# A Biologically Inspired Four Legged Walking Robot

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Shiqi

# Preface

Eight years ago far away in a small town in China, I had the idea of starting a Ph.D. in Australia. At the beginning of the research, I was a little lost, as I knew little about the field of robotics. It was with the help of my supervisors, Graeme and Peng, that I started on a journey of developing a greater understanding of robotics. After several months of reviewing and studying the literature (which I can not deny was a little boring), I found it necessary to build an experimental robot. This would provide a research platform to investigate issues associated with both the static and dynamic balance of a walking legged robot, with a strong emphasis on a biological perspective. The design and construction of the robot provided valuable experience and insight, even though at times, it was very frustrating. The robot "easily" fell down when walking due to a range of factors: narrow base, high centre of gravity, multiple degrees of freedom of limb movements, loose joints, small feet, etc. However this was a deliberate part of the design. In attempting to have a strong biological perspective the robot was modeled loosely on the structure of a dog and as such easily fell over. This was in order to facilitate and more thoroughly investigate the balance issue. In the first stage of the research, Reinforcement Learning alone was used by the robot to learn to keep its balance. The results were encouraging and led to a published paper "Using Reinforcement Learning to Achieve Balance for a Four Legged Walking Robot", presented at the ISTIA 2000 international conference held at Canberra, Australia (2000). However, this work only allowed the robot to keep its balance but was not successful in making the robot walk. I am now in a position to be able to explain why it was difficult to solely use Reinforcement

Learning for getting the robot to walk. The learning space was simply too big for the limited capability of the onboard microcontroller. Given this lack of success in achieving "walking", a parallel Subsumption Architecture approach was developed. It was found that each major element of the robot's walking could be designed as a specific behaviour with the interaction of all the behaviours enabling the robot to walk - an "Emergent Walking Behaviour". A four-phase walking strategy was developed. It was based upon other walking related research and observing videos of how horses and dogs walk. To implement the four-phase walking strategy, it was necessary to develop a central control unit to coordinate the movement of individual legs. This so-called Central Pattern Producer (CPP) coordinated the movements of all four legs of the robot by generating rhythmical walking phase signal sets. Many experiments were conducted to "tune" the entire system and obtain an operationally walking robot including the ability to balance. This work led to two published papers: "A Biologically Inspired Four Legged Robot that Exhibits some Natural Walking Behaviours", presented at the IAT 2001 International Conference (Maebashi City in Japan, 2001), and "A Biologically Inspired Four Legged Walking Robot", presented at the IEEE ICRA 2003 international conference (Taiwan, 2003).

In the process of implementing the proposed four-phase walking strategy, it was found that it was not simple to implement a Subsumption Architecture (SA) from scratch, especially given that there were several parallel SAs in the system. With regards to the robot, the control of each leg was implemented as an independent SA. There were four SAs running in parallel in the system. This precipitated the idea of providing a recipe or implementation framework for implementing such parallel SA

systems. This work led to two other published papers: "An implementation methodology of Subsumption Architecture for Robotics", presented at the ISA 2000 international conference (Wollongong of Australia, 2000), and "A generic framework for implementing Subsumption Architecture", presented at RA2000 international conference (Honolulu, 2000).

In the early stages of the experiments, an empirical value for the CPP was used to generate rhythmical walking phase signals. It would be better for the robot to learn this value through real-time interaction with the environment. This resulted in the idea of again using machine learning, specifically reinforcement learning. Experiments associated with the learning algorithm demonstrated that the robot can successfully learn an "optimal" value associated with a specific terrain.

Although I have reached an end point of my research, there are still many interesting experiments to be carried out to investigate further aspects of the robot's walking, e.g. trotting, pacing, and more complicated learning tasks. These future investigations are left to my successors to carry out. For them, I would like to say "good luck".

This thesis collects together all of the individual components of my research work contained in my published papers. However, it is presented here as a single piece of consolidated work and thus it is hoped that it reads in this way and is not simply an assembly of papers.

# Table of Acronyms

| | |
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| AB | Assisting Behaviour |
| AC | Action Component |
| BSM | Behaviour Suppression Mask |
| CPG | Central Pattern Generator |
| CPP | Central Pattern Producer |
| DOF | Degrees of Freedom |
| DSM | Dynamic Stability Margin |
| EC | Executor Component |
| IW | Ideal Walking |
| IWB | Ideal Walking Behaviour |
| LB | Left Back |
| LF | Left Front |
| NIW | Non-ideal Walking |
| NIWB | Non-ideal Walking Behaviour |
| OO | Object Oriented |
| OWCI | Optimal Walking Cycle Interval |
| PSS | Phase Signal Set |
| PWM | Pulse Width Modulated |
| RB | Right Back |
| RF | Right Front |
| RL | Reinforcement Learning |
| SA | Subsumption Architecture |
| SM | Suppression Mask |
| SSM | Static Stability Margin |
| TC | Trigger Component |
| WCI | Walking Cycle Interval |
| ZMP | Zero Moment Point |

# Abstract

This Ph.D. thesis presents the design and implementation of a biologically inspired four-phase walking strategy using behaviours for a four legged walking robot. In particular, the walking strategy addresses the balance issue, including both static and dynamic balance that were triggered non-deterministically based on the robot's real-time interaction with the environment. Four parallel Subsumption Architectures (SA) and a simple Central Pattern Producer (CPP) are employed in the physical implementation of the walking strategy. An implementation framework for such a parallel Subsumption Architecture is also proposed to facilitate the reusability of the system. A Reinforcement Learning (RL) method was integrated into the CPP to allow the robot to learn the optimal walking cycle interval (OWCI), appropriate for the robot walking on various terrain conditions. Experimental results demonstrate that the robot employs the proposed walking strategy and can successfully carry out its walking behaviours under various experimental terrain conditions, such as flat ground, incline, decline and uneven ground. Interactions of all the behaviours of the robot enable it to exhibit a combination of both preset and emergent walking behaviours.

# List of Published Papers

Below is a list of papers that have been published. These papers essentially represented the results of various stages of the research work carried out during the Ph.D. project and are described within this thesis as a consolidated piece of work.

[1]  S. Peng, C. P. Lam, and G. R. Cole, "Using Reinforcement Learning to Achieve Balance for a Four Legged Walking Robot", presented and published at the international conference ISTIA 2000, Canberra, Australia, 2000.

[2]  S. Peng, C. P. Lam, and G. R. Cole, "A generic framework for implementing Subsumption Architecture", presented and published at the IASTED International Conference on Robotics and Automation (RA2000), Honolulu, Hawaii, USA, 2000

[3]  S. Peng, G. R. Cole, and C. P. Lam, "An implementation methodology of Subsumption Architecture for Robotics", presented and published at the international conference ISA2000, Wollongong, Australia, 2000. [32% acceptance rate]

[4]  S. Peng, G. R. Cole, and C. P. Lam, "A Biologically Inspired Four Legged Robot that Exhibits some Natural Walking Behaviours", presented and published at the international conference IAT 2001, Maebashi City, Japan, 2001. [19% acceptance rate]

[5]  S. Peng, C. P. Lam, and G. R. Cole, "A Biologically Inspired Four Legged Walking Robot", presented and published at the international conference IEEE ICRA 2003, Taiwan, 2003. [55% acceptance rate]

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