Philip Salmony, Wolfson College 21 June 2019

Self-Balancing Bicycle

James Dyson Foundation Undergraduate Bursary 2018/19

1 Introduction

(a) Lego Prototype Bicycle

(b) Full-Scale Bicycle

Figure 1: Implemented Bicycles

Bicycles and their stability properties have been studied for well over a century, ever since their inception. The bicycle is a naturally unstable system but can be self-stable under certain conditions. It is however still commonly unclear what primarily contributes to this self-stability. Unfortunately, the full form of the equations of motion does not aid the intuitive understanding of bicycle stability and dynamics.

In addition to simply understanding the causes of self-stability, there are further considerations to studying a bicycle in the frameworks of dynamics and control theory. For example,

- How does a human stabilise a bicycle and is it possible to replicate this behaviour with motors?
- What makes a bike more or less stable - for instance, changes in geometry, mass distribution, or wheel size?
- Would there be a benefit in having an assisted bicycle for certain people in certain situations?

This project aimed to answer - at least in part - some of these questions. In addition, this project explored the modelling, simulation, control system design, and implementation of two rider-less, self-balancing bicycles.

The first bicycle was chosen to be a Lego Mindstorms prototype and the second one a full-scale, adult bicycle. Both bicycles are depicted in Figures 1a and 1b above in their final, modified forms.

These bicycles however only had a drive actuator, to provide forward velocity, and an actuator placed at the handlebars to provide a steer torque. Without the additional component of being able to provide a lean torque, it is extremely difficult to guarantee stability at near-zero forward speed. The bicycles being studied in this case could therefore be classed as underactuated systems.

2 Project Outline

2.1 Modelling

To be able to design suitable control laws in order to stabilise the bicycle, it was necessary to provide a mathematical description of the system. Additionally, developing a dynamic model of the system gave an insight into what factors influence a bicycle's behaviour in terms of its stability.

The following observations were made:

- Bicycle dynamics are strongly dependent on forward speed.
- The stability of a bicycle can be attributed to the front fork assembly, which means that as a bicycle starts to fall, the front forks lean *into* the direction of the fall. Thus, the bicycle is caught *from underneath* and re-stabilised.
- However, a rider-less bicycle is only self-stable within a certain range of speeds determined by the geometry and mass distribution.
- Lastly, the stability of a bicycle is very similar to that of an inverted pendulum. Imagining an experiment where a person balances a stick on their hand, a longer stick is easier to stabilise. Analogous to the bicycle, a higher center of mass causes the bicycle to be easier to stabilise.

2.2 Controller Design and Simulation

Having provided a mathematical model of the bicycle, several types of control system were investigated.

These controllers were then tested in simulation, for instance, using a custom bicycle simulator developed from scratch. A screenshot is shown in Figure 2.

