extreme, this method would involve a separate hydraulic pump for each actuator. The drawback to this solution is the complexity of the pump arrangement and the amount of space required for

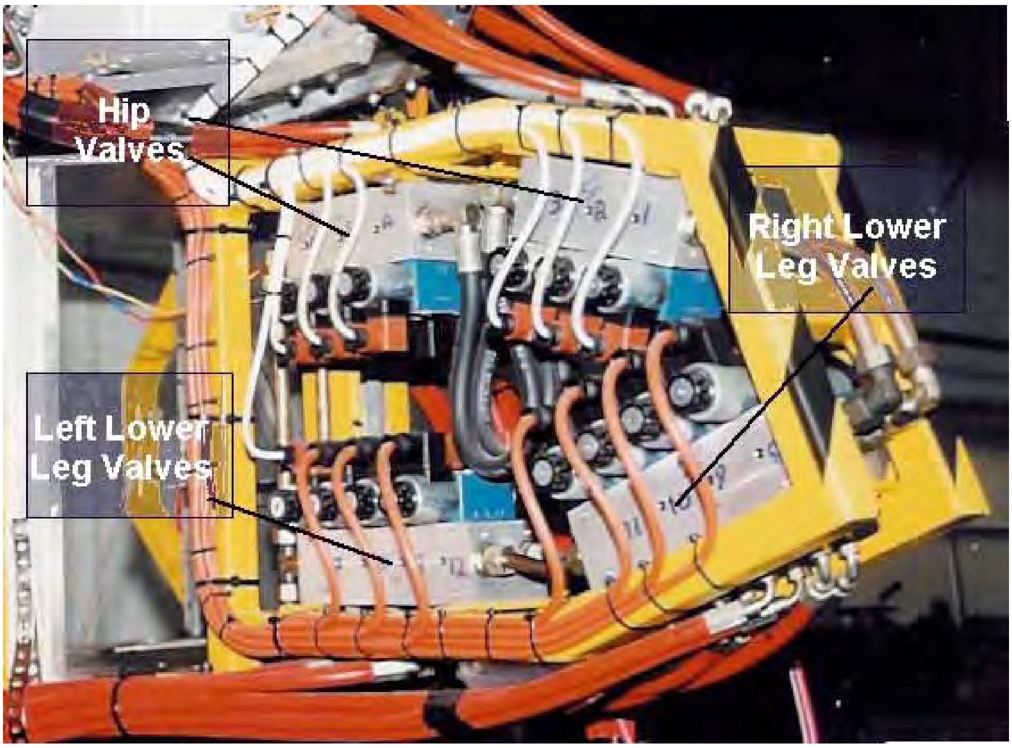


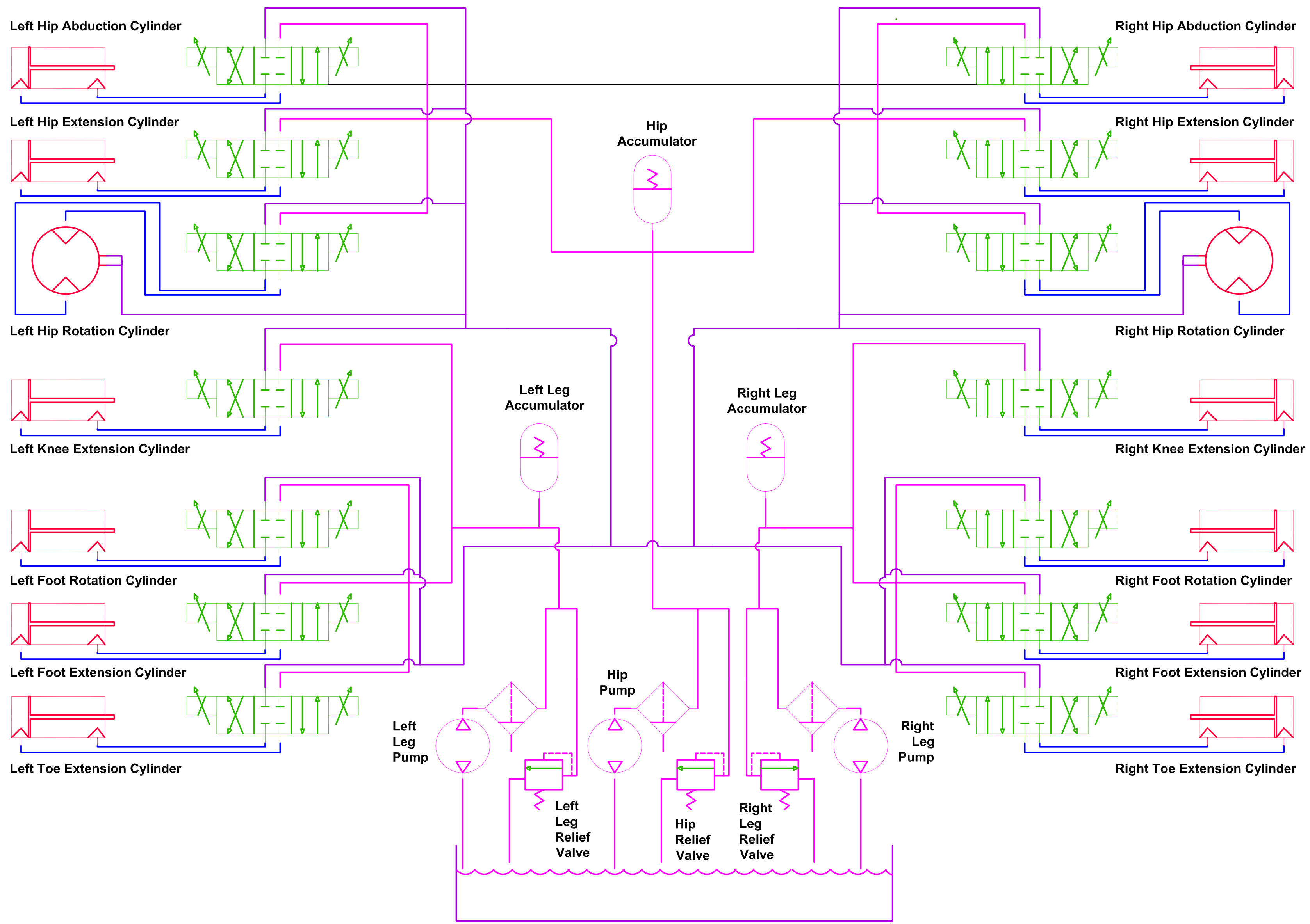
Figure 4.4 hydraulic valve manifolds

the pump units. In the case of Roboshift, the decision was made to use three separate hydraulic pumps. One pump is used to drive the actuators on each of the lower legs with the third pump used to drive the hip actuators. In this way, the large flow requirements of the feet and toe cylinders on one leg do not affect the flow or pressure on the cylinders of the other leg. As seen in Figure 4.2, the flows required by the hip cylinders are not large, therefore given enough pressure and flow, the operation of the hip actuators on one side of the robot should not affect those on the other side. To facilitate supplying the appropriate groups of actuators, the hydraulic valves were mounted on a number of manifolds as shown in Figure 4.4.

The analysis used to determine total flow was used once more to determine the size of pump and accumulator required for each leg and for the hips. Pumps used for the legs were 50 litre/minute and the pump for the hips was sized at 30litres/minute. All of the pumps were selected as gear pumps which required the use of a pressure relief valve to maintain the system's pressure. An advantage of this configuration is that the system pressure can be changed easily by adjustment of the relief setting. The circuit design included an accumulator in each pressure branch