Faculty of Engineering and the Built Environment
Department of Electrical Engineering

Hopping Control of a Single Leg Robot

Prepared for Amir Patel.
Submitted to the Department of Electrical Engineering
at the University of Cape Town in partial fulfilment of the academic requirements
for a Bachelor of Science degree in Mechatronics.

October 18, 2016

Keywords: impedance control, dynamic control, force control, mechatronics

To my dearest...

Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.
2. I have used the IEEE convention for citation and referencing. Each contribution to, and quotation in, this final year project report from the work(s) of other people, has been attributed and has been cited and referenced.
3. This final year project report is my own work.
4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as their own work or part thereof.

Name: Benjamin Scholtz
Signature: ________________
Date: October 18, 2016

Abstract

Acknowledgements

Amir Patel Callen Fisher Craig Burden Gareth Callanan Roberto Aldera

Terms of Reference

Description

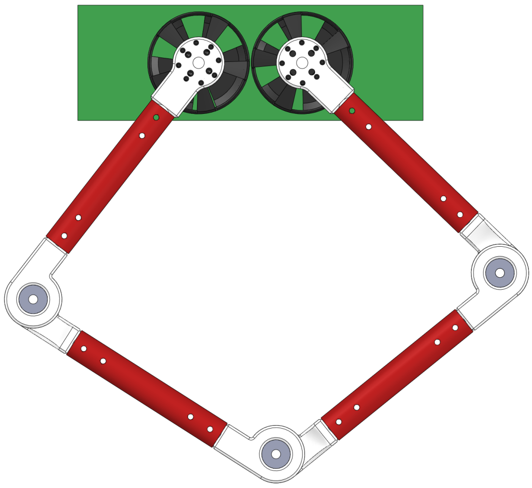

Figure 1: Version 1 of Baleka leg platform (Ben Bingham, 2016).

The Mechatronics Lab has recently developed a single leg, direct drive robot, Baleka, to investigate modelling and control of rapid accelerations. This project will involve the design of a control system to perform stable hopping with the robot. Various controller algorithms will be investigated and compared (eg. PID, MPC, etc.). The project will also involve developing a test rig for the robot.

Deliverables

- Mathematical model of the hopping robot must be developed in Simulink/Matlab
- Hopping controller design
- Mechanical design of the test rig
- Experimental testing of the robot

Skills/Requirements

- Mathematical Modelling
- Mechatronics Design
- Control Systems
- Embedded Systems
- Strong Practical and Mathematical skills required

ELO3: Engineering Design

Perform creative, procedural and non-procedural design and synthesis of components, systems, engineering works, products or processes.

The student is expected to design:

- Robot feedback control system
- Rig for testing of hopping motion

Area of Research

- Bio-inspired robotics
- Control systems

Extra Information

`http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5648972`

`http://kodlab.seas.upenn.edu/uploads/Avik/compositionTR_sc.pdf`

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1 Introduction

> *"Begin at the beginning," the King said, gravely, "and go on till you come to an end; then stop."*
>
> — Lewis Carroll, *Alice in Wonderland*

With a hop, skip, and a jump – the journey begins!

1.1 Background

1.2 Objectives of the Study

1.2.1 Problems to be Investigated

1.2.2 Research Questions

1.2.3 Purpose of the Study

1.3 Scope and Limitations

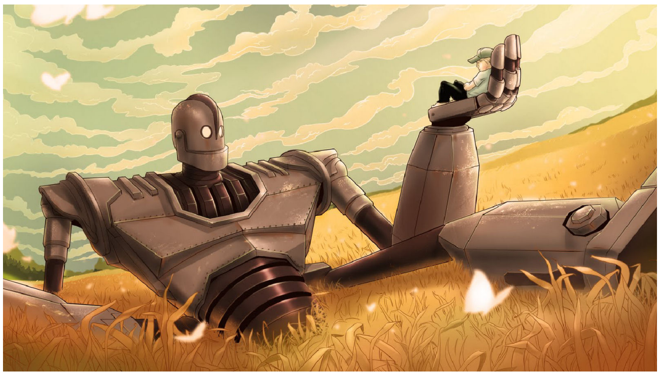
1.4 Plan of Development

2 Literature Review

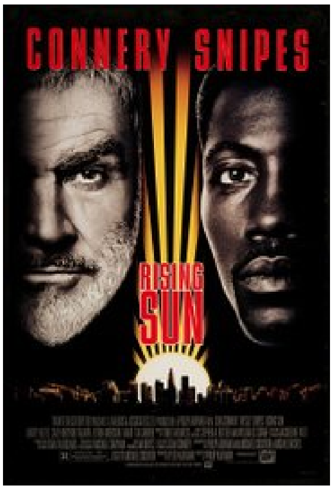
2.1 Introduction

Bio-inspired robots have fascinated humans since the Greek mathematician, Archytas of Tarentum, built the first true mechanical robot, where a robot is some device performing an automated mechanical task. His mechanical steam powered bird was just the start.[4]

Would be engineers take their inspiration from popular culture with The Iron Giant and B.E.N. fresh in mind. The Rising Sun included robots developed by Marc Raibert, founder of the CMU (now MIT) Leg Laboratory, who pioneered self-balancing dynamic control of hopping robots.



