A Steer-by-Wire Test Bed for Position Control and Force Feedback

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ABSTRACT

Steer-by-Wire refers to an automotive steering system in which the mechanical connection between the steering wheel and the road wheels is replaced by an electronic link. Due to the absence of this mechanical link, steering feel is not provided naturally by the steering mechanism and must be simulated for accurate and realistic vehicle control.

Compared to traditional steering methods, Steer-by-Wire presents many advantages in the areas of vehicle functionality, architecture and human interface. It also provides an opportunity for the implementation of driver assistance features such as lane keeping assist and collision avoidance. Advancements and further research in this technology are important so Steer-by-Wire can be implemented on passenger vehicles and its potential can be realised.

This project addresses the problem of how to provide the driver with realistic and accurate vehicle control though a Steer-by-Wire system. To achieve effective control the steer-by-wire model includes control methods, which provide vehicle directional control and simulate road feel through force feedback. A basic lane keeping assistance feature has also been implemented. The control methods used have been developed based on previous research evaluated in the literature review. A test bed for the Steer-by-Wire system has been designed and assembled, which includes a steering wheel assembly and a small demonstration vehicle. The Steer-by-Wire steering control was realised through the use of Simulink and utilised a HILINK control board. The results were recorded for position tracking, with and without the lane keeping assistance feature enabled and the force feedback current.

The test vehicle's recorded results for position tracking between the hand wheel and road wheels indicate successful directional control with and without the lane keeping assistance feature enabled. The current tracking was less effective but still provided force feedback for different road conditions that could be experienced by the driver. The test bed development was successful in demonstrating the functionality of the Steer-by-Wire system. A YouTube video outlining the system's components and operation can be viewed at https://youtu.be/aX-cM1BPF7Q.

Possible future work with the developed Steer-by-Wire test bed may include: the use of different Steer-by-Wire control methods, the implementation of additional driver assistance features or the replacement of the wired connections between the control unit and demonstration vehicle with wireless ones. Control modifications may be implemented in the existing programming and due to the demonstration vehicle's design and assembly using Makeblock components the hardware can be easily modified.

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STATEMENT OF ORIGINALITY

I, Matthew R. Crawford, declare that this thesis, submitted as part of the requirements for the award of Bachelor of Engineering, in the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications or assessment at any other academic institution.

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ABBREVIATIONS AND SYMBOLS

A	Amperes
ADAS	Advanced Driver Assistance
b_{hw}	Hand Wheel Damping Factor
b_r	Road Wheel Damping Factor
°	Degrees
DC	Direct Current
ECU	Electronic Control Unit
EHPS	Electro-Hydraulic Power Assisted Steering
EPS	Electric Power Assisted Steering
f	Sampling Frequency
GPS	Global Positioning System
HPS	Hydraulic Power Assisted Steering
HW	Hand Wheel
I_a	DC Motor Armature Current
i_s	Kinematic Steering Ratio
J_{hw}	Hand Wheel Moment of Inertia
J_r	Road Wheel Moment of Inertia
K_P	Proportional Gain
K_I	Integral Gain
K_D	Derivative Gain
K_u	Ultimate Gain
LKAS	Lane Keeping Assistance
PD	Proportional Derivative
PFTF	Position Follow and Torque Feedback
π	Pi
PID	Proportional Integral Derivative
P_u	Ultimate Period
RW	Road Wheels
SBW	Steer-by-Wire
T	Sampling Period
TFPF	Torque Follow and Position Feedback
T_i	Integral Time
T_d	Derivative Time
θ_{hw}	Hand Wheel Steering Angle
θ_{rw}	Road Wheel Angle
τ	Motor Torque
τ_a	Aligning Torque
τ_h	Driver Applied Hand Wheel Torque
τ_{HWfr}	Hand Wheel Frictional Torque

τ_{HWact}	Hand Wheel Applied Actuator Torque
τ_{RWfr}	Road Wheel Mechanism Frictional Torque
τ_{RWact}	Road Wheel Actuator Torque
V	Volts
ZN	Ziegler–Nichols

LIST OF CHANGES

Section	Statement of Changes	Page Number
Entire Thesis	Updated entire thesis based on comments from ECTE451. Updated reference list and references throughout.	1-67
Appendix D	Updated model to work on Matlab/Simulink 2016.	61-67
Appendix A	Updated project plan and Gantt chart.	49-51
Appendix C	Updated drawings and added a bill of materials for ECTE458.	53-60
Introduction	Updated all parts and added portions for controller design and driver assistance features.	1-4
Literature Review	Updated relevant sections. Added the controller specification and lane keeping assistance sections.	5-18
Experimental Design	Updated relevant sections for ECTE458. Added lane keeping assistance sensors to hardware. Added programming for steering returnability, lane keeping control and gear ratio.	19-35
Results and Analysis	Moved this section to its own chapter. Updated with results for optimised PID control and lane keeping assistance feature.	36-43
Conclusion	Updated with comments relating to ECTE451 and ECTE458. Outlined future work.	44
Abstract	Updated to for ECTE458 additions and results.	ii-iii
Appendix B	Replaced ECTE451 signature sheet with a new one from ECTE458.	52
Entire Thesis	Made final modifications to ensure grammatically and technically correct.	1-67

Chapter 1. INTRODUCTION

1.1 Steering Systems

A steering system is a collection of vehicle components, which the driver interacts with to control the trajectory of the vehicle [1-3]. The steering system also provides valuable feedback about road condition and tyre dynamics [4, 5]. Automotive steering systems have evolved throughout the years from manually operated steering to various forms of power assisted steering [2, 6]. The latest developments in power assisted steering include: Electric Power Steering (EPS), superimposed steering and Steer-by-Wire (SBW) [7, 8]. Unlike EPS and superimposed steering, SBW does not include a mechanical link between the steering wheel and road wheels. Many in industry believe SBW to be the next stage in the evolution of the steering system [6, 9-11].

1.2 Steer-by-Wire

SBW refers to a steering system in which the mechanical connection between the steering wheel and the road wheels is replaced by an electronic link [12-15]. An SBW system is comprised of a hand wheel assembly, a road wheel assembly and an Electronic Control Unit (ECU). The hand wheel assembly includes a steering wheel for driver interaction, a steering sensor to detect steering wheel position and a response actuator to provide force feedback from the road. The road wheel assembly is comprised of a steering actuator to direct the vehicle's wheels in the appropriate direction, a wheel sensor to measure the road wheel position and a force feedback sensor.

SBW has many advantages in the areas of vehicle functionality, architecture and human interface [6, 12, 16]. Technical, economic and regulatory challenges do exist however, and must be addressed for SBW to be widely implemented on passenger vehicles in industry [6, 12]. One specific technical challenge in an SBW system is that, due to the absence of the mechanical link between the steering wheel and road wheels, steering feel is not provided naturally by the steering mechanism [9, 15, 17].

1.3 Steering Feel, Force Feedback and Steer-by-Wire Control

Steering feel is experienced mainly through the steering wheel and is the driver's subjective sensation caused by the interaction between the driver and the vehicle [3, 4]. The driver and vehicle can be considered a closed loop system where feedback from the road is used to influence the driver's reaction to various conditions [4]. Without steering feel the driver's response would not be appropriate and vehicle control and passenger safety would be compromised [4, 6, 18]. In an SBW system the steering feel must be simulated through some form of force feedback [18-20].

Previous research in the area of SBW control has looked at different control methods to provide both directional control and appropriate steering feel through force feedback. SBW control methods include: direct current measurement for force feedback, bilateral control method based on a disturbance observer, position following/torque feedback, torque following/position feedback, robust control and control by a virtual vehicle concept [9, 14, 15, 17, 21, 22]. These studies include the development of modelling control software and experimental validation through simulation on either a steering test bed or on an actual vehicle equipped with an SBW system. An SBW test bed was successfully developed in ECTE451 that utilised the direct current measurement method for the force feedback.

1.4 Steer-by-Wire Controller Selection

A key component in an SBW system's design is controller selection. A controller's purpose is to modify a system in order to provide a desired output from a desired input [23]. A great deal of previous SBW research has involved the use of proportional integral derivative (PID) or proportional derivative (PD) controllers [9, 15, 21]. Originally in ECTE451 the controllers used in the developed test bed were PD controllers for both the position control and force feedback. Due to time constraints, the performance of the original controllers could not be optimised. In ECTE458 the controller performance was increased through the use of established tuning methods [23-27]. The position controller was tuned using the Ziegler-Nichols (ZN) method and the force feedback controller was tuned manually. A comparison of the original and modified results is presented in Chapter 4.

1.5 Driver Assistance Features

An SBW system presents a great opportunity for the implementation of various advanced driver assistance (ADAS) features [6, 28-30]. An ADAS feature increases passenger and road safety by enhancing the driver's ability to avoid a collision [30, 31]. In an ADAS system the ECU takes real time inputs from vehicle sensors and interprets them to produce multiple outputs in the form of a warning signal or a driver intervention [31]. The different ADAS warning systems include: lane departure detection, blind spot monitoring and pre-crash recognition [30-32]. Some examples of ADAS features, which involve direct intervention, include: semi-automatic parking, crosswind stabilization, collision avoidance and lane-keeping assistance (LKAS) [30]. The focus of the research included in this project involves steering intervention, more in the form of LKAS.

A great deal of previous research involving LKAS implementation exists on multiple methods of lane detection. The previously examined methods include camera-based techniques, location/digital mapping technology and the use of other on-board vehicle sensors [32-37]. For an effective system to exist a combination of multiple methods is often utilised [32]. This project will demonstrate the implementation of a basic LKAS feature on the developed SBW test bed. The method used will involve the use of infrared optical sensors and fuzzy logic control [37].

1.6 Problem Definition, Aims and Objectives

This project addresses the problem of how to provide the driver with realistic and accurate vehicle control though an SBW system. To achieve accurate control the project builds on the work conducted in ECTE451 by improving the directional control, force feedback and steering feel emulation of the developed test bed. An LKAS feature was also implemented on the test bed to demonstrate the compatibility of an SBW system with a basic form of driver assistance.

The main objectives of this project include:

- The study of PID control/tuning and LKAS implementation.
- Improvement of the Simulink SBW control system.
- Installation of lane keeping sensors/hardware on the existing SBW test bed.
- Testing of the system's steering emulation.
- Testing of the system's LKAS functionality.
- Analysis of results and conclusion.

This project provides greater understanding of an SBW system. Advancements in this area are important so SBW technology can be implemented on passenger vehicles and the potential of the SBW system can be realised.

1.7 Report Structure

This report provides a detailed explanation of the undertaken work involved in ECTE451/458 to complete the objectives outlined in Section 1.6. Chapter 2 is the literature review, which is the critical analysis of previous research completed in SBW and other topics relevant to this project. Chapter 3 is a detailed description of the experimental design and how the test bed was developed. Chapter 4 includes the analysis and review of the gathered results. The final section provides a summary of the work conducted as part of this project and outlines any future recommended work. A YouTube video outlining the system's components and operation was also developed that can be viewed at https://youtu.be/aX-cM1BPF7Q.

Chapter 2. LITERATURE REVIEW

2.1 Introduction

This chapter is a critical review of research relevant in the area of SBW and research involving the development of an SBW test bed. The literature review includes the following: a brief historic overview of automobile steering systems, a detailed comparison of SBW to currently implemented steering technology, an analysis of previously developed SBW models, a detailed evaluation of different experimental platforms and the associated control methods used in previous SBW research. To improve the performance of the developed SBW test bed and demonstrate additional feature implementation further analysis was conducted in the areas of controller specification, fuzzy logic control and LKAS.

2.2 Historic Overview

The history of automobile steering systems leading up to SBW is outlined by Eckstein et al. [6] and this progression is illustrated in Figure 2.1. A similar but more thorough history is presented by Pfeffer and Ulrich [2], which provides greater detail about the various stages of steering system development. As outlined in [2, 6], motor vehicle steering systems originated as solely mechanical but as steering forces increased, as a result of increased driving speeds and vehicle mass, a demand for improved steering control presented itself. This led to the development of power assisted steering.

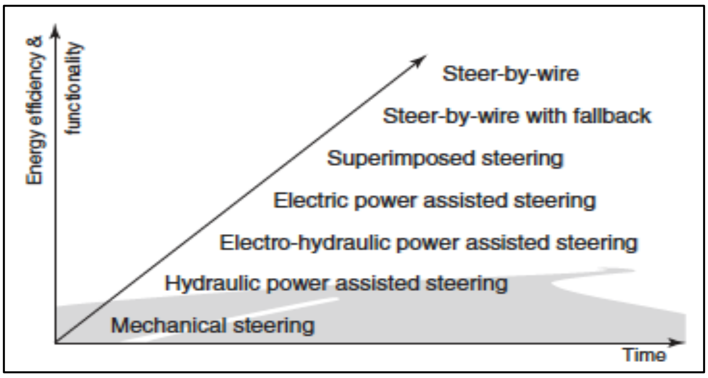


Figure 2.1: Steering Systems Timeline [6]

2.3 Comparison of Steer-by-Wire and Traditional Steering Technology

Power assisted steering reduces driver steering effort and multiplies the driver's input through the application of energy provided by the vehicle's engine or electrical system [2]. Power assisted steering has progressed over the years and the different types of power assisted steering technology presently in use include: Hydraulic Power Assisted Steering (HPS), Electro-Hydraulic Power Steering (EHPS) and Electric Power assisted Steering (EPS) [2, 6]. In HPS the vehicle's engine constantly drives a hydraulic pump, which provides the steering assistance. The driver's applied torque at the steering wheel then controls a valve that dictates how much steering assistance is applied [38]. In an EHPS system the steering assistance is still accomplished through a hydraulic pump but the hydraulic pump is powered by an electric motor through the vehicle's electrical system [39]. In EPS the hydraulic pump is replaced by an electric motor that provides the steering assistance directly and the amount of applied steering assistance is determined by a sensor installed in the steering column [7, 40].

SBW and more conventional EPS systems share many of the same advantages when compared to hydraulic systems (HPS and EHPS). These advantages are outlined in Table 2.1, which has been constructed based on information from numerous sources [6, 7, 38-40]. The main reason that hydraulic power steering systems are still widely used today is due to their relatively low cost [38]. In addition to the advantages EPS and SBW share, compared to hydraulic systems, the implementation of SBW would also provide additional benefits in the areas of vehicle architecture and functionality [6].

Table 2.1: Benefits of EPS and SBW Compared to HPS and EHPS

Type of Benefit	Benefits of EPS/SBW as Compared to a HPS/EHPS
Environmental	No steering fluid or filter requiring disposal or changing. Reduced emissions from better fuel consumption.
Fuel Consumption	Power is provided to the steering system on demand and the power is provided by the vehicle's electrical system. Both features reduce fuel consumption.
Functionality	Presence of an ECU provides the possibility for the implementation of driver assistance features.
Steering Control	Improved response time and steering control.

Vehicle Design/Assembly	Less space required by the steering system, which provides more flexibility in vehicle design.
Vehicle mass	Reduces the vehicle's overall mass due to the removal of the hydraulic pump, filter, hoses and steering fluid.
Driver Comfort	Reduced vibrations and cabin noise.

In a purely SBW system there is no mechanical link or steering column connected between the hand wheel (HW) and the road wheels (RW). This differs from a traditional steering system and is illustrated in Figure 2.2 [15]. Huang and Pruckner [12] state that due to the absence of the steering column, manufacturers have greater freedom when considering front end design and steering wheel placement and are not limited to the traditional steering wheel as the driver’s input device. The absence of the steering column also makes available valuable space in the engine compartment [12]. Another advantage outlined in [6] is that crash performance is improved due to the reduced likelihood of the steering wheel entering the driver’s survival space in a head-on collision. This advantage may be less apparent when compared to new steering systems that include a collapsible steering column [7]. Wurges [7] outlines that in many new EPS systems the steering column is designed to absorb energy from the crash reducing the impact on the driver. In addition to the above mentioned physical advantages of SBW it also provides opportunity for improved functionality and the implementation of ADAS features [6].

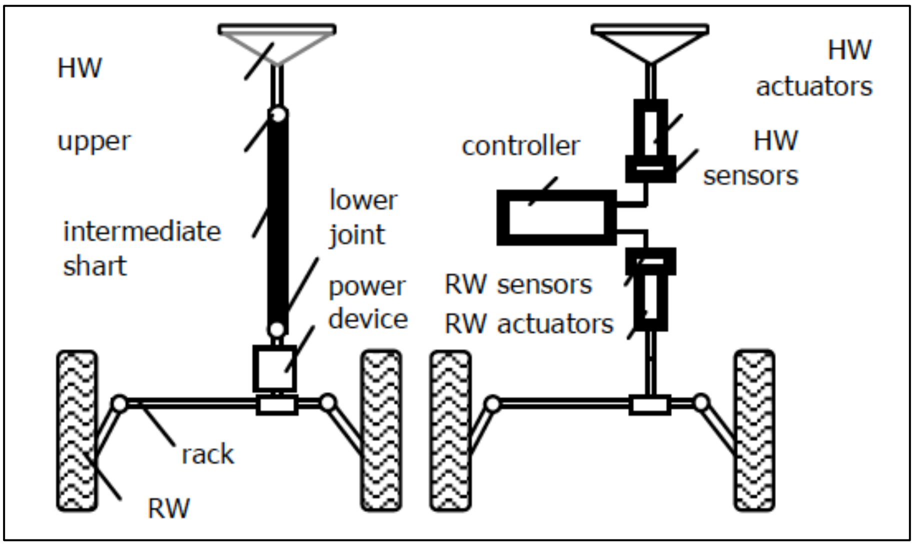


Figure 2.2: Side-by-Side Comparison Traditional (left) and SBW (right) [15]

Functionality can be described as how well a device or system performs the task it is designed to accomplish. With the introduction of ECUs in passenger vehicle steering systems many advanced functions of the steering system can be achieved [11]. These advanced functions exist not only in future SBW systems but also in currently implemented mechatronic steering systems [8]. Advanced steering functions include variable gear ratio, quicker response time, programmable driving style and numerous ADAS features [12]. Eckstein et al. [6] states that SBW is the best possible prerequisite for the implementation of driver assistance features. This is however contradicted by Harrer and Pfeffer [41] who conclude that currently SBW offers no added functionality over existing mechatronic systems with a mechanical backup. For SBW to be widely implemented, based on functionality, over currently used EPS mechatronic systems it must overcome the challenges it faces, making it a more attractive choice.

2.4 SBW System Model

As detailed in Section 1.2, an SBW system differs from a traditional steering system due to the absence of a mechanical connection between the steering wheel and the road wheels. Due to this trait the SBW system must be modelled appropriately. Nguyen and Ryu [15] put forward that an SBW system can be viewed as a two-port network consisting of a hand wheel and road wheel. The basic operation of the system, as described in [15], includes the driver inputting position at the hand wheel, which is then tracked by the road wheel. The system also provides steering feel through torque feedback from the road wheel, which is applied to the hand wheel actuator. This representation of an SBW system is confirmed in [9, 17, 21], which outline and validate similar SBW models. The research and experimentation conducted in [15, 21] involved a similar method of generating the force feedback as used in this project and will therefore be the basis for the hand wheel and road wheel models to follow.

