Development of a neuro-inspired control system for quadrupeds to emulate sensorimotor processes in animals

A project report

submitted by

SHREYAS SHANDILYA

in partial fulfilment of requirements

for the award of the dual degree of

BACHELOR OF TECHNOLOGY IN

ENGINEERING DESIGN

AND

MASTER OF TECHNOLOGY IN

BIOMEDICAL DESIGN

DEPARTMENT OF ENGINEERING DESIGN

INDIAN INSTITUTE OF TECHNOLOGY MADRAS

MARCH 2021

CERTIFICATE

This is to certify that the project titled **Development of a neuro-inspired control system for quadrupeds to emulate sensorimotor processes in animals**, submitted by **Mr Shreyas Shandilya**, to the Indian Institute of Technology Madras, for the award of the degrees of **Bachelor of Technology in Engineering Design** and **Master of Technology in Biomedical Design**, is a *bona fide* record of the research work done by her under my supervision. The contents of this project, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr Asokan Thondiyath
Project Adviser
Professor
Department of Engineering Design
Indian Institute of Technology Madras
Chennai 600 036

Dr V.S. Chakravarthy
Co-guide
Professor
Dept. of Biotechnology
IIT Madras, 600 036

Place: Chennai

Date: March 15, 2021

ACKNOWLEDGEMENTS

ABSTRACT

KEYWORDS: Computational Neuroscience, Neural Networks, Central Pattern Generators, Deep Learning, Robotics, ROS

This project report documents studies towards the development of a neural network control system for quadruped robots. Locomotion and navigation require the perception of the surrounding space and embodied decision making to make an appropriate response to an incoming stimulus. Animals are highly adept at such tasks, and the extraordinary agility and dexterity exhibited by animals are highly desirable for legged robots. A hybrid neural network for the locomotion and navigation control system of a quadruped robot is proposed. The proposed system leverages oscillatory models of brain function to mimic a two-level hierarchy of locomotion control. The lower level is controlled by Central Pattern Generators in the spinal cord and the higher level by the Pedunculopontine Nucleus in the Brain Stem of humans. This project focuses on emulating gait with navigation when the hierarchical controller is trained using Reinforcement Learning and the developed control system's consequent deployment on a quadruped.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

FK	Forward Kinematics
IK	Inverse Kinematics
DL	Deep Learning
RL	Reinforcement Learning
DoF	Degree-of-freedom
CPG	Central Pattern Generator
DNN	Deep Neural Network

NOTATIONS

$\boldsymbol{p}_i$	The *i*th vertex of the moving platform
$\boldsymbol{b}_i$	The *i*th base point, i.e., location of the *i*th revolute joint
$\hat{\boldsymbol{n}}_i$	The unit vector along the *i*th revolute joint axis
l_i	The length of the leg connecting $\boldsymbol{p}_i$ and $\boldsymbol{b}_i$
$\boldsymbol{q}_i$	The *i*th base point of a 6-3 SPM
d_i	The length of the *i*th leg of a 6-3 SPM
$\mathcal{C}_i$	The *i*th constraint circle in a 3-R$\underline{\text{P}}$S-equivalent manipulator
$\mathcal{P}_i$	The *i*th constraint plane in a 3-[PP]S manipulator
$\boldsymbol{p}(x_0, y_0, z_0)$	Centroid of the moving platform of a 3-[PP]S-type manipulator, and its coordinates in the coordinate system specified
$\xrightarrow{\times x}$	Elimination of the variable x from the left hand side equations
$\xrightarrow{x \to y}$	Substitution of the variable x by the expression y
$\boldsymbol{q}$	Vector of configuration-space variables of a parallel manipulator
$\boldsymbol{\phi}$	Vector of passive joint variables of a parallel manipulator
$\boldsymbol{\theta}$	Vector of active joint variables of a parallel manipulator
$\boldsymbol{\eta}$	Loop-closure constraint function
$\boldsymbol{J}_{\boldsymbol{\eta}\boldsymbol{\phi}}$	Constraint Jacobian matrix
$\boldsymbol{J}_{\boldsymbol{\eta}\boldsymbol{q}}$	Configuration Jacobian matrix
$\boldsymbol{M}$	Generalised mass matrix in the equation of motion
$\boldsymbol{B}$	Force-projection matrix in the formulation of dynamics
$\boldsymbol{Q}^{\text{nc}}$	Vector of external forces