(a) The Iron Giant (1999).



(b) Rising Sun (1993).

(c) Treasure Planet (2002).

Figure 2.1: Humanoid robots in popular culture.

2.2 State of the Art

2.2.1 Monoped Robots

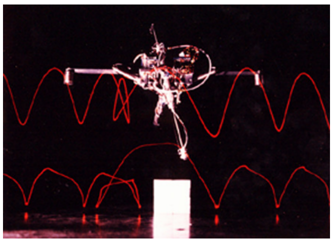
2.2.2 Biped Robots

2.2.3 Quadruped Robots

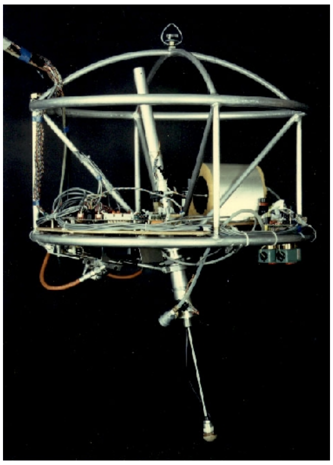
2.2.4 Bio-inspired Legged Robotics

2.2.5 Humanoid Robots

2.2.6 Closed Kinematic Chain Leg



(a) Planar One-Leg Hopper - MIT Leg Laboratory (1980-1982).



(b) 3D One-Leg Hopper - MIT Leg Laboratory (1983-1984).

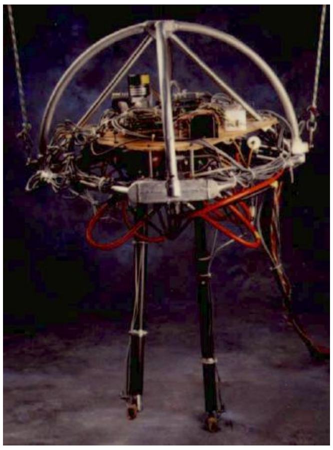
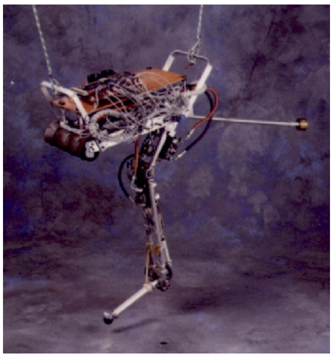


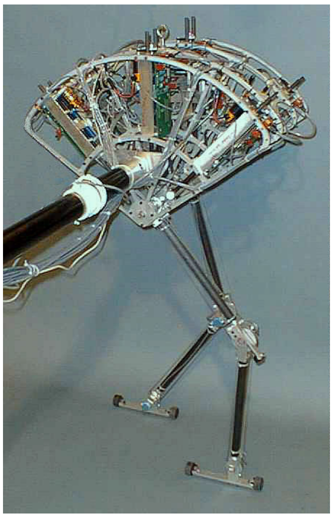
Figure 2.2: 3D Biped - MIT Leg Laboratory (1989-1995).

(a) Quadruped - MIT Leg Laboratory (1984-1987).

(b) GOAT 3-DOF Leg Topology - (Kalouche, 2016).



(a) Uniroo - MIT Leg Laboratory (1991-1993).



(b) Spring Flamingo - MIT Leg Laboratory (1996-2000).

Figure 2.3: Atlas Humanoid Robot - Boston Dynamics (2013).

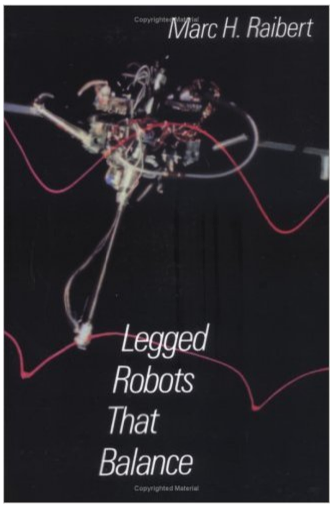
Figure 2.4: Closed Kinematic Chain Leg using Raibert's Scissor Algorithm (Duperret, Koditschek, 2016).[1]

