

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

***Mechatronic Simulation & Exploration of a
Mechanical Context relevant to Quadrupedal
Neuromorphic Walking employing
Nervous Networks for Control***

*A thesis presented in partial fulfillment of the
requirements for the degree of*

*Master of Engineering
Mechatronics*

at

*Massey University,
Albany, New Zealand.*

Matthew Read

2008

Abstract

Neuromorphic engineering is the study and emulation of neural sensory and control structures found in the natural world. Currently a significant research focus in this field, and indeed, in engineering at large, is the research of robotic walking platforms – an ideal application for artificial neural controllers.

To design such neuromorphic controllers, significant knowledge is needed of the robotic context to which they will be applied. The focus of this research is to explore the relationship between the mechanical design of a robot, and its resultant walking proficiency.

A neuromorphic controller utilizing Nervous networks was constructed, and embedded into a typical & useful mechatronic context. This consists of a simple walking platform, of a type commonly used in Nervous network research. This robot was used to provide intuition and a reference point for development of a simulation for empirical testing.

A physical simulation of the mechanical context was developed, allowing for the exploration of its behaviour, particularly with regard to the type of walking “caused” by the integration of an appropriate Nervous network controller.

To evaluate the behavioural fitness of this context in various configurations, empirical simulations were run using the developed simulation, and heuristic results derived to develop optimized parameters for causing walking behaviours in the studied context. Further simulations were then run to evaluation the efficacy of these developed heuristics.

From these simulations & explorations, the presence of an identifiable “critical point phenomenon” in the interaction between the robot’s legs was demonstrated. This critical point was then used for parameter extraction; further simulation demonstrated that parameters extracted from this critical point provided near-optimal walking behaviour from the robot in a variety of leg topologies.

These results provide significant knowledge and intuition for designers of quadrupedal walking platforms, particularly those driven from Nervous network derived neuromorphic controllers. Implementation of these results in such a robotic platform will provide useful new “real world” data, allowing the developed models & heuristics to be further refined.

Acknowledgements

*Though completed now this thesis is,
But by long labour it would not have been;
So many hours of solder, sweat, and tears,
Were given, and never shall be seen again.*

*But not just by my merit, not just by my toil,
Did this research happen or this thesis be wrote;
A vast host of helpers, motivating, encouraging,
Were oft all that gave me inspiration and hope.*

*At home, ever steadfast, with wisdom and patience
Ideas, support, and good food gave my parents to me;
At my first home away, my flatmates, my brothers,
Buoyed up my spirits in such times I had need.*

*My second home away, the house of the Creator,
With prayer and counsel, my friends and pastors e'er were there;
My third home, the Institute, the ceaseless office-moving,
Yet never-the-less from my supervisor, support always I found here.*

*Johan, Peter and Olaf, Lim, Baden, Gordon and Jonty,
Colleagues many and varied there be;
Sound advice, handy components, and friends to commiserate,
Though I'm sure some will be glad to see the back of me.*

*To Amber, my dear friend, I owe ever so much,
The ear to listen, and the heart to care;
And last but not least, to the God of the Universe
I owe my life, my sanity, my freedom, my gifts and my mind.*

Without you all, this thesis would never have existed.

Thank you.

Table of Contents

ABSTRACT	I
ACKNOWLEDGEMENTS	II
TABLE OF CONTENTS	III
LIST OF FIGURES	VI
LIST OF EQUATIONS	VIII
LIST OF TABLES	IX
ABBREVIATIONS	X
1 GENERAL INTRODUCTION	1
1.1 Aim	1
1.2 Introduction	1
1.3 Robotic Walking	2
1.4 Design Approaches	4
1.4.1 Classical	4
1.4.2 Mechatronic	6
1.4.3 Neuromorphic	7
1.4.4 Biomorphic	9
1.4.5 BEAM	11
1.5 Neuromorphic Walking	13
1.6 Nervous Network	15
1.6.1 Introduction	15
1.6.2 Nervous Neurons	15
1.6.3 Nervous Networks	21
1.6.4 Applications	26
1.7 Summary	28
2 ROBOTIC PLATFORM	29
2.1 Introduction	29

2.2	Controller	29
2.3	Actuators	32
2.4	Sensors	33
2.5	Power Supply	34
2.6	Interface	36
2.7	Legs	37
2.7.1	Material characteristics	38
2.7.2	Shape	38
2.8	Chassis	39
2.9	Robot Stepping Stances	40
2.9.1	Stance 0	41
2.9.2	Stance 1	42
2.9.3	Stance 2	43
2.9.4	Stance 3	44
2.9.5	Stance 4	45
2.10	Untuned Behaviours	46
2.11	Summary	47
3	SIMULATION	49
3.1	Introduction	49
3.2	Simulation Tool	49
3.3	Pilot Run	50
3.4	Environment	53
3.5	Mechanical Model	55
3.5.1	Vertical Leg	55
3.5.2	Horizontal Leg	57
3.5.3	Chassis Link	57
3.6	Motion Model	58
3.6.1	Joints	58
3.6.2	Contact	60
3.7	Simulation Settings	61
3.8	Summary	62
4	METHODOLOGY	64
4.1	Introduction	64

4.2	Experimental Design	64
4.3	Research Questions	70
4.4	Simulation Runs	71
4.4.1	Alpha	71
4.4.2	Beta	74
4.4.3	Gamma	77
4.4.4	Delta	79
4.4.5	Epsilon	80
4.5	Selection of Driver Functions	82
4.6	Summary	84
5	RESULTS	87
5.1	Introduction	87
5.2	Alpha Run	87
5.2.1	Variations	87
5.2.2	Results	87
5.3	Beta Run	94
5.3.1	Variations	94
5.3.2	Results	97
6	DISCUSSION & CONCLUSION	112
6.1	Discussion	112
6.1.1	Simulation Run Alpha	112
6.1.2	Simulation Run Beta	115
6.1.3	Other Simulation Runs	123
6.1.4	Summary	124
6.2	Recommendations	125
6.2.1	Further Model Development	125
6.2.2	Further Research Development	126
6.3	Research Application	127
6.4	Conclusion	128
7	REFERENCES	131
7.1	Images	134