2.4.1 Hand Wheel Assembly Model

The hand wheel assembly provides the interface between the driver and the SBW system. The driver applies a torque to the hand wheel (τ_h). This applied torque dictates the steering angle (θ_{hw}), which is tracked by the road wheels. The road wheel torque is monitored and provided as feedback to the hand wheel actuator. The actuator applies this torque (τ_{HWact}) based on the received feedback to simulate road feel. The moment of inertia (J_{hw}), damping factor (b_{hw}) and the torque generated from hand wheel friction (τ_{HWfr}) must also be considered. The described relationship can be represented as a second order differential equation as derived by Nguyen and Ryu [15] in Equation 1. A visual representation of the hand wheel model is provided in Figure 2.3. The hand wheel or steering angle acts as an input for position tracking of the road wheel.

$$\mathbf{J_{hw}\ddot{\theta}_{hw} + b_{hw}\dot{\theta}_{hw} + \tau_{HWfr} = \tau_h + \tau_{HWact}} \quad (1)$$

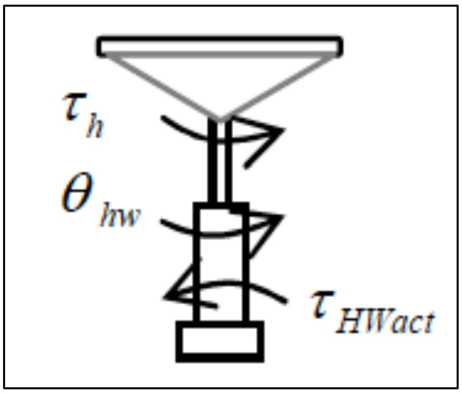


Figure 2.3: Hand Wheel Model [15]

2.4.2 Road Wheel Assembly Model

In the road wheel assembly, the driver's inputted steering angle causes the road wheel actuator to apply an appropriate torque (τ_{RWact}). This applied torque dictates the road wheel angle (θ_{rw}). If there is contact between the wheels and the road, aligning torque (τ_a) will be present. The road wheel moment of inertia (J_r) and damping factor (b_r) must also be considered along with the frictional torque (τ_{RWfr}) generated from the entire road wheel mechanism. The described relationship can be represented as a second order differential equation as derived by Nguyen and Ryu [15] in Equation 2. A visual representation of the road wheel model, with wheel to road contact, is provided in Figure 2.4.

$$\mathbf{J_r\ddot{\theta}_{rw} + b_r\dot{\theta}_{rw} + \tau_{RWfr} + \tau_a = \tau_{RWact}} \quad (2)$$

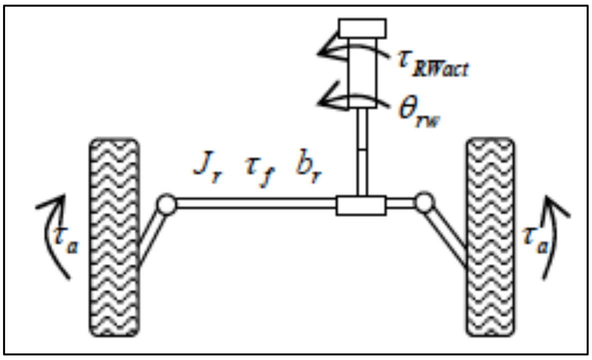


Figure 2.4: Road Wheel Assembly Model [15]

2.5 Steer-by-Wire Control Concept and Test Bed Development

2.5.1 Direction Tracking Control and Force Feedback

An SBW system has two basic functions, which are to provide accurate directional control and suitable force feedback [9]. The forces involved are included in the simplified models presented in Sections 2.4.1 and 2.4.2. Based on these models, a great deal of research has been conducted using different control methods to provide these two basic functions. The methods described in this section illustrate how direction control and haptic road sense are provided through various forms of bilateral control.

A method of bilateral control in an SBW system is described in [17] and involves the design of disturbance and sliding mode observers. The basic SBW system is modelled as in Section 2.4 and the front wheel aligning torque is described as being related to the yaw rate and side slip angle. Im et al. [17] includes the state space equations for the single track vehicle model. The states are given as the sideslip angle and yaw rate. The disturbance observer is constructed by appending the disturbance aligning torque to the vehicle's state vector. This method allows the aligning torque to be estimated without any sensors based on the inputs and outputs of the system. The experimental setup for this design was implemented on an EPS system and Im et al. [17] concluded that this was an effective method of providing force feedback to the driver through the hand wheel. Nguyen and Ryu [15] state that although model based methods for force feedback, such as utilising a disturbance observer as done in [17], are effective but they require the use of more complicated modelling and microcontrollers. The next method analysed focuses on the use of position and torque sensors.

The research presented by Wu et al. [9] involved the investigation of two separate methods to achieve position tracking and force feedback. The first method involved was termed “position follow and torque feedback” or PFTF. In this method the driver set the wheel angle at the steering wheel and an angle transmission ratio was applied. The modified angle was then inputted to the road wheel actuator through a Proportional Differential (PD) controller. At the road wheel a tension and compression force sensor installed on the steering mechanism measured the aligning moment. The aligning moment was used to calculate the required amount of opposing, aligning torque. This aligning torque was then converted to a corresponding current, which was used to simulate the torque feedback at the hand wheel. The second method used in [9] was termed “torque follow and position feedback” or TFPF. This method differs from the first in that a torque sensor on the hand wheel determined the direction control input and a road wheel position sensor measured the road wheel position, which was used to initiate the applied torque feedback at the hand wheel actuator through a PD controller.

The two control methods proposed in [9] used an EPS system to evaluate position following and the sensory force of the steering rack. Wu et al. [9] concluded that the performance of the PFTF method was better than that of the TFPF for a SBW system. The PFTF system is similar to the method described in [15] but has one key difference in that the road wheel torque is measured and converted to a current whereas in [15] the input current at the road wheel is measured directly. Properties of the PFTF method presented in [9] are relevant to the control model design developed in this project as it provides an effective method of achieving direction control and force feedback in an SBW system.

Further research in regards to providing effective position tracking and force feedback is presented in [15]. Nguyen and Ryu [15] conduct a comparison of currently utilised techniques and present a method to provide force feedback that involves measuring road wheel motor current directly. The motor torque can then be determined due to its direct relationship to the armature current in a DC motor. The measured current from the road wheel includes multiple torques dependent on the steering system itself, road conditions and various other factors. The concept of adding “free control torque” to the system to adjust the experienced force feedback for different situations [15] is also examined. The position tracking in [15] utilises a PID controller but the force feedback is in an open loop system. The validation of the presented direct current method is completed by Nguyen and Ryu [15] through a series of simulations. These simulations demonstrate that their proposed method is effective for applying force feedback at the hand wheel.

Additional research in the area of SBW, using the direct current method for force feedback, was conducted in [21]. Zhai et.al [21] presented similar models for the hand wheel and road wheel systems as in [9, 15] but the road wheel’s aligning torque was analysed more thoroughly. The aligning torque was implemented into the system through a torque map. The control model in [21] also involved the use of PID controllers in both the position tracking and force feedback loops unlike [9, 15], which only utilise controllers for position tracking. The main focus of [21] was how to provide a variable gear ratio in an SBW system.

2.5.2 Variable Gear Ratio

The kinematic steering ratio (i_s) of a vehicle is defined in [42] as the ratio of the hand wheel angle (θ_{hw}) to the road wheel angle (θ_{rw}). This relationship is shown in Equation 3.

$$\boldsymbol{\theta_{hw} = i_s * \theta_{rw}} \tag{3}$$

To provide the driver with improved control and comfort, the steering ratio is not generally the same over the whole steering range or at different velocities [42]. The concept of implementing a variable gear ratio in an SBW system is analysed in [21]. The variable gear ratio implemented in [21] used vehicle velocity and steering wheel angle to determine the appropriate steering ratio. The applied variable gear ratio was then validated by Zhai et.al [21] by plotting the front wheel angle at different velocities illustrating the effect of the variable gear ratio.

2.5.3 PID Controller Optimisation and Tuning

The SBW systems discussed in Section 2.5.1 utilised some form of conventional control and were the basis of the developed SBW test bed in ECTE451. This section provides details in regards to general PID controller theory and operation. It also outlines possible tuning procedures, which may be utilised to improve the performance of the developed SBW test bed. In this thesis when referring to the ZN method it shall be assumed that this is the ZN frequency response method.

PID controllers have been commercially available since the 1930's and are still considered to be the most widely used controller in industry today [26]. PID control has retained its popularity mainly due to the controller's relatively simple design, online tuning capabilities and wide availability [23, 25, 26]. The structure of a PID controller is outlined in [23] and illustrated, for both the time and frequency domain representations, in Figure 2.5. Johnson and Moradi [23] describe the PID controller as a three-term device which utilises proportional (K_P), integral (K_I) and derivative (K_D) gains. These gains are applied to the system's error and summed to achieve the desired controller action. Due to the controller performance being dependent on these three terms careful consideration must be made in their selection to ensure desired controller performance.

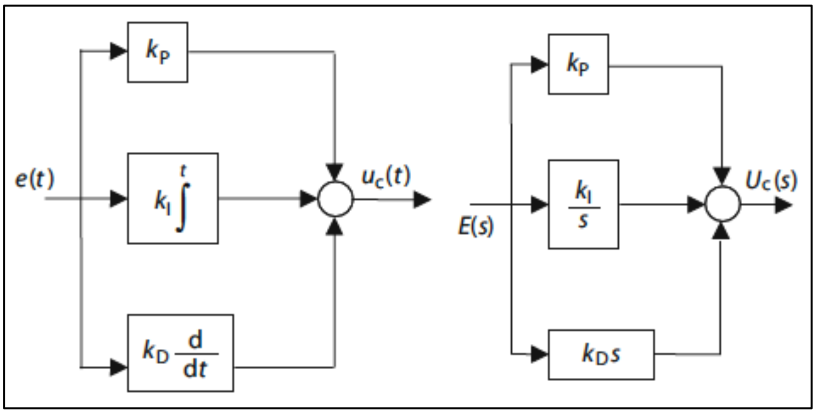


Figure 2.5: PID Structure Time Domain (Left) and Frequency Domain (Right) [23]

The process of selecting controller gains is referred to as tuning [23]. Effective PID controller tuning can be achieved through numerous theoretical or experimental techniques. A detailed comparison of the procedures, strengths and limitations of multiple PID tuning techniques was presented in [26]. To evaluate the different techniques Shahrokhi and Zomorrodi [26] conducted simulations on first, second and third order systems. The tuning methods were appraised by measuring the Integral Absolute Error of the system for both set point tracking and load disturbance. Shahrokhi and Zomorrodi [26] concluded that, based on the good overall performance of the ZN method it can be used with confidence on the majority of systems.

A comparable but more practical study was conducted in [25], which focused on a few well established, experimental PID tuning techniques. Unlike [26], where the methods were compared using a Matlab simulation, in [25] the different methods were tested on a self balancing robot. De Souza et al. [25] indicated that when dealing with a complex system, with an unknown plant, an experimental tuning technique may be utilised to effectively tune the controller. The techniques used in [25] were the manual, ZN and the relay tuning methods. Based on the tabulated results in [25] the ZN method proved, once again, to be the most effective tuning procedure. Similar to the self-balancing robot the developed SBW system has an unknown plant, therefore the manual and ZN tuning methods were utilised to determine the PID gains.

The manual tuning method is a trial and error process based on the heuristic behaviour of the controller gains [23]. Johnson and Moradi [23] state that for a simple plant there are straightforward correlations between the gain terms and the system's response. The manual tuning procedure is outlined in [25, 43] and is as follows.

1) Set K_I and K_D to zero.
2) Increase K_P to improve rise time.
3) Increase K_D to reduce overshoot.
4) Increase K_I to eliminate steady state error.
5) Finely adjust all three terms.

The general effects of the different gain terms are also summarised in [43] and presented in Table 2.2. It should be noted that the listed effects in Table 2.2 should be used with caution, as changing one gain term will affect the performance of the others.

Table 2.2: General Effects of Adjusting PID Gain Terms [43]

	Effect			
Gain Term	**Rise Time**	**Overshoot**	**Settling Time**	**Steady State Error**
K_P	Decrease	Increase	Small Change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_D	Small Change	Decrease	Decrease	No Change

If a system is too complex a more sophisticated tuning procedure may be required [23]. The ZN tuning method has been demonstrated to be effective in simulation as in [26] and while utilised in practical implementation as in [25]. The ZN method identifies the point in which the Nyquist curve intersects the negative real axis [24]. This point is determined by increasing the K_P value until the system experiences sustained oscillation, while setting the K_I and the K_D values to zero. This point is characterised by two parameters, which are termed the Ultimate Gain (K_u) and Ultimate Period (T_u). Using a set of heuristic rules, as summarised in Table 2.3, the PID controller gain terms can then be calculated. One drawback of the ZN method is that the plant must been driven into sustained oscillation [26], which could be destructive depending on the plant. Fortunately the SBW test bed was not adversely affected by this condition making the ZN approach a practical solution for the controller tuning of the SBW test bed position controller.

Table 2.3: Ziegler-Nichols Frequency Response Method Gain Parameters [24]

Controller	K_P	T_i	T_d
P	$0.5*K_u$	-	-
PI	$0.45*K_u$	$T_u/1.2$	-
PID	$0.6*K_u$	$T_u/2$	$T_u/8$

2.6 Lane Keeping Assistance

According to the World Health Organisation [44] road traffic injuries were globally the ninth leading cause of death in 2014. Due to this troubling statistic there is great motivation to improve vehicle and road safety worldwide. One method to accomplish improved vehicle safety is through the development of intelligent vehicle systems and ADAS features [31]. One such feature is LKAS which has been largely researched due to the high fatality rate caused by unintended lane departures [30, 35]. An LKAS system is defined by Brosig and Lienkamp [30] as a complex system which provides active intervention to correct unintended lane departure by imposing additional steering torque on the steering actuator. An LKAS system requires the following components: an ECU, an electromechanical steering actuator, vehicle sensors and a lane detection device [30]. An SBW system also employs the use of an ECU, multiple sensors and an electromechanical actuator, making it an ideal prerequisite for LKAS implementation [6].

The implementation of an LKAS system has many considerations including how the driver will share the steering control of the vehicle with the lane-keeping controller. In [30] multiple guidelines are outlined for controller steering intervention which include: steering interventions must be understandable by the driver, they must not surprise the driver and the driver must be able to override the steering intervention at any time. Nguyen et.al [36] outline similar requirements in their study of the cooperation between the human driver and an active steering system. In [36] shared control of an LKAS system is modelled to demonstrate the driver's real time interactions. The developed LKAS control system model is then validated through the use of a driving simulator. The system and driver are tested in different driving scenarios and the results indicate that the developed system successfully reduces driver/controller conflict improving LKAS performance.

The most common method of lane detection is accomplished through the use of a camera and image processing [30]. This is demonstrated in [35] through the development of a lane keeping system that uses a camera with pattern recognition to provide the driver with both a warning signal and a steering intervention. Unlike the system developed in [36], which had autopilot capabilities, this system can only assist the driver in staying in the lane. To avoid conflict between the LKAS system and the driver Liu et.al [35] use additional vehicle sensors to determine the driver's intention. For instance if the left or right turn signal is detected then the system concludes that the driver is changing lanes and the LKAS is deactivated. The amount of torque assistance is determined using fuzzy logic control with inputs including vehicle lateral deviation, speed, road curvature and the applied driver's torque. The developed system is proven to be successful in providing LKAS through both simulation and in an actual test vehicle.

Additional LKAS research is presented in [32] which combines a vision based lane keeping system with location technology. Wang et.al [32] put forth that vision based and Global Positioning Systems (GPS) both have their limitations while applying them to LKAS. It is proposed that by combining the two an improved LKAS system may be developed. The system outlined in [32] also required the development of digital maps with lane level precision. To validate the system a high precision digital map was developed for a test section of road in Germany. The vehicle's position was then projected on to the digital map and its location as well as the vision-based inputs determined the corrective action to be taken. Based on the gathered test results Wang et.al [32] concluded that the robustness of a vision based LKAS system could be increased through the use of location technology.

A basic method of LKAS was applied to a remote control vehicle in [37]. The developed system outlined by Basjaruddin et.al [37] used line detecting infrared sensors for the lane detection and fuzzy logic control to determine the corrective steering action. The inputs for the fuzzy logic control were lane deviation and vehicle speed. Using four infrared sensors the vehicle's lane position was determined as illustrated in Figure 2.6. The system was successfully implemented using an Arduino Uno R3 microcontroller and demonstrated the effectiveness of using the developed fuzzy logic control algorithm for LKAS. The research conducted in [37] shall be modified to implement a similar LKAS feature on this project's developed test bed.

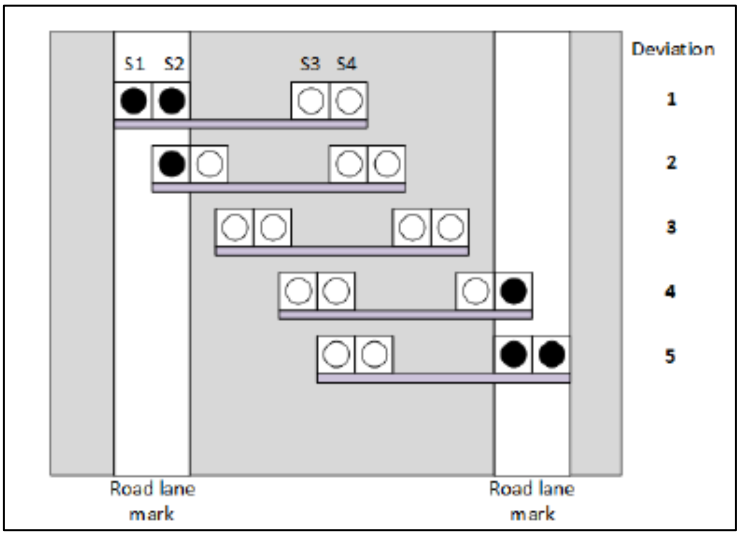


Figure 2.6: Deviation Definition Based on Infrared Sensors [37]

Chapter 3. EXPERIMENTAL DESIGN

3.1 Introduction

This section outlines the design and assembly of the experimental platform used in this project to evaluate a basic SBW system. The test bed was assembled in ECTE451 and its functionality and performance was improved in ECTE458. The design includes a control station, complete with hand wheel assembly, and a small demonstration vehicle. This section also provides details in regards to the design criteria, hardware components, software used and programming.

3.2 Design Criteria

The SBW test bed developed in ECTE451 was designed to evaluate the steering control and force feedback functionality of an SBW system. In the next stage of the project, ECTE458, the test bed's steering emulation was improved and an LKAS feature was added. For accurate and realistic evaluation the demonstration vehicle was designed to operate at various velocities. The allocated budget for ECTE451/458 was $700 dollars and the total duration was 26 weeks. Due to the restricted budget parts from the SECTE stores office were utilised as much as possible.

