May 12, 2020

FYP PART a Report

Control of rolling-balancing mechanical system – disk on disk

Timothy Dunn

c3234207

The University of Newcastle

# Abstract

This report details the steps taken to produce a balancing type II inverted pendulum robot. Balancing an inverted pendulum robot is a typical project for university level students learning advanced mechatronics control. Through the selection of components, mechanical design, derivation of mathematical models, controller and observer design, and finally embedded C implementation, a student forms an understanding of how the different aspects of control of physical systems relate. This project is considered a major steppingstone in the Mechatronics Engineering degree at the University of Newcastle.

During this project, a suitable type II inverted pendulum robot, actuated by stepper motors, was manufactured and controlled using model-predictive control. State estimation was performed by a time-varying Kalman filter. A STM32 microcontroller was used to perform tasks written in C code and enable communication between several peripheral sensors and actuators. Ultimately, a balancing robot was demonstrated.

Table of Contents

[1 Abstract 2](#_Toc40730865)

[2 Introduction 4](#_Toc40730866)

[3 Literature Review? 5](#_Toc40730867)

[4 Modelling and Simulation 6](#_Toc40730868)

[4.1 Euler-Lagrange Method 6](#_Toc40730869)

[4.2 The Disk-on-Disk System 7](#_Toc40730870)

[4.3 Simulation 9](#_Toc40730871)

[5 Control 9](#_Toc40730872)

[5.1 Controller design 9](#_Toc40730873)

[5.2 State estimation 9](#_Toc40730874)

[6 Experiment Apparatus Design 11](#_Toc40730875)

[7 Manufacture 11](#_Toc40730876)

[8 Appendices 12](#_Toc40730877)

[9 References 13](#_Toc40730878)

# Introduction

The stabilisation of an inverted pendulum robot represents an ideal opportunity for a student to implement advanced design, modelling, and control techniques. In conjunction with appropriate electrical and mechanical designs, the derivation of a mathematical model for plant dynamics, alongside the design of a suitable controller and observer, is an invaluable learning experience.

The type II inverted pendulum robot (hereafter ‘inverted pendulum robot’) refers to the configuration of a pendulum robot in which the centre of mass of the system is above the wheel axis of rotation, such as a Segway. A type I robot refers to a cart system with a pendulum mounted to the top. This report and project exclusively refer to a type II configuration. A system of this configuration is inherently unstable, and control requires robust implementation of advanced control methods onboard an embedded system at high control-loop rates.

In order to demonstrate a balancing inverted pendulum robot, the following steps must be undertaken:

* Derive a mathematical model of the plant dynamics
* Determine a suitable design for the inverted pendulum robot
* Determine suitable hardware, such as actuators and sensors, to provide measurements
* Determine optimal configuration of hardware and electronics to achieve desired dynamics
* Commission a printed circuit board with suitable power electronics to act as a motherboard
* Develop a simulation model of the plant in Simulink
* Derive and develop a control model and controller
* Derive and develop an observer model and state estimator
* Conduct experiments to determine plant parameters
* Simulate behaviour of system
* Implement state estimator and controller in embedded C code
* Develop remote interface for communication
* Test and tune system

In order to demonstrate the following capabilities [1]:

* Functioning sensors and actuators
* Remote interface for commanding actuators, reading sensors, and setting reference velocity
* Stabilisation of chassis angle
* Velocity regulation
* Chassis stabilisation on an inclined slope
* Chassis stabilisation during transition between ground plane and inclined plane

Information and resources necessary to complete this task are presented in the MCHA3500 course notes and laboratory exercises. This material is the foundation of the work undertaken and provides the major building blocks of the entire system. Several components of the embedded C implementation and simulation tools are provided as part of the laboratory documents, with adaptation required to suit the type II robot.

Must have note about hand and object here.

# Literature Review?

# Modelling and Simulation

Simulation and modelling are the foundation upon which a mechatronic system is built. A model of a system is a mathematical description of the output behaviour given an input. By taking this model and applying known inputs, the behaviour of the system can be recorded, and a simulation has occurred. If a particular output or system behaviour is desired, then the system must be influenced in such a way that the desired behaviour is realised. Influencing a system in this way is called control. Control without a working model and simulation is impossible.

The modelling of a system is often the first step taken in this process. The physical arrangement of the DoD system is already defined, and the physical phenomena at work are well known. The kinematics of the disk on disk system is adequately captured through use of the Euler-Lagrange modelling method.

## Euler-Lagrange Method

The Euler-Lagrange method is an energy-based method of modelling. The Euler-Lagrange method is often used for rigid body dynamic systems as it can be immediately apparent which components of the system are energy storing elements, and what their associated degrees of freedom are. In the case of the DoD system there are two main energy storing elements: the hand and the object. The driveshaft of the hand may also be considered to be energy storing.