List of Figures

FIGURE 1: MECHATRONICS OVERVIEW	7
FIGURE 2: OUTPUT FROM A NEUROMORPHIC AVLSI IMPLEMENTATION OF A FLY'S EYE (NETTER, 2004)	8
FIGURE 3: AN OVERVIEW OF BIOMORPHIC ROBOTICS (SMITH, 2001).....	10
FIGURE 4: NERVOUS NEURON (SOLARBOTICS.NET).....	16
FIGURE 5: SCHMITT-TRIGGER INVERTER THRESHOLD VOLTAGES	17
FIGURE 7: A TYPICAL BICORE NERVOUS NETWORK CIRCUIT (SOLARBOTICS.NET).....	21
FIGURE 8: A TYPICAL QUADCORE NERVOUS NETWORK CIRCUIT (SOLARBOTICS.NET).....	22
FIGURE 9: INPUT/OUTPUT BEHAVIOUR (ATTRACTOR DIAGRAM) FOR A QUADCORE NERVOUS NETWORK (RIETMAN ET. AL., 2003).....	23
FIGURE 10: AUTOCORRELATION FUNCTION PLOTS FOR 5-NEURON NV-NETWORK COMPARED TO RANDOM (RIETMAN ET. AL., 20030).....	25
FIGURE 11: QUADCORE CIRCUIT IMPLEMENTATION (RITGER, 2002)	30
FIGURE 12: SECOND REVISION CIRCUIT PCB SCHEMATIC	31
FIGURE 13: H-BRIDGE CIRCUIT DIAGRAM.....	37
FIGURE 14: STANCE ZERO (V-LEG JOINT UNROTATED, H-LEG JOINT UNROTATED).....	41
FIGURE 15: STANCE ONE (V-LEG JOINT CCW, H-LEG JOINT CCW).....	43
FIGURE 16: STANCE TWO (V-LEG JOINT CCW, H-LEG JOINT CW).....	44
FIGURE 17: STANCE THREE (V-LEG JOINT CW, H-LEG JOINT CW).....	45
FIGURE 18: STANCE FOUR (V-LEG JOINT CW, H-LEG JOINT CCW).....	46
FIGURE 19: ROUGH SOLIDWORKS MODEL OF THE MECHANICAL CONTEXT.....	51
FIGURE 20: INITIAL COSMOS/MOTION GROUND SURFACE CONTACT PROPERTIES.....	52
FIGURE 21: SQUARE STANCE VERTICAL OFFSET	53
FIGURE 22: SEQUENCE OF EVENTS FOR TIPPING WITHIN A STEP	56
FIGURE 23: SIMULATED H-LEG GEOMETRY	57
FIGURE 24: HORIZONTAL-STEPPING LEG JOINT ON SIMULATED MECHANICAL CONTEXT.....	59
FIGURE 25: VERTICAL-STEPPING LEG JOINT ON SIMULATED MECHANICAL CONTEXT.....	60
FIGURE 26: 3D CONTACT DEFINITION FOR SIMULATED MECHANICAL CONTEXT	61
FIGURE 27: SIMULATION SETTINGS.....	62
FIGURE 28: EXPLODED VIEW OF SIMULATED ROBOT SHOWING JOINT/LINK GEOMETRY	66
FIGURE 29: H-LEG GEOMETRY.....	67
FIGURE 30: GAMMA RUN VARIABLES & OUTPUTS	78
FIGURE 31: DELTA RUN VARIABLES & OUTPUTS	79
FIGURE 32: EPSILON RUN VARIABLES & OUTPUTS.....	80
FIGURE 33: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-1, WH=90 MM.....	88
FIGURE 34: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-2, WH = 100 MM	88
FIGURE 35: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-3, WH=110 MM.....	89
FIGURE 36: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-4, WH=120 MM.....	89
FIGURE 37: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-5, WH=130 MM.....	90
FIGURE 38: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-6, WH=140 MM.....	90
FIGURE 39: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-7, WH=150 MM.....	91
FIGURE 40: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-8, WH=160 MM.....	91
FIGURE 41: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-9, WH=170 MM.....	92
FIGURE 42: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-10, WH=180 MM.....	92
FIGURE 43: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-11, WH=190 MM.....	93
FIGURE 44: ANGLE RELATIONSHIP, ALPHA RUN, GEOMETRY ALPHA-12, WH=200 MM.....	93
FIGURE 45: COM PATH, BETA RUN, GEOMETRY BETA-1, SAMPLE C.....	97
FIGURE 46: COM PATH, BETA RUN, GEOMETRY BETA-1, SAMPLE B.....	98
FIGURE 47: COM PATH, BETA RUN, GEOMETRY BETA-1, SAMPLE A.....	98
FIGURE 48: COM PATH, BETA RUN, GEOMETRY BETA-1, SAMPLE D.....	99
FIGURE 49: COM PATH, BETA RUN, GEOMETRY BETA-1, SAMPLE E.....	99

FIGURE 50: COM PATH, BETA RUN, GEOMETRY BETA-2, SAMPLE C	100
FIGURE 51: COM PATH, BETA RUN, GEOMETRY BETA-2, SAMPLE B	101
FIGURE 52: COM PATH, BETA RUN, GEOMETRY BETA-2, SAMPLE A	101
FIGURE 53: COM PATH, BETA RUN, GEOMETRY BETA-2, SAMPLE D	102
FIGURE 54: COM PATH, BETA RUN, GEOMETRY BETA-2, SAMPLE E	102
FIGURE 55: COM PATH, BETA RUN, GEOMETRY BETA-3, SAMPLE C	103
FIGURE 56: COM PATH, BETA RUN, GEOMETRY BETA-3, SAMPLE B	104
FIGURE 57: COM PATH, BETA RUN, GEOMETRY BETA-3, SAMPLE A	104
FIGURE 58: COM PATH, BETA RUN, GEOMETRY BETA-3, SAMPLE D	105
FIGURE 59: COM PATH, BETA RUN, GEOMETRY BETA-3, SAMPLE E	105
FIGURE 60: COM PATH, BETA RUN, GEOMETRY BETA-4, SAMPLE C	106
FIGURE 61: COM PATH, BETA RUN, GEOMETRY BETA-4, SAMPLE B	107
FIGURE 62: COM PATH, BETA RUN, GEOMETRY BETA-4, SAMPLE A	107
FIGURE 63: COM PATH, BETA RUN, GEOMETRY BETA-4, SAMPLE D	108
FIGURE 64: COM PATH, BETA RUN, GEOMETRY BETA-4, SAMPLE E	108
FIGURE 65: COM PATH, BETA RUN, GEOMETRY BETA 5, SAMPLE C	109
FIGURE 66: COM PATH, BETA RUN, GEOMETRY BETA 5, SAMPLE B	110
FIGURE 67: COM PATH, BETA RUN, GEOMETRY BETA 5, SAMPLE A	110
FIGURE 68: COM PATH, BETA RUN, GEOMETRY BETA 5, SAMPLE D	111
FIGURE 69: COM PATH, BETA RUN, GEOMETRY BETA 5, SAMPLE E	111
FIGURE 70: SIMULATION RUN ALPHA ROBOT, SQUARE STANCE, H-LEG WIDTH = 140 MM	113
FIGURE 71: JOINT ANGLES THROUGHOUT ALPHA RUN SIMULATION, H-LEG WIDTH = 130 MM	114
FIGURE 72: "ELBOW POINT" DETERMINATION	117
FIGURE 73: ESTIMATED V-LEG PARAMETERS FOR DETERMINING "ELBOW POINT" OPTIMALITY	117
FIGURE 74: "CLOSEST MATCH" SELECTION TO PROVIDE PARAMETERS SURROUNDING "ELBOW POINT"	118

List of Equations

- EQUATION 1: OUTPUT VOLTAGE OF AN RC HIGH PASS FILTER..... 16
- EQUATION 2: VOLTAGE RESPONSE OF A NERVOUS NEURON 18
- EQUATION 3: BETA RUN PARAMETER VECTOR CONSTRUCTION..... 75
- EQUATION 4: VERTICAL & HORIZONTAL LEG DRIVER FUNCTIONS FOR BETA SIMULATION RUN..... 75
- EQUATION 5: DRIVING EQUATIONS FOR H-LEG WIDTH $W_H = 150$ MM 116
- EQUATION 6: DRIVING FUNCTION GENERATOR EQUATION (EXCEL) 118

List of Tables

TABLE 1: BICORE NETWORK STATES21

TABLE 2: QUADCORE NETWORK STATES23

TABLE 3: SUMMARY OF RESEARCH QUESTIONS.....71

TABLE 4: ALPHA RUN VARIABLES AND OUTPUTS.....71

TABLE 5: BETA RUN VARIABLES AND OUTPUTS74

TABLE 6: FRICTION COEFFICIENTS FOR EXECUTIONS OF EPSILON RUN SIMULATIONS81

TABLE 7: SUMMARY OF SIMULATION RUNS.....86

TABLE 8: DRIVING FUNCTIONS, BETA RUN, GEOMETRY BETA-1, WH = 100 MM.....97

TABLE 9: DRIVING FUNCTIONS, BETA RUN, GEOMETRY BETA-2, WH = 120 MM.....100

TABLE 10: DRIVING FUNCTIONS, BETA RUN, GEOMETRY BETA-3, WH = 150 MM.....103

TABLE 11: DRIVING FUNCTIONS, BETA RUN, GEOMETRY BETA-4, WH = 170 MM.....106

TABLE 12: DRIVING FUNCTIONS, BETA RUN, GEOMETRY BETA-5, WH=200 MM109

TABLE 13: BETA RUN PARAMETERS DERIVED FROM ALPHA RUN SIMULATIONS119

TABLE 14: BETA RUN COM DISPLACEMENTS120

TABLE 15: BETA RUN PEAK POWER DISSIPATION - VERTICAL LEG121

TABLE 16: BETA RUN PEAK POWER DISSIPATION - HORIZONTAL LEG122

Abbreviations

Nv-neuron	Nervous Neuron
Nu-neuron	Neural Neuron
Nv-net	Nervous Network
CPG	Central Pattern Generator
ITE	Institute of Technology & Engineering, Massey University
aVLSI	Analogue Very Large Scale Integration
BEAM	Biology, Electronics, Aesthetics, Mechanics
LANL	Los Alamos National Laboratory
IEEE	Institute of Electronic & Electrical Engineers
V-leg	Vertical Stepping leg, i.e. the leg with a rotational axis along the Z-axis (along the "spine" of the robot)
H-leg	Horizontal Stepping leg, i.e. the leg with a rotational axis along the Y-axis.