At the start of the project it was decided that the steering control would be accomplished through the use of Simulink and a HILINK control board. This platform for the steering control was chosen due to availability of parts and previously developed skills from ECTE344 (Control Theory). The use of the HILINK control board did however present a challenge. Without additional multiport software only one HILINK board could be operated from a computer at a time and that board could only control two DC motors. The test bed required the control of four separate DC motors therefore to provide the vehicle's forward and reverse motion an Arduino Uno and motor shield were utilised.

3.3 Design Overview

The SBW experimental platform developed for this project includes a control station/steering wheel assembly and a small demonstration vehicle. The overall hardware configuration is illustrated in the electrical wiring diagram (WIRING-001) and all the utilised parts for ECTE451 are listed in the bill of materials (BOM-001). Both of these drawings are located in Appendix C. The control station assembly and demonstration vehicle are connected together by a multicore trunk cable. This enables the power supply and controllers to be located at the control station, which keeps the demonstration vehicle's weight to a minimum.

The experimental platform can also be separated by the demonstration vehicle's functionality of forward/reverse motion and steering control. The forward and reverse motion is controlled by a momentary pushbutton, which initiates the forward and reverse sequence of the demonstration vehicle through the Arduino Uno and motor shield. The steering control input is measured in real time at the steering assembly and the demonstration vehicle's wheel angle is controlled through the HILINK board and Simulink program. Multiple current readings measured at the demonstration vehicle's road wheel motor and the steering assembly's motor are also used to provide force feedback through the HILINK board. The direct current method proposed by Nguyen and Ryu [15] has been used to provide the directional control and force feedback for this project. The Simulink programming is a modification of the models outlined in [15, 21].

In ECTE458 the previously developed test bed's performance was improved through controller tuning, steering emulation enhancement and the addition of an LKAS feature. The system's position controller was tuned using the ZN frequency response method and the force feedback controller's proportional gain was increased. The steering emulation enhancement involved the modification of the position control subsystem, which included the implementation of a steering returnability function and a steering gear ratio. The implementation of the LKAS feature required both hardware and programming modifications.

The LKAS hardware modifications involved the demonstration vehicle and the trunk cable. The main hardware addition was the installation of four line sensing modules. These modules were attached to the front of the demonstration vehicle and were used to provide digital signals for lane detection. All the additional parts required for this stage of the project are outlined in a second bill of materials (BOM-002), which is located in Appendix C. To reflect the overall hardware changes the wiring diagram (WIRING-001) was also updated. The Simulink model was modified to include a function to interpret the line detecting digital inputs and a fuzzy logic controller to achieve the automatic steering control. The general concept of the implemented LKAS system, using fuzzy logic control, was a modified version of the method employed in [37].

3.4 Hardware Components

The hardware modules, used in this project, are detailed in Appendix C.

3.4.1 Control Station

The control station layout is outlined in the control station layout drawing (CONTROLLAYOUT-001), which is located in Appendix C. This drawing was used by the UOW mechanical workshop to create the control station base, steering motor platform, pushbutton mounting plate and the steering wheel. The control station houses the Arduino UNO/motor shield, the HILINK control board, the steering assembly, the steering side current sensor, and multiple Vera boards (see Figure 3.1). The wiring of all the control station components is illustrated in the electrical wiring diagram (WIRING-001).

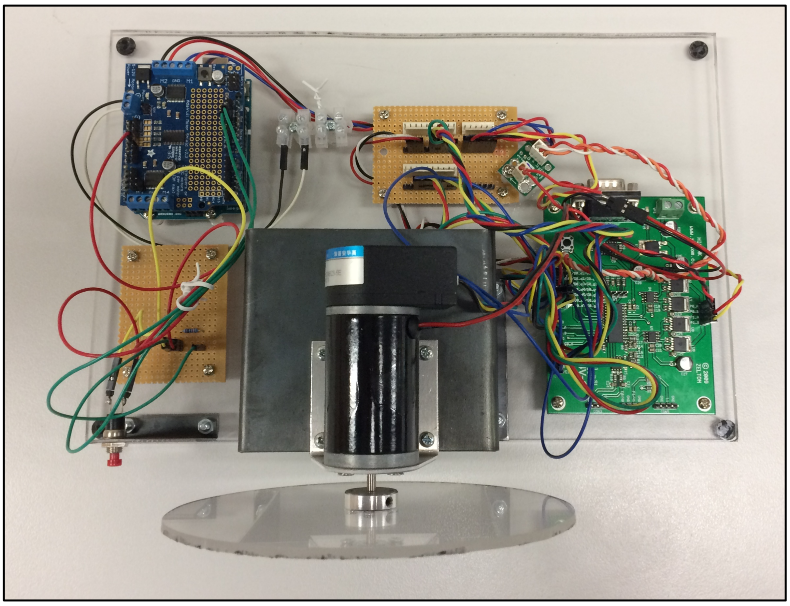


Figure 3.1: Control Station/Steering Assembly

3.4.2 HILINK Board (Steering Control)

The HILINK control board [45], as seen in Figure 3.2, was utilised to provide a real time interface between the steering motor/encoder, road wheel motor/encoder, the current sensors and the line tracing sensors. The control software used was Simulink, which includes a HILINK library. The inputs and outputs required for this SBW system include: encoder inputs E0 and E1, analogue inputs A0 and A1, digital inputs D0/d4-D0/d7 and H-bridge DC motor outputs P0 and P1. The HILINK board is powered by a regulated 6-15V supply and is connected to a computer through a serial port.

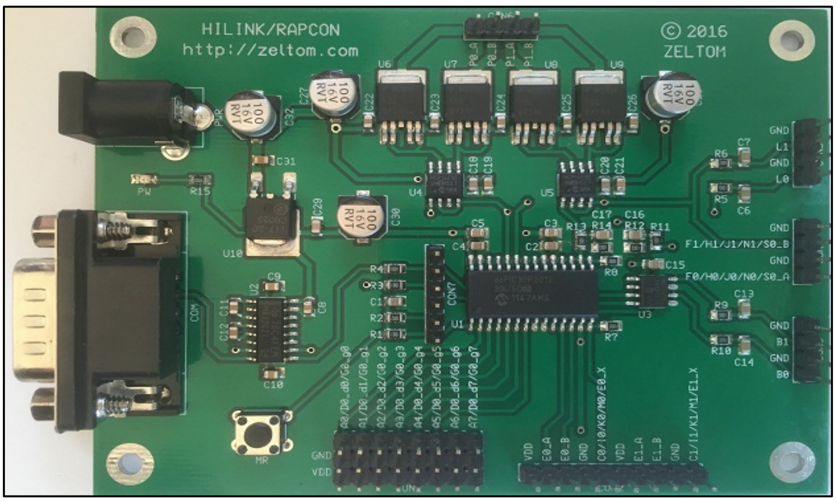


Figure 3.2: HILINK Control Board [45]

3.4.3 Arduino Uno/Motor Shield (Forward and Reverse Control)

An Arduino Uno and motor shield, as seen in Figure 3.3, were utilised to provide the forward and reverse motion for the SBW demonstration vehicle. These components were selected based on availability in the SECTE stores office and due to their simple operation. The motor shield can be directly attached to the Arduino through the provided pins. The Arduino and motor shield were connected to a 6V, 1A power supply. The power supply was connected to the motor shield's power terminals. Two DC motors were connected to the motor shield's motor terminals and powered through the h-bridge of the motor shield. One digital input of the Arduino was also utilised. This digital input was connected to a momentary pushbutton, which was used to initiate the forward and reverse motion sequence.

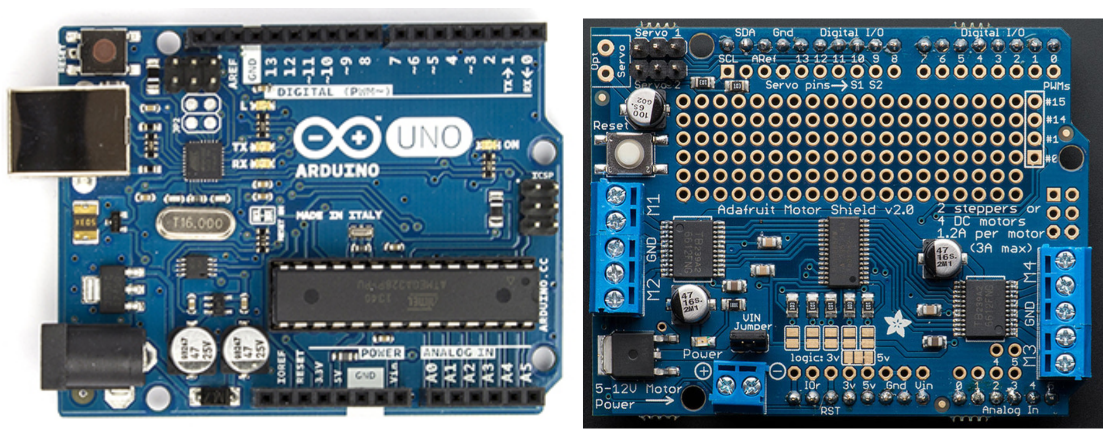


Figure 3.3: Arduino Uno (left) and Adafruit Motor Shield (right) [46, 47]

3.4.4 Steering Wheel Assembly

The steering wheel assembly includes: a 12V DC motor, a 1024-cycles per revolution encoder and a perspex steering wheel. The motor and encoder are both connected to the HILINK board. The DC motor is connected to the h-bridge output P0 and the encoder is connected to the encoder input E0. When the driver turns the steering wheel the steering angle is measured through the encoder and inputted into the HILINK board. The motor acts as an actuator for the force feedback of the system and is operated based on current readings from the road wheels and steering motor itself.

3.4.5 Demonstration Vehicle

The demonstration vehicle's design is a modified version of the "Skill Racing Car" that is outlined in a Makerwork's Instructable [48]. From the online instructions the demonstration vehicle parts layout (CARLAYOUT-001) was developed, which is located in Appendix C and was used to construct the vehicle (see Figure 3.4). The vehicle uses: Makeblock components for the frame, two 6V DC motors for forward/reverse motion, a 12V DC motor for the steering control, a 1024-cycles per revolution encoder for the road wheel angle measurement, a current sensor to measure the steering motors applied current and four line detecting sensors for lane detection. The forward/reverse 6V DC motors are connected to the motor shield's motor terminals. The 12V DC steering motor and encoder are connected to the HILINK boards h-bridge output P1 and encoder input E1. The four line detecting sensors are connected to the HILINK board's digital inputs D0/d4-D0/d7. All connections from the controllers to the vehicle's electronic components are made through a trunk cable and terminal blocks.

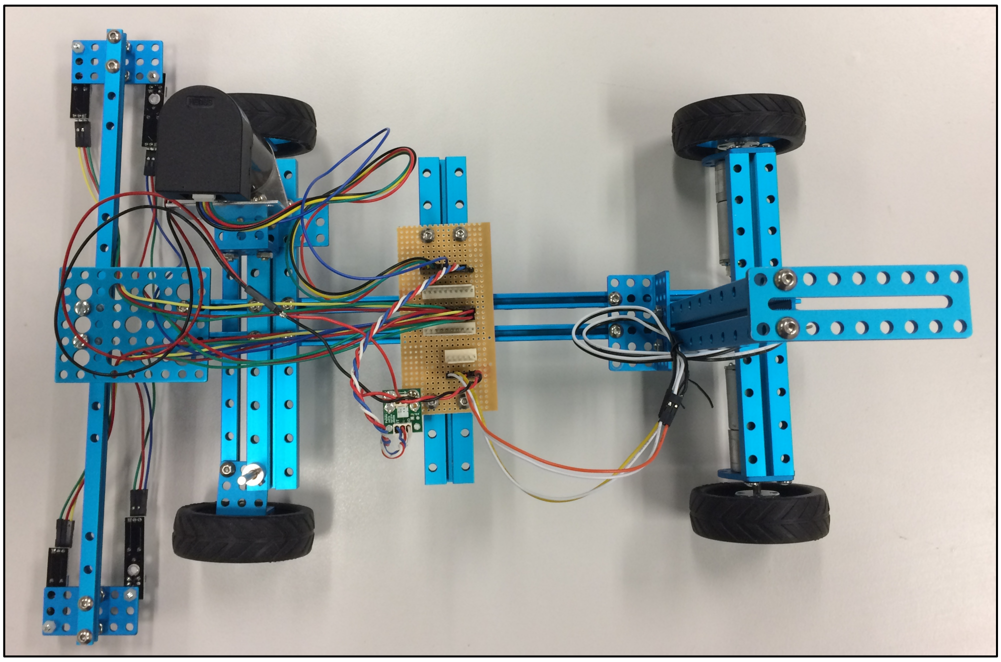


Figure 3.4: Demonstration Vehicle

3.4.6 Hall Effect Current Sensors (Force Feedback)

The system utilises two ACS714 Hall effect current sensors (see Figure 3.5) to measure the input currents of the steering assembly and road wheel steering motors. The current sensors are rated for an input current of -5A to +5A. This current range was suitable for the selected 12V DC motors that draw a maximum of 2.2Amps [49]. The current sensors are connected to analogue input terminals A0 and A1 of the HILINK board. Each analogue input also requires a connection from the HILINK board to the current sensor to provide a 5V and ground connection.

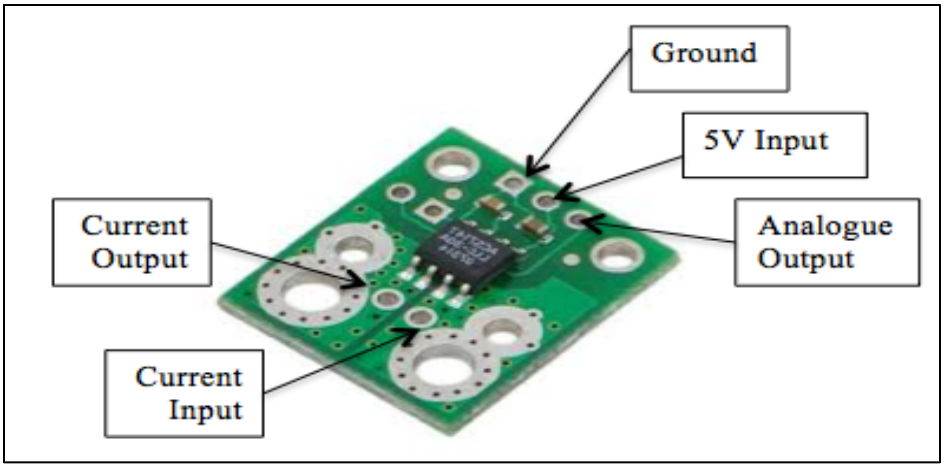


Figure 3.5: ACS714 Hall Effect Current Sensor [50]

The current sensors measure the input current and the value is translated to an output voltage centred at 2.5V, with a full-scale voltage of 5V. Equation 4 gives the relationship between the input current and output voltage. The measured currents at the steering wheel and road wheel motors can be used to determine the torque applied to the road. This is due to the linear relationship between motor torque (τ) and armature current (I_A) in a DC motor. This relationship is given by Equation 5 and includes a k value, which is the DC motor constant. The measured current is used in the force feedback function of the SBW system.

$$\mathbf{V_{output}} = (\mathbf{0.185} * \mathbf{i_{input}}) + \mathbf{2.5V} \quad (4)$$

$$\boldsymbol{\tau} = \mathbf{I_A} * \mathbf{k} \quad (5)$$

3.4.7 Line Trace Sensor Modules (Lane Keeping Assistance)

The system utilises four XC-4474 Line Trace Sensor Modules (see Figure 3.6) to achieve lane detection. The sensors are active low and measure the reflectivity of a surface using an infrared emitter/detector pair [51]. In the case of a road the white line is highly reflective and the black road surface is not. When a line is crossed the sensor is triggered and the voltage output goes low. The sensors have adjustable sensitivity and a rated working current of 18-20mA. The line detecting sensors are connected to digital input terminals D0/d4-D0/d7 of the HILINK board. Each digital input also requires a connection from the HILINK board to the sensor to provide a 5V and ground connection.

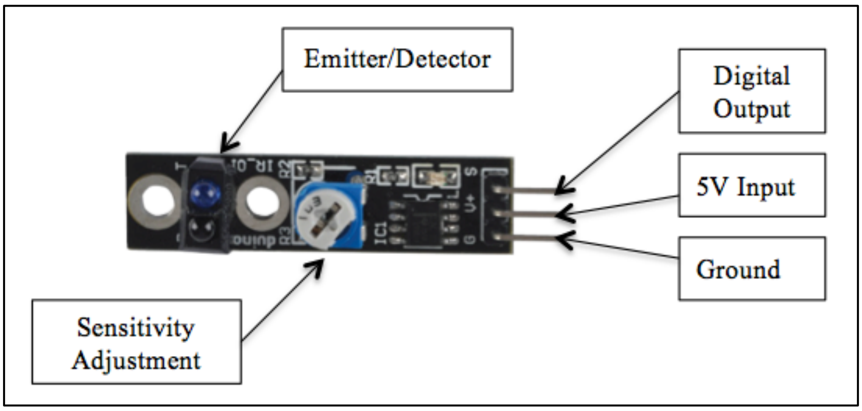


Figure 3.6: XC-4474 Line Trace Sensor Module [51]

3.5 Software/Programming

The software component of this SBW experimental platform can be separated into two parts: forward/reverse and steering control. As outlined previously an Arduino Uno was utilised for the forward/reverse control and a HILINK board was used for the real time steering control. The respective programming methods were C/C++ and Simulink. Further details in regards to the software modules, used in this project, can be found in Appendix D. The main focus of this section is the method used for the steering control.

3.5.1 Simulink Model for Steering Control

The steering control programming platform used in this project was Simulink. Simulink provides a method of object-oriented programming to analyse and simulate various control systems in real time. Simulink includes numerous standard blocks and built in functions. The HILINK control board also comes with it's own set of Simulink blocks. These blocks were used to interface the analogue current inputs (A0 & A1), the position encoder inputs (E0 & E1), the digital LKAS inputs (D0/d4-D0/d7) and the motor outputs (H0 & H1).