as well as an inline filter to protect the valves. Valves chosen were Rexroth WRE10-6 proportional valves. A common return was used for the three branches of the hydraulic system. A schematic of the hydraulic circuit can be seen in Figure 4.5 on the following page. The flow of hydraulic oil through the system and particularly the flow of oil over pressure relief valves leads to a build up of heat in the oil due to friction losses. In the majority of hydraulic applications, the oil reservoir is sized so that heat is dissipated via natural radiation through the tank walls and via convection from the tank walls. As well, the majority of hydraulic systems are designed to be run on a non continuous basis. In the case of this robot, not only must the system run continuously, but space and weight constraints reduce the size of hydraulic oil reservoir able to be carried on board. To address the build up of heat in the hydraulic oil, a fan forced radiator was placed in a branch of the common return line. By the setting of a needle valve, the proportion of oil returning to the tank via the cooler can be adjusted.

Once the decision was made to dissipate heat via a forced fan radiator, the main design criteria for the hydraulic tank became:

- Size to be able to fit between the robot's legs



NOTES:

1 -> Remove all sharp edges

2 -> All dimensions in millimeters

DRAWING NO:		UNIVERSITY OF NEW SOUTH WALES SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING	
TITLE:		SCALE NTS	Block Import Scale
DRAWN	Joe Cronin	REVISION	1
CHECKED		SHEET SIZE	A2
APPROVED			
MASS			
MATERIAL	Aluminium (5803)		

