Bounding and Stair Descent in the Hexapod RHex

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Abstract

RHex is a man-packable, six-legged robotic platfrom capable of traversing highly varied and rugged terrain, as well as running up to five body lengths per second. This thesis describes the development of two gaits for RHex: bounding and stair descent. The procedures involved in the development of these gaits are the analysis of video footage of experimental operation and logged-data analysis. Important elements of the functioning bounding gait are proper touchdown detection and energy storage in the compliant legs. For stair descent, the important element is control of the sliding motion of the robot body on the stair. A description of the platform is also presented.

Résumé

RHex est un robot portable à six pattes pouvant traverser divers types de terrains raboteux, ainsi que se déplacer a cinq longueurs par seconde. Cette thèse décrit le développement de deux types de démarches, le bond et la descente d'escaliers. Pour ses recherches l'auteur s'est servi de séquences vidéo et d'information enregistré pendant les expériences. Une bonne sensation de l'impact avec le sol ainsi que l'entreposage de l'énergie dans les composantes flexibles des jambes sont nécessaires au succès du bond. Par ailleurs, il est important de bien contrôler la glissade du robot pour descendre les escaliers. Une description du robot est aussi présenté.

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Chapter 1

Introduction

1.1 Mobile Robotics Background

When the term "robot" was coined by Czech playwright Karel Capek in 1921 it referred to lower class workers, not far removed from slaves. Later, in *Metropolis*, a Fritz Lang film made in 1927, a robot had the role of being used to control the masses of lower-class workers. Through the science fiction of the fifties, sixties, and seventies they started to be portrayed as something better than human, often feared, or at least misunderstood, as was Gort in 1951's *The Day the Earth Stood Still.* In other situations, however, there could be no misunderstanding their intentions. In the BBC series *Dr. Who*, the doctor was repeatedly confronted with the threat of the Daleks and their threats to "exterminate" human life. These robots can be seen in Figure 1.1.

Today robots are more often seen as helpers, enabling people to explore new reaches of the ocean, land and space. They go places that such as the surface of Mars where people have not yet been able to tread. They take on the dangerous tasks and the dirty tasks that people are not well suited to complete. They do not tire of repetitive operations and can perform the same motions endlessly with better precision than people can manage. They have also begun to become replacements for pets. Programmable puppies who



Figure 1.1: The robot from *Metropolis*[42] (upper-left), Gort, of *The Day the Earth Stood Still* [2] (upper-right), Dr. Who and some Daleks [8]

don't need to be fed or cleaned up after, yet can still provide some of the same companionship. Some examples of such machines can be found in Figure 1.2



Figure 1.2: JPL's Sojourner, for exploring the surface of Mars [25], a bomb disposal robot [54] and a Sony entertainment robot [58]

The field of mobile robotics is concerned with the study of robots that can move around in various environments. That environment can be the factory or lab floor, where surfaces are flat and very regular. It can be the more general urban environment that encompasses stairwells, sidewalks, paved and dirt roads, curbs and slopes. It can also be the completely unstructured terrain of the forest, desert, ocean or building rubble. In short, there is a wide range of operating theatres for mobile robots, and the design of the robot determines where it will be able to operate.

1.2 Legged Robots

While legged robots have been prevalent in science fiction, it is only relatively recently that they have begun to be seen in the real world. One of the first was the General-Electric quadruped truck built by Mosher in 1968. Shown in Figure 1.3, the machine was controlled by a human operator using hydraulic controls. The 1300-plus kilogram machine could move at 8 kph and could carry a 227 kg payload [55]. The machine was not autonomous, as the operator in fact controlled each axis of motion with his own.



Figure 1.3: The G.E. Quadruped Truck climbing a pile of rail ties, image taken from [52]

Ohio State University created a number of platforms including the Phony Pony and the OSU Hexapod, both of which used electronic controls to generate patterns of leg motion and were powered through a tether. The Pony was

capable of crawling and trotting, but was unable to turn. Its wide feet were required for stability in the trotting gait [55]. The Hexapod, on the other hand, was much more capable. It could walk, turn and negotiate shallow stairs [55]. The Adaptive Suspension Vehicle was later developed, similar to the General-Electric truck in that it required a driver. In this instance, however, the task of moving the legs was much more automatic and less strenuous for the driver [55] since he was there to supervise and direct the motion, rather than command leg movements directly. The O.S.U. machines are shown in Figure 1.4.



Figure 1.4: A number of early walking machines from Ohio State University. Images taken from [55]

The Odetics Functionoid (Figure 1.5) is a hexapod that uses a large amount of energy to move, but very little when standing still. motors as brakes during certain phases of motion to regain some energy. The batterypowered device locomotes by moving three legs at a time, using the remaining three to support the weight of the robot [55]. A number of revisions of the machine exist, from Odex-1 through Odex-3, with improvements in power consumption, sensor feedback and range of motion through the series.

In the 1980's Raibert [52] built a number of simple machines that ran dynamically using simple, low degree-of-freedom (DOF) legs. Two are shown in Figure 1.7. Using simple control laws, the robots were capable of running, walking, hopping in place, bounding, trotting, hopping up steps, jumping over obstacles and even performing summersaults. Some were constrained to the sagittal plane — a longitudinal plane that divides the body of a bilaterally symmetrical animal into left and right sections — by a boom mounted on a pivot while others were able to control their motion in all three dimensions.



Figure 1.5: An early walking hexapod that uses a tripod gait. Image taken from [55]

The Ambulatory Robotics Laboratory, under the supervision of Martin Buehler, used similar control laws to control legged robots built with electric, rather than hydraulic and pneumatic, actuators. Over a decade of research has produced two planar monopods, Monopod I and Monopod II, and a number of quadrupeds. Scout I is a small quadruped robot with hobby servos as actuators that is power autonomous and uses an off-board computer. Despite the use of simple legs with only one degree of freedom each, the robot is able to walk, turn in place, side-step and climb a step one third the height of the leg [10]. Scout II is a scaled-up version of Scout I with compliant legs to store and release energy during different phases of the motion, and was the first robot to gallop [50]. The compliance was necessary to decrease the impacts created while walking with rigid legs. More recent productions are RHex, a six-legged cockroach-like robot that navigates broken terrain, and PAW, a *P*latform with Articulated Wheels, a quadruped similar to Scout II with the addition of active wheels at the end of each leg. RHex is the platform used

for the research presented here, and is described in detail in Chapter 2, and the project that brought it to "life" is described in Section 1.3. A number of the lab's creations are shown in Figure 1.8.

From the research departments of large companies such as Honda and Sony and come a number of prototype and production robots. Honda has several fully-autonomous biped robots that are capable of walking, balancing, climbing stairs and slopes and interacting with the public. Their P3 and Asimo humanoids are the latest in their series, Figures 1.6(a) and 1.6(b), though they are not available to the public. Sony, on the other hand, has recently released another version of their Dream Robot, the SDR4X (Figure 1.6(c)), a small biped robot capable of walking, dancing and climbing up and down small steps with a sophisticated embedded control system. Their Aibo series of robots have been popular with both artificial intelligence research groups and the public.



Figure 1.6: Power and computation autonomous bipeds from Honda and Sony

A gait is defined as "a particular way or manner of moving on foot" [4] That is to say, a pattern of movement that the legs of a moving system, be it man, animal or machine, undergo to achieve locomotion. The motivation behind gait development is to improve the mobility of the platform through new, more robust or more sophisticated behaviours. The goal of mobile robotics is to build or study robots that have the ability to move around in their environment, and new gaits increase that mobility. Animals are much more mobile



Figure 1.7: The M.I.T. Leg Lab quadruped [34] and 3D biped [33]



Figure 1.8: The ARL Monopod II [29], Scout I [31] and Scout II [32] robots

than any robot created to date, it may be some time before a robot can climb slopes like mountain goat, run like a cheetah or climb like an ape. The animal systems have much more evolved control and feedback systems which are far beyond the capabilityies of today's sensing, computation and actuator technologies. Many animals, especially mammals, also have highly complex leg morphologies.

1.3 The RHex Project

The RHex project grew from a Defense Advanced Research Projects Agency (DARPA) and Office of Naval Research (ONR) grant to study the locomotion of cockroaches. Work done by Dr. Robert Full at the University of California at Berkeley showed that cockroaches can run very quickly without nervous feedback [9][18], with their legs moving along pre-determined trajectories with no inputs from the environment. Despite their ignorance of the obstacles in



their environment they are still able to traverse a wide variety of terrain.

Figure 1.9: RHex climbing a slope[30]

From this insight was born the concept for a mobile robot, a *R*obotic *Hex*apod, RHex (Figure 1.9), a simple robot that would move its simple legs according to predetermined trajectories, grouped in two groups of three, called tripods, as shown in Figure 1.10. Keeping the two motion of the tripods completely out of phase leaves at all times three legs on the ground, forming a triangle of support above which the centre of mass is always located. This is often referred to as static stability because at any point during the motion the system can be stopped without falling over. This leads to a large degree of natural stability and extensive mobility over broken terrain.



Figure 1.10: RHex's tripod stance forms a triangle of support under the centre of mass (COM) of the robot. A filled circle indicates that the leg is in contact with the ground. Left: tripod A, Right: tripod B

RHex implements the tripod gait by rotating the leg-trios a full circle

in unison. This is the single most distinguishing feature of RHex compared to other robots, and eliminates toe-stubbing problems while allowing a single actuator-per-leg design. The motion profile for each leg is parametrized by four values: the cycle time, the sweep angle, the offset and the duty cycle. The cycle time is the amount of time one cycle takes, or the period of the rotation. The sweep angle is the portion of the rotation for which the leg moves at a slower rate, by design while the toe is on the ground. The offset controls the angle about which the sweep angle is centred. Leaning forward, for example, can enable better slope climbing. The fraction of the cycle time that the leg spends in the sweep angle is the duty cycle. This parameter adjusts the relative speeds of the slow and fast portions of the leg cycle. Some interpolation is done to blend the two phases of motion. The trajectory used for the basic walking gait is shown in Figure 1.11.