1 General Introduction

1.1 Aim

This Masters thesis will explore and investigate, in simulation, the influence of various factors in the design of a neuromorphic walker's mechanical context on the robot's walking behaviour, through a fusion of mechatronic and neuromorphic engineering techniques.

1.2 Introduction

Robotic walking has been a much pursued field of study for many years now, for a wide variety of research aims, and from the perspective of a broad spectrum of disciplines, both within engineering, and as part of the wider study of science (Paulsen, 2004). This project will focus on a particular subset of the possibilities for robotic walking offered by the fields of mechatronics and neuromorphics, applied through the perspective of BEAM design philosophy.

The particular robot design to be used, to be detailed in section 2: Robotic Platform, is a simple quadrupedal walker driven by two motors, with the control provided by a nervous network, or Nv-net. Nervous networks are a type of artificial neuronal system that has not yet been explored widely. Despite their successful implementation across dozens of robotic designs, academic investigation into their properties and behaviour has been scarce, due in part to the underdeveloped theory currently underlying their operation (Tilden, 1997).

Many of the design philosophies applicable to the design and research of systems using this type of neuronal network (to be outlined in section 1.4: Design Approaches) espouse the usage of tightly integrated multi-disciplinary techniques. And indeed, due to the "bounded chaos" nature of Nv-nets (Tilden, 1997), it is very difficult to abstractly

understand how a robot designed with such a controller will react and behave in the “fractal environment” of the real world (Rietman et al., 2003).

As such, the author proposes that much meaningful research into the behaviour of Nv-nets will require them to be embedded into “environmental interfaces” – robots or other similar systems that provide the network with an environment to interact with, be stimulated by, and respond/react to. One of the simplest such situations developed is a small, two-motor, quadrupedal walker. This design has been used extensively by both researchers and amateur roboticists, but also has a poorly developed theoretical underpinning.

This can significantly complicate the study of the Nv-net’s behaviour in this context, and thus it is necessary to facilitate better causal isolation between the influence of the controller upon the robot’s behaviour, and the influence of the mechanical geometry on the robot’s behaviour. This study intends to explore the influence of the mechanical platform of such robots, from a geometrical perspective, in the hopes of providing a better defined platform and context within which more dedicated Nv-net research can take place.

1.3 Robotic Walking

In recent years, a major focus of study within the field of mobile robotics has been the study and development of perambulatory robots – robots that employ legs as their primary means of locomotion (Wahde & Petterson, 2002). Many of these robots draw at least minimal inspiration from the natural world, and are developed for a wide variety of applications and motivations.

Current research into walking and legged robots is driven by a wide variety of motivations, but some generalizations can be drawn. One very common such “high level” goal is to produce robots that are able to operate within the same environment and “task domain” as humans. An excellent example of this is Honda’s ASIMO robot, which

appears very human-like, and has demonstrated the ability to climb up and down stairs, as well as natural-looking walking behaviour (Hirai et al., 1998).

Such an approach aims for several advantages, in particular the ability of the robot to use equipment and facilities designed originally for human use. Although this also extends significantly to the manipulators etc... or the robot, the legged locomotion system is also a very important consideration when developing robots towards this aim. Any robot expected to work in such environments will need to be capable of handling stairs, avoidance of moving obstacles (i.e. humans) in narrow passages, and ideally be able to deal with sitting and standing at workstations designed for human use, all while maintaining its balance.

Liu et. al (2007) note that, in addition to this, legged robots designed to operate in outdoor environments hold significant advantages over equivalent wheeled/tracked designs. Particularly, a walking robot requires only to make contact with discrete points of the environment in order to move, whereas a wheeled robot requires a safe, continuous path to achieve motion between two points. In rough terrain, this can significantly limit the number of potential paths for a wheeled robot, or may present no traversable path at all; a legged robot would however have the ability to evaluate a path as a discrete series of safe "stepping stones" that were within the capabilities of its walking mechanism and controller.

Further to this, another major rationale for the research of humanoid walking robots, is to learn and understand more about how the human body deals with walking. Most humans learn to walk very early in their life, and with the exception of severe neural or muscular damage, rarely struggle with or lose this ability until well into old age (Guralnik, et. Al., 2001). By conducting research into what allows a robot to walk, we thus gain further insight into the internals and control techniques that allow humans to walk so intuitively; this in turn will result in new techniques and viewpoints for the development of robotic walking systems (Paluska, 2000).

At a somewhat simpler level, and perhaps more useful in the short term, is the similar pursuit of walking systems modeled of insects, arachnids, and simple quadrupeds such as lizards or salamanders (Long Jr., J. H., 2007). As the neuromuscular complexity of these organisms is much less than that of a human, these studies offer the opportunity for more immediately accessible insight, and thus provide clues and inspiration for the pursuit of understanding regarding biological walking movement.

1.4 Design Approaches

As robotics is both a diverse and rapidly-evolving field of engineering, a wide variety of approaches and philosophies have been applied to robotic design.

1.4.1 Classical

Classical robotics is used here as a rather broad term, but in essence refers to the prevailing design philosophy for a significant proportion of the “Age of Robotics” – the process of mathematically modeling the robotic mechanism in question, and using this model to produce analytical control expressions that can be used to determine the joint angles required of a mechanism to reach a certain position or stance (Goldenberg, 1985).

This approach has been used successfully in many areas of robotics, and particularly the field of industrial robotics, where robotic manipulators are required to perform a consistent series of algorithmic steps many times over.

In this situation, the ability to apply rapidly calculable mathematical equations to compute the robot actuations required to fulfill a particular algorithmic step provides a simple and reliable system. The most common analytical method applied to such tasks is that of Inverse Kinematics. Kinematics is the study of motion, and by applying its methods to a robot, it is trivial to develop an equation that can express the position and orientation of an end effector as a function of its actuator angles. The Inverse Kinematic

model of a robot, however, attempts to express the actuator angles of a robot as a function of the position and orientation of the end-effector (Goldenberg et. al., 1985).

Additionally, many robots operate in situations where, despite the repeatability of the overall task, small variances may occur between iterations of a task, such as picking fruit from a conveyor belt (Corke, 1994). This necessitates additional computational capability in the robot to calculate, with the aid of relevant input data provided from sensors (such as video cameras, for the fruit picking example), the modifications to the algorithm's defined motion paths and operations to allow the robot to adapt.

The generation of dynamic paths, however, rapidly becomes more complex as DOFs are introduced to the system, or if constraints or motion paths are applied to the individual links composing the robotic system, rather than just the end effector (Shiller & Dubowsky, 1989). The primary cause for this increase in computational burden is because the system can no longer choose any available path to move the end-effector in a particular way – it must now evaluate a motion path that is subject to strict constraints, and may even require backtracking of some joints. To express this another way – although fewer choices are now available to the system, the computational burden is increased simply because a choice must now be made.

Veering away somewhat from industrial robotics, the above principle particularly comes into effect in the development of robots to interact or work in environments where humans are significantly present. Robots must be able to accurately sense and rapidly adapt to human presence within their operating domain, as many robots are capable of harming a human being within their normal operating cycle (Ikuta et. al., 2003).

While these problems require serious design consideration in fixed robots, the difficulties they can cause increase by an order of magnitude when factored into the development of mobile walking robots. As a walking robot moves, joints must not only be actuated such as to effect the robot's motion, they must also be managed to keep the robot balanced (Pratt, 2000).

To this end, extensive onboard processing must be done to evaluate the robot's position and motion relative to its environment, and to thus produce a series of real-time movements that will allow the robot to remain upright in the environment, while achieving the movement goals required of it. McGeer (1990) refers to the differentiation between static and dynamic walking – static walking operates off a cycle of step-balance-plan, whereas dynamic walking involves continuous movement without pauses between steps for planning and/or balancing. Dynamic walking is particularly employed by robots that attempt to employ the natural physical dynamics of their mechanism to assist them in walking, as pausing with each step would disrupt the flow of their motions.