Once the energy storing elements of the system are identified, the kinetic co-energy, , and potential energy, , can be determined. The kinetic co-energy and potential energy must be determined for each energy storing element in each associated degree of freedom. By taking the difference of the kinetic co-energy and the potential energy, the Lagrangian of the system is found. [[1]](#footnote-1)

|  |  |  |
| --- | --- | --- |
|  |  |  |

where is column vector of position coordinates. The kinetic co-energy can be factored into quadratic form if the component constitutive relationships are linear in velocity[[2]](#footnote-2). The component constitutive relationships describe how a component of the system relates certain magnitudes[[3]](#footnote-3).

|  |  |  |
| --- | --- | --- |
|  |  |  |

where is the symmetric positive definite mass matrix.

If the effects of damping are to be considered, the impact of the generalised resistors of the system can be accounted for using the Rayleigh dissipation function . This function is also factored into quadratic form. The dissipation function must satisfy the inequality for all .

|  |  |  |
| --- | --- | --- |
|  |  |  |

where is the symmetric positive semi-definite damping matrix.

If the system in question has non-conservative input forces, these can be included in the Euler-Lagrange equation alongside the dissipation forces.

|  |  |  |
| --- | --- | --- |
|  |  |  |

By substituting (1), (2) and (3) into (4), the following is found,

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  |  |

is grouped to form the centripetal-Coriolis matrix and the gradient of the potential energy function is represented by , giving

|  |  |  |
| --- | --- | --- |
|  |  |  |

A model of this form for the DoD system is developed in 4.2.

## The Disk-on-Disk System

A simplified model of the DoD system is considered for the modelling process. This simplification process is based upon several assumptions:

1. Torque transfer between the actuator and the hand is not subject to any dissipation effects
2. The object and hand interact without slipping
3. The hand and object are always in contact
4. The system is always operating near the upright balancing point

The model developed will be unable to perfectly describe the system dynamics if one or more of these assumptions is not met. Figure 1 shows the layout of the DoD system.

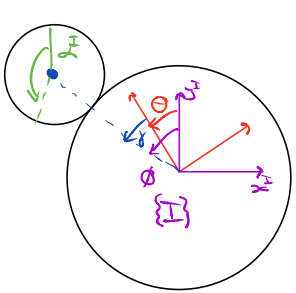


Figure 1. Layout of ideal DoD system.

The energy storing elements and their associated degrees of freedom can be identified via inspection. The hand has a single degree of freedom: the angle of rotation about point XX. The object has two associated degrees of freedom: the angle of rotation about its centre and the angle of rotation about the point XX. Assumption (A2) allows to be described as a function of and , reducing the system to two degrees of freedom.

There are two scenarios to consider when developing the kinematic model: the case where and the case where .

In the first case, if then

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  |  |

Similarly, when

|  |  |  |
| --- | --- | --- |
|  |  |  |

This then gives the relationship:

|  |  |  |
| --- | --- | --- |
|  |  |  |

The kinetic co-energy of the object can then be described as

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  |  |

The conversion between translational and rotational coordinates is most easily accomplished using the single-axis rotation matrices. Alternatively, the parallel axis theorem may be used to find the rotational inertia of the object about the point XX and solve directly.

The kinetic co-energy of the hand is

|  |  |  |
| --- | --- | --- |
|  |  |  |

The total kinetic co-energy can then be factorised to find the mass matrix with the generalised coordinates .

|  |  |  |
| --- | --- | --- |
|  |  |  |

The potential energy is given by

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  |  |

There is only one input force, the torque applied to the hand, giving

|  |  |  |
| --- | --- | --- |
|  |  |  |

As the mass matrix is not time varying and the kinetic co-energy is not a function of the centripetal-Coriolis matrix is zero. This leaves the final Euler-Lagrange equation as

|  |  |  |
| --- | --- | --- |
|  |  |  |

## Simulation

SIMULINK

# Control

intro

## Controller design

SS model – then LQG (MPC?)

## State estimation

Kalman filter state estimator and computer vision

Naïve attempts to model the system may also a case where , but this case is in violation of Newton’s Third Law. This case would amount to having two geared cogs rotating with the same sign angular velocity due to assumption (A2).

# Experiment Apparatus Design

# Manufacture

# Appendices

# References

[1] C. Renton, "Project Outline," in *MCHA3500 Semester 2 2019*, ed: The University of Newcastle, 2019.

1. 3k modelling notes [↑](#footnote-ref-1)
2. Linearity in velocity occurs when the magnitudes are significantly below the speed of light. 3k notes [↑](#footnote-ref-2)
3. 2k notes [↑](#footnote-ref-3)