Figure 1.11: Tripod gait leg trajectories, solid blue: tripod A, dashed red: tripod B

The adjustment of these parameters and the use of compliant elements in the leg has proven very effective in increasing the mobility in many modes of operation while enhancing stability and lowering power consumption in others. The compliance allows energy that would otherwise be lost in the impact with the ground to be stored for later release. An automated adaptation algorithm has been used to tune the four gait parameters to obtain gaits for high-speed or high-endurance.

The machine can be steered by either a human operator through a joystick interface to a laptop or by the on-board wision system, which enables line and blob tracking and return-to-home abilities.

For a further description of the mechanical, electrical and software systems of the robot, see Section 2.1.

1.4 Motivation

For the flat factory floor, wheeled robots are effective since there is no vertical translation of the centre of mass and the environment is well controlled. More time can be put into developing higher levels of automation such as autonomous navigation and mapping. For "real-world" environments, tracked and legged robots are better suited due to their increased versatility. They are able to climb over obstacles that would leave simpler platforms spinning their wheels. Tracked platforms offer stability and speed but encounter highcentring and de-tracking problems. Legs, on the other hand, do not have de-tracking issues but are often less stable.

Perhaps best recognized from fiction are biped droids such as Star Wars' C3P0 and those from the Terminator film series. Attempts to mimic in detail the degrees of freedom of humans have been neither cheap nor practical for unstructured environments. Such robots require considerable effort and sophistication to be made to balance. Additionally, the number of actuators increases the complexity of the system and makes it more difficult to carry the power supply. A robot that cannot carry its own power supply is of limited use in the field due it its infrastructure requirements.

The approach in the Ambulatory Robotics Lab (ARL) at McGill University, on the other hand, is to make legged robots as simple as possible, often using only one actuator per leg. This cuts down greatly on the complexity of the mechanical, electrical and software systems that comprise the robot. It follows that less complex systems are less likely to fail and are likely to be less expensive to fabricate.

The bounding gait used by some animals, such as dogs and squirrels, is characterised by two distinct ground contact phases separated by intervals where the robot is not in contact with the ground. This clearance, or flight phase, allows the animal to clear obstacles and save energy because it doesn't need to exert force on the ground during the whole motion. The bound is also currently the gait most used by the ARL's Scout II.

Stair traversal, both ascent and descent, is important as the urban environment abounds with stairs to traverse. Wheeled and tracked vehicles can be foiled when it comes to stairs due to their geometry. Stairs were designed for legged beings, providing horizontal footholds for vertical displacement, and legged robots should therefore have an advantage. The stair traversal gait therefore enhances mobility.

Many of the possible applications for RHex such as law enforcement, bomb disposal, firefighting, or search and rescue are set in urban areas where stairs are a frequent obstacle. The discontinuous nature of stair geometry lends itself well to legged platforms, whereas wheeled platforms can encounter great difficulty in stair negotiation. Tracked vehicles must be large enough to span three steps in order to overcome these obstacles in a stable fashion, and may still suffer from slipping due to low traction on the edges of the steps.

The motivation for designing gaits through empirical research is a common thread for robotics in the ARL. Through experimentation, the dynamics of the robots are studied. This method involves many experimental "runs," testing the gait and tuning the parameters. Video and data analysis are used extensively to correlate how the robot is behaving with what the input are telling the actuators to do. The alternative to empirical research is the development of a model for the dynamic system. This task requires a thorough and accurate understanding of the system's dynamics. Also important to model

accurately are the interactions between the robot and the world. The impact of the compliant leg with the ground, the friction force between the toe and the ground, with the toe subject to wear, the sliding friction of the body against the stair, all these must be accounted for in a model. The validation of such a complex system model would be a thesis of its own.

Once an accurate model exists, a controller must still be developed and tested. The implementation of a controller that is derived from a system model is another non-trivial task. In a simulation environment it is easy to determine the exact timing of touchdown events and the exact robot's state. Often in the real-world environment the machine does not have access to the same quantity nor quality of data. Often the sensors may exist for accurately measuring the state of the robot, but they cannot be integrated into a mobile platform for reasons of size, weight, power consumption or cost.

1.5 Scope of Thesis

This thesis contains several sections, each pertaining to relevant work. Chapter 2 consists of more detailed descriptions of the presented behaviours and what other researchers have done to implement similar gaits. The platform used for the experimental portion of this work is also described in some detail.

Chapter 3 describes the new contributions of this thesis research: the development of stair descent and bounding algorithms, and their experimental validation. Some of these results have already been published [11, 12].

Chapter 4 consists of conclusions drawn from this work and some ideas of possible directions for further investigations.

Chapter 2

Background

2.1 RHex Platform Description

This section describes RHex as a mix of mechanical, electrical and software systems. While it is often desirable to use commercial off-the-shelf components (COTS) in a design to minimise the design effort, it is not always possible. RHex is no exception. Virtually every mechanical component on the machine is custom designed, relying on COTS motors, bearings, gears and fasteners for the rest. As for the electronics, most parts are COTS, save for the i/o card, the motor drive and some interface circuitry. The software is of similar origins, a custom-written control library running on a commercial operating system. Where possible, datasheets for the COTS components, or excerpts thereof, are attached in the appendix. The use of custom components frees designers from the constraints of what are considered normal applications, stretching the limits to obtain high performance.

2.1.1 Mechanical Description

The mechanical system of RHex (Figure 2.1) consists of a set of two main rails that run the length of the robot. Perpendicular to these and in the same plane

as the ground are three crossbeams that hold the two sides together. At each end of each of these crossbeams is mounted a motor stack. This assembly consists of a quadrature encoder that provides feedback of motor angular position, a Maxon DC brushed motor, a Maxon 33:1 planetary gearhead and a custom-designed motor shaft support and extension. The batteries that power the system mount below the crossbeams, protected from impact by the cross-section of the main rails. The PC/104 computer stack that controls the robot's limbs is supported at either end by brackets mounting it to the rails.



Figure 2.1: RHex's frame in front view (top) and side view (bottom). For clarity, the legs and "skin" are not shown

The legs themselves consist of a semi-circular custom layup of fibreglass, manufactured in the Ambulatory Robotics Lab, bolted to a machined hip with a hexagonal interface to mate with the shaft extension. A strip of bicycle tire is glued to the outside circumference to increase traction.



Figure 2.2: The legs used on RHex, thickness exagerated to show lamination detail

An aluminium crash frame extends above the crossbeams to protect the sensitive electronics of the robot from the abuse that it incurs in the field. The sides of the robot are enclosed within Lexan plates that mount to both the main frame as well as the crash frame. These also provide attachment points for some of the electronics contained within, such as the motor drive board and rate gyro. A thin Lexan sheet wraps around the robot as barrier to keep out the sticks, stones, and dirt and gives the robot a more sleek appearance.

A generalized diagram of the robot's geometry can be found in Figure 2.3 with the values of the indicated dimensions in Table 2.1.



Figure 2.3: Key dimensions of RHex

2.1.2 Electrical Description

The electrical hardware can be broken into three basic sections, the power system which deals with high power control, storage and distribution, the

| Table 2.1: Basic RHex Char | acteristics | | | |
|--|----------------|--------------------|--|--|
| Parameter | Notation | Value | | |
| Body Mass | M_B | $7.5\mathrm{kg}$ | | |
| Body Length | L_B | $0.51\mathrm{m}$ | | |
| Body Height | H_B | $0.13\mathrm{m}$ | | |
| Leg Mass | M_L | $0.08\mathrm{kg}$ | | |
| Leg Length (unloaded) | L_L | $0.16\mathrm{m}$ | | |
| Leg Spring Constant (Linear Approximation) | K_L | $1900\mathrm{N/m}$ | | |
| Maximum Hip Torque (intermittent) | $	au_{max}$ | $7\mathrm{Nm}$ | | |
| Maximum Hip Speed | ω_{max} | $5\mathrm{rev/s}$ | | |

computation block, which makes the calculations required for the robot to perform a task, and the sensors, which give the robot an idea of what its limbs are doing and some information about its state in the world.



Figure 2.4: The main electrical systems in RHex and their interconnections

Power System

The first main component of the power system is the battery, which stores the energy required to make the robot move. RHex uses nickel-metal hydride (NiMH) batteries designed for the radio-controlled car market. These off-theshelf batteries provide 3 amp-hours (Ah) of capacity at a nominal voltage of 24 volts. Runtime with a fully charged set of batteries varies depending on the gait used and the terrain traversed. It ranges from several hours when merely running the computer to 50 minutes when walking at a speed of roughly 1 m/s to about a half hour when running bounding experiments.

The batteries deliver controlled power to the motors through the motor drive board. This circuit is based on the SA60 hybrid amplifier chip from APEX Microtechnology, and includes filtering to drive the low-inductance motors and battery current and voltage measurement to be able to sense the power consumption of the robot during operation. A large heat sink is attached to the six driver chips — one for each motor — to dissipate the heat generated in the amplifiers, which can deliver in excess of 200 W to each of the motors.

The motors are Maxon 20W, 18 V DC brushed motors capable of delivering the high torques required on a small legged platform affected by intermittent loading of the legs.



Figure 2.5: The main electrical systems on RHex and their interconnections

Computation Block

The processing on RHex is done by a PC/104 form factor computer stack. PC/104 is a modified version of the standard PC/AT bus for use in more compact embedded systems. The CPU is a Lippert CoolRunner II 300 MHz Pentium 2 class processor board based on the National Semiconductor Geode processor with 256 MB of RAM. It also has many onboard peripherals including a VGA controller, 10/100 Ethernet support, 2 RS-232 serial ports, and

uses a 256 MB Compact-Flash memory device as the hard disk. The system runs QNX, a free (for non-commercial use) realtime operating system. GNU's GCC compiler is used to develop the application which controls the robot.