2.3 Legged Locomotion in Nature

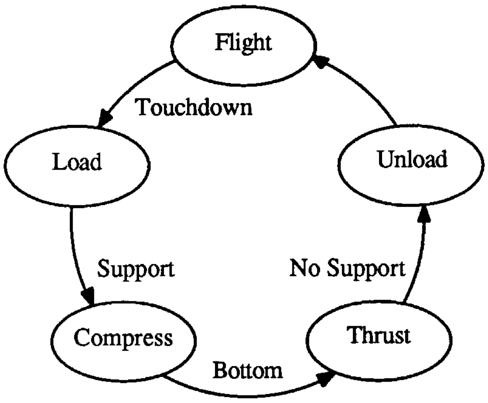
2.4 Raibert Control

2.4.1 Raibert's Scissor Algorithm

2.4.2 Phases of Motion



(a) Legged Robots That Balance - Marc H. Raibert (1986).



(b) Raibert control state machine.

Figure 2.5: Legged Robots That Balance cover page and exert.[2]

2.5 Applications in Industry

2.5.1 Soft-robotics

Factories safe human robot interaction Handling of compliant products (farming, manufacturing)

[5]

2.5.2 Bose Active Suspension

2.5.3 Dynamic Stability vs Static Stability

2.5.4 Phases of Motion

2.5.5 Leg Stance Control

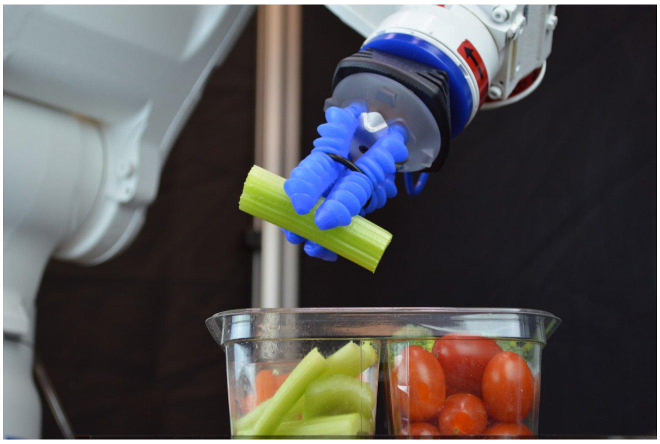


Figure 2.6: Compliant soft robotic handling (Forbes, 2016).

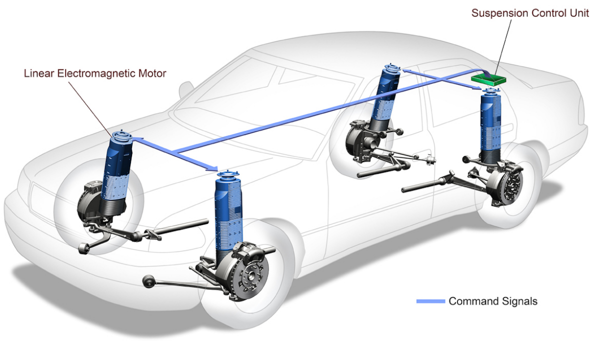


Figure 2.7: Bose Active Suspension (Bose Corporation, 1980s)[3].