While some of the most capable walking robots in the world, such as Honda's ASIMO (Advanced Step in Innovative Mobility) robot, are developed and controlled using this model, significant processing power and development time is required to support perambulatory motion in this context (Chestnutt et. al., 2005).

1.4.2 Mechatronic

Mechatronics as an engineering discipline primarily evolved out of Electromechanical engineering during the 1970s, however it exhibits significant philosophical differences (Comerford, 1994). Mechatronics places a higher emphasis on integration of technologies, particularly between the software, mechanical and electronic engineering, and thus attempts to create a field of engineering that is intrinsically multi-disciplinary; a diagram expressing this disciplinary fusion is shown in Figure 1 below.

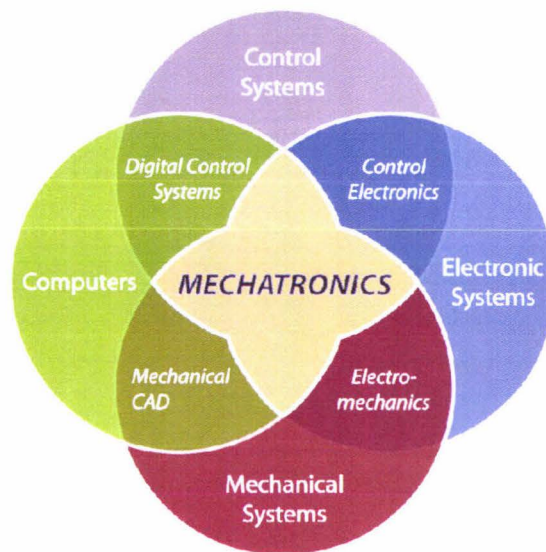


Figure 1: Mechatronics Overview

This emphasis on systems integration by mechatronics lends itself well to the design of all types of robots, including mobile “intelligent” robotic agents. It is thus difficult to define particular examples of Mechatronic robotics project, as almost all robotic research could be classified, to some extent or another, as an exercise in mechatronics (Ferretti, et. al., 2004).

1.4.3 Neuromorphic

Neuromorphic research is primarily categorized by the emulation and imitation of neural and sensory systems from natural organisms. A major theme in recent neuromorphic research has been the development of “neural” sensors that attempt to perceive & process information and stimuli in a similar fashion to equivalent biological sensors (i.e. sensory organs) (Bains, 2004).

A typical example of such research is the work of Netter (2004) in designing and implementing a neuromorphic equivalent of a fly’s eye. The developed sensor’s

perception is highly pixilated (much like the image received by a fly's compound eye), however it is able to perform high level feature identification in real time, without the aid of a DSP or microprocessor. Figure 2 below shows an example of the output generated by this sensor.

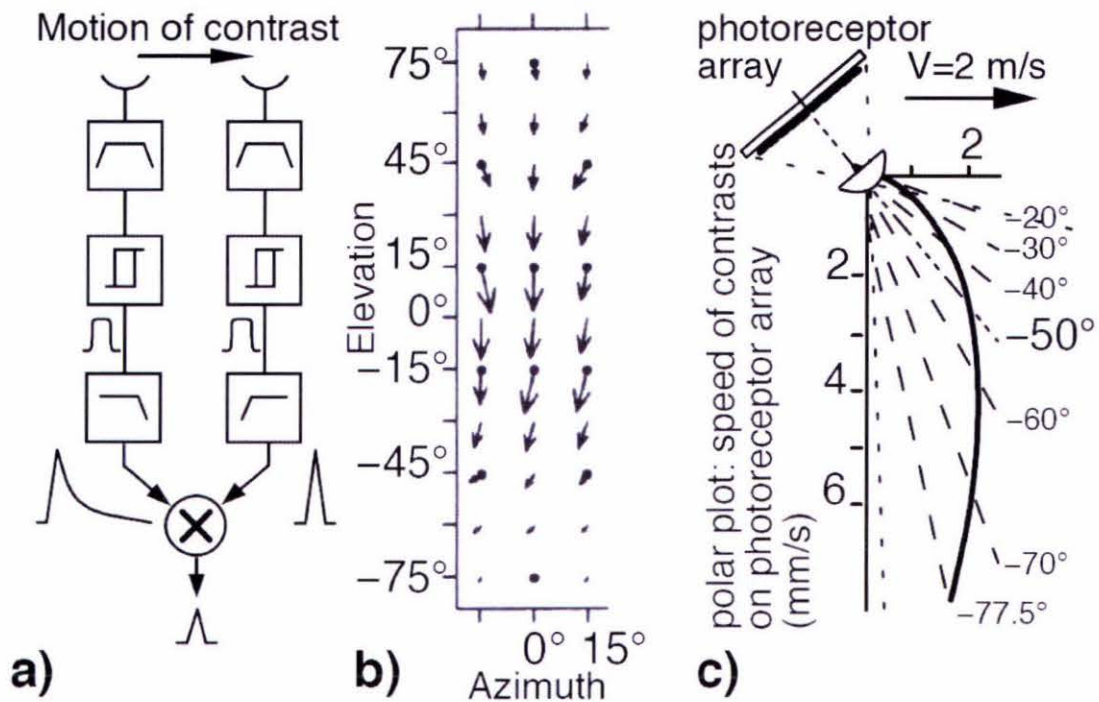


Figure 2: Output from a Neuromorphic aVLSI Implementation of a Fly's eye (Netter, 2004)

In “true” neuromorphic fashion, this sensor not only emulates the stimulus collection method (a low-resolution array of grayscale sensors), but also the stimulus processing technique and the information transmission protocol from the target organism.

While much research has indeed been focused on the study & development of this type of “artificial sensory organs”, two other significant avenues of research are observed by the author in current literature. As opposed to the experimental & practical implementation research being pursued towards neural sensor technologies, a significant body of research has been performed to develop the enabling technology of aVLSI (Analogue Very Large Scale Integration) as well; indeed, the field of neuromorphics developed out of research in this area (Mead, 1990)

Although Tilden has demonstrated the potential to mass-produce neuromorphic machines using discrete components (Hyrnkiw & Tilden, 2002), implementing neuromorphic systems in aVLSI has significant advantages, particularly in terms of miniaturisation (allowing for smaller systems which require less power to operate) and mass production (making such systems viable for everyday application). Additionally, the ability to create abstracted, modular, aVLSI “organs” that can be used as discrete processing components is also popular among neuromorphic researchers (Haefliger, 2005, Vogelstein et. al., 2004).

1.4.4 Biomorphic

Strongly related to neuromorphic engineering, biomorphic engineering involves considering an entire organism, rather than focusing on the neural and sensory elements thereof, as shown in Figure 3 (Smith, 2001). The name is a reference to “biological morphology” – morphology being the study of shape and form, and biology referring to natural organisms – thus the engineering study of biological organisms in their entirety.

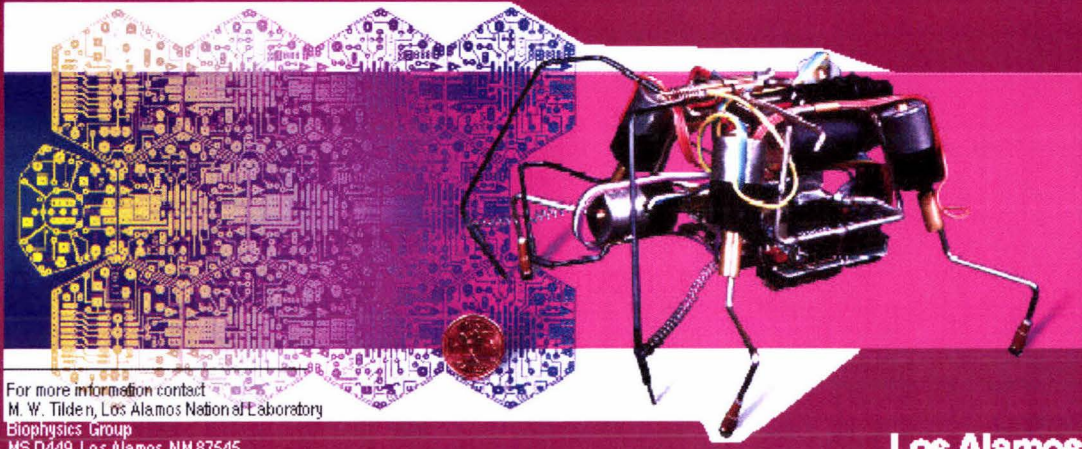
CIC-125-484vq 12/04

Biomorphic Machines

A *revolutionary* approach to robotics

- Versatile, inexpensive, survival-oriented living machines
- Intelligence achieved through artificial Nervous Net™ systems
- Applications
 - Environmental sensing, remediation
 - Security and maintenance
 - Mine detection and detonation
 - Domestic appliances

This solar-powered engineering prototype can be constructed at low cost (less than \$20).