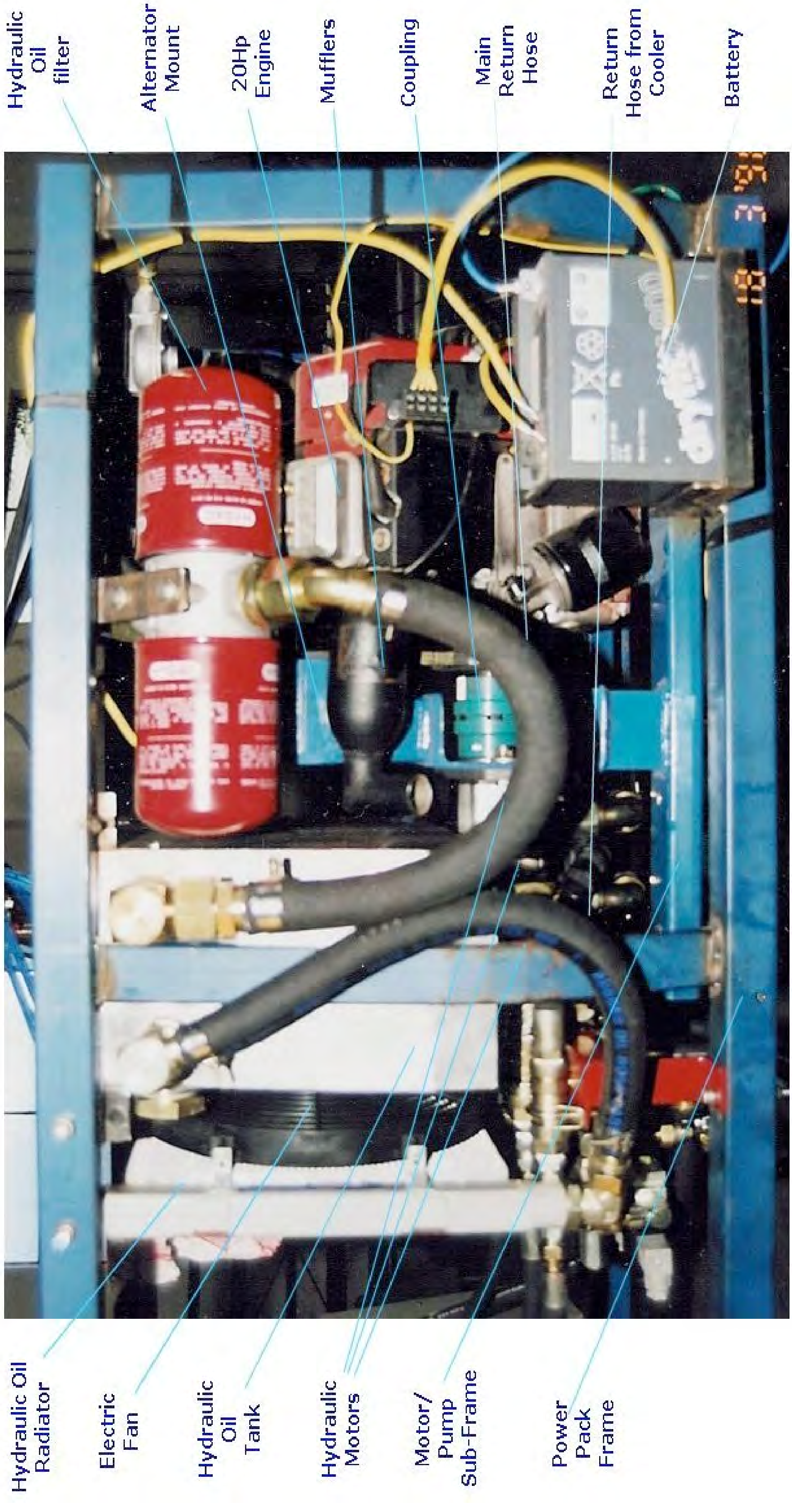


Figure 4.6 Hydraulic power pack

- Sufficient length of flow and baffling to ensure separation of entrained air
- Sufficient volume to provide positive pressure in the suction area
- Positioned so that suction pipe length was kept to a minimum

The installed 35 litre stainless steel tank can be seen in Figure 4.6.

Proportional directional hydraulic control valves require amplifiers to convert an analogue control signal to a coil control current. Rexroth/Bosch VT1001 valve amplifiers were used to control the 4WRE6 valves installed on the robot. As the current is controlled by pulse width modulation, the amplifier wires and valve coils can generate significant electro magnetic fields. To reduce any interference effects, the amplifiers are mounted in an enclosure that is placed away from transducers and other electronic equipment that may be sensitive to electronic noise. As well, the valve banks have been mounted as far as possible from the body of the robot, under the amplifier box so that the lengths of valve control wires could be kept to a minimum. Figure 4.7 shows the control valve enclosure.