2.6 Force Control

3 Project Plan and Methodology

4 Theory Development

4.1 General Co-ordinates

5 System Modelling and Simulation

6 Leg Design and Construction

6.1 Geometry

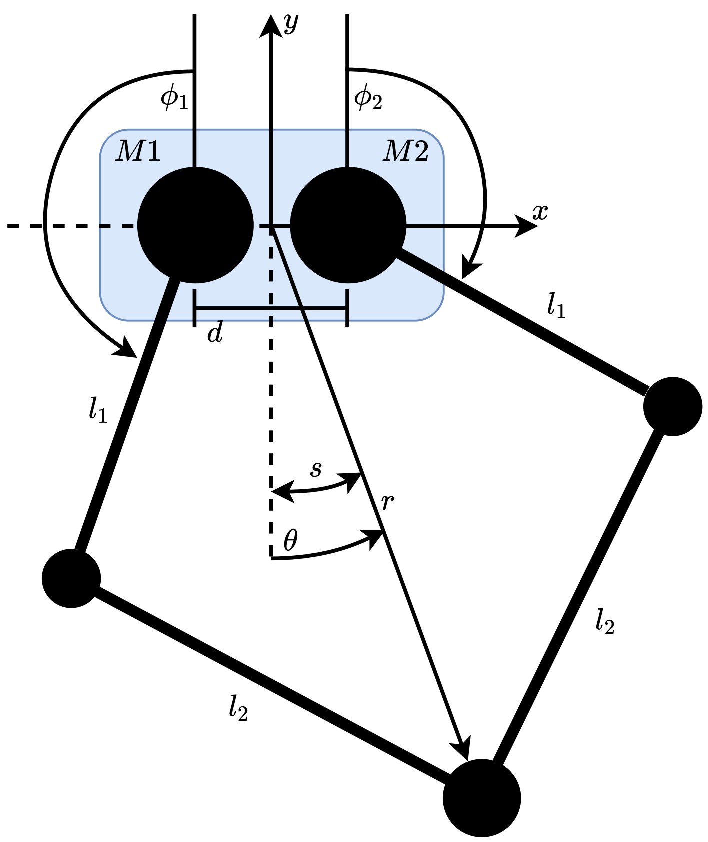
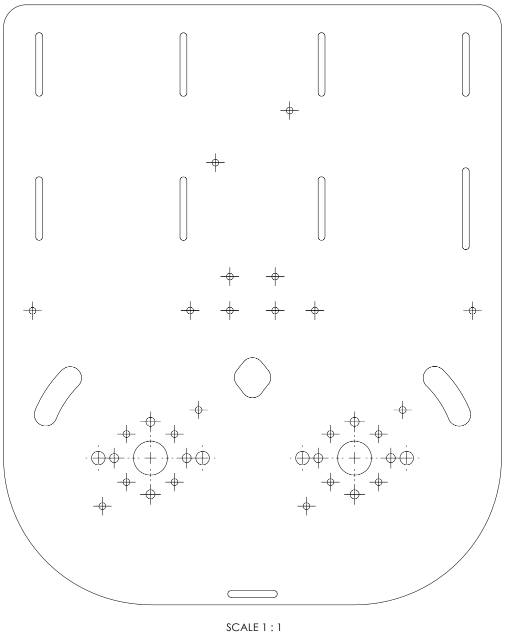
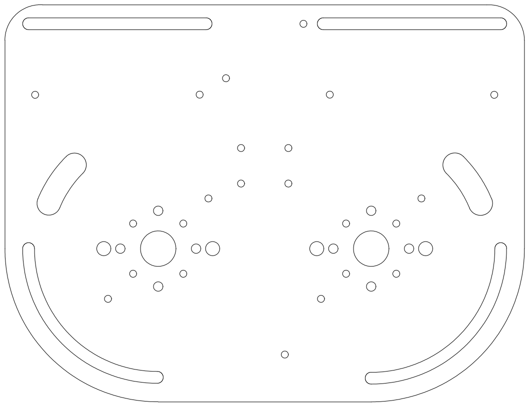


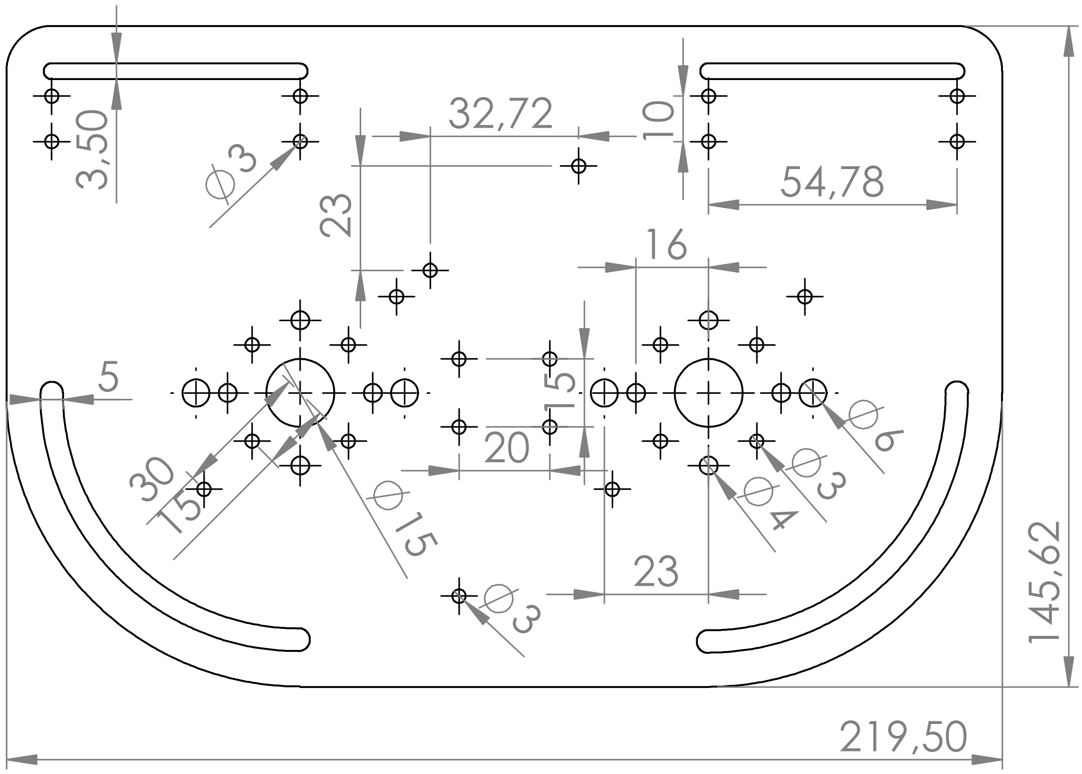
Figure 6.1: Geometric view of leg.