For communication with the robot the stack has an Orinoco Wavelan 802.11b wireless Ethernet card which is connected to the stack with a Versalogic PCM-3115B PCMCIA-PC/104 adaptor card. The card is used in both managed (accesspoint) and peer-to-peer (adhoc) modes, depending the availability of a network where the experiments are being conducted.

A custom-designed analog/digital interface card, RHio, is used to communicate with the actuators and with many of the sensors on the robot. This card was designed by the author during the last year of his undergraduate engineering degree, specifically for use in RHex.

An MSI-P400 quadrature decoder card handles the decoding of the leg angle sensors mounting on the motors. It provides 6 channels of 16bit counters to accumulate the pulses from the sensors.

A second stack sharing only the power from the first has been added for the purposes of vision processing. It uses an identical Lippert CoolRunner II but runs Linux instead of QNX. The second stack includes a Firewire high speed serial interface card to connect to a Sony digital camera onboard. The vision and main stacks communicate through wired Ethernet.

Sensors

A number of things are sensed on RHex. Perhaps the most important of these is the angle of the leg. This measurement is made indirectly by measuring the rotation of the motor. Since the motor and leg are coupled through a gear, leg rotation is a fraction of the motor rotation. Agilent HEDS series quadrature angular encoders provide 2000 counts per revolution of resolution when interfaced through the quadrature decoder card in the stack. Since the motor rotates 33 times for each rotation of the leg, this yields very good



Figure 2.6: The computation system in RHex

measurement of the leg angle. Angle changes as small as 0.0054° can be resolved. Unfortunately, the reduction ratio also leads to uncertainty in the absolute position of the leg. With magnets fixed to the legs, Hall-effect sensors mounted on the body can signal when the leg is in a particular position. That position can be pre-determined and used to initialize the leg angle sensor from the software side.

Also attached to the motor is a temperature sensor which permits monitoring situations where the motors are in danger of being destroyed due to an overtemperature condition. These sensors are interfaced through the custom I/O card. The case temperature can be used in conjuction with a motor model to estimate the core temperature of the winding, which is the temperature that dictates when a motor is in risk of failure [41].

A Fizoptika fibre-optic gyroscope measures the angular rate of motion in three perpendicular axes. Along with software running on the robot these rates are integrated to give the pitch, roll and yaw angles of the robot. As with the leg angle encoders, this sensor must be initialized during the startup routine. In this case, the angles reported for roll, pitch and yaw are simply referenced to the starting orientation of the robot.



Figure 2.7: The sensing systems in RHex and their interconnections

2.1.3 Software Description

The software environment — beyond the operating system as described earlier — consists of a C++ library, called RHexLib, providing the framework for lowlevel motor control, sensor interfaces, timing, gait description, data logging and operator interface. Connected with this is a dynamic simulator and a Graphical User Interface (GUI), or Operator Control Unit (OCU). RHexLib was developed initially by members of the RHex team at the University of Michigan and is used on both the robot and the OCU. The dynamic simulator, SimSect++, was developed by Uluç Saranli and can be useful in the early stages of gait development.

The OCU runs on a Linux laptop and uses the communication facilities of RHexLib to send commands from the operator such as "forward", "turn left", speed and gait selection. Data flow in the other direction — from robot to operator — includes such information as motor temperatures and power consumption. The data logger also uses the communication routines to store data at the operator end of the link, where there is more storage available on the laptop's larger hardrive. Commonly logged variables include, but are not limitted to, those presented in Table 2.2.



Figure 2.8: The main software components in RHex and their interactions with each other

| Table 2.2: Common loggable variables | | | | | | |
|--------------------------------------|---|--|--|--|--|--|
| Parameter | Note | | | | | |
| Leg angle | one per leg | | | | | |
| Leg angular velocity | one per leg | | | | | |
| Desired leg angle | one per leg, reference input to PD controller | | | | | |
| Desired leg velocity | one per leg, reference input to PD controller | | | | | |
| Estimated actuator current | one per leg, based on a motor model | | | | | |
| Battery voltage and current | one of each for the whole system, used to compute | | | | | |
| | power consumption and for the current estimation | | | | | |

2.2 RHex Behaviours

RHex's behaviours, or gaits, are specialized motion patterns for the legs that allow the robot to negotiate different types of terrain. This section specifically discusses the bounding and stair descent gaits that are the focus of this thesis. The gaits are described and other robots capable of the same behaviours are discussed. RHex's other gaits include walking on even and highly irregular terrain [56], stair-climbing [46, 47], flipping [57] and pronking [40], as well as bipedal running [48]. Two sealed variants of the robot have also swum [1].

2.2.1 Bounding

A bounding gait is characterized by a pairing of the fore and hind leg pairs such that the two act simultaneously, as a single leg. The mass of the robot is supported by different pairs of legs throughout the motion. If the legs were to be frozen in place during locomotion, the machine would collapse. By remaining in motion, the machine stays upright. This is oftern called dynamic stability.

Few groups have produced bounding gaits in robots — Raibert's [52] quadruped used the concept of virtual legs, symmetry and partitioned controllers to achieve a bounding gait. Simple control laws governed the placement of the foot with respect to the body as a function of desired and actual velocity and the leg properties.

Scout II [62, 15, 7] at McGill made advances in power and computation autonomy, and control, with a mechanically simple machine. Also, Scout II was to the best of the author's knowledge the first, and is to date still the only existent power autonomous quadruped robot capable of bounding.

Scamper [20], at the University of Electro-Communications, is a quadruped with multiple degrees of freedom per leg. The machine was designed to bound, where their previous machine, Colt-3, was too heavy. Shown in Figure 2.9, the machine uses body velocity and touchdown events to switch between the eight states of the state-machine. That gait acheives roughly 10cm of ground clearance.

Kimura [27] built a small quadruped, Patrush (Figure 2.10), whose bounding dynamics are excited by neural oscillator signals. The robot uses springy legs to store energy for later release, much like RHex. Small changes in the input to the neural oscillators change the gait from a level-surface gait to a step-climb gait [28]. The machine has no control in the body's roll axis, and therefore two struts extend above the robot as part of a planarization mechanism.



Figure 2.9: Scamper, capable of bounding. Image from [19]





Researchers at Sony and Boston Dynamics Inc. implemented a bounding gait on an AIBO entertainment quadruped [66]. Hardware modifications were required, including the use of compliant legs and a more powerful leg actuator. Additionally, an external power source was employed to drive the new motors. Touchdown events are used to switch between states of the state-machine based controller.

RHex joins these few bounding robots by adding a quadrupedal bounding gait, utilizing the front and rear leg pairs of legs, to its already large repertoire of gaits. Dynamic running gaits, such as bounding and pronking, make explicit use of the robot's compliant legs, and have the potential for increased speed and energy efficiency, when compared to static walking tripod gaits.

2.2.2 Stair Traversal

RHex's stair ascent gait is a metachronal gait where legs opposite each other on the body of the robot are paired — that is to say that they follow the same trajectory. RHex essentially climbs stairs one step at a time by advancing one set of legs at a time onto the next stair. Generally, two stairs are spanned at once, with the front legs touching one stair higher than the back legs. The gait relies on a simple synchronization mechanism to enable it to successfully negotiate a large range of stairs using a single set of trajectories. The shape of the legs also improves performance as the hip undergoes an effective length change without requiring a true second degree of freedom.

Despite the apparent suitability of legged systems to negotiate stairs, there are very few robots that successfully do so. Notable exceptions are the Honda bipeds — P2, P3 and Asimo, and Raibert's tethered biped, yet no specific publications describing the stair climbing algorithms and performance seem to be available. As far as the literature reveals, the Honda bipeds and RHex are the only untethered legged robots to ascend and descend full size stairs. The ability of RHex to ascend a variety of stair geometries reliably has been previously published [46][47].

Descending stairs can be a more difficult problem, as gravity accerates the robot in the same direction as the desired motion. Some mechanism must be found that allows the motion to be controlled. Without this control, the machine can destabilise and become damaged in the fall. For some robots the interaction with the stair is very similar to that during ascent.

The Autonomous Systems Lab at l'École Polytechnique Fédérale de Lausanne (EPFL) has produced a robot called Shrimp that uses an interesting bogey mechanism to enable a wheeled robot to climb stair cases. The following sequence (Figure 2.11) of images from their work illustrates how the mechanism allows negotiation of steps larger than the diameter of one of the six powered wheels [16]. However, they make no claims about the machine's stair descent capabilities. A similar robot (Figure 2.12) from Yujin Robotics

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uses three side-by-side pairs of wheels and a four-link mechanism to acheive stair climbing. The Yujin robot is shown to descend stairs in the same manner as it climbs them; it simply drives down them.



Figure 2.11: The EPFL Shrimp wheeled platform nogotiating a step [16]. The same method is used for stair traversal



Figure 2.12: The Six-Wheel Service Robot from Yujin ascend and descends stairs [13]. Image from [14]

Another wheeled platform that uses a novel method to climb stairs is the Deka Independence IBOT Mobility System. The device is mobile wheelchair
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like no other. It is able to ascend and descend normal sized stairs. It does so by balancing upright on two of its four wheels. While the machine and its occupant are balanced on one pair of wheels, the other pair flips over to the next step. The process continues until the top of the staircase is reached. To descend, the same sequence is carried out in reverse. A drawing describing this is adapted from [26] and presented in Figure 2.13.



Figure 2.13: The DEKA Wheel chair climbs stairs by lifting up on two wheels while the other pair recirculates over to the next stair

The Packbot robots from iRobot, are tracked robots with flippers at one extremity for increased maneuverability. This tracked platform, much like the Shrimp and Six-Wheel, simply drives at the stair to traverse the flight. The articulation provided by the flippers allows a better transition from flat ground to the stairs and extends the effective body length on the stair. Some research used a vision-based system is used to guide the ascent [60]. While little information as available about the descent, the symmetry of the system makes it reasonable to suppose that the same procedure can be used for stair descent.