For more information contact
M. W. Tilden, Los Alamos National Laboratory
Biophysics Group
MS D449, Los Alamos, NM 87545
(505) 667-2902

Los Alamos
NATIONAL LABORATORY

Figure 3: An Overview of Biomorphic Robotics (Smith, 2001)

There exists considerable overlap in neuromorphic & biomorphic research, making it difficult sometimes to distinguish between the two fields. As such, the term “neuromorphic” is used relatively loosely throughout this thesis, referring not only to biomorphism & neuromorphism as engineering disciplines, but also to the concept of biomimetism (engineering imitating nature) as a whole.

This confusion exists partly due to the fact that any biomorphic design will inherently incorporate neuromorphic elements, as any biological organism inherently contains a neural component. An example of a typical biomorphic research project is Rodriguez' (et. al., 2006, 2006) work with deriving biomorphic designs from *Coleoptera Scarabaidae*, a type of scarab beetle.

Rodriguez' team constructed a robot closely imitating the morphology of the scarab beetle, and developed a controller to imitate its walking gaits and behaviour. They were able to use this model to then explore the changes that a scarab's "walking controller" had to implement in order to effect proficient locomotion across a wide variety of terrain types, as well as providing comparative studies of the relative performance of traditional control systems and locomotion platforms.

In simulating such organisms, it is thus possible to gain considerable and valuable insight into the engineering design of the natural world: our ability to imitate these natural sensory & mechanical systems is growing rapidly due to concerted biomimetic research, allowing us to engineer "better" systems from lessons learned from nature. There is still much to learn so we can more closely emulate nature's elegantly designed systems, thus necessitating continued research into this field.

1.4.5 BEAM

BEAM robotics forms a significant sub-discipline of Biomorphic engineering, however it is significant in that a large amount of activity in this area is carried out in non-academic circles. In particular, an extremely active community of amateur roboticists has made significant contributions to the practical implementation and design of a veritable plethora of robots. From a research perspective, however, this can create difficulties due to the low level of academically-recognised published theoretical advancement carried out by such experimenters. Additionally, significant advances have certainly been made by notable "consumer robots" such as the Robosapiens, BIO-Bug, and related robots, however due to the commercial nature of their designs, few results or theoretical research have been made publicly available.

As a design philosophy, however, BEAM is well developed, and provides an interesting "worldview" combining biomorphic, biomimetic and mechatronic approaches. BEAM robotics requires an approach that considers all aspects of a robotic system as influencing

all other aspects – for example, adjusting the shape of the legs on a walker is as much “programming” the behaviour of the resultant robot as altering its controller (Geng, 2007). This mirrors both the mechatronic approach of tight integration with the biomorphic consideration of an organism as an entire system.

Additionally, BEAM also places considerable emphasis on aesthetics as a design tool – as many BEAM designs are biomimetic in nature, this draws off the observation that many natural systems not only work well, but also look good – function follow form. However the inverse is also true, and many BEAM-designed systems are relatively minimalist, allowing form to follow function, with little extraneous “eye candy” or non-functional cosmetic components (Tilden, 1997). As an example of this, the Robosapiens 2 consumer robot has what appear to be purely cosmetic kneecaps on its legs; on closer observation of the walking robot however, it becomes apparent that these kneecaps form an integral part of its walking gait.

Many of these principles are expressed by BEAM’s name, a very flexible acronym from which several apt descriptions of this design philosophy have been constructed, including:

- **B**iology, **E**lectronics, **A**esthetics, **M**echanics
- Biotechnology Ethology Analogy Morphology
- Building Evolution Anarchy Modularity

The first of these is the most commonly used acronym to describe the field due to its broad scope, as many of the other “backronyms” describe only particular facets of the philosophy in detail.

Another distinguishing feature typical of BEAM designs is the lack of a microcontroller. The primary reason for this is, in following the philosophy of elegant imitation of nature, it is more suitable to employ neural controllers (Bain, 2004). While in amateur circles it is common to construct the desired artificial neuronal network from discrete components,

a significant level of research into aVLSI has been undertaken by the neuromorphic community, and is relevant for academic research into complex BEAM “organisms”.

An important aspect of BEAM design philosophy is the distinction between designing robots as creatures instead of machines – organisms instead of automata. As described by Tilden (2004), robots have been developed that are survival-, as opposed to task-, oriented – and as such are designed to a) require some resource to “survive”, and b) employ some strategy to acquire this resource.

A practical example of the possibilities of this approach to robotic design is the BIObug – a commercial toy developed by Tilden. The BIObug was produced in several different “species” (each with an identifying colour), each with different behavioural characteristics. Two of these “species” were coloured blue and red – blue bugs are “right handed” and can only approach “food sources” (i.e. an IR transmitter) by orbiting in a clockwise direction; red bugs lacked this trait, and could directly approach a food source.

The resulting behaviours of this combination bear eerie similarity to the behaviour of natural creatures. Blue robots tended to cluster around the IR “food” sources, jostling for position, while their red counterparts tended to make high-speed passes towards the food source. Amazingly, the blue bugs would then tend to cluster around such an intruder and force it away from the light source, before returning to the feeding circle. As Tilden (2006) describes it as, “... just one of a billion experiments I've done where the behavior is obvious to a child, but alas, mathematically intractable despite the minimality of the control and sensor networks.”

1.5 Neuromorphic Walking

As outlined earlier, neuromorphic engineering focuses on technologically emulating neuronal & sensory systems found in natural organisms. When this approach is applied to the study of legged locomotion, the author proposes that this requires special consideration. Particularly, this approach requires that neural systems responsible for

walking in an organisms must first be studied in a "mechanical context" similar to that of the organism concerned. Only then can meaningful exploration or conclusions be pursued with regard to constructing knowledge relevant to walking as a whole.

This view is supported by Lewis et. al. (2003) and others, and is a corollary of physical computation. As summarised by Lewis, physical computation refers to the common natural theme of simplifying control requirements by employing mechanical structures which effectively provide computational assistance/complexity to simpler neural behaviours. The physical dynamics of the mechanical context in which a controller is embedded thus has the potential to exhibit significant influence on the overall behaviour of the robot, justifying the examination of the mechanical context in this thesis in order to provide a platform for future work with the intended Nv-net controller.

In natural organisms, two predominant walking paradigms exist: reactive walking, and CPG-driven walking (Geng, 2007) Most creatures employ one or the other of these methods, or a combination of the two.

As an example of predominantly reactive walking, Cruse et. al. (1998) point out that a significant body of research has suggested that stick insects (*Carausius morosus*) have no central rhythmic generator to control their walking. Rather, purely reactive models have been created which accurately model the walking behaviours of such insects in slow walking gaits. Cruse models the stick insect walking controller as consisting of three distinct networks: one to perform the forward return "swing" leg movement, one to perform the driving "stance" leg movement, and a "selection" network to switch between the two as the leg reaches the extremes of its motion. These networks exist independently for each leg, and although some synchronisation between legs occurs during stick insect walking, each leg is capable of perform steps without any central driving factor.

Contrast this form of perambulatory control with that discussed by Duysens et. al. (2002). It is pointed out that many "higher" organisms rely not on purely reactive systems, but

rather have some form of central rhythmic controller which "manages" the walking behaviour of the organism - a Central Pattern Generator, or CPG. This may range from relatively simple neuronal networks in organisms such as the Salamander (Aoi & Tsuchiya, 2006), to more complex mammals such as cats (Duysens, 2000). Regardless of the complexity or arrangement of these networks, they all serve the same purpose - to generate and regulate patterns of motor impulses to regulate walking.