CHAPTER 1

INTRODUCTION

1.1 Background

Animals are highly adept at locomotion and navigation under challenging terrains, capable of responding to a sudden stimulus with extraordinary agility and dexterity. They exhibit behaviour like gait switching, rapid acceleration and deceleration, evasive manoeuvres, climbing, jumping and search. The seamless transition between different behaviours and agile response to an incoming stimulus results from the evolution of neural pathways for adaptive locomotion, perception and embodied decision making. A model of such integrated sensorimotor processing can provide greater autonomy and deftness to robotic locomotion and navigation.

Among animals, quadrupedal locomotion is the most common, with some animals capable of limited bipedal locomotion. Such prevalence of quadrupedal locomotion in nature may be attributed to the inherent stability and wide range of available configurations of locomotion. These characteristics of quadrupedal locomotion make it suitable for several applications such as last-mile delivery and search and rescue to the potential to work in unstructured, severe and dangerous environments. Consequently, several quadruped robots have been developed over the years. The TITAN series [1], Tekken IV [2], MIT Cheetah [3] and BigDog [4] have been some of the successful quadruped robots capable of gait in severe and difficult environments. The aforementioned quadruped robots' critical technologies attributed to their success are their biomimetic structure, a high power density of actuator, real-time control methods, and integrated environment perception [5]. All the developments through these quadrupeds lead to an integrated environment perception and decision-making system.

Neuroscientific models of cognition have explained information processing in living organisms at varying degrees of details. Available models range from bio-molecular models operating at the synaptic levels to aggregate oscillatory models operating at the level of neuron ensembles. Since animal behaviour is desired in quadrupeds, neuroscientific models of sensorimotor processes to emulate such behaviour seem logical.

Moreover, such models also benefit from the massively parallel and efficient computations seen in the brain, making such models ideal for robotics' resource-constrained applications.

This report documents the design and development of a neural network architecture for autonomous control. The neural network combines Central Pattern Generator(CPG) theory with Deep Neural Networks to emulate different aspects of a hierarchical multi-loop sensorimotor processing with a one-to-one mapping between the proposed architecture modules and the nervous system's involved processing centres. Furthermore, a Deep Deterministic Policy Gradient is used to learn sophisticated behaviour with experience. An incremental methodology is followed to learn increasingly complex behaviour by the formulation of appropriate reward functions. The developed neural network is tested and deployed on a prototype quadruped platform, built as a part of this project.

1.2 Motivation

The primary motivation for this work is the need for adaptive gait generation for an efficient control strategy for legged robots based on biological locomotion principles. Animal locomotion requires multi-dimensional coordinated rhythmic patterns that need to be correctly modulated to satisfy multiple constraints such as generating forward motion with low energy, without falling over, adapting to possibly challenging terrain, and allowing the modulation of speed and direction [6]. In vertebrates, CPGs are the essential building blocks that generate and modulate the rhythmic patterns required for locomotion. The neuroscientific theory defines CPGs as non-linear dynamical systems with limit cycle behaviour given the dynamical system's parameters. CPGs have been successfully used to control a variety of robots. A distributed control strategy was proposed in [7] for a modular quadruped robot. The strategy proposed used N coupled amplitude-controlled Hopf oscillators to control the N degrees of freedom in the quadruped. Similarly, a four oscillator CPG model that integrates sensory feedback into the CPG for gait modulation was proposed in [8]. This model was further extended in [9] by introducing a two-level hierarchy, such that the higher level modulates the CPG model by appropriately modifying CPG parameters.