A number of leg-wheel hybrid machines have been created which are capable of negotiating small steps by changing their configuration. Researchers as MITI in Japan have built machines [37, 36] that can climb small steps, and, in the case of the latter, stairs. Note that in neither case are the steps full size. The Machines operate by rolling along the step to the approprite place and then balancing like an inverted pendulum to transfer the contact up to the

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next stair. The machine are shown in Figure 2.14. Stair descent is achieved is a similar fashion, executed in reverse.



Figure 2.14: Variable-structure type four-wheeled robot (left) and biped-type leg-wheeled robot (right) from MITI

The Waseda Leg 12 Refined III (WL12-RIII) [61] is a biped able to climb 10 cm steps and descend 5 cm steps, as well as walk on slopes up to 10°. The machine has a trunk, or upper body, that is used to assist with balance. This is a refinement of the Waseda Leg 10 Refined Dynamic (WL10-RD), which relied on leg motion to both balance its body and position the feet to ascend the steps or slope. Both these machines are shown in Figure 2.15



Figure 2.15: Two of the Waseda Leg bipeds, the WL10-RD (left) and WL12-RIII (right). Images from [64] and [65], respectively

Legged robots that are able to climb full-size stairs are few and far between. P2 [22], the predecessor to the Asimo and P3 bipeds from Honda, is specified as being able to both ascend and descend stairs 20 cm high and 22 cm long. Where most of the legged and hybrid platform mentioned previously require a priori knowledge of the location and dimensions of the stairs the Honda machines do not.

Chapter 3

Experimental Development

This chapter describes the development of two gaits, a quadrupedal bounding gait and the stair descent gait. Both are important for legged mobility, as described in the previous chapters. The key procedures involved in this development are the analysis of video of experimental attempts and the analysis of logged data.

Video is used to capture how the robot is interacting with the environment. Depending on the duration of these interactions, two different approaches are used. For slower-moving gaits, such as the stair descent, camcorder footage can be watched either frame by frame or in slow motion. For higher speed gaits, such as bounding, more sophisticated technology is required – high-speed video capture systems. Through the sequences of images, the actual behaviour of the robot can be compared to the intended motion. This leads to new insights into what affects the robot and how changing the interactions changes the gait.

The analysis of logged data is made possible thorough the data-logging facilities of RHexLib, a software library described in Section 2.1.3. Data such as the desired and actual leg angles and velocities, the body pitch, the state of the state machines, the desired torque output from the position control loop, the estimated motor current and the main battery voltage and current are logged for the bounding gait. By looking at this data, the cause and effect of events can be closely investigated, furthering insight into the robot's behaviour.

3.1 Bounding

In the development of a bounding gait for RHex, several important considerations need to be taken. A quadrupedal gait is used because it is not evident how to use the middle set of legs of the six-legged RHex robot in a high-pitch oscillation gait. It should also be noted that the gait runs in the opposite direction than most of the other gaits on RHex, for which the "Front" and "Back" labelling in Figure 2.3 is intended. The reasoning behind this is that the gait operates more easily in reverse, which is attributed to the manner in which the legs interact with the ground. Since the leg is not symmetric about the vertical axis neither are its spring properties. In the normal forward direction the legs initially make contact at a point on the circumference away from the toe. As the leg starts to sweep it loads a torsional spring in the sagittal plane. Due to the structure of the leg, the linear and sagittal-rotation components of compliance are not independent. A linear compression induces a change in angle and likewise, a rotational compression induces a change in leg length. This causes the ground force to decrease. From the radial and tangential force diagrams in Figure 3.1, it can be seen that the iso-force lines are not at an equal radius from the centre. As the leg is compressed by decreasing the 'x' co-ordinate, the line of zero force displaces in the 'y' direction. To account for the change in convention in the nomenclature, references to front and back within Section 3.1 are made with reference to the intended direction of motion for the bounding gait.

The setup used, shown in Figure 3.3, consists of a laptop, a high speed camera system, a remote trigger for the camera, a good surface to run on and a floodlight. The laptop runs the graphical user interface for the robot. Figure 3.2 shows the panel responsible for the interface to the bounding gait.



Figure 3.1: Force as a function of toe position for the half-circle leg [45]. The hip is located at the origin and the toe at approximately (0.16,0)

The eight input boxes allow the operator to change four parameters for each pair of legs used in the gait.



Figure 3.2: User interface for bounding gait. A typical parameter set is shown

The parameters often experimented with are the touchdown angle, the sweep limit the sweep speed and the "jump angle," which are described the the following sections. By allowing the the parameters to be tuned while the robot is running, the effects of changing values on the machine's performance can be seen.

The high speed camera system consists of a desktop computer with an acquisition board and a high speed camera. In general a frame rate of 125 frames/s was used. With such a short exposure, a floodlight is used to shed more light on the scene. The remote trigger allows the experimenter to start or stop the acquisition sequence. The trigger was normally used to indicate the end of acquisition. The surface on which most of the testing was done is the linoleum lab floor.



Figure 3.3: The test setup used for bounding experiments in the lab

The methodology for experimentation can be outlined as an iterative process. The first step is to have a idea of what the desired characteristics of the gait are. Next, a controller – the specific pattern for leg motion – is written into the code library for the robot. The code is then tested by running it on the robot. The behaviour of the machine is observed, possibly with the assistance of a video recorder, to determine whether it performs as desired. When it doesn't, and it rarely does the first time, the video and logged data, if available or applicable, are analysed to determine the source of the problem. Different parameters are tried, either through the graphical interface, or through the run-time configuration files, which allow changes to the controller to be made without the delay of compilation. A sample configuration file for bounding can be found in Appendix A.1.

Typically, a great deal of time and effort is put into determining whether the controller is behaving as designed. The task of determining whether it is designed to do the right thing builds from that point.

3.1.1 Bound Controller

Inspired by successes of the controllers in the Scout II quadruped that excite the robot's passive dynamics [62], the controller used for bounding has two different states for each of the front and back pairs of legs. The middle legs are kept parallel to the body where they cannot touch the ground for the duration of the bounding gait. For this gait there is no notion of an overall body state for control, the coupling between the front and rear leg pairs comes from the excited natural dynamics of the system. A graphical representation of the state machine for one of these pairs of legs is shown in Figure 3.4.



Figure 3.4: A graphical representation of the state machine controlling the bounding behaviour

3.1.2 Touchdown Detection

Written to get the basic motion of the gait working first, the controller expects both front and rear pairs of legs to be in flight initially. Essentially, this requires a manual start for the gait. During the flight phase, the legs are servoed via a proportional-derivative (PD) loop to a touchdown angle, ϕ_{td} , relative to the body's vertical axis as per Figure 3.5. In order for the touchdown event to take place, both legs in a pair are required to have made contact with the ground. This is done so as to reduce the roll moment that would be created if the left or right leg made contact with the ground – initiating the next phase – before the other is near enough to the ground to exert force. It may, however, cause the same roll moment due to uneven compression of the legs at touchdown if the roll angle of the robot is too large.



Figure 3.5: Bounding Leg Angle Notation

In reference to the state machine illustrated in Figure 3.4, a starting point for the gait can be chosen as the detection of the touchdown event. The morphology of the leg used on the robot and the fully-recirculating nature of some of the gaits used on RHex make simple switch or strain-based touchdown detection difficult, as any wires connected to the legs would be destroyed in normal operation. Instead, a virtual sensor based on an estimate of the motor current is used, which was developed for the pronking gait on RHex [40]. By thresholding this current the joint error that arises when the toe makes contact with the ground can be detected. The current in the motor is given by

$$i_{motor} = \frac{V_{motor} - V_{BackEMF}}{R_a + R_{drive}},\tag{3.1}$$

where V_{motor} is the terminal voltage applied to the motor, $V_{BackEMF}$ is the electro-motive force created by the spinning rotor and given by $K_s \cdot \omega$. R_a and R_{drive} are the resistances of the armature and the drive electronics, respectively. While V_{motor} is not measured directly, it can be written as $V_{motor} = D \cdot V_{batt}$ where D is the duty cycle of the drive and is commanded explicitly by the control software. V_{batt} is the battery voltage, measured by a sensor on the motor-drive board. For more details about the motor model, see McMordie et al. [41].

Early implementations of the touchdown detector use a state machine to keep track of the state of each leg with respect to touchdown [11]. The detector responds to noisy data in some circustances, while in others it misses valid touchdown events. In order to see what is happening with the touchdown detection, it is necessary to watch the legs contacting the ground and correlate what is known to be happening with what the the robot "thinks" is happening based on its sensory input. The technology for the latter has been in place for some time, in the form of a datalogger that can log any variable at an interval as short as 1 ms. For the former, a combination of a high-speed digital camera from Redlake and a number of LEDs mounted at strategic locations on the robot are used. The LEDs are connected to RHio and driven by the code so as to indicate the state of the legs with respect to touchdown. This is the state that the state machine for each of the front and rear pairs of legs is presently in. By watching high speed video taken at 125 frames per second, missed or false touchdown detection events can be seen and their cause found by looking at the logged data. Corrective measures can be taken to avoid false triggering once the causes are known.