The total number of inputs and outputs determined what sampling frequency was required for the program to run. The sampling frequency for the SBW program was calculated using Equation 6 from [45] and was based on eight inputs and two outputs. The calculated maximum sampling frequency was 677Hz therefore 512Hz was used. The sampling period could then be calculated based on its relationship to the sampling frequency.

$$\mathbf{f} = \frac{\mathbf{1}}{\mathbf{T}} = \frac{\mathbf{11520}}{\mathbf{2\,max(\#inputs,\#outputs)+1}} \qquad (6)$$

The Simulink program developed for this SBW system can be separated into four parts. The first part involves the position control, the second simulates road feel through force feedback, the third involves the LKAS and the fourth outlines the implementation of additional steering functions. The entire SBW Simulink block diagram is included in Appendix D. The position and force feedback portions are a modification of the programming outlined in [15] and [21]. The LKAS portion of the program is based on the fuzzy logic control presented in [37]. The position control portion of the program is outlined in Section 3.5.1.1, the force feedback in Section 3.5.1.2, the LKAS in Section 3.5.1.3, and the additional steering system functions in 3.5.1.4

3.5.1.1 Position Control Block Diagram

The position control portion of the program is illustrated in Figure 3.7. The main components, forming a closed loop system, include: the hand wheel position input (E0), the road wheel position input (E1), the summing block, the position controller and the road wheel actuator output (H1). The steering angle of the hand wheel and the applied angle of the road wheel are measured through their respective encoder inputs. These position values then go to the summing block to calculate the position error. The error is then sent to the position controller, which applies proportional, integral and derivative gains to improve position tracking. It shall be noted that without the controller in place the road wheel angle could not be tracked at all. In ECTE458 the position PID controller was tuned using the ZN method.

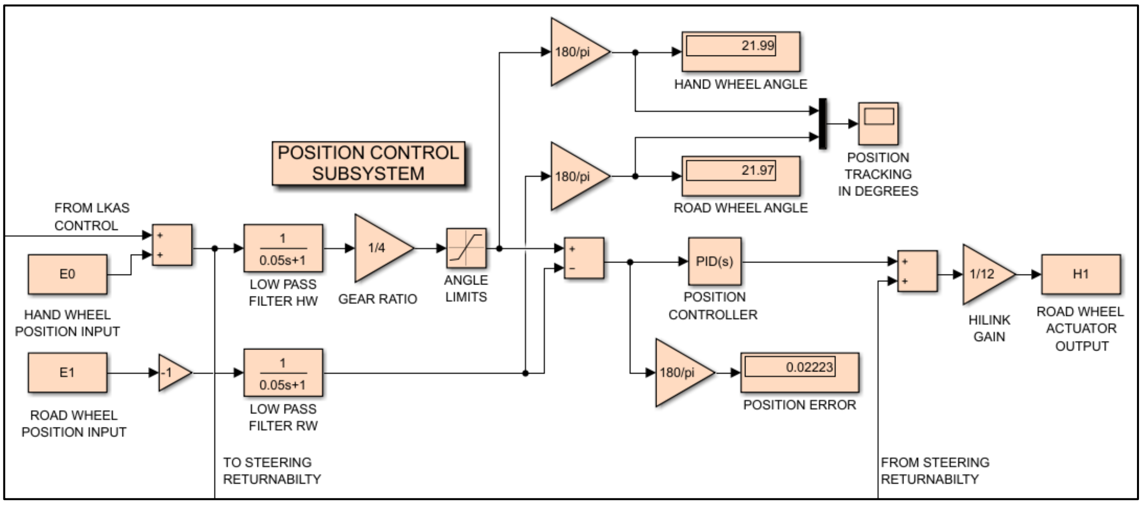


Figure 3.7 Position Control Portion of Simulink Model

The ZN tuning method, as outlined in Section 2.5.3, was used to bring the position control subsystem into sustained oscillation. This involved increasing K_P until the demonstration vehicle's front wheels rapidly turned back and forth while setting K_I and K_D to zero. Using a scope block the waveform was recorded (see Figure 3.8) and the ultimate period (T_u) was measured. The recorded value for T_u was 0.425 seconds and was obtained with the K_u value set at 195. Based on the measured values using Table 2.3 the values for K_P, T_I and T_D were determined. The values for K_I and K_D were then calculated using Equation 7 and Equation 8. The proportional, integral and derivative gain settings for the position controller in ECTE458 were 117, 550 and 6.2 respectively.

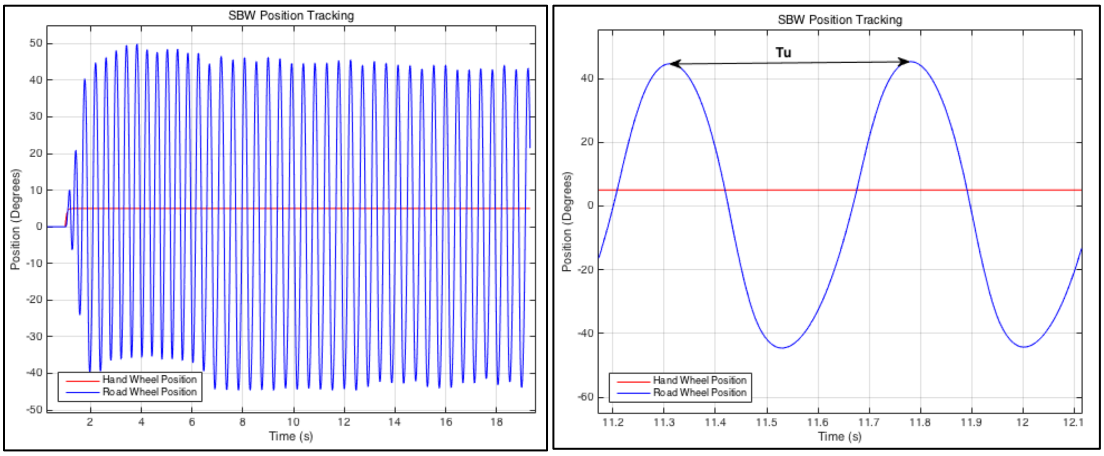


Figure 3.8: Ziegler-Nichols Ultimate Period Measurement Waveform

$$K_I = K_P / T_i \tag{7}$$

$$K_D = K_P * T_d \tag{8}$$

The output from the position controller then connects to the road wheel actuator output to adjust the road wheel angle appropriately. Other essential blocks have been included in the program to display results, ensure correct program operation and provide improved steering emulation. The first of the required additional blocks is a gain block of 1/12 at the input to the road wheel actuator (H1). The value of 12 is determined by the power supply input of the HILINK board. This requirement is specified in the HILINK manual [45]. A second gain block, with a value of negative one is also required. This block is placed after the road wheel position input. This negative one multiplier was required due to the hand wheel and road wheel motors being physically set up to rotate in opposite directions. A negative one gain was also multiplied by the gains of the position controller. By multiplying the encoder input and position controller gains by negative one the position between the hand wheel and road wheels can be inverted and tracked.

Low pass filters were also used to reduce the noise being read at the encoders. The low pass filter is a transfer function block as studied in ECTE 344 (Control Theory) [52]. The low pass filters were tested by varying the time constant from 0 to 0.1, it was found that the optimal results were achieved with a value of 0.05. Following the low pass filters, the hand wheel encoder value goes into a saturation block to limit the angle transferred from the hand wheel to the road wheel. The saturation block limits the input angle between -35° and 35°. Any value inputted that exceeds these limits will be outputted as the limit value itself. This restriction is required due to the maximum road wheel angle being less than that of the hand wheel angle. If the limits are exceeded the road wheels make contact with the vehicle's chassis.

To display and record the position control system's results multiple display blocks and a scope block were used. The angle inputs and error were multiplied by 180/π to convert the readings to degrees. The scope block provided a comparison of the hand and road wheel angles in real time, which was used to tune the position controller and evaluate the position tracking.

3.5.1.2 Force Feedback Block Diagram

The force feedback control portion of the program is illustrated in Figure 3.9. The main components, forming a closed loop system, include: the hand wheel current input (A0), the road wheel current input (A1), the current conversion blocks, the summing block, the current controller and the hand wheel actuator output (H0). The road wheel and hand wheel actuator currents are measured through the current sensors and inputted into the program through analogue inputs A1 and A0. As discussed in Section 3.4.6, the currents are read as an equivalent voltage and must be converted back to their corresponding currents. The current conversion block achieves this through the implementation of Equation 4. Once converted these values then enter a summing block to calculate the current error. The error is then sent to the current controller, which applies the set gains to improve the force feedback.

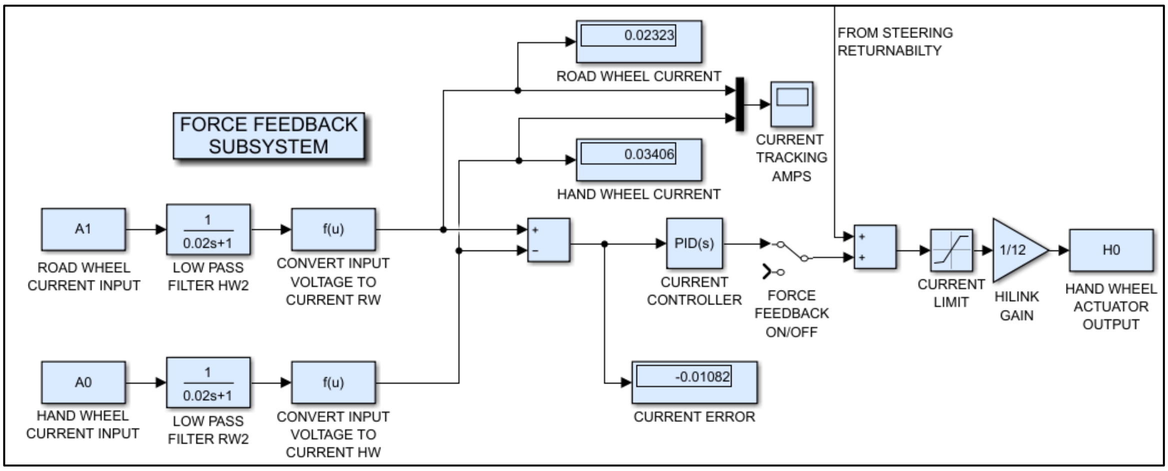


Figure 3.9 Force Feedback Control Portion of Simulink Model

The ZN method was not successful in tuning the force feedback controller. The current changed much more sporadically than the position and the system could not be taken into sustained oscillation. For this reason the force feedback controller was tuned by trial and error. A high proportional gain was required in order to feel the effect of the road torque at the hand wheel. The proportional gain setting used was 5000. The output from the current controller is then connected to the hand wheel actuator output to provide a sensation of steering feel through force feedback. Other essential blocks have been included in the program similar to those used in the position control portion.

The readings from the current sensors include a great deal of noise, as illustrated in Figure 3.10. For this reason low pass filters were used to reduce that noise. The low pass filter's impact on the system was tested with varying time constants of 0 to 0.05 and found that the system became unstable when a time constant greater than 0.04 was used. A value of 0.02 was selected for the time constant, which removed a large amount of the noise. A saturation block was also included which was fed from the output of the current controller to ensure that the input into the hand wheel actuator would not be excessive. There is also a switch at the output of the controller to turn the force feedback function of the steering system on and off. The model also includes the HILINK specified gain block of 1/12, display blocks and a scope block.

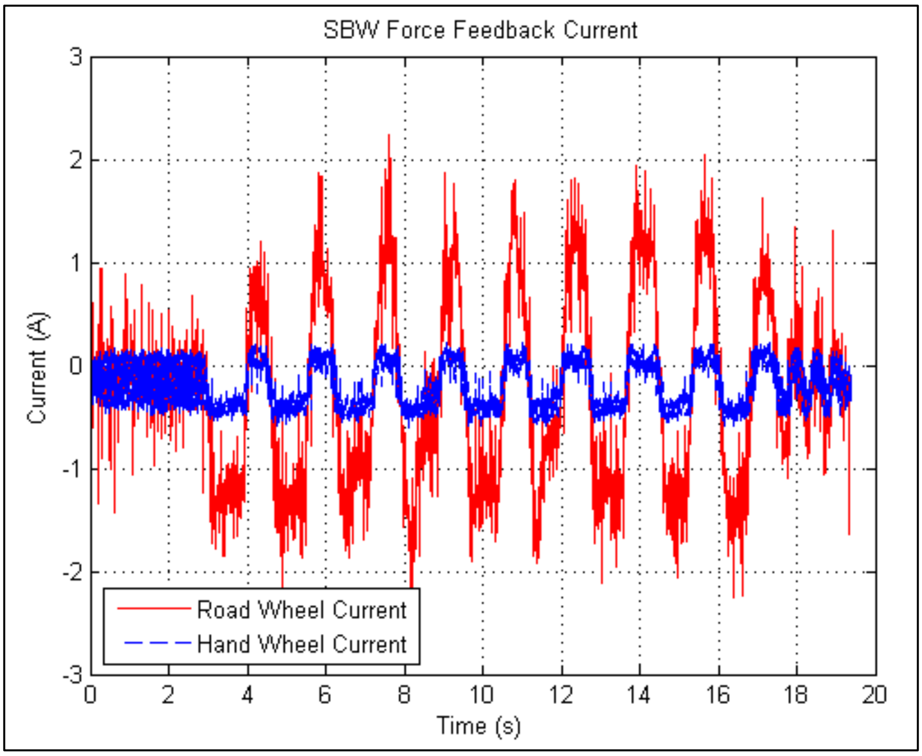


Figure 3.10: Unfiltered Current Inputs from Hall Effect Current Sensors

3.5.1.3 Lane Keeping Assistance Programming

The LKAS control portion of the program is illustrated in Figure 3.11. The main components include: the digital input block (D0/d4-D0/d7), the lane position function block, the fuzzy logic controller and the rate limiter block. The digital inputs from the line detecting sensors are multiplexed together to form a binary number representing the lane position. Due to the line detecting sensors being active low, a value of zero indicates that the corresponding sensor has crossed a lane. For each situation, as illustrated in Figure 2.6, a different binary value is read into the program. The decimal representation of this value is then interpreted by the lane position function, which can be found in Appendix D, to determine the vehicle's lane deviation from centre. The vehicle's manually entered speed and the lane deviation are then used as the inputs to the fuzzy logic controller. The required steering angle, to correct the vehicle's lane position, is then determined.

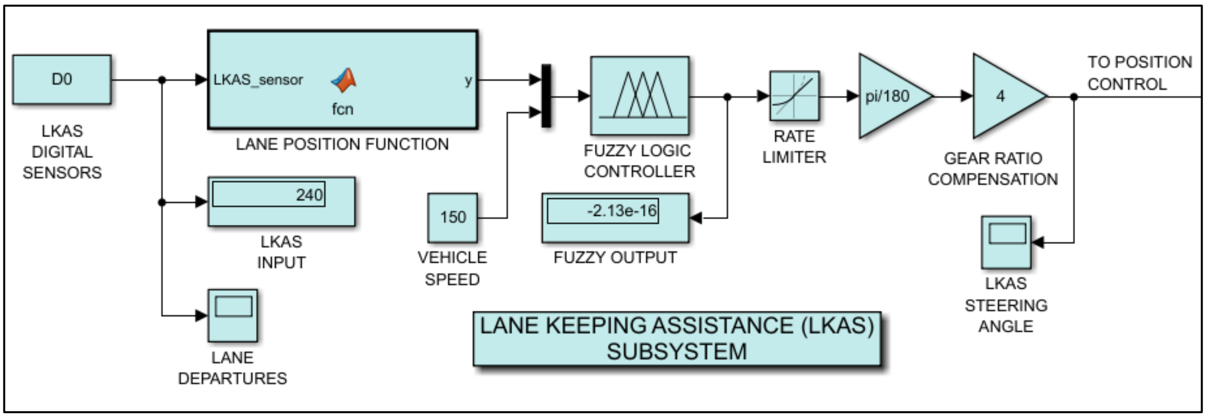


Figure 3.11: LKAS Portion of Simulink Model

The Mamdani type fuzzy logic control was designed using Matlab's Fuzzy Logic Toolbox [53] and the method employed in [37]. The input membership functions for deviation and speed are presented in Figure 3.12. The output steering angle and the generated surface view are displayed in Figure 3.13. The rules of the fuzzy logic inference system are summarised in Table 3.1. Multiple tests were conducted to determine the applicable membership functions and rules for the optimal lane keeping control at various vehicle speeds.

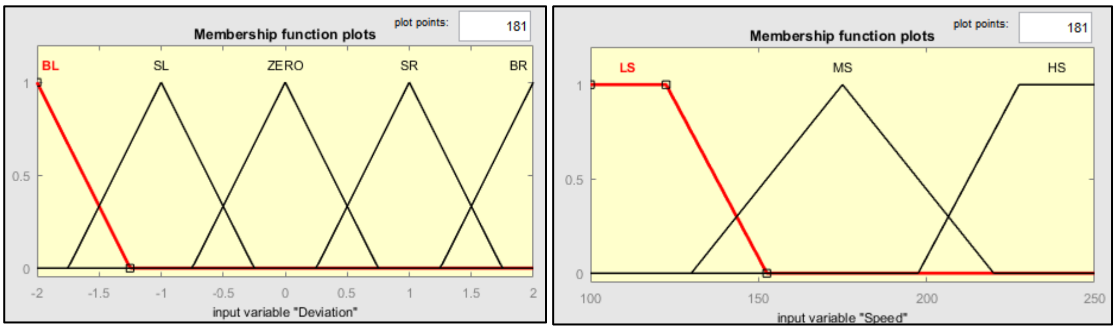


Figure 3.12: LKAS Input Membership Functions Deviation (left) Speed (right)

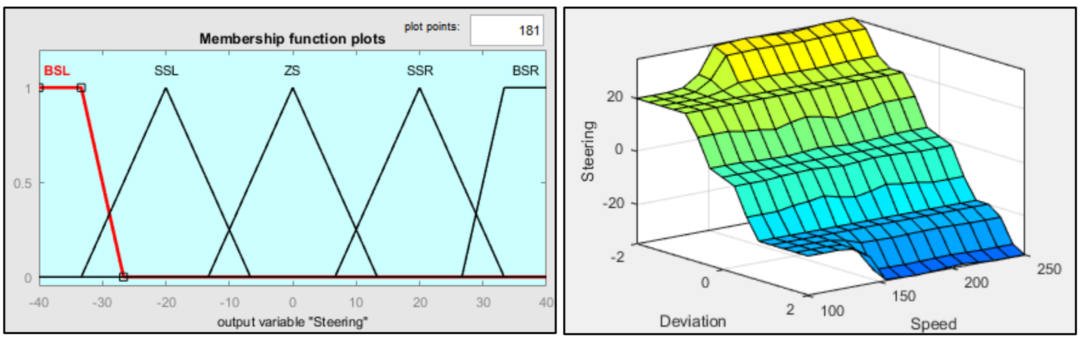


Figure 3.13: LKAS Output Membership Function (left) and Surface View (right)

Table 3.1: Fuzzy Logic Inference System Rule Base

		Speed		
		Low Speed (LS)	**Medium Speed (MS)**	**High Speed (HS)**
Deviation	**Big Left (BL)**	Small Steer Right (SSR)	Big Steer Right (BSR)	Big Steer Right (BSR)
	Small Left (SL)	Small Steer Right (SSR)	Small Steer Right (SSR)	Small Steer Right (SSR)
	Zero	Zero Steer (ZS)	Zero Steer (ZS)	Zero Steer (ZS)
	Small Right (SR)	Small Steer Left (SSL)	Small Steer Left (SSL)	Small Steer Left (SSL)
	Big Right (BR)	Small Steer Left (SSL)	Big Steer Left (BSL)	Big Steer Left (BSL)

Following the fuzzy logic controller the steering angle enters a rate limiter block. This block ensures that a gradual change in steering angle is sent to the position control subsystem. A gear ratio compensation gain block was also used to counteract the gear ratio applied to the manual steering control. Various display and scope blocks were also included in the subsystem.