In biology, CPGs are activated and modulated by simple tonic signals from higher parts of the brain, and they are strongly coupled with the body they control and the environment via sensory feedback. The strong coupling via sensory feedback allows for integrated environment perception and embodied decision making. Although current CPG models are successful in gait generation, gait modulation and learning with CPGs remain challenging. Moreover, the integration of higher-level control with a CPG requires modulating high dimensional parameter vectors that determine CPG behaviour instead of simple tonic signals. Furthermore, there have been very few instances where a CPG is a part of the learning system. For instance, a CPG model was implemented as a layer in a deep neural network to facilitate backpropagation in [10]. However, in most cases, behaviour like gait transition and modulation is achieved using predefined relationships to produce appropriate CPG parameters. Due to such shortcomings in CPG models, learning with experience is challenging, and genuine animal-like behaviour can not be achieved.

On the other hand, Deep Neural Networks (DNNs) are capable of universal approximation and have standard learning rules for updating parameters. Gradient-based or gradient-free techniques may be used to optimize the parameters of a DNN. The optimization technique used constrain the structure of DNN to a specific class of networks. For instance, backpropagation requires the network to have no loops, whereas CPG coupling almost always forms loops. Although the integration of DNNs with CPGs constrains network structure choice, the ability of universal approximation added to the network allows for the transformation of a low dimensional desired motion or state vector into a tonic signal that can be used to modulate the CPG for rhythm generation. The hierarchical controller proposed in [11] uses a DNN whose outputs are used to regulate selected CPG network parameters. Though the CPG is not a part of the learned network, the use of the DNN allows for the integration of a low-dimensional feedback signal for control.

Emulation of more sophisticated behaviour like obstacle avoidance and search can be achieved using Reinforcement Learning (RL) to learn an appropriate policy. For instance, a hierarchical controller was proposed in [12] that applies RL to negotiating obstacles with a quadruped robot. Since a DNN-CPG architecture requires only low dimensional desired motion or state vector to modulate the network output, a hierarchical controller similar to those proposed in [12] and [11] can be developed using RL to emulate a particular animal behaviour. Such a controller, combining the universal approximation and learning abilities of DNNs with the adaptive rhythm generation of CPGs, is expected to be successful in the nimble, autonomous control of a quadruped in challenging terrains.

1.3 Objectives

The primary aim of this work is to develop a generalized DNN-CPG architecture for autonomous control problems. The developed architecture is a model of the sensorimotor processing typical across vertebrates, and its functioning is to be demonstrated on a quadruped platform, also assembled as a part of this project. It is also intended to study the evolution of quadruped behaviour as it interacts with its environment. The developed model is limited to the emulation of the behaviour of obstacle avoidance and path planning.

1.4 Scope

The following have been achieved in the present work as direct objectives of its initiation.

1. Assembly of a Quadruped Platform for the testing and deployment of developed neural network
2. Development of ROS-Gazebo simulation environment for RL
3. Development of a DDPG for RL
4. Formulation reward functions to quantize different aspects of quadruped behaviour
5. Development of a DNN-CPG architecture for autonomous control

Additionally, the following are expected to result from the investigation of related topics.

1. An improved understanding of the nervous system and distributed processing seen in the brain
2. An improved understanding of quadruped kinematics and dynamics

The following do not fall within the intended scope of this work.

1.

1.5 Contributions

The contributions of this report, summarised below, are discussed in greater detail in Chapter 6.

1.

1.6 Possible Extensions

1.7 Organisation of the Report

The remainder of this report is organised as follows.