(a) CAD mounting plate V1.



(b) CAD mounting plate V3.1.3.



(c) CAD mounting plate final design.

Figure 6.2: Leg mounting plate iterations.

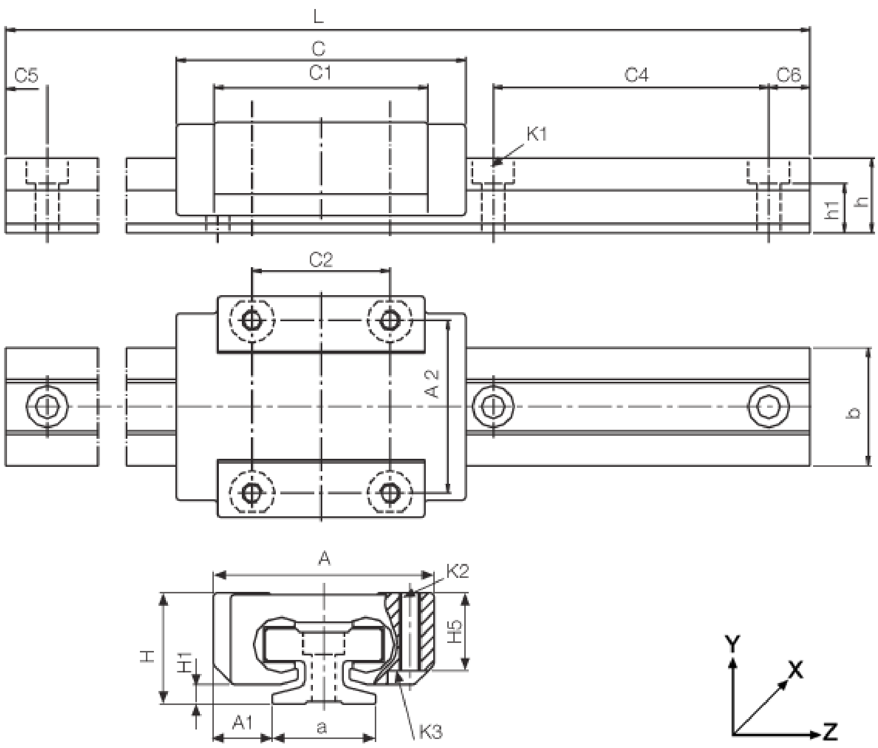


Figure 6.3: igus DryLin T - Low-profile linear guide.