One major cause of missed touchdown events that was found was the requirement that the current drop below a threshold for a certain amount of time following the sweep from the sweep limit to the touchdown angle before retriggering. If the gait was not getting sufficient clearance for the legs to clear



Figure 3.6: A valid touchdown detection. The bright circle is a lit LED that indicates that the state machine for the back pair of legs is in the stance phase



Figure 3.7: An event that is classified as a false trigger, with the video frame and corresponding data plot. The circle encloses the estimated motor current at the time that the image was captured. The dashed horizontal lines are the threshold

the ground during this sweep, the toes would stub against the ground. In so doing they do not allow the touchdown detector to re-arm and effectively the virtual sensor is "blind" to the touchdown event. By eliminating the threshold below which the current must drop, the missing of an event due to toe stubbing can be diminished. An extra complication to the triggering mechanism is the requirement that the estimated current for both legs in a pair drop below the threshold for the specified interval and then both must be triggered. In Figure 3.7, the problem that prevents proper triggering is that one of the two rear leg touchdown sensors did not reset. Simply shortening, or entirely removing, the blanking period is not a solution, as false triggering occurs due to the current spikes produced in tracking a large step input in desired angle, as shown in Figure 3.8. A modification of the trajectory followed to get the legs from the sweep limit to the touchdown angle is required, and will be discussed in a later section.



Figure 3.8: With the blanking period too small, the legs trigger themselves at the end of the flight trajectory

3.1.3 Stance Trajectory

In the original controller the desired angle after the touchdown event was a fast ramp to a sweep limit. Due to actuator limitations this quickly results in saturation. A fast ramp trajectory will saturate the actuators very easily but was thought necessary to inject enough energy into the system. The original gait, it is believed, is strongly determined by the actuators and natural dynamics as opposed to being determined by the trajectories commanded along with the actuator limits.

The new trajectory shape consists of a jump, or step, input followed by a slower ramp to the sweep limit. This is done to allow a little more flexibility in the energy injection. By increasing the jump height more energy is injected into the vertical mode of the gait, while the sweep, if properly tracked, influences the forward speed of the robot. With a slower sweep, the trajectory does not saturate the motors as easily and thus there is more control available to affect the performance of the gait.



Figure 3.9: Jump-ramp-limit trajectory used in the enhanced version of controller

3.1.4 Liftoff

The transition event from stance to flight cannot be based on whether the toes are in contact with the ground using the virtual sensor based on motor current. The estimation method and the large current that is commanded during this phase make robust "lack-of-ground" detection difficult. Instead, a time-driven event is used. A specified amount of time after the touchdown event has occurred, it is assumed that the pair of legs is no longer in stance. The state-machine returns to the first phase, where a touchdown angle is tracked.

3.1.5 Flight Trajectory

Instead of a step change trajectory, a fixed acceleration curve trajectory that brings the legs to a smooth stop at the touchdown angle is implemented. The start point chosen is the mean of the actual angles of the legs in the pair at the end of the stance phase. The trajectory continues from that point at a constant acceleration until the half-time point of the desired trajectory time is reached. At that point the constant acceleration reverses direction, maintaining the same magnitude, for the second half of the time interval. This brings the legs to a complete stop at the desired touchdown angle after the desired time has elapsed. The stop is smooth, as the acceleration cancels itself out by running for a certain time in one direction followed by an equal acceleration in the opposite direction.

| | <u></u>] | Table 3.1: S | -Curve Formulation | |
|---------------|----------------|------------------------------|---|--|
| Parameter | symbol | $0 < t < \tfrac{T}{2}$ | $\tfrac{T}{2} < t < T$ | |
| initial angle | θ_o | sw | eep limit | |
| final angle | $	heta_{f}$ | touchdown angle | | |
| interval time | T | T = | $\left \frac{2(\theta_f-\theta_o)}{a}\right ^{1/2}$ | |
| acceleration | $\ddot{	heta}$ | -a | a | |
| velocity | $\dot{	heta}$ | -at | a(t-T) | |
| position | θ | $\theta_o - \frac{1}{2}at^2$ | $\theta_o - aTt + \frac{1}{2}at^2$ | |

Because the acceleration is a constant, finite value, the velocity is also smooth, and finishes at rest at the desired final angle. Thus the current required is likewise smooth and finishes at a low value. This requires only a small settling time during which triggering is inhibited. Early triggers due to triggering by the current required to follow the desired trajectory and missed triggers due to toe contact before the detector has re-armed are thus avoided.

3.1.6 Resultant Gait

With the controller tuned, trials reveal the form that a bounding gait takes on RHex. Driven by a simple controller, the robot exhibits a periodic oscillation in the pitch axis. Occasional failures (missteps) are recoverable without operator intervention. The contact pattern of the legs is illustrated in Figure 3.11. The best view of what the robot does is obtained from the following key frames captured with a high speed camera (Figure 3.12).



Figure 3.10: Fixed-acceleration trajectory used for a smooth motion return to the touchdown angle



Figure 3.11: Foot-contact pattern for the Bounding Gait. A solid circle indicates ground contact. Robot traveling from left to right



Figure 3.12: Bounding motion in RHex. Frames are $8\,\mathrm{ms}$ apart. Robot moves from left to right

3.2 Stair Descent

Some initial thoughts suggest that stair descending should be easier than ascending, after all, gravity is helping during the descent. While this is true, the difficulty comes in descending the stairs in a controlled, stable fashion, in the absence of a sensor-rich robot, and thus without complete knowledge of either the stair geometry or information about the robot state with respect to the stair geometry. The algorithm for ascending stairs works very well over a wide range of stair geometries and construction materials, due to an effective, open-loop, synchronization feature [47]. A simple time reversal of the trajectories seemed like a good starting point for a descent algorithm. This approach however was unsuccessful on steep stairs (greater than 30°). The robot quickly lost synchronization with the stair, leading to jamming or irrecoverable pitch or yaw motion. The algorithm used for descending stairs is instead based on the idea of sliding the robot down the stairs on its belly. The robot progresses down the stairs in reverse, with the rear legs leading the motion and the front legs higher up the flight. The legs work in contralateral pairs, a gait which avoids inducing a yaw moment by left-right leg contact imbalance. One of two different sets of trajectories is used depending on the slope of the staircase, with the threshold between the two gaits at approximately 30°. Synchronization with the step is accomplished differently depending on the parameter set used, and is described below. Despite the reversed direction of motion for this gait the nomenclature is kept as referenced in Figure 2.3, unlike the bounding gait.

The setup used for testing the gait as it is developed consists of a flight of stairs upon which to test the robot, a digital video camera to film the motion of the robot, and when possible, a gracious assistant to keep the camera aimed at the legs. This is illustrated in Figure 3.13. Changes to the trajectories are not mode as the gait operates, as with the bounding gait. Instead, the gait uses parameters from a configuration at run-time. This is attached in the appendix for reference.



Figure 3.13: The experimental setup used for stair descent testing. For clarity the gracious assistant is not shown

3.2.1 Steep Stair Gait

Through video analysis of the failures of the previous stair descent gait, a hypothesis was formed that the failures were caused by the robot gaining too much kinetic energy while the lower legs were recirculating as the robot was not fully supported by either the stair-body or the stair-leg interaction. The previous gait featured a recirculation phase for the front legs. On some stair geometries the recirculation introduced additional pitching moment when the toes collided with the stair riser. By removing this phase, there is no collision to impart the pitching moment on the robot. The legs that are now held at a fixed angle in front of the robot are also useful for assisting in a repetitive placement with respect to the stair. The repetitive placement was found to be very important in the stair ascent gaits to be able to consistently traverse flights of any number of steps using a single set of parameters. In descent mode, the same synchronization is important to avoid slipping down the stairs in an uncontrolled fashion. While synchronization was attainable for the ascent algorithm by pushing the robot against the next stair, the direction of the motion during the descent phase prohibits a similarly active method. Instead, the front legs slide down the stair, leaving the robot at a similar distance from the edge every step. The role of the rear legs of the robot, at the low end of the robot, is to catch and then lower the body of the robot as it slides down the stair on its belly. During this phase, as with the ascent gait, the shape of the leg plays a key role. When the toe of the leg touches the stair it is near the greatest extension of the leg and as the hip rotates the distance between the hip and the contact point of the leg decreases, effectuating a passive leg length change. The middle set of legs is recirculated but does not touch the stair during most descents of steep staircases. Occasionally the legs touch the vertical riser of the stair, but do not affect the motion of the robot.



Figure 3.14: Trajectories used on steep-sloped stairs. Solid: Actual, Dashed: Desired

3.2.2 Shallow Stair Gait

The shallow stair gait algorithm closely resembles the algorithm originally used to descend a single, fixed stair geometry [46], with all three sets of legs recirculating for every step descended. The problem with the steep stair algorithm on shallow stairs was that the front legs rubbed on the step instead



Figure 3.15: Key positions for steep descent gait parameter set. A filled circle indicates a leg in contact with the horizontal surface of the stair

of sliding to position the robot consistently. In addition, the rear and middle legs exert a great deal of force in order to drag the robot down the stairs, rather than merely catching the robot and gently lowering it (Figure 3.16). The recirculation phase for the front set was re-added in order to circumvent this problem.

When the front legs of the robot recirculate, the toes push the body backwards through contact with the vertical riser of the stair. This causes the robot to slide farther backwards when the rear legs lower the back of the robot and recirculate themselves. The trajectories for the other pairs of legs remain unchanged, shown in Fig 3.17.

The shallow and steep stair algorithms depend on two assumptions about



Figure 3.16: Robot stuck on a shallow stair, using gait paramters for steep stairs



Figure 3.17: Trajectories used on shallow-sloped stairs. Solid: Actual, dashed: desired

the stairs. First, the vertical riser of the stair must be closed. For the shallow stair gait this is fairly evident since it relies on the toes pushing off the riser, but



Figure 3.18: Key positions for shallow descent gait parameter set. A filled circle indicates a leg in contact with the horizontal surface of the stair

it is also a problem on some steeper stairs as the toes catch on the underside of the step. The second assumption is that there is no large ledge on the step. This corresponds to dimensions (c) and (d) in Figure 3.19, below. If there is a ledge (i.e. (d) is not zero) then the toes may catch and disturb the descent of the robot, just as when there is no riser at all.