The hydraulic hosing of the robot was completed in situ as it would be exceedingly difficult to model the hose work in three dimensions. Given the complexity of the circuit,

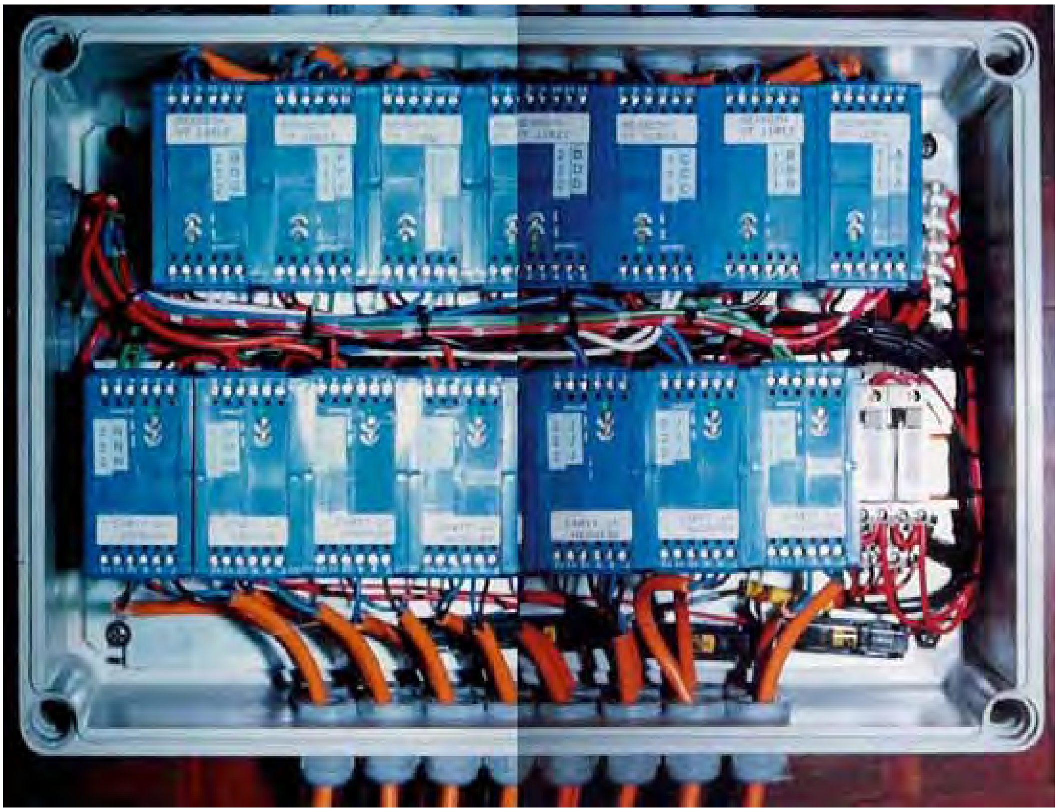


Figure 4.7 VT1001 hydraulic valve control amplifier enclosure

the hoses are tightly packed and proved extremely difficult to connect and tighten.

4.1.3 CONCLUSIONS ON HYDRAULIC DESIGN

The research conducted during the design and construction of the robot has led to the identification of a number of design challenges that will be in common with any other industrial biped robot that will be built in the future. Certainly, any large organisation equipped with sufficient resources will be able to design and produce custom hardware to solve a number of design issues such as hosing. However, flow requirements, dissipation of heat, hydraulic crosstalk, location and sizing of reservoirs and the production of power to drive the hydraulic system represent design issues for an industrial scale biped which have been addressed for the first time by this project.

4.2 ELECTRICAL DESIGN

Design criteria four and five required that the robot be self contained and capable of continuous operation. As the project is based on an industrial scale biped, it should be expected that the robot would be able to work continuously for a four hour period. Brief analysis suggested that a load of twenty to thirty Amps of 12V and 24V power would be required to maintain on board systems. Given that an internal combustion engine was available, the use of an alternator was deemed to be more efficient than batteries to supply power. This section details the various on board systems requiring electrical power and outlines the circuitry that provides it.

4.2.1 ELECTRICAL POWER REQUIREMENTS

To determine the amount of on board power required, an inventory of electrical equipment was produced as found in Table 4.1.

In the case of the hydraulic valve amplifiers the average flow of all valves over a gait

System	Power
Valve amplifiers	3A @ 24VDC
Oil cooling fan	14A @ 12VDC
Artificial horizon compressor	8A @ 12VDC
Inverter 1	12A @ 12VDC
Inverter 2	12A @ 12VDC
Microprocessor enclosure	4A @ 12VDC, 1A @ 24VDC, 1A @ -24VDC
Audible alarm system	5A @ 12VDC

Table 4.1 Inventory of on board power requirements

cycle was determined to be 2.6 litres/minute. This equates to an average flow of 0.19 litres/valve/second. Based on the data sheet for the 4WRE6 valves, this flow rate equates to a coil current of 0.15 Amps. Conservatively, the hydraulic amplifier demand was deemed to be of the order of 3 amps at 24 Volts DC. Ideally, a separate alternator would be provided for both 12V DC and 24V DC power. However, due to space constraints, only a 12V alternator was fitted to the robot. For this reason, the alternator provides 3 Amps @ 12VDC to the amplifiers with a battery also supplying 3 Amps @12VDC in series.