6.2 Mechanics and Construction

6.2.1 Alumnium Mounting Plate Design

6.2.2 Linear Guide

6.2.3 CAD Robotic Leg Assembly

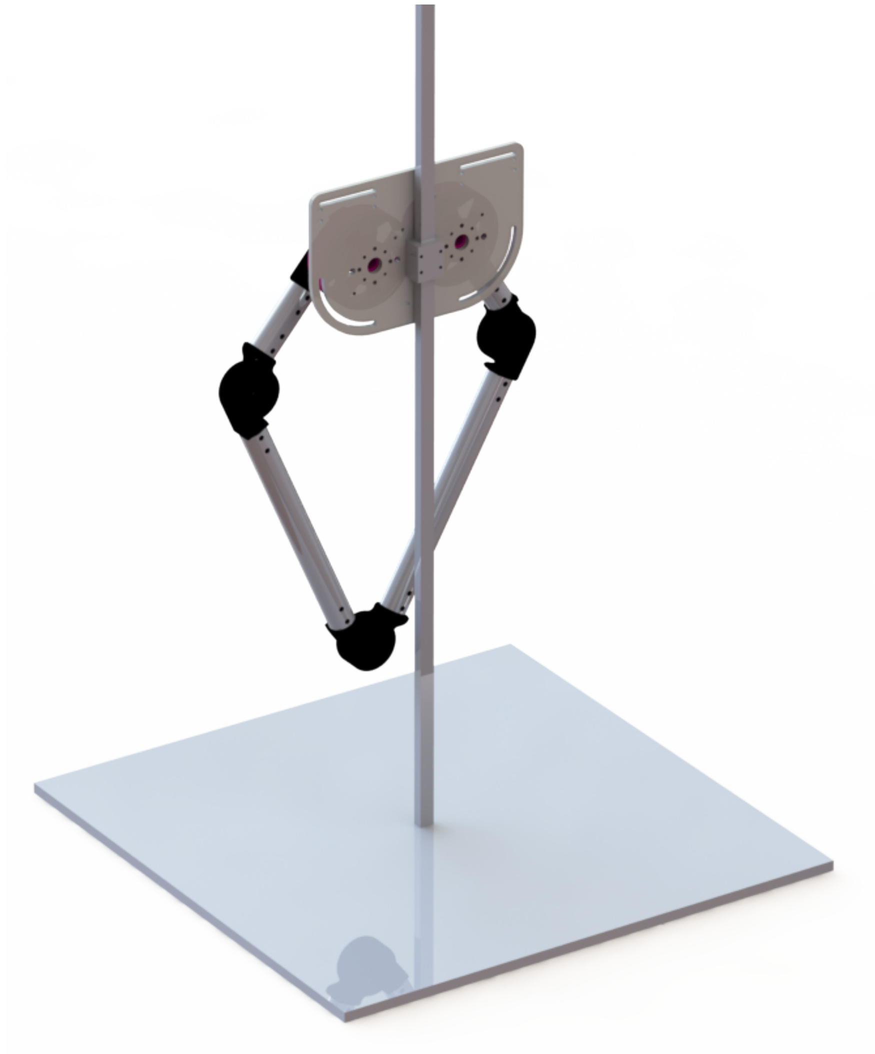


Figure 6.4: Linear guide mounted leg model (CAD Solidworks assembly).

6.3 Electronics and Communication

6.3.1 Accelerometer and Gyroscope

6.3.2 Distance Sensor

6.3.3 Microcontroller

6.4 Communication Interfaces

6.4.1 Shielding

6.5 Motors and Drivers

6.5.1 Driver Configuration

6.5.2 Motor Encoders

6.5.3 Tuning and Optimisation

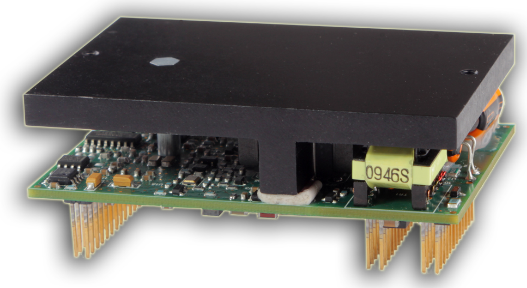


Figure 6.5: AMC DigiFlex Performance Servo Drive.

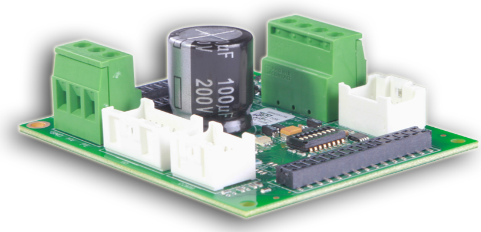


Figure 6.6: AMC DigiFlex Performance Servo Drive mounting card.

7 Communication Protocol

A useful tool when calculating and confirming CRC values of various types:

`https://www.lammertbies.nl/comm/info/crc-calculation.html`

Command	**Index**	**Op-Code**	**TX CB**	**TX CRC1**	**RX CB**
Kill Bridge	1	0001	0x06	0xCBB6	0x04
Write Enable	2	0010	0x0A	0x3624	0x08
Bridge Enable	3	0100	0x12	0x1AE0	0x10
Set Current	4	0011	0x0E	0xBF7B	0x0C
Read Current	5	1100	0x31	0x9772	0x32
Read Position	6	1111	0x3D	0xD310	0x3E
Read Velocity	7	0101	0x15	0x5EAF	0x16
Set Position	8	1010	0x2A	0x42C4	0x28

Table 7.1: Motor driver command protocol.