3.2.3 Experimental Stair Descent Results

We tested the descent algorithms on a variety of the stairs found around the McGill campus. All stairs selected as test sets were of the variety that have closed risers, though some also had small ledges. The stairs, described in Table 3.2, range in slope from 24 to 35 degrees, and are made of various textures of concrete and stone. Stairs consisting of only a few steps were avoided since there is insufficient space for synchronization errors to build up.



Figure 3.19: Stair varieties and dimensioning

| | | Table 3.2: Stairs Tested | | | | |
|---|--------|--------------------------|--------|--------|------------|----------------|
| # | a (cm) | b (cm) | c (cm) | d (cm) | # of steps | Slope $(^{o})$ |
| 1 | 36 | 15.5 | 0.8 | 0 | 9 | 24 |
| 2 | 30.8 | 15.4 | 0.4 | 0 | 12 | 27 |
| 3 | 28 | 17 | 0.7 | 0 | 11 | 32 |
| 4 | 29 | 17.8 | 2.5 | 4.3 | 12 | 34 |
| 5 | 29.5 | 18.9 | 2.3 | 4.0 | 17 | 35 |

For the purposes of these experiments the robot was manually placed on the top step in order to simplify the testing. Further research will include the development of a startup algorithm to get the robot into position, similar to the startup algorithms for stair ascending [47]. Battery voltage and current were measured to determine power consumption of the whole system, not just the actuators. During the testing we found that the robot could recover well from occasional missteps, as long as the yaw angle was less than about 10 degrees. Shallow stairs were more difficult to negotiate because the behaviour depends highly on the leg properties and toe positioning. This is due to the active nature of forcing the sliding motion on these stairs. The crossover point between the shallow and steep gaits occurs at a slope of 30°. Below this angle the steep gait had difficulty getting the robot to descend smoothly without getting stuck on a stair. On stairs steeper than this angle, the shallow gait, with the recirculating front legs, was more prone to causing skipping or pitching over backwards.



Figure 3.20: Flights of stairs on which the descent algorithm was tested

3.2.4 Energetics

The average power consumed over the different stairs ranges from 95 to 135W over a small number of full cycles. As a measure of energetic efficiency the specific resistance is used [21]. The measure of the energetic cost of locomotion is calculated as

$$\varepsilon = \frac{P}{mgv},\tag{3.2}$$

where P is the average electrical power consumed, m is the mass of the robot, g is the gravitational constant, and v is the speed of locomotion along the stair inclination. Note that this number is somewhat imprecise in our application because it does not consider the change in potential energy.

| # | Average Electrical Power | Specific Resistance |
|---|--------------------------|---------------------|
| 1 | 95.9 | 4.82 |
| 2 | 120.5 | 5.31 |
| 3 | 135.2 | 7.01 |
| 4 | 101.8 | 5.31 |
| 5 | 105.9 | 7.45 |

Table 3.3: Specific resistance for stairs tested

Even though stair descent has the potential for great energy efficiency, at present the robot still consumes more power descending stairs than it does walking on even terrain (Figure 3.21). However, when compared to ascent, descent is roughly twice as efficient. When compared with other gaits, the efficiency of the current stair descent gait leaves much room for improvement. For example, the bulk of the power consumption takes place during the phase when the back of the robot is lowered down the step (Figure 3.22). If this phase were sped up, the specific resistance could be lowered.



Figure 3.21: Specific resistance of some legged platforms. Numbers indicate stair number



Figure 3.22: Power Consumption over four steps of stair #3 with average value of 144 W

Chapter 4

Conclusions

4.1 Bounding Gait

A quadruped bounding gait is implemented on RHex that uses the detection of leg-ground contact events to co-ordinate the action of the legs. Driven by a simple state machine for each pair of legs, body pitching motion is obtained through the natural dynamics of the system without forced coupling between the two state machines. Upon contact, a quick push loads the compliant legs and then a constant angular rate sweep imparts forward energy. After a fixed amount of time, the legs sweep forward to the touchdown angle following a smooth trajectory. The gentle slope of the trajectory brings the legs to a halt with little oscillation, which requires little current to control. This, in combination with a short delay, results in reliable touchdown detection. From this comes a gait that is able to re-start itself from stumbling and is not extremely sensitive to the initial conditions provided by the operator. The analysis of captured video and logged data are useful and important in the development of gaits in legged robotics.

Future enhancements to the gait could be made through more sophisticated feedback schemes. Some work was done in measuring the time intervals between leg pair touchdowns, but no strong control input was found to steer

CHAPTER 4. CONCLUSIONS

the motion towards known-good values. Likewise, the amplitude of the pitch oscillation was measured but no good input was found to affect it reliably. Another possible avenue for research is commanding the touchdown and sweep limit angles with respect to the floor instead of the body. This, it is hoped, would allow the gait to attain some equilibrium trajectory.

4.2 Stair Descent Gait

In the pursuit to traverse terrains in the human and urban environments, an important gait to complement the previously discussed stair ascent gait has been added. Descending stairs is a challenging task that is at first taken for granted because of its apparent simplicity compared to ascending stairs. Yet descending stairs still requires more complex shallow/steep stair algorithms, compared to the single algorithm for stair ascent. Still, in the end, despite its small size and simple design, the robot is able to accomplish the stair descent repeatedly.

In the near future, improvements in the range of stairs that can be traversed can be made. It is possible that a gait could be designed that would automatically select an appropriate parameter set for a particular staircase. A further enhancement is the development of an algorithm to automatically position the robot on the top step without operator intervention. A more complete study of the reliability of the descent algorithm also needs to be made, with more trials per stair attempted.

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Appendix A

Experiment Notes

A.1 Bound Controller Configuration File

```
# config file for bounding
# not all values used at all times
# angles and rates (in DEGREES)
float front_sweep_angle = 18;
float front_td_angle
                       = -30;
float front_sweep_speed = 720;
float jump_angleF = 10;
float middle_angle
                     = -90;
float back_sweep_angle = 18;
float back_td_angle
                      = -30;
float back_sweep_speed = 720;
float jump_angleB = 10;
# startup sequence data
float startup_time = 1.0;
float startup_angleF = -36;
```
```
float startup_angleB = -30;
# Stance Torque
float stance_torqueF = 10;
float stance_torqueB = 5;
# control used
# 0: trajectory in stance
# 1: const torque in stance
float control_type = 0;
# Flight Gains (also middle leg gain for all phases)
float frontKpF = 25;
float frontKdF = 1;
float midKpF = 20;
float midKdF = 0.2;
float rearKpF = 25;
float rearKdF = 1;
# Stance Gains
float frontKpS = 60;
float frontKdS = 1.1;
float rearKpS = 60;
float rearKdS = 1.1;
# Wait Gains
float frontKpW = 31;
float frontKdW = 0.4;
float rearKpW = 31;
float rearKdW = 0.4;
# Stance time limits
float front_stance_time = 0.08;
```

APPENDIX A. EXPERIMENT NOTES

float back_stance_time = 0.08;

TouchDown Detection thresholds
float SettleTime = 0.01;
float TouchCurrent = 2.5;
float ReleaseCurrent = 0.8;

float arming_delay = 0.03;

Scaling factor for angle adjusts
float MaxAngleOffset = 50;

float aMax_front = -25220;
float aMax_back = -25280;

. .

A.2 Bounding Experimental Values

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A.3 Stair Negotiation Configuration File

```
# Parameter configuration for stairclimbing (with NewStairMachine)
# Note that direction of rotation is forced for the legs
# Parameter modification may result in massive chaos
# and possible injury...
# YOU HAVE BEEN WARNED
# Stair Ascent Parameters
struct nstair_up {
 float UStart_time = 2.0;
 float UOne_time = 0.5;
 float UTwo_time = 0.35;
 float UThree_time = 0.4;
  float UFour_time = 0.15;
 float front_kp = 22.0;
  float front_kd = 0.22;
  float mid_kp = 22.0;
  float mid_kd = 0.22;
  float rear_kp = 35.0;
  float rear_kd = 0.35;
  # order is 2->3->4->1
  float start_angle = 45 -30 -30 -30 -30 ;
  float one_angle = -15 65 0 -15 65 0 ; # mid recirc
 float two_angle
                   = 45 -5 -40 45 -5 -40 ; # front recirc
 float three_angle = 45 -65 -50 45 -65 -50 ; # mid push
 float four_angle = 45 -65 85 45 -65 85; # rear recirc
}
# Special sequence to start stair descent
struct nstair_down_start {
```

```
float DStart_time = 2.0;
 float DZeroB_time = 6.0;
 float start_angle = -15 55
                             -40 -15 55
                                               -40
                                                     ;
 float zerob_angle = 25 110
                                    25 110
                               20
                                                20
                                                     ;
}
# Stair Descent Parameters
struct nstair_down {
 float DOne_time
                   = 0.4;
 float DTwo_time = 0.3;
 float DThree_time = 0.3;
 float DFour_time = 0.25;
 float DFive_time = 0.3;
 float DSix_time
                   = 0.3;
 float front_kp = 8.0;
  float front_kd = 0.14;
  float mid_kp = 14.0;
  float mid_kd = 0.14;
  float rear_kp = 14.0;
  float rear_kd = 0.14;
  # order is 6->1->2->3->4->5
  float one_angle = 10 - 45 15
                                     10 -45 15; #
  float two_angle =
                      90 15
                               15
                                     90 0 -30;
                             -30
  float three_angle =
                      90 15
                                    90 0 -30
                                                ÷
  float four_angle =
                      90 90
                               0
                                     90 90
                                               0;#
  float five_angle =
                      10 90
                               15
                                     10 90
                                              15
                                                   ŝ
                                                   ; #pause phase
  float six_angle =
                      10 90
                               15
                                     10 90
                                              15
  float direction = 0 \ 1 \ 1 \ 0 \ 1 \ 1;
}
```

```
struct nstair_swup {
 float time = 0.15;
 float angle = 150 -10 20 150 -10
                                          20 ;
}
float nstair_offset_scale = 1.0;
# The first test is to see if I can have a second parameter set...
float nstair_B_params_exist = 1.0;
struct nstair_downB {
  float DOne_time = 0.2;
  float DTwo_time = 0.15;
  float DThree_time = 0.2;
  float DFour_time = 0.15;
  float DFive_time = 0.3;
  float DSix_time
                  = 0.3;
  # order is 6->1->2->3->4->5
  float one_angle = -16 33.75 -145 -16 33.75 -145 ; # Rear Recirc
  float two_angle = 1 42.5 - 28.2 1 42.5 - 28.2;
                                -11 24 95 -11
  float three_angle = 24 95
                                                  ;
                               -0.7 41 -40
                                            -0.7 ; # Mid Recirc
  float four_angle = 41 - 40
                                    95 -20
  float five_angle = 95 -20
                                15
                                              15 :
  float six_angle = -51 - 10
                                 38 -51 -10
                                               38 ;# front recirc
}
```