Table 4.1 details several electrical units that require -24V DC power. In general this voltage is required for the instrumentation amplifiers found in the strain gauge amplifier enclosures and for the analogue output generated by the I/O boards in the microprocessor enclosure. Two 80 Amp hour batteries are used in series to provide this power.

In addition the starter motor of the engine would require about 35 Amps at 12VDC which is another major current draw. However, the demand is brief and would not contribute to the overall power requirements during normal operation. As the starter motor will create a significant voltage drop during starting, the electrical circuit has been designed so that all onboard systems can be supplied by the battery charger during engine starting. The switch panel is designed so that the alternator circuit can be connected prior to the battery charger being disconnected.

4.2.2 CIRCUIT PROTECTION

One of the interesting questions facing the designer of mission critical electronics is that of circuit protection. This is particularly the case in the aviation industry where a loss of power to flight critical components will cause a total loss of control. In these applications the use of circuit breakers is augmented by redundant systems, so that if one circuit blows, the alternate system provides the functionality to keep the plane flying. Like a modern fighter, a biped robot relies on automatic control systems to stay up right. The potential for a failure to cause catastrophic damage to the vehicle, to property or to the pilot or other persons is extremely high. In the case of this project all electrical and electronic systems are protected by fuses. At the time of writing, all testing of the vehicle has been conducted while the robot has been loosely tethered from an overhead suspension point. During testing the safety slings are lowered to provide the robot unrestrained movement. However, in the event of a failure, the device can only lean to a limited extend before the tension in the slings prevents further falling. In the critical

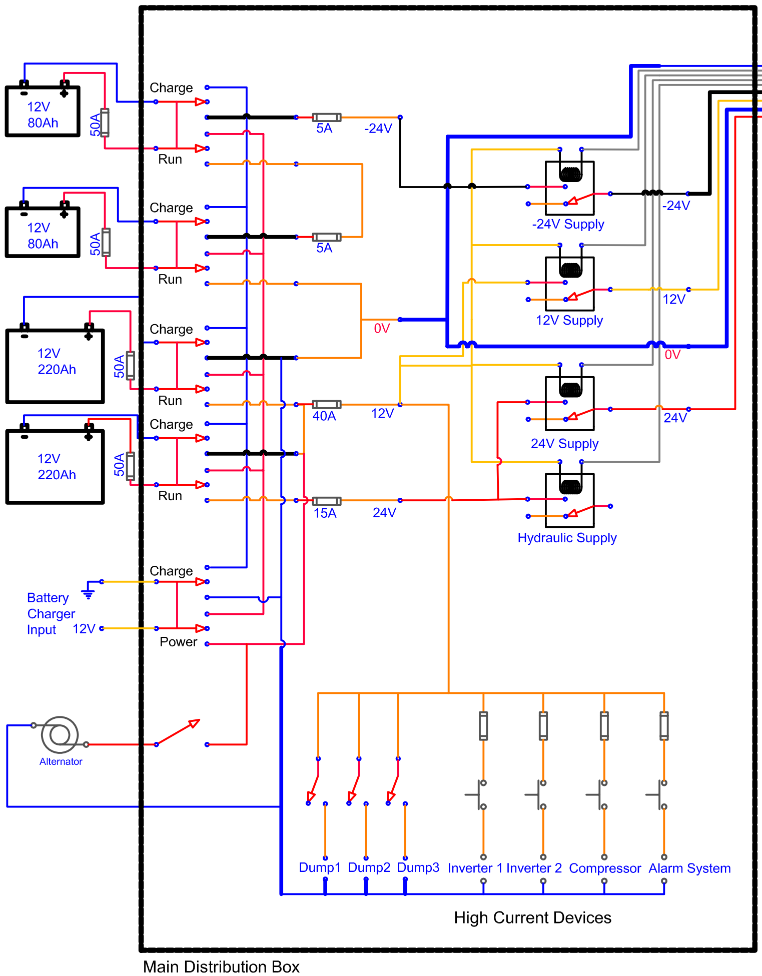
Figure 4.8 Main distribution enclosure

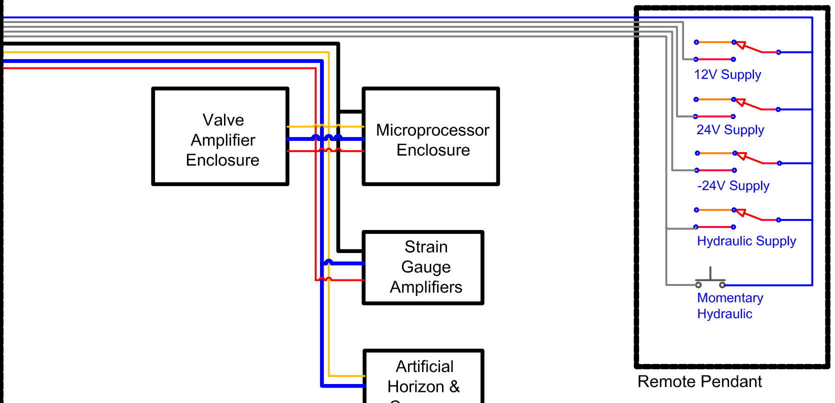
event of a circuit fuse blowing, the robot will lose control and become unstable.