3.5.1.4 Additional Steering Functions

To improve the overall steering emulation a gear ratio gain block and steering returnability feature were both implemented in the developed SBW program. The gear ratio gain block was inserted into the position control portion of the program. The gear ratio modifies the relationship between the hand and the road wheel angles as described in Equation 3. The selected gear ratio was ¼ as it provided the most realistic steering control of the test bed. Steering returnability is the tendency for the steering wheel to return to centre while the vehicle is completing a turn. To implement this the error of the steering system was calculated between the hand wheel angle and zero. This error was then fed into two gain blocks, which provided proportional gains. The proportional gains were then used to provide a small force at both the hand and road wheels to return the steering system to centre. The steering returnability programming is outlined in Figure 3.14 and the gains used were 2.5 and -2.5.

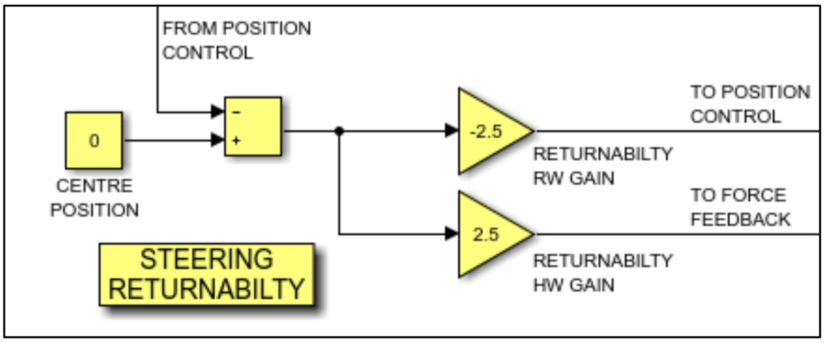


Figure 3.14: Steering Returnability Simulink Model Additions

3.5.2 Arduino Programming for Forward and Reverse Control

The forward/reverse movement of the demonstration vehicle is initiated by a push button. Once the pushbutton is pressed the vehicle will move forward and backward at a set speed for a set duration. The program developed to accomplish this is a combination of a motor control program [47], which utilises existing DC motor control libraries, and the momentary pushbutton tutorial [54] from the Arduino website. The program reads the pushbutton input into a variable and when this value is set high the motor control function is called. The user can input a value for the motor speed and a time delay in milliseconds for the duration. The Arduino code used is provided in Appendix D and the flow chart outlining the program's operation is detailed in Figure 3.15.

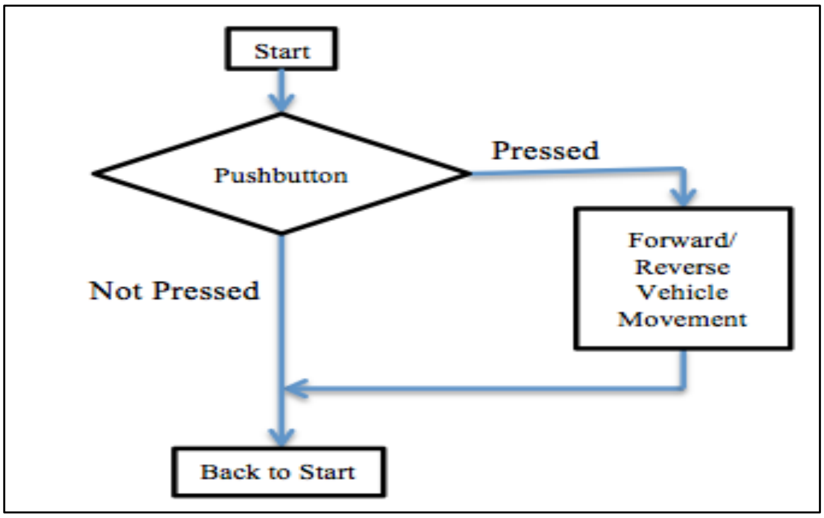


Figure 3.15: Arduino Programming Flow Chart

Chapter 4. RESULTS AND ANALYSIS

The experimental platform was designed to evaluate the position control, force feedback and LKAS function of a basic SBW system. The developed SBW system uses a simple means of measuring motor angle to transfer motor position from the hand wheel to the road wheel. The force feedback was realised through current measurements at the hand wheel and road wheel actuators. The current measurements can be used to represent the applied torque of the road wheel for various road conditions. As more torque is applied to the road wheel actuator the current increases, which is inputted into the force feedback sub-system and transferred to the hand wheel. The LKAS function was evaluated on a small section of artificial road constructed in the lab for its ability to keep the demonstration vehicle within the lanes. The steering emulation was evaluated qualitatively throughout the various tests. All evaluation has been completed using the developed control unit and test vehicle

4.1 ECTE451 Experimental Results

The position tracking was initially tested with no surface contact between the road wheels and the road surface. Placing the demonstration vehicle on blocks and modifying the position subsystem model accomplished this. The subsystem was first tested with no position controller at all. With no controller present the hand wheel position was not tracked and there was no rotation of the road wheels. This was due to the opposing forces generated by the steering system's friction and inertia being too great. A proportional gain was then introduced and once a relatively small error was obtained a derivative gain was also implemented. With the position controller proportional and derivative gains set at 16 and 0.025 respectively position control was realised as illustrated in Figure 4.1.

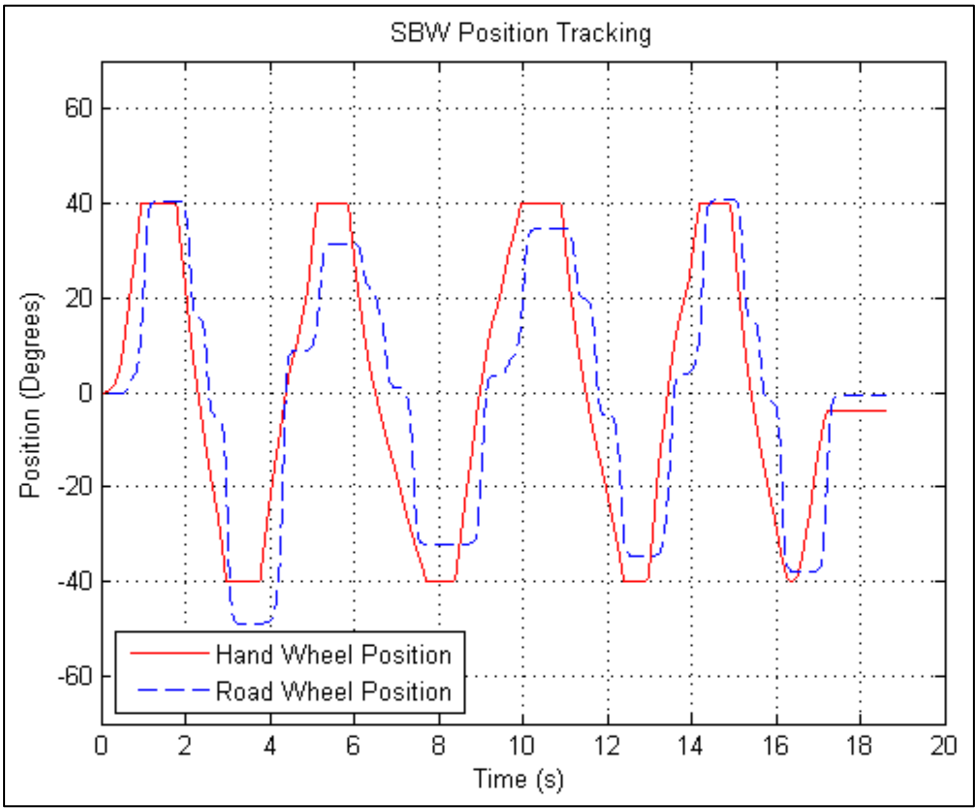


Figure 4.1: ECTE451 Position Tracking with No Road Surface to Wheel Contact

The above-described method of providing force feedback is based on the concept that for different road surfaces, different amounts of torque are required to turn the road wheels. As the road surface friction increases more torque is required. To test the generated current, for different road surfaces, the current scope in the force feedback subsystem was monitored while steering the test vehicle for three different road contact conditions. The conditions included: no road contact at all, road wheel contact with a smooth surface (floor) and road wheel contact with a rough surface (carpet). The results are outlined in Figure 4.2 and the comparison illustrates that the current magnitude and duration increases as the amount of surface friction increases. The current tracking between the road wheel and hand wheel is also illustrated for the different cases.

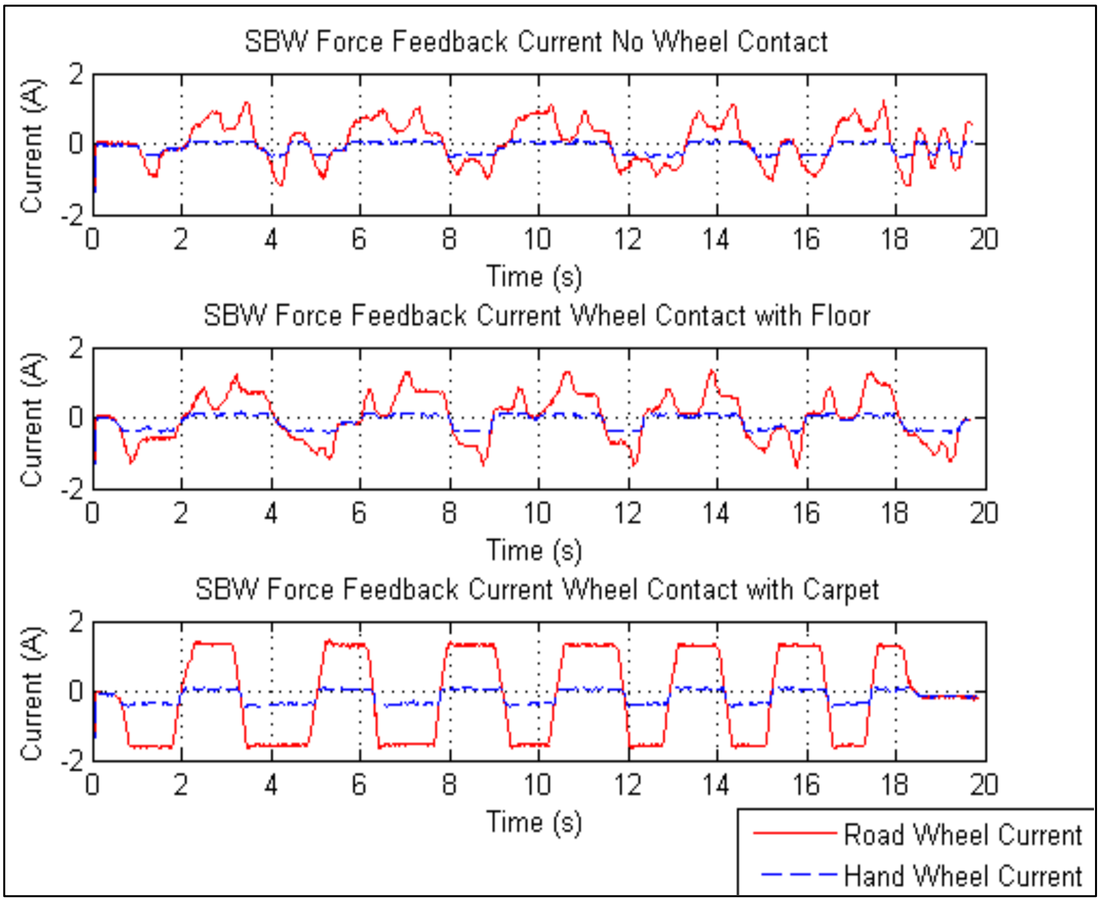


Figure 4.2 Comparison of Current Readings for Different Road Surfaces

The SBW system was next tested while applying a forward force to the vehicle through the Arduino Uno and the Motor shield. The Arduino program was set up to move the vehicle forward at a constant velocity for 15 seconds. During this movement the vehicle was turned back and forth while recording the position and current tracking. The position tracking of the vehicle is illustrated in Figure 4.3 and the force feedback current in Figure 4.4. By testing the system while the vehicle was moving a self-aligning torque was experienced. This self-aligning torque was not considered in the previous evaluations. It can be seen that the position tracking is effective in controlling the vehicle's direction and that force feedback has been achieved.

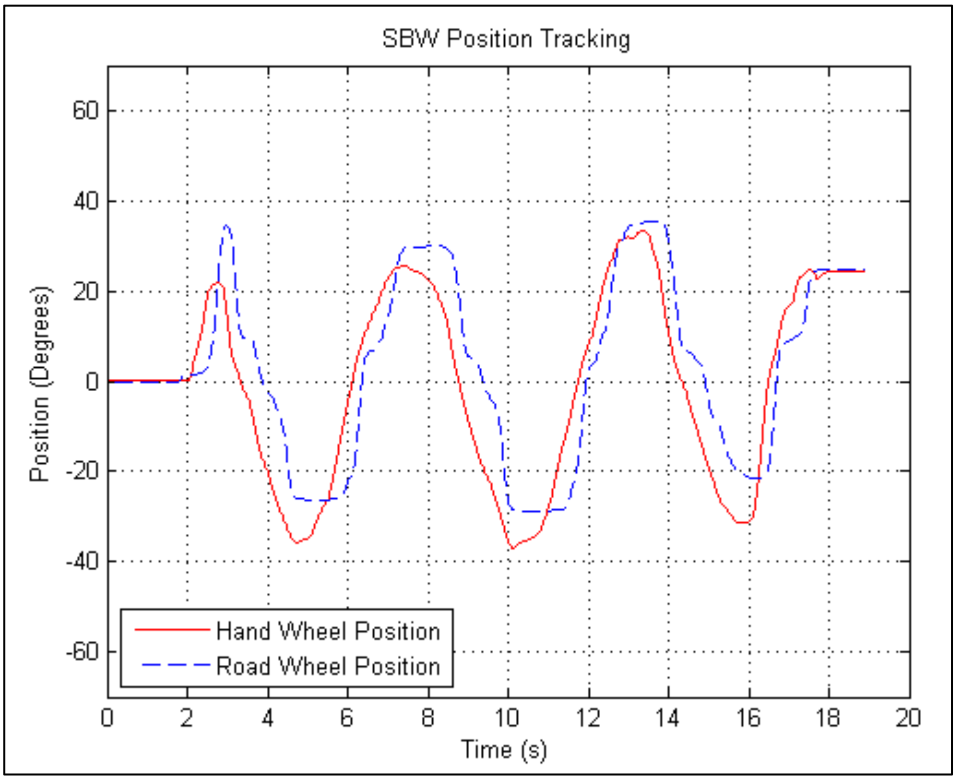


Figure 4.3 ECTE451 Position Tracking of Vehicle at a Set Velocity

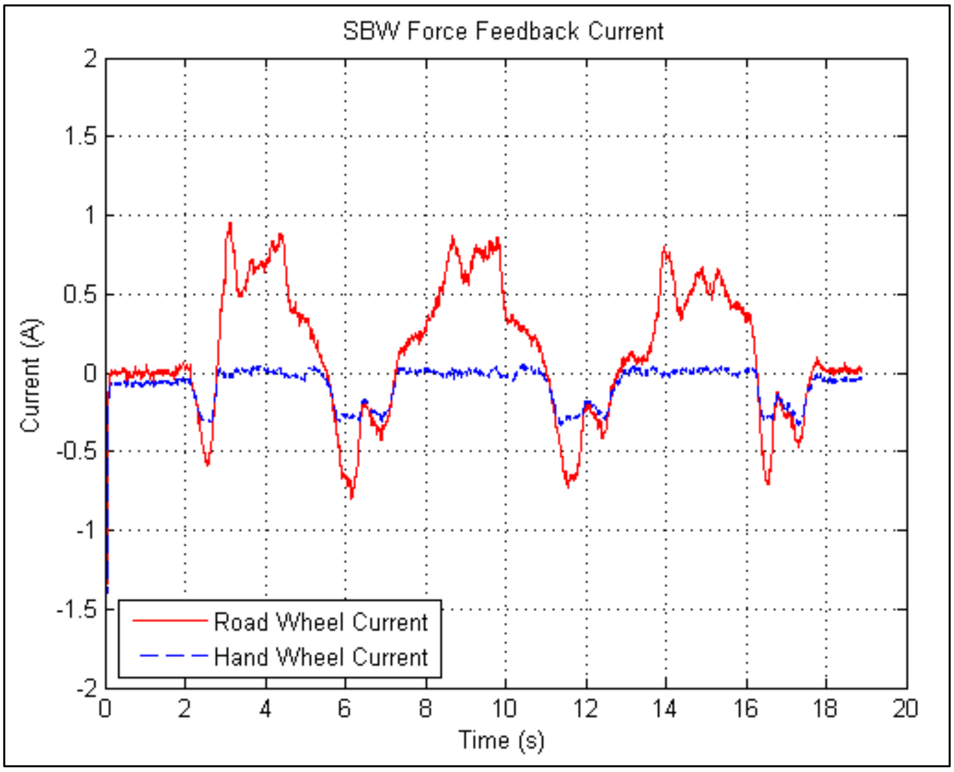


Figure 4.4: ECTE451 Force Feedback Current of Vehicle at a Set Velocity

4.2 Finely Tuned PID Experimental Results

The position control was improved through the use of the ZN tuning method as outlined in Sections 2.5.3 and 3.5.1.1. The position tracking was once again recorded with no surface contact between the road wheels and the road surface. With the position controller proportional integral and derivative gains set at 117, 550 and 6.2 respectively improved position control was realised as illustrated in Figure 4.5. It is apparent that the position tracking has been immensely improved indicating that the ZN tuning method is effective in the case of the developed SBW system's position control. The improved control also provided much smoother steering and improved steering emulation.