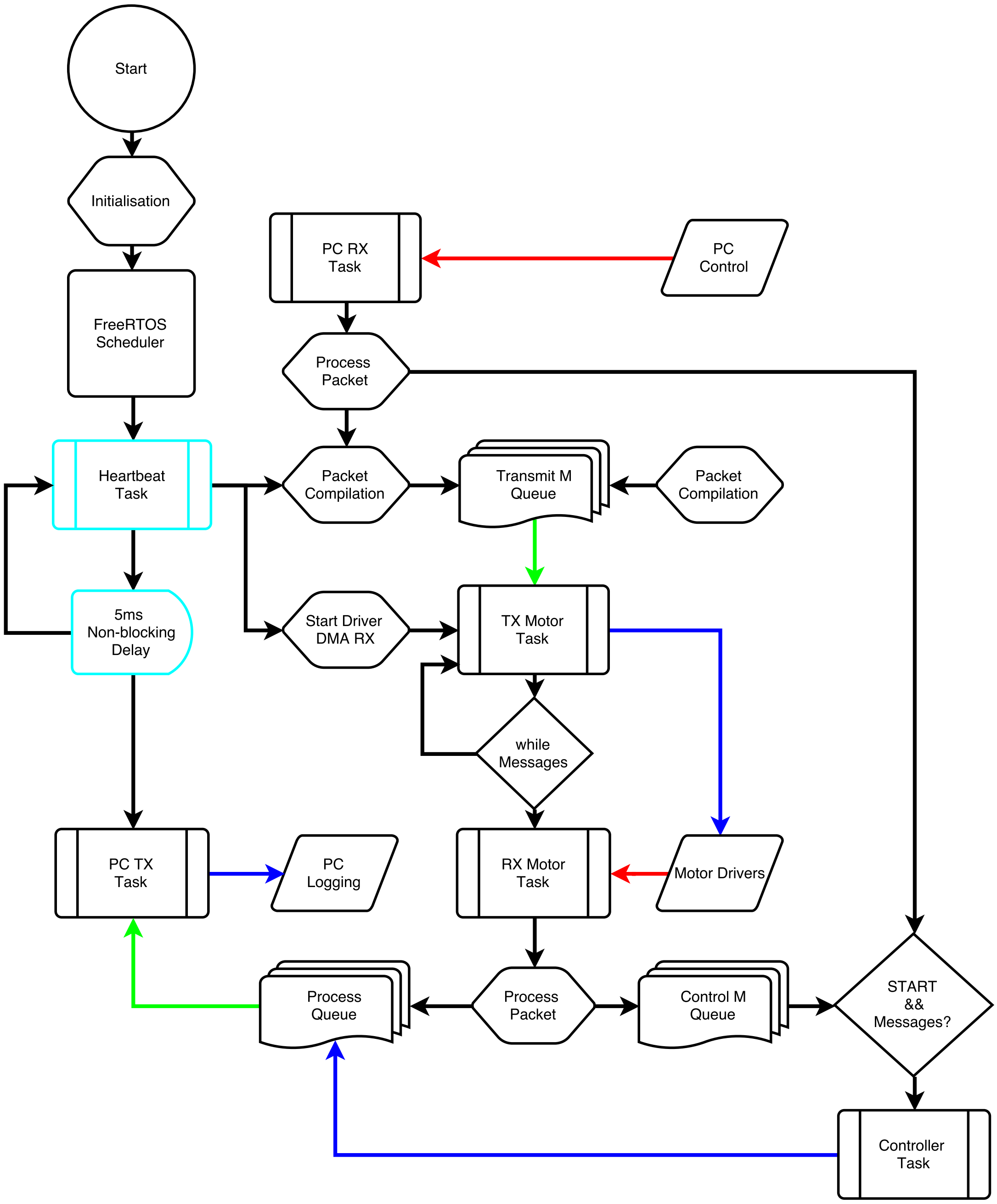


Figure 7.1: FreeRTOS communication protocol flow diagram.

8 Kinematics

$$f(\phi_1, \phi_2) = \left(\sqrt{\frac{9}{100} - \frac{9\sin\left(\frac{\phi_1}{2} + \frac{\phi_2}{2}\right)^2}{400}} - \frac{3\ \cos\left(\frac{\phi_1}{2} + \frac{\phi_2}{2}\right)}{20} \quad \frac{\phi_1}{2} - \frac{\phi_2}{2} \right) \tag{8.1}$$

$$g(r, \theta) = \begin{pmatrix} \pi - acos(\frac{r^2+l_1^2-l_2^2}{2rl_1}) + \theta \\ \pi - acos(\frac{r^2+l_1^2-l_2^2}{2rl_1}) - \theta \end{pmatrix} \tag{8.2}$$

Taking the Jacobian of the kinematic mapping $f(\phi_1, \phi_2)$ the foot force vector, F, can be transformed to the motor torque commands, τ:

$$J = \left[\frac{\partial \mathbf{f}}{\partial \mathbf{X}} \right] \tag{8.3}$$

where **X** = [r θ].