As can be seen in the robot's electrical circuit found in Figure 4.7, all of the 12V DC batteries are protected by 50 Amp fuses. These batteries are Sonnersheim gel cell type batteries capable of providing up to 270 amps in a short circuit situation. The fuses are located immediately at the positive terminal of the batteries to minimise the possibility of fire or explosion in the event of a battery circuit shorting. The main distribution box also includes fuses on the incoming -24V, 0V, 12V and 24V DC circuits as well as 10 Amp fuses on the supply to heavy current devices. Finally, all of the major electrical components and enclosures include fuses in their incoming circuits. The primary purpose of the fuses is to protect the electronics on the robot which have consumed considerable resources during their manufacture and installation. As the device and the majority of the electrical componentry are of a prototype nature, the probability of circuit failure is significantly higher than that which could be expected of mass produced devices and components certified by quality assurance procedures. Any commercial device would require the use of redundant components and circuitry to ensure that if one fuse were to blow, the continuity of mission critical functionality would be assured.

4.2.3 POWER DISTRIBUTION

As previously discussed, power from the batteries is fed to the main distribution





Main Distribution Box

Remote Pendant

DRAWING NO:	
TITLE:	

NOTES:

ROBOSHIFT - Electrical Distribution Circuit.

DRAWN	Joe Cronin
CHECKED	
APPROVED	
MASS	
MATERIAL	

UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING

SCALE		REVISION	SHEET SIZE

Figure 4.10 main distribution panel

enclosure (see Figure 4.7). As shown in the circuit diagram of Figure 4.8, the four main switches of the enclosure allow the batteries to be disconnected, switched to the battery charger or switched to the main circuit to provide power for the robot. The battery charger connection can also be switched from charging mode to a boost mode for the primary 12V battery. In the boost configuration, the battery charger is connected in parallel with the primary battery and is used when testing the robot for long periods when the alternator is not providing power. An additional four switches provide power to the two inverters, the air pump and the audible alarm system. Finally, power to the three hydraulic dump valves is provided by the operation of three switches. When energised the dump valves close, forcing the hydraulic fluid past the three relief valves sustaining system pressure. The purpose of the dump valves is to decrease the starting torque of the engine.

Power to the rest of the system is controlled by the remote pendant (see Figure 4.9). This enclosure houses a number of switches which activate relays in the main distribution box. Primarily the pendant is a safety device that allows all power to be cut in the event of malfunction. Particularly valuable during initial testing, the box allowed power to be cut to the hydraulic valve amplifiers when potentially damaging motion was observed. Cutting power to the amplifiers immediately centred the valve spools, cutting all flow to the hydraulic actuators. The “momentary” switch on the pendant allowed the operator to energise the hydraulics for brief periods so that direction and velocity of actuation could be confirmed.

4.2.4 WIRING

All power wiring has been completed in silicon rubber high temperature cabling. This material was used as it presents a high resistance to hydraulic oil as well as resistance to heat generated by the engine exhaust components and hydraulic lines. Neutrix Type and Contact Type connectors have been used for cable terminations as they provide positive locking to prevent intermittent connections caused by vibration from the LPG engine. All battery cables consist of 18mm^2 cable, however the immediate connection to the battery is of 6mm^2 cable, so that in the event of a complete short circuit the smaller cable becomes a fusible link.

4.2.5 CONCLUSIONS ON ELECTRICAL POWER

From Table 4.1, it can be seen that, even though the robot is hydraulically actuated, up to 60 Amps of 12VDC power is required to maintain auxiliary and control systems. This represents up to 0.75 kW of engine output. A forklift truck may require three or four Amps of 12VDC power during normal operation. At such time as a large manufacture commences production of biped materials handling platforms, economies of scale may result in substantial rationalisation of electrical power requirements. However, the work conducted in this project has identified the efficient use of electric power as another challenge associated with the development of industrial scale biped robots. Further, the large disparity in the electrical power requirements of a biped robot compared to that of a wheeled vehicle demonstrates the increase in the level of complexity between wheeled and legged vehicles so that the supply to the microprocessors will not be interrupted.

4.3 THE ENGINE

Traditional materials handling equipment relies on low speed, reliable, heavy engines as power sources. As the vehicles are wheeled and are designed to be heavy in order to counterbalance the load, there is no requirement to lighten the engine or to increase its power to weight ratio. A forklift with a similar capacity and size to that of the industrial biped proposed in this project, the Toyota 40-3FG7, is powered by a 4 cylinder gasoline engine with a displacement of 1486cc delivering 31Hp @ 2400rpm and 98Nm @ 1800rpm[1]. Clearly, the motor is designed to produce high torque at low motor speed.