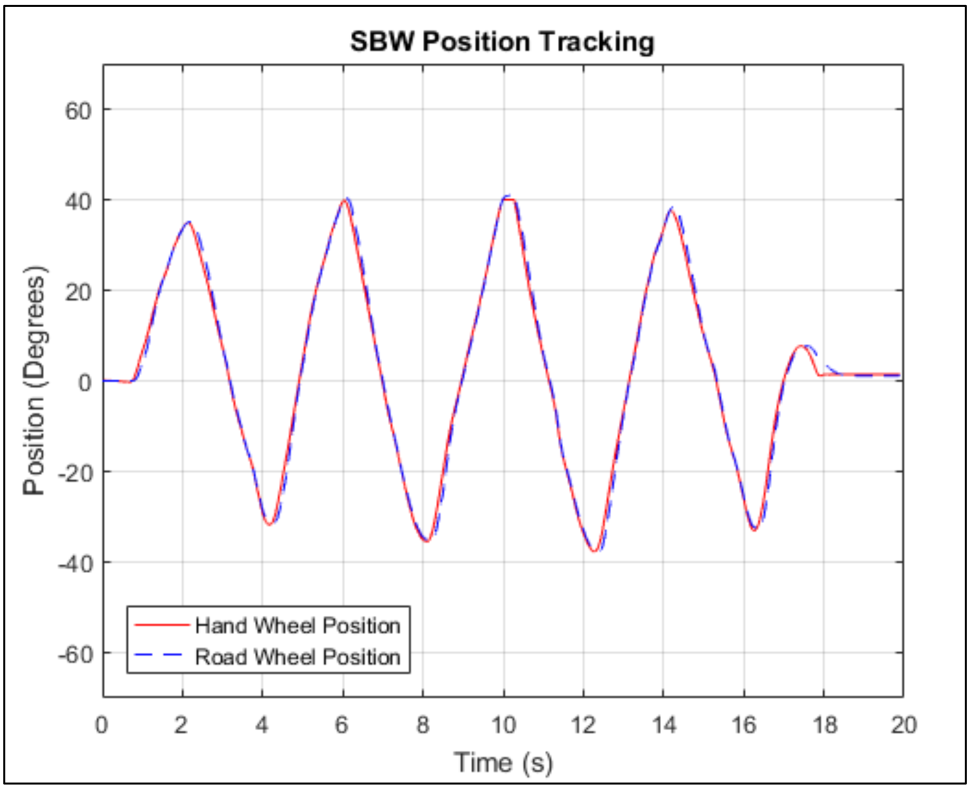


Figure 4.5: ECTE458 Position Tracking with No Road Surface to Wheel Contact

The improved SBW system was next tested while applying a forward force to the vehicle through the Arduino Uno and the Motor shield. The test was conducted in the same manner has previously outlined in Section 4.1. The position tracking of the vehicle is illustrated in Figure 4.6 and the force feedback current in Figure 4.7. It is apparent that once again there is improved position tracking and that the system experiences force feedback through the direct current method.

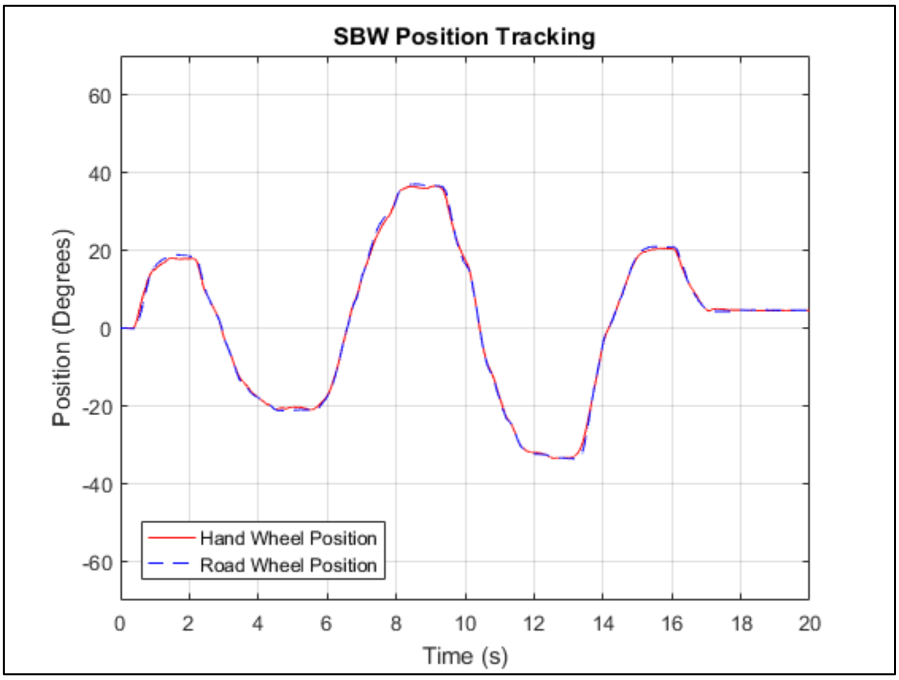


Figure 4.6 ECTE458 Position Tracking of Vehicle at a Set Velocity

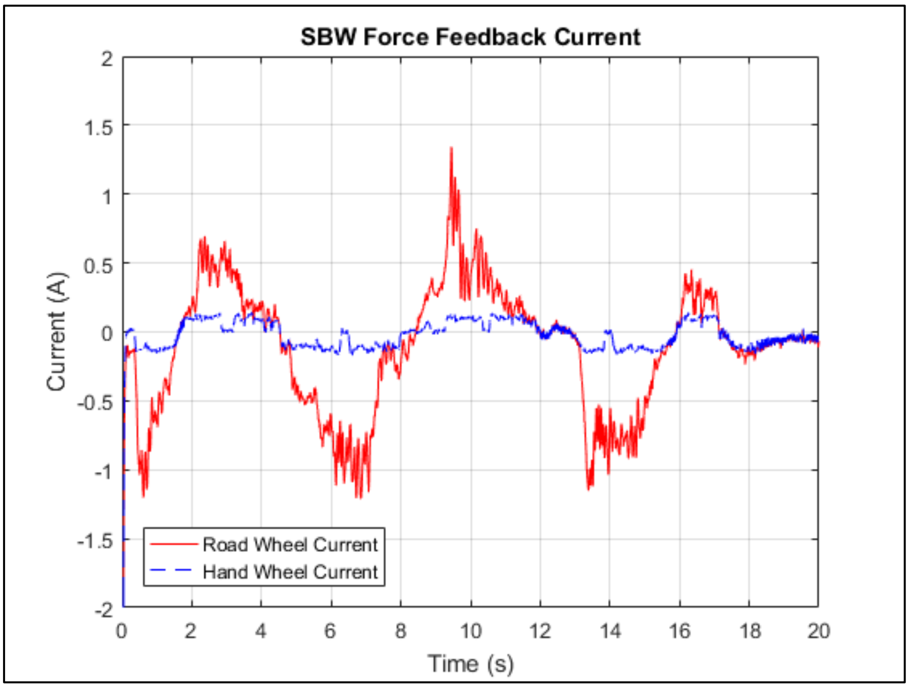


Figure 4.7: ECTE458 Force Feedback Current of Vehicle at a Set Velocity

4.3 Lane Keeping Assistance Experimental Results

The LKAS feature involved the use of fuzzy logic control as outlined in Section 3.5.1.3. The inputs to the fuzzy logic controller were speed and the lane deviation. The lane deviation was measured in real time using the four line trace modules and the speed was set at the start of each test sequence. Multiple tests were required to tune the fuzzy logic controller at the various speeds. Once the controller was tuned an effective LKAS feature was in place which could be turned on and off through a manual switch in the SBW program. The vehicle's lane keeping capability is displayed in Figure 4.8, which includes screenshots of the vehicle under test with an elapsed time of 1 to 6 seconds. It can be seen that the demonstration vehicle is in fact maintaining its position between the lanes.

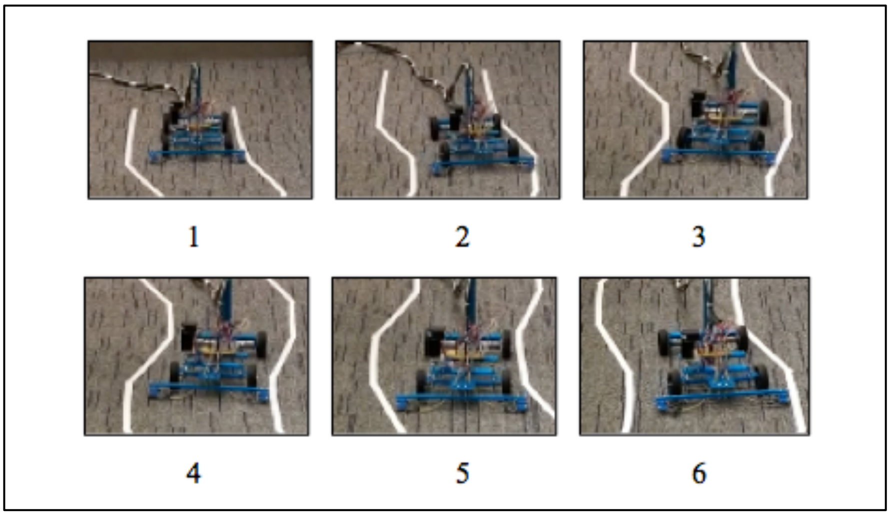


Figure 4.8: Demonstration Vehicle Maintaining Lane Position

The position tracking of the system was recorded with the demonstration vehicle operating at both low and high speeds. See Figure 4.9 and Figure 4.10 for the position tracking of the vehicle at low speed and high speed respectively. While the demonstration vehicle's position is maintained between the lanes the different imposed steering angles are displayed. In comparison the applied angles of the LKAS system are different for each case demonstrating that the fuzzy logic inputs determine the steering angle output.

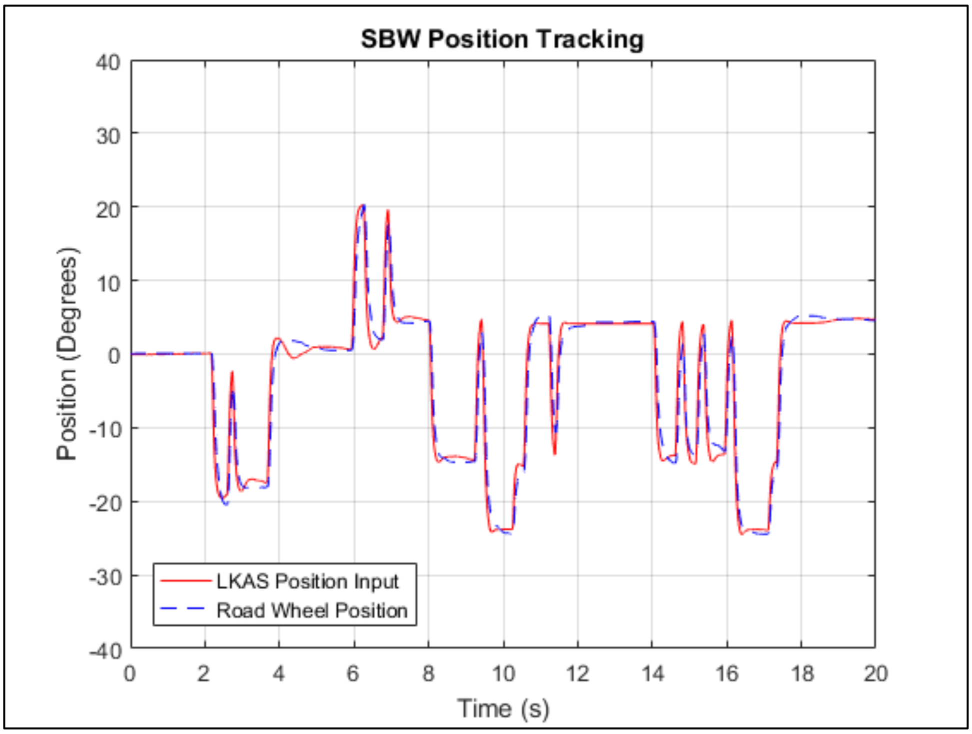


Figure 4.9: Position Tracking of LKAS at Low Speed

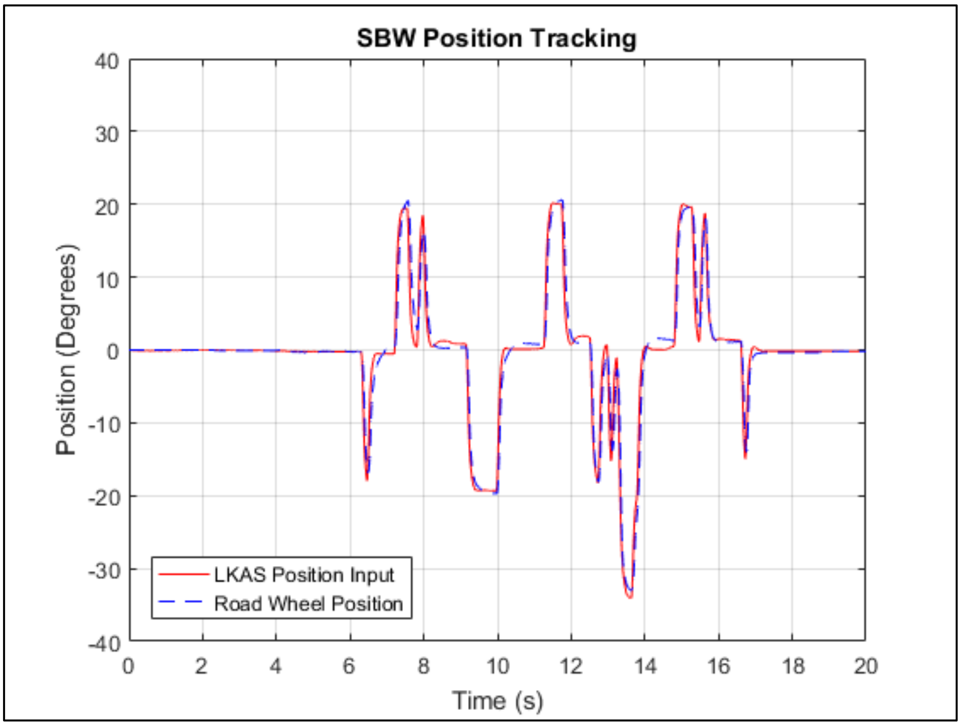


Figure 4.10: Position Tracking of LKAS at High Speed

CONCLUSIONS AND RECOMMENDATIONS

In this project a test bed to evaluate the position control, force feedback and LKAS functions of a basic SBW system is presented. The control methods used were developed based on previous research evaluated in the literature review. The SBW steering control was realised through the use of Simulink and utilised a HILINK control board. The experimental platform involved the design and assembly of a control station and demonstration vehicle. The experimental platform made it possible to test the SBW system's position and current tracking capabilities at different velocities, with or without an LKAS feature enabled.

The project was successful in the development of an operating SBW test vehicle with position control, force feedback and LKAS functionality. The position control was achieved through PID controller implementation and ZN tuning. The force feedback was achieved through a manually tuned, proportional controller. The recorded results for position tracking between the hand wheel and road wheels indicate that the road wheel angle follows the hand wheel angle and provides effective directional control. The current tracking was less effective but still provided force feedback for different road conditions to the driver. The LKAS feature was proven effective though both visual observation and position tracking.

Possible future work with the developed SBW test bed may include: the use of different SBW control methods, the implementation of additional driver assistance features or the replacement of the wired connections between the control unit and demonstration vehicle with wireless ones. Control modifications may be implemented in the existing programming and due to the demonstration vehicle's design and assembly using Makeblock components the hardware can be easily modified.

REFERENCES

[1] A. E. Cetin, M. A. Adli, D. E. Barkana, and H. Kucuk, "Implementation and Development of an Adaptive Steering-Control System," *IEEE Transactions on Vehicular Technology,* vol. 59, pp. 75-83, 2010.

[2] P. Pfeffer and H. Ulrich, "Introduction and History," in *Steering Handbook*, ed: Springer, 2017, pp. 1-25.

[3] J. P. Pauwelussen, "Chapter Six - The Vehicle–Driver Interface," in *Essentials of Vehicle Dynamics*, ed Oxford: Butterworth-Heinemann, 2015, pp. 195-238.

[4] M. Harrer, P. Pfeffer, and H.-H. Braess, "Steering-Feel, Interaction Between Driver and Car," in *Steering Handbook*, ed: Springer, 2017, pp. 149-168.

[5] S. Anand, "Personalizing steering experience using steer-by-wire systems," Technische Universiteit Eindhoven, 2014.

[6] L. Eckstein, L. Hesse, and M. Klein, "Steer-by-Wire, Potential, and Challenges," in *Encyclopedia of Automotive Engineering*, ed: John Wiley & Sons, Ltd, 2014.

[7] M. Würges, "New Electrical Power Steering Systems," in *Encyclopedia of Automotive Engineering*, ed: John Wiley & Sons, Ltd, 2014.

[8] M. Wiedmann, "Active Front Steering for Passenger Cars," in *Encyclopedia of Automotive Engineering*, ed: John Wiley & Sons, Ltd, 2014.

[9] X. Wu and L. Y. M. Xu, "Two-port network based bilateral control of a steer-by-wire system," in *Industrial Electronics Society, IECON 2015 - 41st Annual Conference of the IEEE*, 2015, pp. 002184-002189.

[10] M. Buechel, J. Frtunikj, K. Becker, S. Sommer, C. Buckl, M. Armbruster*, et al.*, "An Automated Electric Vehicle Prototype Showing New Trends in Automotive Architectures," in *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 2015, pp. 1274-1279.

[11] P. Yih and J. C. Gerdes, "Modification of vehicle handling characteristics via steer-by-wire," *IEEE Transactions on Control Systems Technology,* vol. 13, pp. 965-976, 2005.

[12] P.-S. Huang and A. Pruckner, "Steer by Wire," in *Steering Handbook*, ed: Springer, 2017, pp. 513-526.

[13] Y. Yao, "Vehicle steer-by-wire system control," SAE Technical Paper 0148-7191, 2006.

[14] H. Wang, Z. Man, W. Shen, Z. Cao, J. Zheng, J. Jin*, et al.*, "Robust Control for Steer-by-Wire Systems With Partially Known Dynamics," *IEEE Transactions on Industrial Informatics,* vol. 10, pp. 2003-2015, 2014.

[15] B.-H. Nguyen and J.-H. Ryu, "Direct current measurement based steer-by-wire systems for realistic driving feeling," in *2009 IEEE International Symposium on Industrial Electronics*, 2009, pp. 1023-1028.

[16] R. Kazemi and I. Mousavinejad, "A Comprehensive model for developing of Steer-By-Wire System," *World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering,* vol. 5, pp. 1688-1694, 2014.

[17] J. S. Im, F. Ozaki, N. Matsunaga, and S. Kawaji, "Bilateral Control for Steer-by-Wire Vehicles," in *2006 SICE-ICASE International Joint Conference*, 2006, pp. 528-533.

[18] A. Balachandran and J. C. Gerdes, "Designing Steering Feel for Steer-by-Wire Vehicles Using Objective Measures," *IEEE/ASME Transactions on Mechatronics,* vol. 20, pp. 373-383, 2015.

[19] D. I. Katzourakis, D. A. Abbink, R. Happee, and E. Holweg, "Steering Force Feedback for Human–Machine-Interface Automotive Experiments," *IEEE Transactions on Instrumentation and Measurement,* vol. 60, pp. 32-43, 2011.

[20] A. Bertacchini, L. Tamagnini, and P. Pavan, "Force Feedback in Steer-by-Wire Systems: Architecture and Experimental Results," in *2006 IEEE International Symposium on Industrial Electronics*, 2006, pp. 3050-3055.

[21] P. Zhai, H. Du, and Z. Li, "Bilateral control of vehicle Steer-by-Wire system with variable gear-ratio," in *2013 IEEE 8th Conference on Industrial Electronics and Applications (ICIEA)*, 2013, pp. 811-815.