The following force vector provides a constant angular force, f_{theta}:

$$F = [f_r\ f_\theta]^T \tag{8.4}$$

by using f_s, a force related to the arc-length of a polar system, the relation $s = r\theta$ exists:

$$F = [f_r\ f_s]^T \tag{8.5}$$

$$f_a = k_s(a_{fbk} - a_{cmd}) + k_d(\dot{a}_{fbk} - \dot{a}_{cmd}) \tag{8.6}$$

$$\tau = J^T F \tag{8.7}$$

9 Dynamic Modelling

9.1 System Modelling

9.1.1 SLIP Model

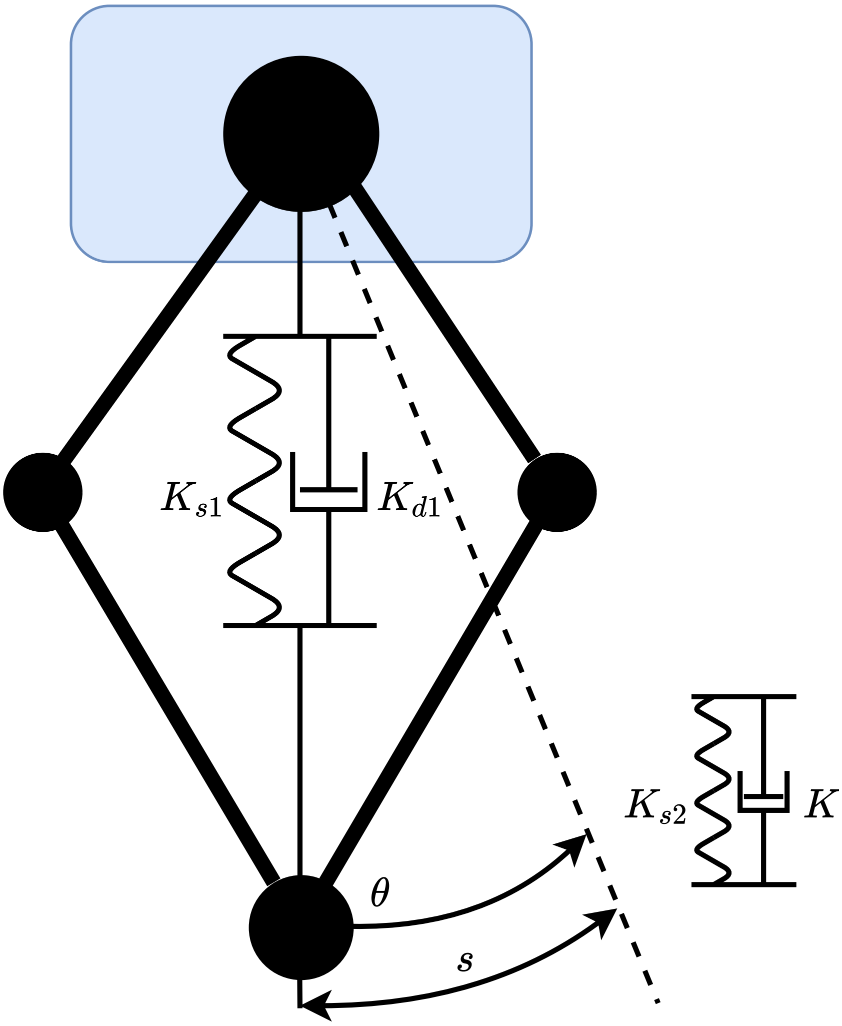


Figure 9.1: Leg spring-damper virtual model.

9.2 Virtual Compliance Model

10 Controller Development

10.1 Dynamic Actuation

11 Experimental Testing

"Jump!"

— Van Halen, *1984*

$r_0 = 0.3\ m$

$r_{offset} = r - r_0 = 0.13\ m$

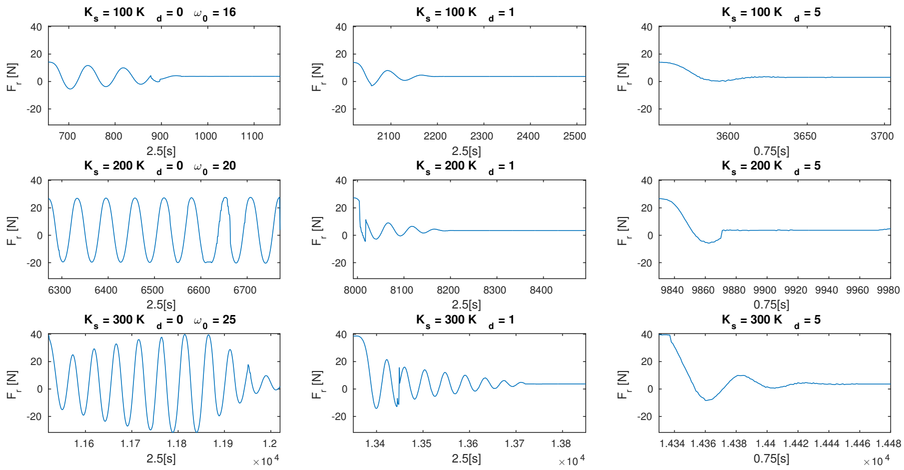


Figure 11.1: Leg spring damper testing for radial offset.

12 Design Validation

13 Conclusions

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14 Recommendations and Future Work

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