However, rather than exhibiting a pure approach, many natural organisms employ some combination of these two control techniques. For example, Geng (2007) summarises results confirming the existence of both CPG and reaction-based contributory systems to walking in cats. In this case, CPGs are located within the spinal column, and provide "high level" motor control to the walking, whereas reactive systems manage some lower level functionality, such as maintaining a walking gait despite a limb encountering an obstacle.

1.6 Nervous Network

1.6.1 Introduction

Nv-networks were developed as a technology by Mark Tilden & Brosl Haslacher during the 1990s, at Los Alamos National Laboratory, in the USA. Stemming from research into non-linear oscillators (Tilden, 1997), they quickly realized the potential of this technology for novel forms of controllers and sensory processing. The BEAM design approach was developed by Mark Tilden during this time, and remains a predominant school of thought in the development of Nv-net based robots.

1.6.2 Nervous Neurons

An Nv-neuron consists of a high-pass RC filter attached to the input of Schmitt trigger inverter logic gate, shown in Figure 4 below:

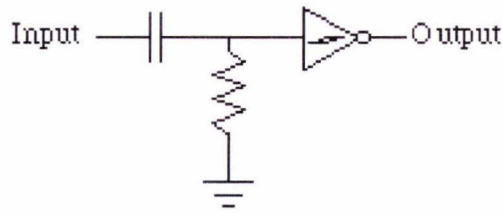


Figure 4: Nervous neuron (Solarbotics.net)

1.6.2.1 High-Pass RC Filter

A high-pass RC filter is a simple passive network that "blocks" low frequency signals by means of a capacitor. It can be analysed as a simple voltage divider, providing that the complex impedance of each component is considered, not just the real resistance (i.e. impedance = resistance + j x reactance). This calculation is shown below as Equation 1:

$$X_C = \frac{1}{\omega \cdot C}$$

$$X_R = R$$

$$\therefore V_o = \frac{V_i \cdot X_o}{X_i + X_o} \text{ (Voltage divider equation)}$$

$$\Rightarrow V_o = \frac{V_i \cdot X_R}{X_C + X_R}$$

$$\Rightarrow V_o = \frac{V_i \cdot R}{R + \frac{1}{\omega \cdot C}}$$

$$\therefore V_o = \frac{V_i \cdot \omega \cdot R \cdot C}{1 + \omega \cdot R \cdot C}$$

Equation 1: Output voltage of an RC High Pass Filter

1.6.2.2 Schmitt Trigger Inverter

For the Nv-neuron implementation used in this project, the Schmitt trigger inverter was replaced by a Schmitt triggered NAND gate with its inputs connected together – this is computationally & logically equivalent to the inverter component. The characteristic curves as defined by the chip's datasheet (available at: <http://library.solarbotics.net/datasheets/MM74HC14.pdf>) are shown below in Figure 5:

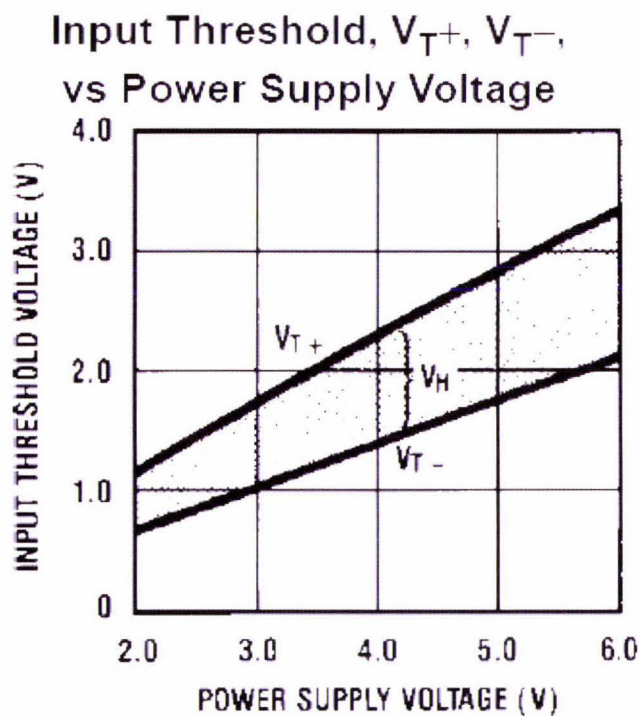


Figure 5: Schmitt-Trigger Inverter Threshold Voltages

A schmitt-triggered circuit implies that, in signal processing terms, it has some degree of “memory”, as it exhibits *hysteresis* – the switching thresholds are different depending on whether the input is a rising or falling edge. As can be seen in Figure 5 above, V_{T-} is the threshold voltage for a falling input signal, and V_{T+} is the threshold for a rising input. This behaviour significantly increases the noise tolerance of a circuit, as well as allowing the component to “fuzzily” respond to real input as well.

1.6.2.3 Combined Behaviour

In order to express the behaviour of the entire neuron, it is necessary to combine the individual behaviours of the individual components present in the neuron. The behaviour, assuming a compatible input from an identical neuron “upstream”, is shown in the following diagrams:

$$V_m(t) = V_n(-u(t-t_0) + u(t-t_1))$$

$$u(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases}$$

$$V_a(t) = \begin{cases} 0 & , t < t_0 \\ -V_n \left(\frac{-e^{-(t-t_0)}}{RC} \right) & , t_1 < t < t_0 \\ \frac{(v_n + V_a(t_1^-)) \cdot e^{-(t-t_1)}}{RC} & , t > t_1 \end{cases}$$

$$V_{out} = \begin{cases} V_{cc} & , t < t_1 \\ 0 & , t_1 < t < t_2 \equiv V_{cc}(-u(t-t_1) + u(t-t_2)) \\ V_{cc} & , t > t_2 \end{cases}$$

$$t_2 - t_1 = -RC \cdot \ln \left(\frac{V_{th}}{V_{cc} \left(1 - e^{\frac{-(t_1-t_0)}{RC}} \right)} \right)$$