[22] E. Mehdizadeh, M. Kabganian, and R. Kazemi, "A new force feedback for Steer-by-Wire vehicles via virtual vehicle concept," in *2011 50th IEEE Conference on Decision and Control and European Control Conference*, 2011, pp. 2281-2286.

[23] M. A. Johnson and M. H. Moradi, *PID control*: Springer, 2005.

[24] K. J. Åström and T. Hägglund, "PID controllers: theory, design, and tuning," 1995.

[25] M. R. S. B. de Souza, R. H. Murofushi, J. J.-P. Z. de Souza, and J. F. Ribeiro, "Comparison Among Experimental PID Auto Tuning Methods for a Self-balancing Robot," in *Latin American Robotics Symposium*, 2016, pp. 72-86.

[26] M. Shahrokhi and A. Zomorrodi, "Comparison of PID controller tuning methods," *Department of Chemical & Petroleum Engineering Sharif University of Technology,* 2013.

[27] D. I. Wilson, "Relay-based PID tuning," *Automation and Control,* pp. 10-11, 2005.

[28] E. J. Rossetter, J. P. Switkes, and J. C. Gerdes, "A gentle nudge towards safety: experimental validation of the potential field driver assistance system," in *American Control Conference, 2003. Proceedings of the 2003*, 2003, pp. 3744-3749 vol.5.

[29] S. M. Erlien, S. Fujita, and J. C. Gerdes, "Shared Steering Control Using Safe Envelopes for Obstacle Avoidance and Vehicle Stability," *IEEE Transactions on Intelligent Transportation Systems,* vol. 17, pp. 441-451, 2016.

[30] S. Brosig and M. Lienkamp, "Overview: Driver Assistance System Functions," in *Steering Handbook*, ed: Springer, 2017, pp. 527-544.

[31] A. Shaout, D. Colella, and S. Awad, "Advanced driver assistance systems-past, present and future," in *Computer Engineering Conference (ICENCO), 2011 Seventh International*, 2011, pp. 72-82.

[32] J. Wang, S. Schroedl, K. Mezger, R. Ortloff, A. Joos, and T. Passegger, "Lane keeping based on location technology," *IEEE Transactions on Intelligent Transportation Systems,* vol. 6, pp. 351-356, 2005.

[33] M. B. de Paula and C. R. Jung, "Automatic detection and classification of road Lane markings using onboard vehicular cameras," *IEEE Transactions on Intelligent Transportation Systems,* vol. 16, pp. 3160-3169, 2015.

[34] M. Huang, W. Gao, and Z.-P. Jiang, "A data-based lane-keeping steering control for autonomous vehicles: A Human-in-the-loop approach," in *Control Conference (CCC), 2016 35th Chinese*, 2016, pp. 8974-8979.

[35] J.-F. Liu, J.-H. Wu, and Y.-F. Su, "Development of an interactive lane keeping control system for vehicle," in *Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE*, 2007, pp. 702-706.

[36] A.-T. Nguyen, C. Sentouh, and J.-C. Popieul, "Driver-Automation Cooperative Approach for Shared Steering Control under Multiple System Constraints: Design and Experiments," *IEEE Transactions on Industrial Electronics,* 2016.

[37] N. C. Basjaruddin, D. Saefudin, and S. A. Aryani, "Lane Keeping Assist System based on fuzzy logic," in *Electronics Symposium (IES), 2015 International*, 2015, pp. 110-113.

[38] D. Semmel, "Hydraulic Power Supply," in *Steering Handbook*, ed: Springer, 2017, pp. 357-379.

[39] J. Gessat, A. Seewald, and D. Zimmermann, "Electrically Powered Hydraulic Steering," in *Steering Handbook*, ed: Springer, 2017, pp. 381-401.

[40] A. Gaedke, M. Heger, M. Sprinzl, S. Grüner, and A. Vähning, "Electric Power Steering Systems," in *Steering Handbook*, ed: Springer, 2017, pp. 403-467.

[41] M. Harrer and P. Pfeffer, "Outlook: The Future of Steering Systems," in *Steering Handbook*, ed: Springer, 2017, pp. 545-551.

[42] M. Trzesniowski, "Steering Kinematics," in *Steering Handbook*, ed: Springer, 2017, pp. 63-90.

[43] W. C. Messner, D. M. Tilbury, and A. P. R. Hill, *Control Tutorials for MATLAB® and Simulink®*: Addison-Wesley, 1999.

[44] W. H. Organization, "Global status report on road safety 2015," *Geneva: WHO,* 2015.

[45] Zeltom. (August 28). *Hilink User Manual for version 1.7*. Available: http://www.zeltom.com/documents/hilink_um_15.pdf

[46] Arduino. (September 5). *Arduino & Genuino Products > Arduino/Genuino UNO* Available: https://www.arduino.cc/en/Main/ArduinoBoardUno

[47] Adafruit. (October 2). *Adafruit Motor/Stepper/Servo Shield for Arduino v2 Kit*. Available: https://www.adafruit.com/product/1438

[48] M. s. Instructables. (September 1). *How to Build a Skill Racing Car With Makeblock*. Available: http://www.instructables.com/id/How-to-Build-a-Skill-Racing-Car-With-Makeblock/

[49] Zeltom. (August 26). *DC Motor Control with HILINK 1.4*. Available: http://www.zeltom.com/documents/dcms_um_14.pdf

[50] Pololu. (October 3). *ACS714 Current Sensor Carrier -5A to +5A*. Available: https://www.pololu.com/product/1185

[51] J. Electronics. (April 12). *Arduino Compatible Line Trace Sensor Module*. Available: https://www.jaycar.com.au/arduino-compatible-line-trace-sensor-module/p/XC4474

[52] U. O. W. SECTE. (September 10). *Control Laboratory*. Available: http://secte1.elec.uow.edu.au/weblab/index.htm

[53] J. R. Jang, *MATLAB: Fuzzy logic toolbox user's guide: Version 1*: Math Works, 1997.

[54] Arduino. (September 5). *Tutorials > Built-In Examples > 02.Digital > Button*. Available: https://www.arduino.cc/en/Tutorial/Button

APPENDIX A PROJECT PLAN

See the below project specification/plan, which was included in the project proposal submitted in week 4.

Project Specification/Plan

For my project to be a success in ECTE458 the following milestones must be achieved.

Project Milestones:

6) Update literature review with relevant material.
7) Determine design modifications to the experimental setup.
8) Modify the Simulink/Matlab control model.
9) Complete modifications of the demonstration vehicle.
10) Test/analyse the SBW System for steering emulation with PID control.
11) Test/analyse the SBW System for steering emulation with Fuzzy control.
12) Test/analyse the implemented lane keeping assistance feature.
13) Produce final report and poster.
14) Present the final project in the demonstration/seminar.

The first step of the project is to add relevant information to the literature review. Research has already commenced and the literature review additions will focus on: PID tuning and control methods, Fuzzy Logic control and lane keeping assistance. The literature review will be an ongoing process throughout the project. The next step will be to complete design modifications to the experimental setup using the applicable reviewed papers from the literature review and following the advice of my supervisor.

Design modifications and testing of the Simulink model will occur throughout the session. Once all the improvements have been made to the original control system a Fuzzy Logic controller will be implemented to provide automatic PID tuning or replace the PID controller completely. A comparison will then be made between the two control methods. Once the SBW control has been optimised the lane keeping assistance portion of the project will be developed. This will include the addition of infrared optical sensors on the demonstration vehicle and further modification of the Simulink control model. The performance of the lane keeping assistance feature will then be evaluated.

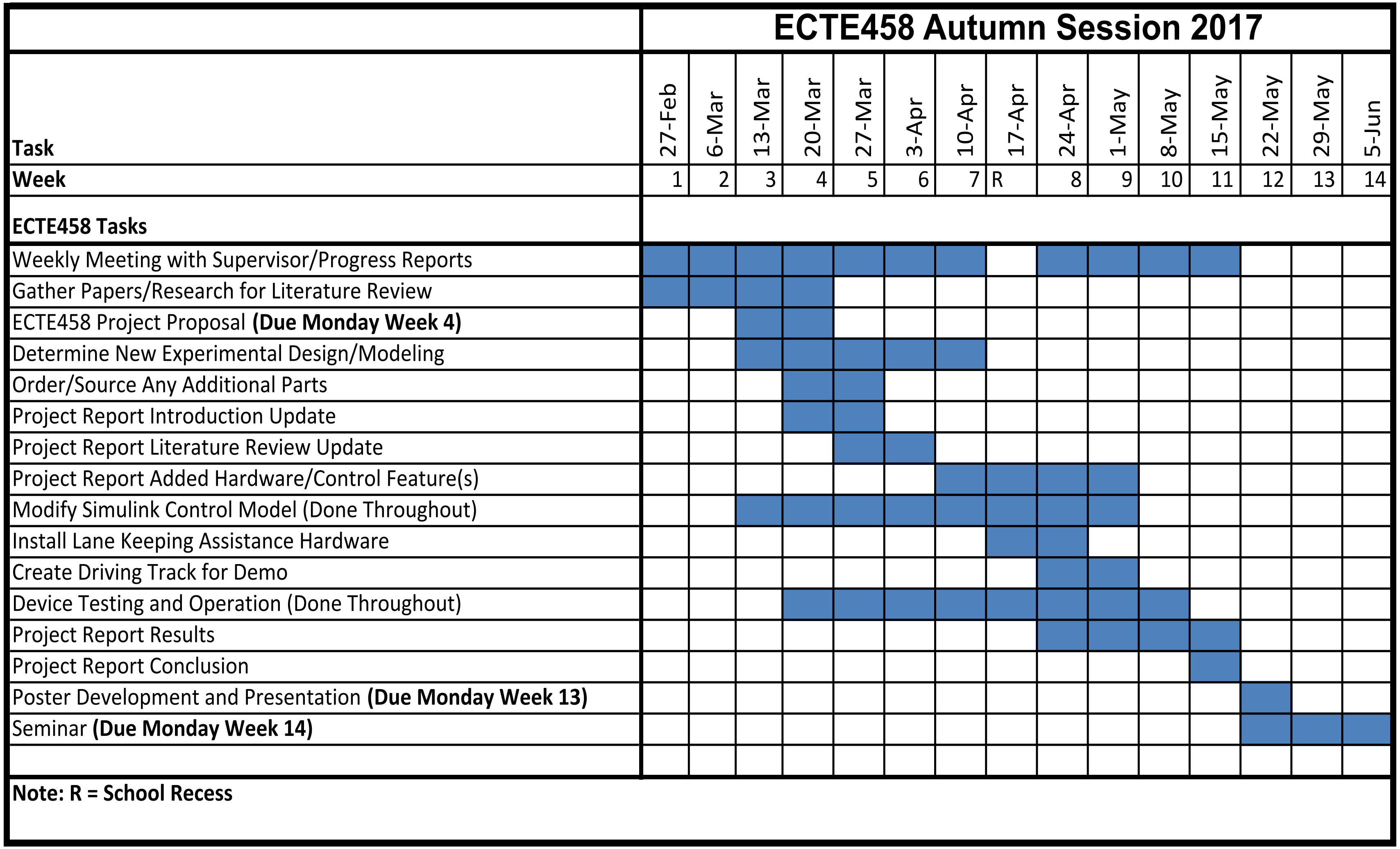
See the included ECTE 458 Gantt chart for the breakdown of tasks and the schedule of work.

Unlike ECTE451, where there was little slack in the schedule, there is quite a bit of flexibility this session for ECTE458. The required parts for this session are minimal and they are for the lane keeping assistance portion of the project only. They have already been specified and will be ordered in week 4. The test bed has already been constructed therefore testing and implementation can occur throughout the session. If any issues arise there is plenty of time to decide on alternative measures to improve the steering emulation of the developed test bed.

The system will be validated through experimentation and recording results for: PID controller performance, Fuzzy Logic implementation, steering torque transfer from the steering wheel to demonstration vehicle and the force feedback felt by the driver. The performance of the lane keeping assistance feature will also be analysed. These results will then be compared with the findings of simular studies and the test results from ECTE451.

The ultimate goal of this project, to be realised by the end of session, is the further development of a demonstration device to analyse and evaluate a SBW system with force feedback, realistic steering emulation and demonstrate how driver assistance features can be easily implemented on a SBW system.

ECTE458 Gantt Chart



APPENDIX B LOGBOOK SIGNATURE SHEET

A Logbook Summary Signature Sheet ECTE 458

SCHOOL OF ELECTRICAL, COMPUTER AND TELECOMMUNICATIONS ENGINEERING

ECTE451 Thesis: Logbook Summary Signature Sheet

Week No.	Date	Comments, if applicable	Student's Signature	Supervisor's Signature
1	1/03/2017	- initial 458 discussion	[illegible]	ZL
2	8/03/2017	N/A	[illegible]	ZL
3	15/03/2017	N/A	[illegible]	ZL
4	22/03/2017	N/A	[illegible]	ZL
5	29/03/2017	N/A	[illegible]	ZL
6	5/04/2017	N/A	[illegible]	ZL
7	12/04/2017	N/A	[illegible]	ZL
8	26/04/2017	N/A	[illegible]	ZL
9	3/05/2017	No meeting, away at job interviews.	—	—
10	10/05/2017	N/A	[illegible]	ZL
11	17/05/2017	N/A	[illegible]	ZL

APPENDIX C HARDWARE DOCUMENTATION

Included in this section is a detailed description of all hardware modules used in the development of the SBW test bed. This section also includes all relevant drawings created for the hardware design and a detailed list of materials.

Module Name: HILINK Board			
Drawing Reference	WIRING-001, CONTROLLAYOUT-001, BOM-001, BOM-002		
Description	Controller for steering control. Reads inputs for position and current and sends outputs through H-bridge to steering motors.		
Connections	Power supply, serial cable to computer, analogue inputs from current sensors, encoder inputs from steering motors and H-bridge outputs to steering motors.		
Test Procedure	Tested functionality of analogue inputs, encoder inputs, and H-bridge outputs separately prior to testing the whole system.		
Specifications	6-12V regulated power supply, analogue inputs 0-5V 12-bit resolution, encoder inputs 0-5V 16-bit resolution and H-bridge outputs 0-12V with 5A max.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
23.9.16	0	MRC	Setup initial system.
3.10.16	1	MRC	Changed board and steering motor.
1.4.17	2	MRC	Connected LKAS digital inputs.

Module Name: Arduino UNO/Adafruit Motor Shield			
Drawing Reference	WIRING-001, CONTROLLAYOUT-001, BOM-001		
Description	Controller and motor shield used to control two 6V motors for demonstration vehicle's forward/reverse movement.		
Connections	6V Power supply to motor shield, pins from Arduino Uno to motor shield, motor outputs on shield to 6V DC motors and from a momentary pushbutton to a digital input.		
Test Procedure	Tested operation of pushbutton and operation of DC motors through the use of a variable voltage source.		
Specifications	Arduino Uno input voltage is 7-12V with an operating voltage of 5V. Adafruit motor shield motor supply voltage 6V.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
21.9.16	0	MRC	Setup initial system with 4A Seeed motor shield from stores.
25.9.16	1	MRC	Replaced 4A Seeed motor shield with Adafruit motor shield.

Module Name: ACS714 Hall Effect Current Sensor	
Drawing Reference	WIRING-001, CONTROLLAYOUT-001, BOM-001
Description	Current sensor used to measure the steering motors current to

	provide force feedback.		
Connections	Current terminals connected to positive leg of steering motor, HILINK board connection to sensor ground, 5V and analogue output.		
Test Procedure	Tested module by reading current input for the operation of a standalone 12V DC motor.		
Specifications	+5A to -5A current input from the motor. 5V supply voltage.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
23.9.16	0	MRC	Installed chips on control assembly and demonstration car.

Module Name: XC-4474 Infrared Emitter/Detector Module			
Drawing Reference	WIRING-001, CONTROLLAYOUT-001, CARLAYOUT-001, BOM-002		
Description	Infrared emitter/detector module to sense lane markings.		
Connections	Connected through the trunk cable to a digital input, plus 5 volts and ground of the HILINK board.		
Test Procedure	Tested module by reading viewing the module LED, which lights up when a line is detected.		
Specifications	2.5-12V supply voltage, 5V output @ 18-20mA. Device is active low with adjustable sensitivity.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
24.3.17	0	MRC	Installed chips on demonstration vehicle and wired to HILINK.

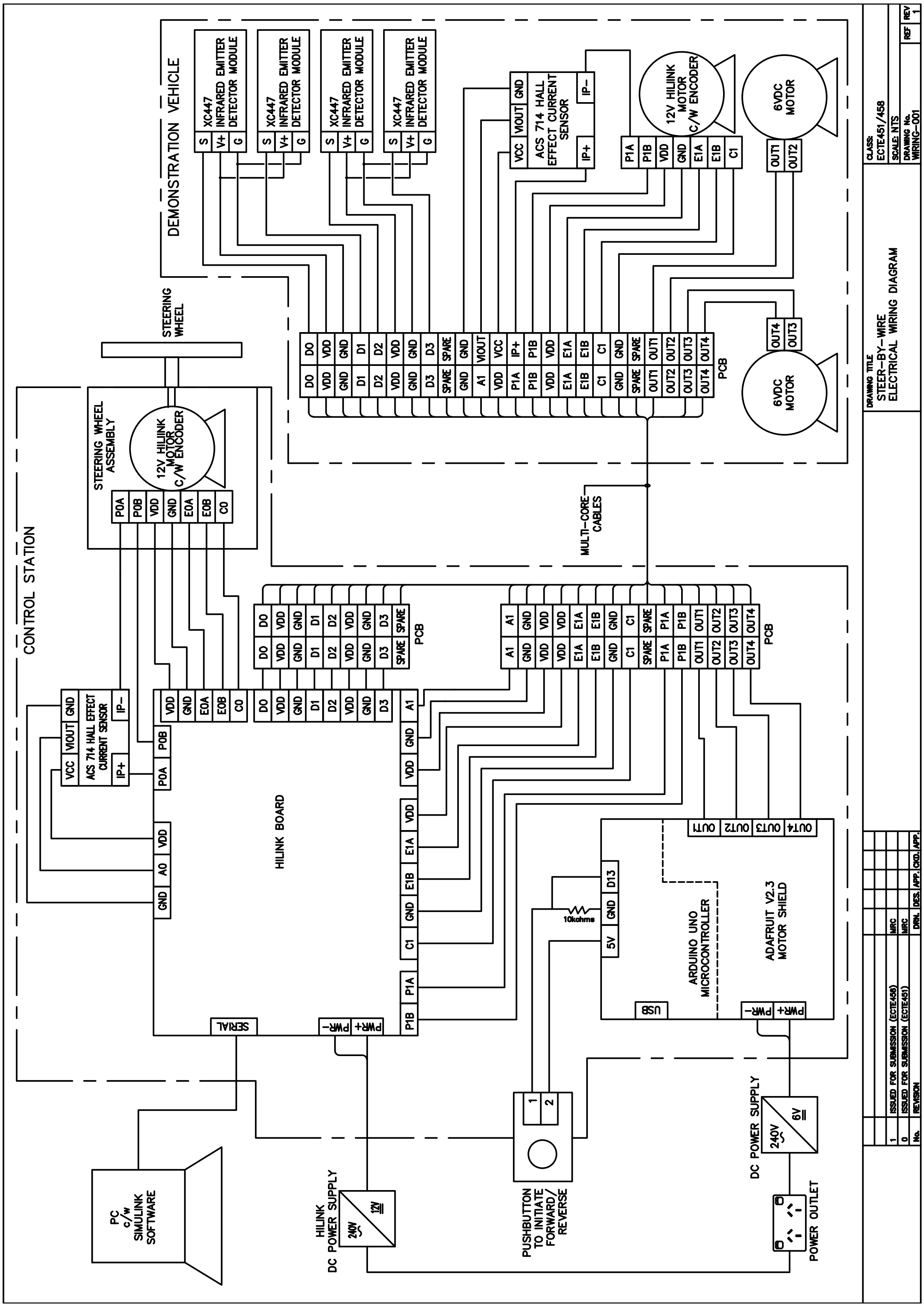
Module Name: Steering Motors/Encoders (road wheel and hand wheel)			
Drawing Reference	WIRING-001, CONTROLLAYOUT-001, BOM-001, CARLAYOUT-001		
Description	Motors used for steering control.		
Connections	Hand wheel motor connected to HILINK board directly. Road wheel motor connected to HILINK board through trunk cable.		
Test Procedure	Tested encoders for position tracking and motor operation.		
Specifications	12V DC, max current 2.3A, PM motor with 1024 cpr encoder. 3mm shaft diameter.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
23.9.6	0	MRC	Installed motors on car and control unit.
4.10.16	1	MRC	Replaced road wheel motor.