Just as the first powered flight only became possible after the advent of higher speed lighter engines, industrial bipeds will also rely on lighter, more powerful engines than those found in traditional materials handling equipment. The selection of engine for the robot was based on the following criteria:

- Readily available with a ready supply of parts
- Proven industrially robust
- Extensive knowledge base of performance characteristics
- Lightweight

1 www.hino.com.tw/toyota/B2_3_1a_2.asp

• Able to provide the required power and torque

An extensive knowledge-base of the performance characteristics was required as the engine aboard an industrial biped would be subjected to a range of conditions that may be beyond the design envelope of some engines. As the space requirements of the biped are at a minimum, the engine would be difficult to access and overhaul. For this reason, the engine would need to be robust and relatively maintenance free. The engine would be subject to forces and accelerations that no other industrial engine has ever seen before; that of biped locomotion. While not considered excessive, the motion may interfere with such processes as carburation and fuel flow. It would be expected that an engine used in a wide range of machinery would stand the highest probability of withstanding such forces with no degradation in performance. The first stage of engine selection was to choose engines that provided the required torque and power to drive the hydraulic and electrical systems. The second was to consider these environmental effects.

4.3.1 ENGINE POWER

To determine the required power to drive the hydraulic system, the system operational pressure and the system flow rate are required. The system operational pressure for each pump is calculated from the maximum pressure required by any one cylinder supplied with oil from that pump. To determine which actuator in each pump system required the maximum pressure, forces and pressures within all hydraulic actuators must be calculated. As the exact gait of the robot had not been determined at this stage of the design, such an analysis would be based on a level of estimation that would make detailed analysis superfluous. Alternatively, as dynamic calculations had been used to verify the hip slung body configuration of the robot, it was decided to analyse the kinematic model used for the mechanical design of the robot to determine the stages of the gait where maximum acceleration occurred. Investigation of the kinematic model showed that toward the end of swing phase, the foot and toe cylinders of one leg accelerate the entire robot in the vertical direction. At this point in the gate cycle, the entire weight of the robot is taken by the two foot cylinders and toe cylinder of one leg. The triangle of contact of these cylinders fits inside a 100mm circle drawn on the ground. It was unrealistic to attempt to determine the weight distribution within this triangle without knowing the exact gait of the robot and within the limits of error introduced by compliance, expansion of hydraulic hoses and other unknowns. To continue the analysis, it was assumed that the load would be shared by the two foot cylinders combining to take half the load and the toe cylinder taking the other half of the load. This assumption leads to the toe cylinder supporting half of the total load of the robot and accelerating that load

$$F_{Cyl} = \left(\frac{600}{2}\right) \cdot (1 + 0.15) \cdot g = 3.4kN$$

by 0.15g. The cylinder force would then be, with an estimated total weight of 600kg:

$$P_{Cyl} = \left(\frac{F_{Cyl}}{A_{Cyl}}\right) = \left(\frac{3400}{1134}\right) = 3Mpa = 30bar \approx 500psi$$

Given an internal cylinder diameter of 38mm, the pressure was calculated as:

Essentially the system pressure would be in the order of 3Mpa. However, this figure does not take into account pressure drop and power loss through friction in the hydraulic system. It is at this point that the "black art" of hydraulic system design comes into play[2]. Using an efficiency of 0.6, and a duty cycle of 0.7 (assuming that the swing leg of the robot would not require the full system pressure), the power requirement for the system

$$P_{\mathrm{Re}\,quired} = \left(\frac{Q_{Average} \cdot p_{System} \cdot C_{Duty}}{\eta_{System}}\right)$$

was calculated as:

= 9.1kW = 13Hp.

The electrical load of 0.75kW, calculated in the previous section is added at this stage of the analysis. Under most safety legislation, there is a recommendation[3] that internal combustion engines are fuelled by liquid petroleum gas (LPG) when working in confined industrial environments. A power loss of 15% to 20% can be expected from the use of LPG which would increase the required standard engine power to approximately 12kW or 15Hp. To determine the required torque of the engine, the pump displacement per revolution is required. Given that gear pumps will be used with an optimal

2 Given sufficient resources, time and expertise, it may be possible that the exact dynamics of the robot and the of the hydraulic system could be determined. However, given the time available to complete this project, such an analysis was not possible, nor would such an analysis be completely accurate. Having access to a number of highly respected hydraulic experts (acknowledged at the front of this document), after inordinate arguments over countless cups of coffee, it was decided that a factor of 0.6 be used to take into account pump efficiency, loss and friction in cylinders.