Equation 2: Voltage Response of a Nervous Neuron

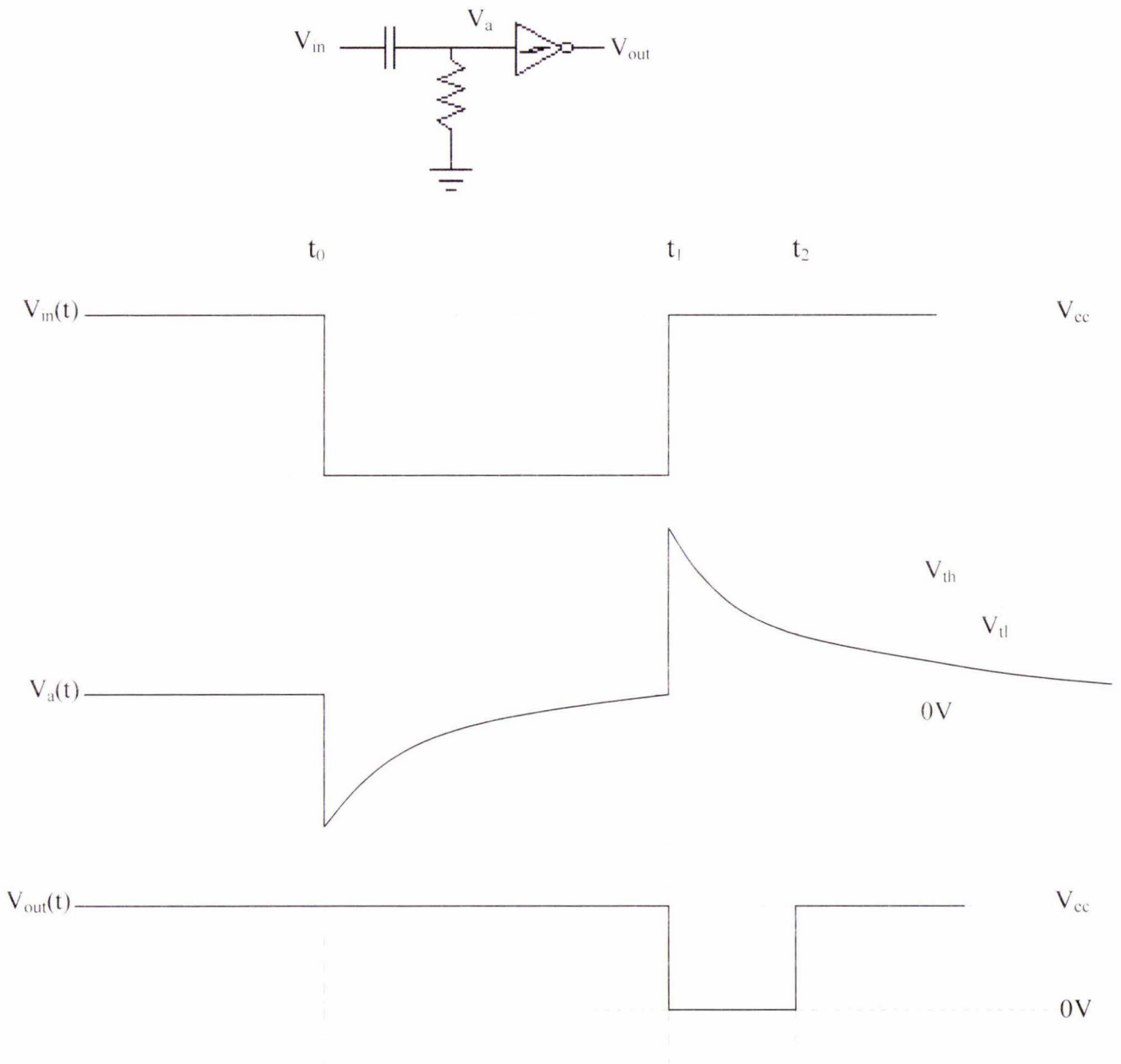


Figure 6: Voltage Response of a Nervous Neuron

The following implications are evident from the preceding equations and figures:

- As expressed by these equations, the neuron will only become "active" when there is a change of states at the neuron's input - more precisely, a falling edge.
- No matter what type of pulse is input to the neuron, the output will only be one of two things: 0, or a "square" pulse with a duration related to the amplitude and "frequency" of the input pulse.
- Likewise, no matter what kind of pulse train, sinusoid, or other periodic signal is input to the neuron, the output will be only one of two possibilities - a pulse train of frequency and duty cycle related to the frequency and amplitude of the input, or 0. It is also likely possible to "saturate" an Nv-neuron with a suitable high frequency input, however this case is not relevant to this thesis, and will not be considered.

Of particular note is the nature of the RC circuit – unlike traditional Nu-neurons (i.e. "neural neurons", the type commonly used in classical neural networks), which predominantly employ integrative & summative techniques to process their inputs, Nv-neurons employ a differentiator in their input path. The result of this is that Nv-neurons are effectively edge triggered, as the neuron's response will be based on the first derivative of the input signal.

One result of this is that Nv-neurons are very tolerant of both static biases and low-level noise, while still remaining sensitive to signals of the "correct" format.

1.6.3 Nervous Networks

1.6.3.1 Bicore

As its name implies, the bicore consists of two Nv-neurons connected in a loop topology. This circuit represents the simplest possible Nv-net topology; however its behavioural patterns can be exploited to control robots at many levels of complexity, particularly if multiple bicores are coupled together. The schematic of a typical bicore network is shown in Figure 7 below:

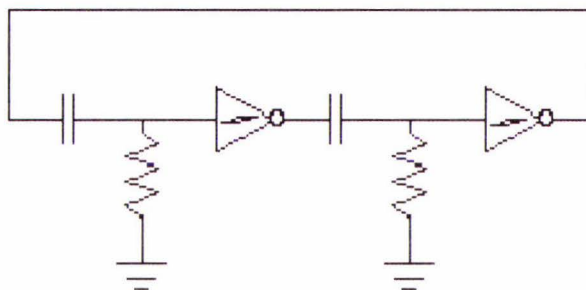


Figure 7: A typical Bicore Nervous Network Circuit (Solarbotics.net)

If each neuron is treated as having a binary state (1 = 'activated' = output low, 0 = 'off' = output high), the bicore network can be shown to only produce the following "binary" network states:

State	Neuron 1	Neuron 2
0	0	0
1	0	1
2	1	0
3	1	1

Table 1: Bicore Network States

The “states” 1 & 2 are equivalent, as they each represent only one “active” neuron on the network. This circuit thus has only one stable mode of oscillation (with respect to neuron excitation) - in order for the bicore circuit to be useful for more complex applications, it must be used in a coupled network topology.

1.6.3.2 Quadcore

The quadcore is an Nv-network that follows the same basic loop topology as the bicore; the quadcore is however made up of four neurons. The schematic for the quadcore circuit is shown in Figure 8 below.

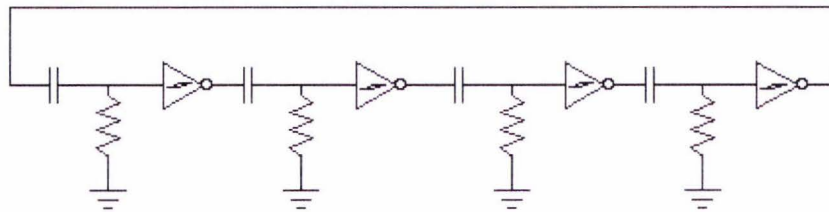


Figure 8: A typical Quadcore Nervous Network Circuit (Solarbotics.net)

The equivalent “binary” analysis of a quadcore network yields Table 2:

State	Neuron 1	Neuron 2	Neuron 3	Neuron 4
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1

10	1	0	1	0
11	1	0	1	1
12	1	1	0	0
13	1	1	0	1
14	1	1	1	0
15	1	1	1	1

Table 2: Quadcore Network States

Thus there are only six distinct patterns that can be present in the network’s operation, only two of which represent a stable network state: 5, and 1. This being the case, the full state diagram for the quadcore network is in the Figure 9 following:

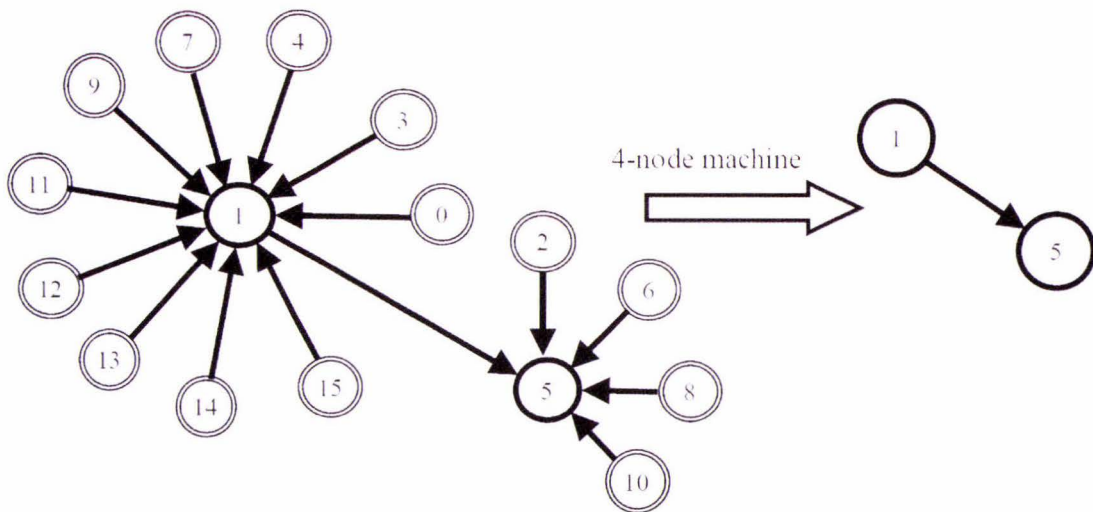


Figure 9: Input/output behaviour (attractor diagram) for a Quadcore Nervous Network (Rietman et. al., 2003)

While a simple robot (such as the context studied by this thesis) may use only one of the “behaviours” represented by a particular pattern/rhythm present on the network, more complex controllers may utilize the additional possible patterns to provide advanced functionality & adaptive behaviours. Research by Tilden & Haslacher (1995), the founding researchers of the Nv-neuron technology, proposed chaos theory as a potential

means of understanding the operation of Nv-nets, and Rietman et. al. (2003) developed a model based on necklace functions; neither of these are complete, however, and thus research is ongoing into the theoretical underpinnings of nervous networks.