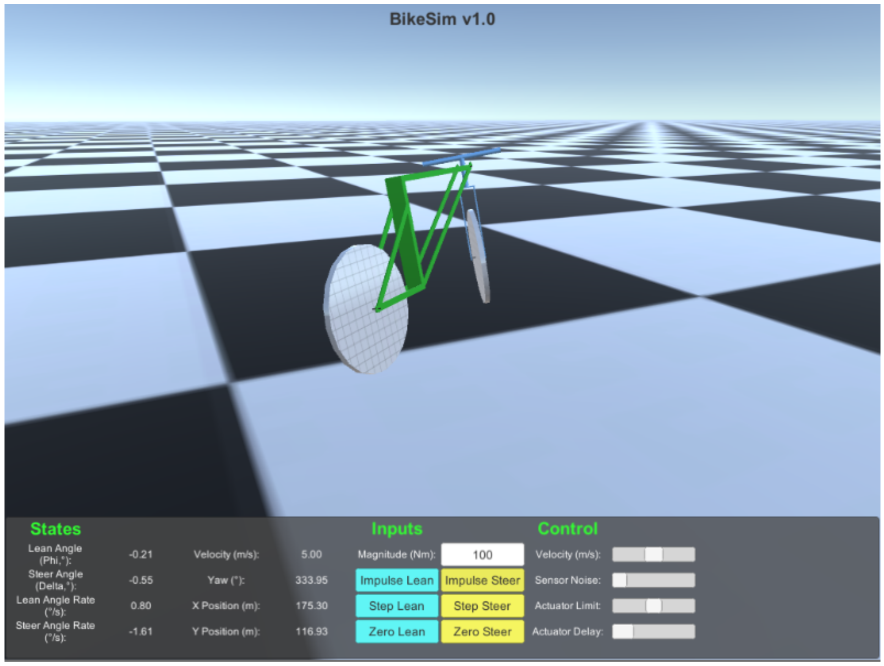

Figure 2: Bicycle Simulator

The developed controllers all performed well at stabilising the bicycle in simulation. This is shown in Figure 3 for the full-scale bicycle.

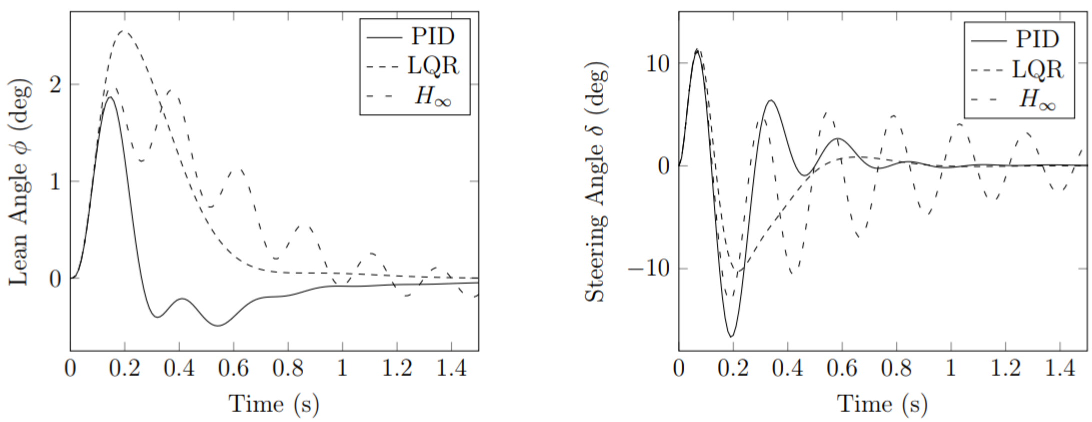

Figure 3: Simulated Bicycle Controller Response

2.3 Implementation

After having designed various control systems, it was time to implement them on real-world bicycles.

Firstly, the Lego prototype bicycle was investigated. Two controllers were implemented successfully on this system. However, due to the limited amount of sensors fitted to the bicycle, the control performance was worse than seen in simulation.

Secondly, after having successfully tested the Lego prototype, the full-scale bicycle was developed. This was an extraordinary amount of work and proved to be a real challenge. Areas of work included: component sourcing, mechanical design, electrical design, software development, as well as weeks and weeks of testing. Close-up pictures of the final bicycle can be seen below.

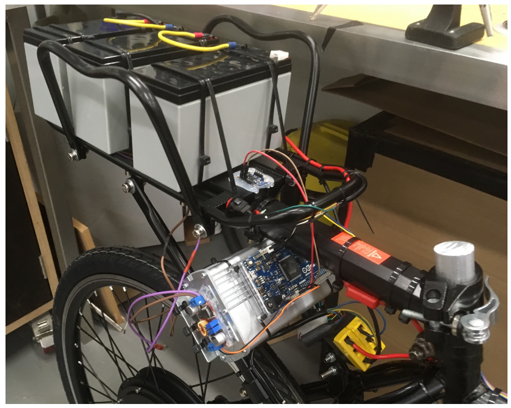

Figure 4: Power and Control Section

(a) Drive Actuator

(b) Handlebar Actuator

Figure 5: Full-Scale Bicycle Close-Ups

Unfortunately, the full-scale bicycle was only able to be stabilised over a short period of time. The reason for this was assumed to be the handlebar actuator, which did not meet the manufacturer's specifications and introduced excessive delays into the system. Additionally, there was not enough time remaining in the academic year to re-design the handlebar actuator assembly.

Pictures and Videos

Videos and further pictures of the bicycles can be found using the following link:

http://philsal.co.uk/projects/self-balancing-bike