While some may argue that there is no place in a scientific document, such as a PhD, for such engineering, the system to be modelled was small compared to other systems that have been modelled using proprietary hydraulic software from companies such as Rexroth. Copies of the software were made available to the writer, however the results were inconclusive as often the input was interpreted from tables that did not provide data for the flow levels and pressures that were expected to be used in the robot. Again, given access to respected experts in their field, the writer argues that where definitive technical analysis is not available, the combined experience of those available represented valid data from which to make sound and reasonable judgement..

3 www.ohsrep.org.au/hazards/confinedspaces.html

$$D_{ispl.} = \frac{Q}{\omega} = \frac{2.6}{\frac{3000}{60}} = 0.0624l$$

hydromechanical efficiency of 0.85 at 3000rpm, this gives a displacement of:

This equates to a torque of:

$$= 0.0624 \cdot 3000 \cdot 0.7 / \pi$$

$$= 41\text{Nm}$$

Effectively the engine specifications are 12kW and 41Nm @ 3000rpm.

4.3.2 ENGINE SELECTION

Fortunately, these specifications lead to the upper end of the industrial range of air cooled stationary engines from a number of manufacturers. Table 4.2 shows the three main contenders from Kawasaki, Honda and Briggs & Stratton. Comparison suggests that this size of engine is widely used for industrial applications as the specifications are almost identical.

These engines are used in equipment as varied as pumps, generators, concrete cutters, ride-on mowers etc. Such wide usage suggests that the forces generated from biped locomotion would not interfere with the operation of the engines. The flange mount dimensions on these three engines are identical. The base mount dimensions on the Briggs and Stratton and the Honda are identical. Essentially these engines are designed to be interchangeable in most applications. On face value, it can be seen that the Honda possesses slightly more torque due to the increased stroke, but loses power and torque at higher RPM. However, the Briggs and Stratton motor maintains power at higher rpm with a torque curve that displays a steeper positive slope at the operating point. As the engine speed drops, torque would increase under load.

Due to the allowances made during the analysis, all of these engines were expected to be oversized for the task. However, the engine is a major piece of hardware; difficult to replace, even more difficult to replace with a larger one. The Briggs and Stratton motor is an extremely reliable engine that has been available for approximately 10 years in the

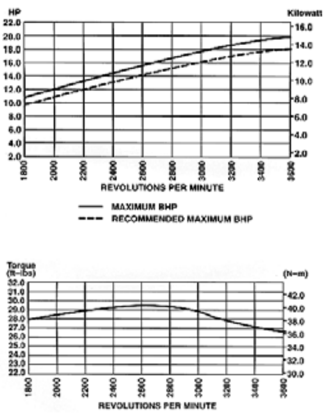
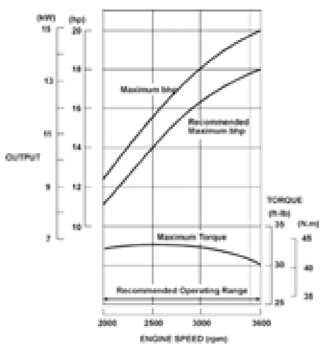
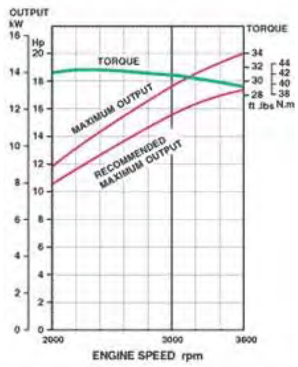
			
Manuf.	**Briggs & Stratton**	**Honda**	**Kawasaki**
Model	VT-20HP	GX-620	FD-611V
Cyl.	90 Degree V-Twin	90 Degree V-Twin	90 Degree V-Twin
Valve	OHV	OHV	OHV
Displ.	570cc	614cc	585cc
Bore	72mm	77mm	74mm
Stroke	70mm	66mm	68mm
Weight	42kg	42kg	44.7kg
Curves			
KW @3000	16.0	16.1	15.5
Torque @3000	41	42	41

Table 4.2 Engine comparison.

same basic configuration.

An extensive knowledge base exists on the performance, durability and strength of this engine as it is used for kart and small car racing[4]. If required, parts, instructions and fuels

4 www.briggsracing.com/racing_engines/vanguard.html

Figure 4.10 Briggs & Stratton 20Hp Vanguard

are readily available to increase the power of the engine from 20 to 60 horsepower. Should the standard engine prove to be undersized, the ability to increase its size without changing the actual engine is available. With all other parameters essentially similar, this factor lends the engine (Figure 4.10) to the solution of the power requirement for the project.

It is interesting to note that the engine selected is in the same order of power as that for a similar sized forklift. However, it is lighter, has two less cylinders and will run at almost twice the speed. This work has established that biped materials handling platforms will sound far more like motorbikes or aeroplanes than the slow thud of existing forklifts. More importantly, they will require a much higher level of maintenance.