1.6.3.3 Other Topologies

Other topologies have been developed to exploit the behaviour of nervous networks, varying in size, complexity and the difficulty of their analysis. A short list of some of the principal alternate topologies not already discussed is shown below:

- Large Rings

Topologically identical to the bicore and quadcore designs discussed earlier, these networks simply include higher numbers of neurons. For all such networks with an even number of neurons, their behaviour is similar to the smaller networks discussed earlier, however significantly more complex (Rietman et. al., 2003). As the network grows, the number of stable states able to exist on the networks grows super-linearly. Particularly, these networks rapidly become very difficult to analyse, as their phase-space grows exponentially with the number of neurons.

- Odd-numbered networks

Little work has been done in analyzing rings of Nv-neurons containing an odd number of neurons, however a brief exploration was published by Rietman et. al. (2003). They demonstrated that, while observed network behaviour appeared to be chaotic, there may be some form of underlying order. A statistical analysis (Autocorrelation function; lag represents time-distance for correlation) undertaken to determine whether the neuron states were purely random showed a small, but statistically significant, skew in the correlation distribution. This is shown in Figure 10 below:

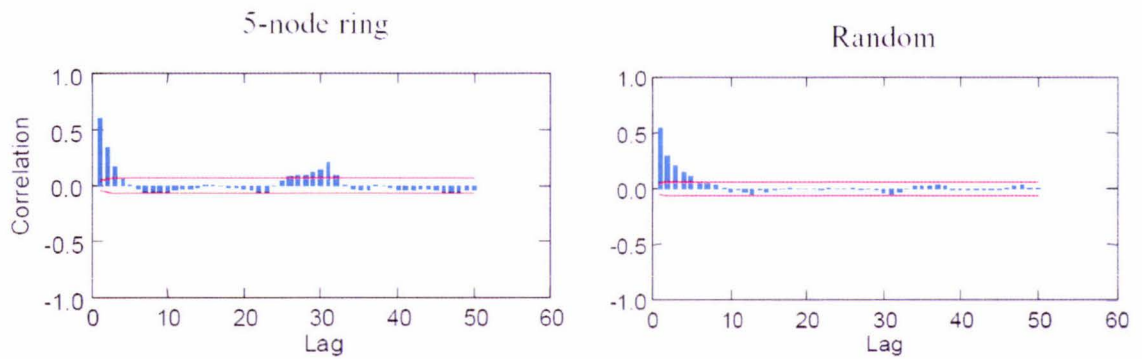


Figure 10: Autocorrelation Function plots for 5-neuron Nv-network compared to Random (Rietman et. al., 20030)

Many current models of Nv-nets do not deal with the behaviour of odd-numbered networks, and thus there is little or no research into their behaviour and application. However considerable work will be needed to understand whether useful work can be extracted from this type of topology.

- Wave Processor

Whereas Nv-nets such as the quad core use a form of one dimensional coupling between neurons (i.e. each neuron is connected to only one other neuron in each direction), the “wave processor” type topology employs a two dimensional “hexagonally beaded” grid of *quadcores*. It is proposed by Haslacher & Tilden (1995) that this topology may be ideal for modeling fluid dynamic problems.

- Coupled Rings

In order to derive more complex behaviours than can be obtained from a single Nv-net, instead of increasing the number of neurons serially in the loop of the network, a second loop can be placed in parallel with the first. By varying the level of connectivity between the rings, it is possible to vary their interaction and the resulting behaviour of the overall controller structure.

Coupled rings suffer from rapid growth of their phase-space, as the number of “layers” increases, additional to the complexity caused by the number of neurons in each of the constituent loops (Tilden, 2006).

1.6.4 Applications

Since its development, nervous network technology has been employed in a diverse range of applications, particularly in those areas where conventional control techniques have had little success. One example of this is in the development of microsattellites to study the magnetosphere, a project undertaken at the Los Alamos National Laboratory.

Moore et. al. (1998) developed this system, designed to be deployed as a cloud of small satellites to perform measurements of the strength and direction of the earth’s magnetic field, each satellite serving as a “pixel”, allowing a three dimensional, real-time map of a portion of the earth’s magnetic field. Nervous networks were used for the control of these satellites, as their analogue design allows them to operate within the “flow” of the surrounding environment, rather than being limited by the time-discrete nature of digital algorithmic control.

Particularly, nervous networks were used in this application due to their inherently adaptive nature, allowing for a system that was much more capable of responding “naturally” to changes in its capabilities and the environment around it than traditionally designed systems.

Another example of this is the development of biomorphic robots for the purpose of detecting and removing UXO – Unexploded Ordnance, such as mines or unexploded shells or bomblets from cluster munitions. UXO is a major logistical and humanitarian problem across many areas that have experienced wars and armed conflict in the past (Nicoud, 1997). Currently, the only UN approved method of mine removal is a slow and labour-intensive process undertaken by humans. As this process is both very tedious and

also dangerous to the individuals performing it, the development of a robotic tool to assist in this effort has been a major research goal in recent years.

Nervous network based designs have been proposed for this task due both to the adaptable nature of the controller, and because of the typical minimalistic design of such robots. The lightweight design of the robots allows them to withstand considerable buffeting from any ordinance explosion, and their adaptive characteristics allow the robot to compensate for any damage caused by such detonations. One trial of a hexapedal walker used in this application operated by “stomping” across a UXO-covered area with the intent of triggering detonations – although the robot lost several legs throughout the trial, it was able to successfully adapt to each loss, and reform a capable walking gait with each new leg topology (Tilden, 1995).

Another application area in which the minimalistic nature of nervous network-based designs is useful is in the development of commercial “toy” robots. Tilden, particularly, has been very successful in the adaptation of this technology to “toy” robots, which often have robust capabilities that are difficult to similarly implement using purely traditional robotic techniques. Examples of this include the Robosapiens – a series of capable humanoid walking robots – the FlyTech Dragonfly – a biomorphic flyer that *flaps its wings* – to name a few. The Robosapiens, the flagship model of robot produced by Tilden, is designed to be easily “hackable” by amateur roboticists, and as such serve as simple field testbeds for amateur experimentation and modification. The simplicity and elegance of the biomorphic design techniques used in the development of these robots means that the Robosapiens, a humanoid walking, is able to walk out of the box in a wide range of situations and surfaces, for around NZ\$200, whereas a comparable “classical” humanoid, such as the Pirkus robot (www.robot-labs.jp), costs around NZ\$3500, requires extensive programming and robotic knowledge in order to effect competent walking, and is limited in the adaptability of its walking algorithms by the capabilities of its onboard processor.

1.7 Summary

The study of robotic walking has a rich and varied history, and many design methodologies have been explored and/or created in the pursuit of this goal. A significant body of contemporary research, however, has focused on imitating nature more closely, both mechanically and with respect to controller, sensor and actuator design.

Nervous networks are a powerful and developing technology that employs non-linear dynamics to extract useful work. They are capable of producing competent biomimetic behaviours in many applications, and have demonstrated great potential for the development of adaptive, bio-mimetic, robotic “organisms”, capable of dynamically adjusting to survive rapidly changing, unpredictable environments. Additionally, long-term study of Nv-neuron technology will likely result in the development of new mathematical techniques and theories in order to model and understand this type of neuronal controller.

This Masters thesis will explore & simulate the mechanical behaviour of a quadrupedal neuromorph which uses an Nv-net as its controller. The robot will only be considered at a geometrical level, with the controller and its expected behaviour providing contextual structure to the simulations. The behaviour of the Nv-net core will not be analyzed, nor will the influence of the interface electronics between the controller and its actuators/sensors. This scope will produce useful & significant results to be produced in this rapidly developing field, while providing opportunities for future work to build on these results.