Appendix B

Selected Datasheets

B.1 Agilent HEDS Series Encoders [5]

Agilent Technologies

HEDM-550x/560x HEDS-550x/554x HEDS-560x/564x

Quick Assembly Two and Three Channel Optical Encoders

Technical Data

Features

- Two Channel Quadrature Output with Optional Index Pulse
- Quick and Easy Assembly
 No Signal Adjustment Required
- External Mounting Ears
- Available • Low Cost
- Resolutions Up to 1024
 Counts Per Revolution
- Small Size
- -40°C to 100°C Operating Temperature
- TTL Compatible
 Single 5 V Supply

Description The HEDS-5500/5540, HEDS-5600/5640, and HEDM-5500/ 5600 are high performance, low cost, two and three channel optical incremental encoders. These encoders emphasize high reliability, high resolution, and easy assembly.

Each encoder contains a lensed LED source, an integrated circuit with detectors and output circuitry, and a codewheel which rotates between the emitter and detector IC. The outputs of the HEDS-5500/5600 and HEDM-5500/ 5600 are two square waves in quadrature. The HEDS-5540 and 5640 also have a third channel index output in addition to the two channel quadrature. This index output is a 90 electrical degree, high true index pulse which is generated once for each full rotation of the codewheel.

The HEDS series utilizes metal codewheels, while the HEDM series utilizes a film codewheel allowing for resolutions to 1024 CPR. The HEDM series is nont available with a third channel index.

These encoders may be quickly and easily mounted to a motor. For larger diameter motors, the HEDM-5600, and HEDS-5600/ 5640 feature external mounting ears.

The quadrature signals and the index pulse are accessed through five 0.025 inch square pins located on 0.1 inch centers.

Standard resolutions between 96 and 1024 counts per revolution are presently available. Consult local Agilent sales representatives for other resolutions.



Applications The HEDS-5500, 5540, 5600, 5640, and the HEDM-5500, 5600 provide motion detection at a low cost, making them ideal for high volume applications. Typical applications include printers, plotters, tape drives, positioning tables, and automatic handlers.

Note: Agilent Technologies encoders are not recommended for use in safety critical applications. Eg. ABS braking systems, power steering, life support systems and critical care medical equipment. Please contact sales representative if more clarification is needed.

ESD WARNING: NORMAL HANDLING PRECAUTIONS SHOULD BE TAKEN TO AVOID STATIC DISCHARGE.

APEX SA60 Power Amplifier [6] B.2



FEATURES

- LOW COST COMPLETE H-BRIDGE • SELF-CONTAINED SMART LOWSIDE/HIGHSIDE DRIVE
- CIRCUITRY
- WIDE SUPPLY RANGE: UP TO 80V
- 10A CONTINUOUS OUTPUT
 ISOLATED CASE ALLOWS DIRECT HEATSINKING
 FOUR QUADRANT OPERATION, TORQUE
- CONTROL CAPABILITY INTERNAL/PROGRAMMABLE PWM FREQUENCY GENERATION

APPLICATIONS

- BRUSH TYPE MOTOR CONTROL
- CLASS D SWITCHMODE AMPLIFIER
 REACTIVE LOADS
 MAGNETIC COILS (MRI)

- ACTIVE MAGNETIC BEARING
- VIBRATION CANCELLING

DESCRIPTION

DESCRIPTION The SA60 is a pulse width modulation amplifier that can supply 10A continuous current to the load. The full bridge amplifier can be operated over a wide range of supply volt-ages. All of the drive/control circuitry for the lowside and highside switches are internal to the hybrid. The PWM circuitry is internal as well, leaving the user to only provide an analog signal for the motor speed/direction, or audio signal for switchmode audio amplification. The internal PWM frequency can be programmed by an external integrator capacitor. Alter-natively, the user may provide an external TTL-compatible PWM signal for simultaneous amplitude and direction control for four quadrant mode. for four quadrant mode.

BLOCK DIAGRAM









SA60



A wide variety of loads can be driven in either the voltage mode or the current mode. The most common applications use three external blocks: a low pass filter converting pulse width data to an analog output, a difference amplifier to monitor voltage or current and an error amplifier. Filter inductors must be suitable for square waves at the switching frequency (laminated steel is generally not acceptable). Filter capacitors must be low ESR and rated for the expected ripple current. A difference amplifier with gain of less than one translates the differential output voltage to a single feedback voltage. Dashed line connections and a higher gain difference amplifier would be used for current control. The error amplifier integrates the difference between the input and feedback voltages to close the loop.



+ Required RC network. See paragraph on

transient supression.

Protection diodes are recommended for applications where +Vs exceeds 50V.





APPENDIX B. SELECTED DATASHEETS

臣 فى Fizoptika **Fibre-optic** Gyroscope [17]

B.4 Lippert Cool RoadRunner II [35]



APPENDIX B. SELECTED DATASHEETS

PC/104-Plus SBC National Semiconductor Geode GX1 200 MHz/300 MHz

Technical Specifications Board Format PC/104-Plus lpt Multi-Mode™ bi-directional Parallel-Port IEEE 1284 compliant with EPP/EPC modes Processor NSC Geode GX1 Speed 200 MHz / 300 MHz ١D£ 1 primary EIDE port according to ATA4 with 33 Mbyte/s Core logic CS5530A Super I/O: SMSC FDC37B727 Sound 1/0 AC97 (Line-in, Line-out, Mic-in) Compact Flash RAM (max.) 256 Mbyte SODIMM Header type 2 RAM clock RTC Backup Replaceable battery 75 MHz Graphics CT69000, 2 MB, Watchdog yes up to 1280 x 1024 x 8 bpp Power Consumption ~6 W at 300 MHz Operating temperature -20 °C ...+60 °C (standard) -40 °C ...+85 °C (optional) CRT Analog VGA LCD Display TFT, STN, DSTN, EL, Plasma T¥-0ut PAL & NTSC Cooling passive up to 2.88 Mbyte ISA Bus Standard ISA Bus Гюррү 2 x RS232C with hardware handshake 3.3 V compliant. Serial PCI Bas Peripherals need their own 3.3 V supply Infrared IrDA (SIR) with TTL level to connect an external infrared transmitter Power Supply +5 V only. All necessary voltages are generated USB 2 x USB 1.0 compliant on-board. 10/100 BaseT 1 x Intel 82559ER 810\$ Award BIOS parameters are also saved in Ethernet FEPROM Keyboard, Mouse PS/2 Supported OS Windows, Linux



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B.5 Maxon Motor 117751 [39]



B.6 Maxon Gear 166163 [38]



B.7 Mindready Firewire Card [44]



B.8 Microcomputer Systems, Inc. MSI-P400 Quadrature Decoder [43]

DESCRIPTION

The MSI-P400 is a 15-channel quadrature decoder/counter PC/104 card designed for monitoring up to 15 quadrature encoder inputs used in monitoring motor shaft rotations. Each channel provides a 16-bit binary up/down counter with full 4X decoding using a Hewlett-Packard HCTL-2016 decoder IC. This device provides a digital noise filter network, 4X decoding logic, a 16-bit counter, and a 16-bit latched output. A card outline is shown in Figure 1.

Inputs from quadrature encoders are applied via a 40-pin input connector (J1) that requires a frequency and a reference signal input for each channel in use. Input signals are TTL levels. The clock employed for processing the input signals is derived from SYSCLK (6 to 8.33 MHz, depending on the processor card used) of the PC/104 bus. This clock signal is divided by 4 to provide the clock inputs to the HCTL-2016 decoder



Panasonic HHR-300SCP Battery [49] **B.9**

NICKEL METAL HYDRIDE BATTERIES: INDIVIDUAL DATA SHEET



 After charging at 0.1lt ior 16 hours, discharging at 0.2lt.
 ** For reference only.
 Battery performance and cycle life are strongly affected by how they are used. In order to maximize battery safety, please consult Panasonic when determining charge / discharge specs, warning label contents and unit design. and unit design.