CHAPTER 2

THE MEPED QUADRUPED PLATFORM

2.1 Introduction

2.2 Physics Simulation

2.3 Kinematics Model

2.4 Dynamics Model

2.5 ROS Implementation

CHAPTER 3

SUPERVISED GAIT LEARNING

3.1 Introduction

3.2 DNN-CPG Architecture

CHAPTER 4

REWARD FORMULATION

4.1 Introduction

4.2 Stability Reward

4.3 Energy Efficiency Reward

CHAPTER 5

REINFORCEMENT LEARNING

5.1 Introduction

5.2 Deep Deterministic Policy Gradient

CHAPTER 6

CONCLUSIONS

6.1 Summary

6.2 Contributions

6.3 Possible Extensions

APPENDIX A

Sample Appendix

This is a sample appendix. Appendices must be referred to in the text, wherever relevant (e.g., "...the details of this procedure may be found in Appendix A...").

REFERENCES

[1] S. Hirose and K. Kato, "Study on quadruped walking robot in Tokyo Institute of Technology-past, present and future," in *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065)*, September 2000, pp. 414–419 vol.1.

[2] H. Kimura, Y. Fukuoka, and H. Katabuti, "Mechanical design of a quadruped " tekken 3 4 " and navigation system using laser range sensor," 2005.

[3] D. Hyun, S. Seok, J. Lee, and S. Kim, "High speed trot-running: Implementation of a hierarchical controller using proprioceptive impedance control on the mit cheetah," *The International Journal of Robotics Research*, vol. 11, no. 2, pp. 1417–1445, August 2014.

[4] M. Raibert, K. Blankespoor, G. Nelson, and R. Playter, "Bigdog, the rough-terrain quadruped robot," in *Proceedings of the 17th IFAC World Congress*, 2008.

[5] X. Meng, S. Wang, Z. CAO, and Z. Leijie, "A review of quadruped robots and environment perception," in *2016 35th Chinese Control Conference (CCC)*, July 2016, pp. 6350–6356.

[6] J. H. Barron-Zambrano and C. Torres-Huitzil, "Cpg implementations for robot locomotion: Analysis and design," in *Robotic Systems*, A. Dutta, Ed. Rijeka: IntechOpen, 2012, ch. 9. [Online]. Available: https://doi.org/10.5772/25827

[7] A. Sproewitz, R. Moeckel, J. Maye, and A. J. Ijspeert, "Learning to move in modular robots using central pattern generators and online optimization," *The International Journal of Robotics Research*, vol. 27, no. 3-4, pp. 423–443, 2008. [Online]. Available: https://doi.org/10.1177/0278364907088401

[8] L. Righetti and A. J. Ijspeert, "Pattern generators with sensory feedback for the control of quadruped locomotion," *Proceedings of the 2008 IEEE International Conference on Robotics and Automation (ICRA 2008)*, pp. 819–824, 2008. [Online]. Available: http://infoscience.epfl.ch/record/130740

[9] C. P. Santos and V. Matos, "Cpg modulation for navigation and omnidirectional quadruped locomotion," *Robotics and Autonomous Systems*, vol. 60, no. 6, pp. 912–927, 2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921889012000164

[10] R. J. Szadkowski, P. Cizek, and J. Faigl, "Learning central pattern generator network with back-propagation algorithm," in *Proceedings of the 18th Conference Information Technologies - Applications and Theory (ITAT 2018), Hotel Plejsy, Slovakia, September 21-25, 2018*, ser. CEUR Workshop Proceedings, S. Krajci, Ed., vol. 2203. CEUR-WS.org, 2018, pp. 116–123. [Online]. Available: http://ceur-ws.org/Vol-2203/116.pdf

[11] S. Auddy, S. Magg, and S. Wermter, “Hierarchical control for bipedal locomotion using central pattern generators and neural networks,” in *2019 Joint IEEE 9th International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob)*, 2019, pp. 13–18.

[12] H. Lee, Y. Shen, C. han Yu, G. Singh, and A. Y. Ng, “Quadruped robot obstacle negotiation via reinforcement learning,” in *in In Proceedings of the IEEE International Conference on Robotics and Automation (ICRA*, 2006.