Note: [ii] was previously expressed as [C]. [ii] is an IEC standard expression for the amount of charge or discharge current and is expressed as: [i(A) = C (Ah)/i.n. • [ii] is the reference test current in ampres • [Cn] is the reference test current in ampres n = the time base [hours] for which the rated capacity is declared

Panasonic

NICKEL METAL HYDRIDE HANDBOOK This information is generally descriptive only and is not intende modification without notice. Contact Panasonic for the latest infe

AUGUST 2003

Typical Charge Characteristics 2.0 1.9 A(1 II)X1.2hrs. 1.8 1.7 1.6 Voltage (V) 1.5 1,4 1,3 ---- 0°C ---- 20°C 0.9 0.8 60 90 30 70 20 40 50 10 Charge Time (minutes)

Typical Discharge Characteristics

| | 1.7 | | 4- | | + | | Charge: 3000mA(1 it)×1.2hrs.20°C Disharge Temperature: 20°C | | | | | | | | | | | |
|----|-----|---|--------------|-------|----------------|-------|--|---|---|----------|-----|-------|-------|------|--|--|--|--|
| | 1.6 | | . | | -j- | ~~~~ | ļ | | | ţ | | | | | | | | |
| | 1.5 | | - | | | | <u></u> | | | <u> </u> | | | | | | | | |
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| Š. | 1.3 | 2 | - <u>+</u> | | | e-112 | | ÷ | | ÷ | | ~~~ģ~ | | | | | | |
| ŝ | 1.2 | | Ŧ | | | | <u> </u> | 4 | | <u> </u> | -+- | | | | | | | |
| | 1.1 | | | | - | **** | | ÷ | ~ | <u> </u> | ~}~ | | | | | | | |
| | 1.0 | | | } | - † | | | |) | ļ | | | | | | | | |
| | 0.9 | | | ļ | - | | | | | } | | | 00mA/ | 1103 | | | | |
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APPENDIX B. SELECTED DATASHEETS

PC104.org [3]

B.10

B.11 QNX Neutrino RTOS [51]

QNX NEUTRINO AT A GLANCE

MICROKERNEL ARCHITECTURE Dynamically upgradable services and applications Fine-grained fault isolation and recovery · Message-passing design for modular, well-formed systems

DISTRIBUTED PROCESSING Transparent access to remote resources Simplified design of fault-tolerant clusters

SMP MICROKERNEL True SMP on MIPS, PowerPC, and x86 Automatic scaling of multithreaded applications

INSTRUMENTED MICROKERNEL System-wide performance analysis and optimization Fast detection of timing conflicts, hidden faults, etc.

QNX PHOTON MICROGUI Customizable look-and-feel Sophisticated multilayer displays Extensible multilimedia framework

PROTOCOL STACKS NetBSD (IPsec, IPv6) and tiny TCP/IP stacks

FILE SYSTEMS Image, RAM, Flash, QNX, Linux, DOS, CD-ROM, DVD, NFS, CIFS, Compression, Package

DEVICE DRIVERS Audio, character, disk, graphics, input, networking, parailel, printer, serial, USB

HIGH AVAILABILITY MANAGER Heartbeating for early fault detection Intelligent restart of faulty components

JAVA Certified Java powered runtime environment Java applications have full access to OS services

PREDICTABLE REALTIME PERFORMANCE Preemptive scheduler with choice of scheduling methods Distributed priority inheritance

POSIX SUPPORT POSIX 1003.1-2001, with threads and realtime extensions

PROCESSOR SUPPORT ARM, MIPS, PowerPC, SH-4, StrongARM, XScale, x86

QNX MOMENTICS DEVELOPMENT SUITE Graphical IDE, 8SPs, DDKs, and GNU tools Multi-host, multi-language, multi-target development FOR OVER TWENTY YEARS, OKX OS IECHNOLOGY HAS HELPED DEVELOPERS CREATE THE WORLD'S MOST RELIABLE REALTIME APPLICATIONS – EVERYTHING FROM LIFE-CRITICAL MEDICAL INSTRUMENTS AND IN-CAR TELEMATICS PRODUCTS TO MASSIVELY DISTRIBUTED CONTROL SYSTEMS, AND NOW, THE WORLD'S MOST RELIABLE RTOS ALSO SUPPORTS THE MOST ADVANCED TOOLS.

OW SOTWER SPEEKS OF

PROVEN RELIABILITY, MASSIVE SCALABILITY, UNPARALLELED PERFORMANCE.

B.12 Redlake Motionscope PCI [53]



MotionScope

PCI Series

The Rediake MASD MotionScope PCI system has simplified image acquisition for motion analysis. Designed as a PC peripheral for capturing high-speed digital images directly in the PC, the MotionScope PCI system consists of a high-speed camera, full size PCI camera control and frame store board (onboard memory), installation and user interface software and documentation. System operation is easy with the "point & click" windows based application software. Record rates range from 60 through 8,000 frames per second, depending on the model.

MotionScope PCi cameras can be started or stopped remotely via a handheid switch or from. an external trigger signal generated by an optical, acoustic, or electronic sensor tisandard & Volt TTL signal, or up to 30 Volt DC signal). Once captured, the images of the event reside on the Rediake MASD MotionScope PCI board in the PC until transferred over the computer's PC bus for display and analysis. Playback rates include single, 1, 2, 3, 4, 5, 10, 15, 25, 30, 50, 60, 125, 250, 500, 1,000, 2,000, 4,000 and 8,000 frames per second, forward or reverse. Images are archived in the standard

#MotionScope

for imaging excellence when quality counts



A REPORT OF THE REPORT OF THE REPORT OF

High-Spead Camera PC Peripheral The MotionScope PCI series is a complete, sesy-to-install system.

Easy Operation "Point & Click" operation, learn to operate in minutes.

Flexible Trigger Options Enables record and capture of controlled and intermittent events.

Images in the PC Makes analysis of images easier, faster and more accurate.

Microsoft .AVI file format. Images can be converted to other image file formats.

Because application requirements vary widely, MotionScope PCI systems are available in several configurations. For customer convenience, Redlake MASD offers an accessory kit that contains all the equipment needed for most applications. A complete selection of lenses, lights, tripods, etc. to handle nearly any situation in nearly any industry is also available.



APPENDIX B. SELECTED DATASHEETS

| MotionSco | obe, | |
|------------------------|--|--|
| PERFORMANC | CE SPECIFICATIONS | |
| MotionScope PCi Series | PCI 1000 S, PCI 2000 S, PCI 8060 S, PCI 1050 SC and PCI 2000 SC | |
| Image Resolution | Up to 490 x 420 x 8 bit pixels per frame depending on model | |
| Recording Rates | 60, 125, 250, 500, 1,000, 2,000, 4,000 and 8,000 frames per second depending on model | |
| Shutter Speed | Electronic shutter operates at a factor of 1x to 20x of set recording rates. Ranges from | |
| | 1/60th seconds to 10 microseconds depending upon frame rate and model | |
| Recording Mode | | |
| Manual | Begins recording when the record button is clicked. Continues to record and store | |
| | images in memory until the stop button is clicked | |
| Trigger | Begins recording when the record button is clicked. Continues to record and store | |
| | images in memory until an external trigger signal is received. The adjustable trigger | |
| | position (0% - 100%) determines how many frames are stored before and after the | |
| | trigger signal is received (time zero) | |
| Frame Storage | | |
| Standard | Up to 16,384 frames, depending on model | |
| Enhanced | Up to 32,768 frames, depending on model | |
| Maximum | Up to 65,536 frames, depending on model | |
| Playback Rates | Playback mode at 1, 2, 3, 4, 5, 10, 15, 25, 30, 50, 60, 125, 250, 500, 1,000, 2,000, 4,000 and | |
| | 8,000 frames per second, forward and reverse. Single step mode, forward and reverse | |
| Menu Display | Node (Live, Record Play), France &, Time of Frame (in ms), Camera &, Event #, F/Sec. | |
| • • | Record, Shutter Speed, Trigger Point, F/Sec. Play, Reticle Distance, Velocity, Data, Load and | |
| | Save files, Setup, and Help | |
| Operator Environment | Point & click environment for Windows 2000 and Windows N1* 4.0 with Service Pack | |
| • | 4 and 5 | |
| Trigger input | Standard TTL signal up to 30 Valts DC, BNC comrector | |
| Video Out | RS-170 (NTSC or PAL compatible) output to VCR or external monitor | |
| Phase-Lock | Austriple PCI camera systems can be Phase-Locked to insure that frame zero is identical | |
| | on each PCI camera system | |
| Lens Mount | Standard C-mount | |
| Power Requirement | +5V @ 2 Amps, + 12V @ .6 Amp per PCI Systems (20 Watts total) | |
| Board size | Full size PCI board requires 2 slot spaces to accommodate memory | |
| Camera Size | 2.5" H x 2.5" W x 4" L (63.5 x 63.5 x ×101.6mm) | |
| Weight | 1.Sibs (7kg) | |
| PC Minimum Platform | Minimum Pentium II with MMX technology, 1024 x 768 display resolution. 128MB DRAM, | |
| | 3+GB Hard Drive, CD-ROM Drive, 2 or more PCI slots-CD-9, Zip or Jazz drive recommended | |
| | | |

REDLAKE Redlake MASD, Inc.

tel: 800,462,4307 tel: 858,481,8182 fax: 858,792,3179 email: sales@redlake.com

www.redlake.com

(6 📾 Note: Specifications are typical and subject to change. 4005-02

B.13 VersaLogic PCM-3115 PCMCIA Adapter [63]



PCMCIA adapter for Type I, II, and III PCMCIA cards.

Features

- Two independent slots (accepts separate drivers)
- Supports Type I memory cards (Flash, SRAM, etc.)
- Supports Type II I/O cards (Modem, LAN, etc.)
- Supports Type III cards (ATA mass storage)
- Supports Microsoft's FFS-2

Description

The PCM-3115 provides PC/104 systems with two PCMCIA compatible slots. PCMCIA cards were originally designed for the laptop computer market, but have also proven to be very useful in industrial systems. A variety of functions are available in these plug-in credit card sized cards. These include Flash (non-volatile) memory, modems, LAN interface, and miniature hard drives.

Ordering Information

PCM-3115...... Two Slot PCMCIA Interface VL-HDW-100......Standoff Pkg. English Thread VL-HDW-101.....Standoff Pkg. Metric Thread PCM-3115 Two Slot PCMCIA Interface



Specifications

Specifications are typical at 25°C with 5.0V supply unless otherwise noted. Board Size: 3.55° x 3.775° (PC/104 standard) Storage Temperature: -20° to +85° C Free Air Operating Temperature: 0° to +60° C Power Requirements: +5V @ 70 ma typ. Compatibility:

PC/104 Type I, II, and III PCMCIA cards

Specifications are subject to change without notice. PC/104 and the PC/104 logo are trademarks of the PC/104 Consortium.



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