Module Name: Forward Reverse Motors	
Drawing Reference	WIRING-001, CARLAYOUT-001, BOM-001
Description	Makeblock motors to be controlled by Arduino Uno and provide the vehicle’s forward/reverse motion.

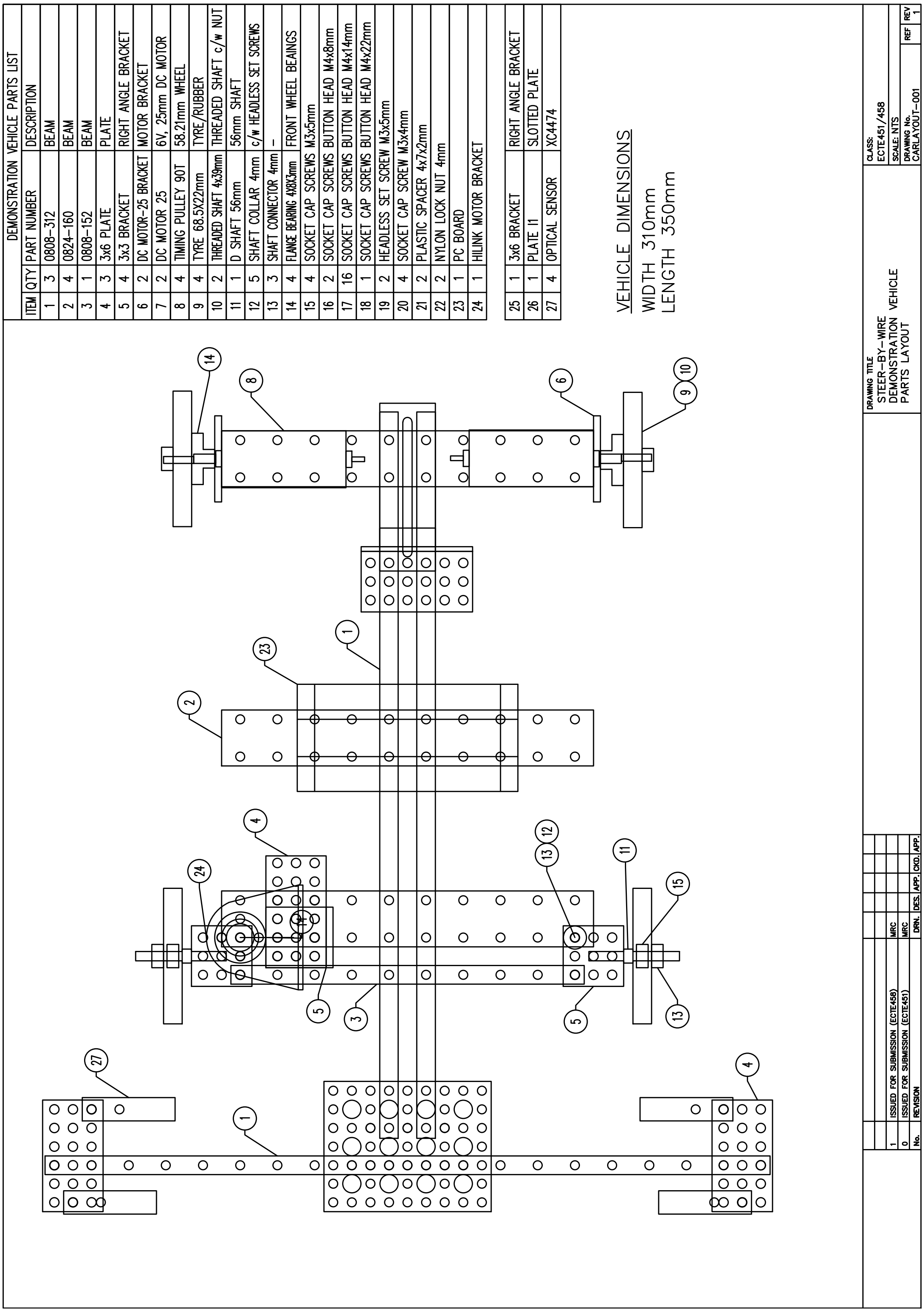
Connections	Connected to the Adrafruit motor outputs through the trunk cable.		
Test Procedure	Tested motors with a variable DC voltage source.		
Specifications	4V to 12V DC, 2.3A max, 0.6A full load.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
23.9.16	0	MRC	Installed on demonstration vehicle.
26.4.17	1	MRC	Replaced right side motor.

Module Name: Demonstration Vehicle			
Drawing Reference	WIRING-001, CARLAYOUT-001, BOM-001		
Description	Demonstration vehicle made from Makeblock components.		
Test Procedure	Checked steering mechanism to be operating correctly and measured road wheel steering angle.		
Specifications	See CARLAYOUT for dimensions.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
23.9.16	0	MRC	Assembled car.
25.9.16	1	MRC	Replaced steering motor bracket.
24.3.17	2	MRC	Added lane keeping assist parts.

Wiring Diagram



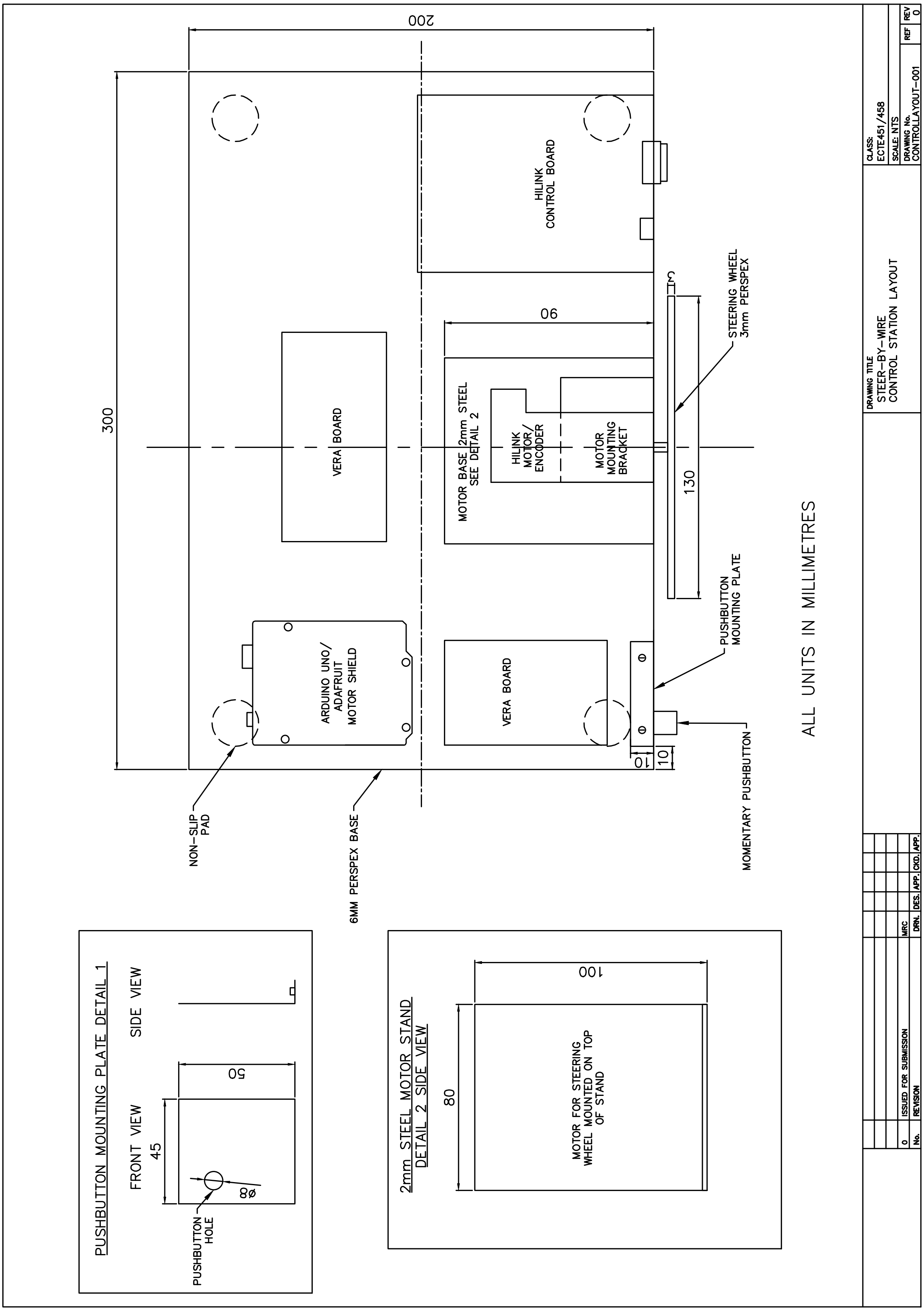
Demonstration Vehicle Layout Drawing



DEMONSTRATION VEHICLE PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	3	0808-312	BEAM
2	4	0824-160	BEAM
3	1	0808-152	BEAM
4	3	3x6 PLATE	PLATE
5	4	3x3 BRACKET	RIGHT ANGLE BRACKET
6	2	DC MOTOR-25 BRACKET	MOTOR BRACKET
7	2	DC MOTOR 25	6V, 25mm DC MOTOR
8	4	TIMING PULLEY 90T	58.21mm WHEEL
9	4	TYRE 68.5X22mm	TYRE/RUBBER
10	2	THREADED SHAFT 4x39mm	THREADED SHAFT c/w NUT
11	1	D SHAFT 56mm	56mm SHAFT
12	5	SHAFT COLLAR 4mm	c/w HEADLESS SET SCREWS
13	3	SHAFT CONNECTOR 4mm	-
14	4	FLANGE BEARING 4X8X3mm	FRONT WHEEL BEAINGS
15	4	SOCKET CAP SCREWS M3x5mm	
16	2	SOCKET CAP SCREWS BUTTON HEAD M4x8mm	
17	16	SOCKET CAP SCREWS BUTTON HEAD M4x14mm	
18	1	SOCKET CAP SCREWS BUTTON HEAD M4x22mm	
19	2	HEADLESS SET SCREW M3x5mm	
20	4	SOCKET CAP SCREW M3x4mm	
21	2	PLASTIC SPACER 4x7x2mm	
22	2	NYLON LOCK NUT 4mm	
23	1	PC BOARD	
24	1	HILINK MOTOR BRACKET	
25	1	3x6 BRACKET	RIGHT ANGLE BRACKET
26	1	PLATE I1	SLOTTED PLATE
27	4	OPTICAL SENSOR	XC4474

Control Unit Layout Drawing



Materials List ECTE451

BOM-001 (Bill of Materials)
Project: Steer-by-Wire
ECTE 451/458
Matthew Crawford (mrc996@uowmail.edu.au)
Student# 4652307
Revision 0

	Item No.	DESCRIPTION	MATERIALS						Total
			QTY	UNITS	UNIT PRICE	TOTAL AMOUNT	SUPP.		
PART NUMBERs		Steering Assembly/Control Board							
	1	Steering Wheel (Perspex)	1	ea	Stock	Stock	UOW		
-	2	DC Motor/Encoder 12V, 1024 CPR Encoder	1	ea	Stock	Stock	UOW		
-	3	HILINK Control Board cw Power Supply	1	ea	Stock	Stock	UOW		
PL-2191	4	Arduino UNO R3	1	ea	Stock	Stock	Personal		
-	5	Adafruit Motor Shield	1	ea	Stock	Stock	UOW		
-	6	Momenttary Pushbutton	1	ea	Stock	Stock	UOW		
-	7	Terminal Strip	1	ea	Stock	Stock	UOW		
-	8	PC Board Vera Type Strip (95 x 152mm)	1	ea	Stock	Stock	UOW		
-	9	Multicore Connecting Cable (9 cores)	6	m	$2.20	$13.20	Jaycar		
	10	DC Power Cable (2 core)	17	m	$1.40	$23.80	Jaycar		
-	11	DC Power Supply	1	ea	Stock	Stock	UOW		
-	12	Control Station Base	1	ea	Stock	Stock	UOW		
		Demonstration Car							
SKU MB60576	13	0808-312 Makeblock Beam	1	(2pk)	$16.49	$16.49	Pakronics		
SKU MB60036	14	0824-160 Makeblock Beam	1	(4pk)	$28.49	$28.49	Pakronics		
SKU MB61200	15	3x6 Plate	1	ea	Stock	Stock	UOW		
SKU MB60536	16	0808-152 Makeblock Beam	1	(4pk)	$19.49	$19.49	Pakronics		
SKU MB61500	17	3x3 Bracket	1	(4pk)	$14.09	$14.09	Pakronics		
SKU MB85001	18	D-Shaft 56mm	1	(4pk)	$8.69	$8.69	Pakronics		
SKU MB95010	19	25mm DC Motor Pack (Includes: 1DC Motor 25, 1 DC Motor-25 Bracket, 1 Shaft Connector-4, 1 Timing Pulley 90T, 4 Screws M4x14, 8 Countersunk Screw M3x8 & 2 Headless Screws M3x5.	2	(Pack)	$25.49	$50.98	Pakronics		
SKU MB84740	20	Shaft Connector 4mm	1	(2pk)	$8.69	$8.69	Pakronics		
SKU MB84750	21	Shaft Collar 4mm	1	(10pk)	$12.29	$12.29	Pakronics		
SKU MB83016	22	Timing Pulley 90T	1	(4pk)	$16.49	$16.49	Pakronics		
SKU MB87030	23	Tyre 68.5x22mm	1	(4pk)	$14.99	$14.99	Pakronics		
SKU MB61804	24	DC Motor-37 Bracket	1	(2pk)	$14.09	$14.1	Pakronics		
SKU MB85008	25	Threaded Shaft 4x39mm	2	ea	Stock	Stock	UOW		
SKU MB87330	26	Flanged Bearing 4x8x3mm	1	(10pk)	$23.99	$24.0	Pakronics		
SKU MB70555	27	Socket Cap Screw Button Head M4x14	16	ea	Stock	Stock	UOW		
SKU MB70561	28	Socket Cap Screw Button Head M4x22	1	(50pk)	$6.89	$6.89	Pakronics		
SKU MB70552	29	Socket Cap Screw Button Head M4x8	2	ea	Stock	Stock	UOW		
SKU MB72342	30	Plastic Spacers 4x7x2	2	ea	Stock	Stock	UOW		
SKU MB71004	31	Nylon Lock Nuts 4mm	2	ea	Stock	Stock	UOW		
SKU MB70512	32	Headless Set Screw M3x5	2	ea	Stock	Stock	UOW		
ACS 714	33	Current Sensor Carrier -5A to +5amp	1	ea	Stock	Stock	UOW		
-	34	Terminal Strip	1	ea	Stock	Stock	UOW		
-	35	PC Board Vera Type Strip (95 x 152mm)	1	ea	Stock	Stock	UOW		
		Additional Costs							
-	36	Paktronics GST	1	ea	$0.10	$23.57	Pakronics		
-	37	Paktronics Freight	1	ea	$11.40	$11.40	Pakronics		
		SUB TOTAL COSTS:				$307.63			
						Real Cost			
		TOTAL COSTS:				$307.63			$307.63

Materials List ECTE458

BOM-002 (Bill of Materials)
Project: Steer-by-Wire
ECTE 458
Matthew Crawford (mrc996@uowmail.edu.au)
Student# 4652307
Revision 0

	Item No.	DESCRIPTION	MATERIALS					Total
			QTY	UNITS	UNIT PRICE	TOTAL AMOUNT	SUPP.	
PART NUMBERs		Lane Keeping Assistance Modifications						
XC4474	1	Line Trace Sensor Module	4	ea	$7.95	$31.80	Jaycar	
WB1578	2	Multicore Connecting Cable (9 cores)	10	m	$2.20	$22.00	Jaycar	
SKU MB61200	3	Makeblock Plate 3x6-Blue(4-Pack)	1	ea	$11.54	$11.54	Pakronics	
SKU MB60576	4	0808-312 Makeblock Beam (2-Pack)	1	ea	$18.14	$18.14	Paktronics	
WH5659	5	Heat Shrink Tape (roll)	1	ea	$12.95	$12.95	Jaycar	
4490251	6	Black Canvas (Road Surface)	3	m	$20.25	$60.75	Bunnings	
1661592	7	Painters Tape (Lane Markings)	1	ea	$6.34	$6.34	Bunnings	
1580682	8	Spray Paint (Lane Markings)	1	ea	$11.95	$11.95	Bunnings	
		Additional Costs						
-	9	Paktronics GST	1	ea	$0.10	$2.97	Pakronics	
-	10	Paktronics Freight	1	ea	$10.00	$10.00	Pakronics	
		SUB TOTAL COSTS:				**$188.44**		
						Real Cost		
		TOTAL COSTS:				**$188.44**		**$188.44**

APPENDIX D SOFTWARE DOCUMENTATION

Included in this section is a detailed description of all software modules used in the development of the SBW test bed. This section also includes all relevant Arduino code and the complete Simulink model.

Forward/Reverse Movement Control Module (Arduino Software)

<table>
<tr><td colspan="4">Module Name: Arduino Programming</td></tr>
<tr><td>Coding</td><td colspan="3">See Arduino code included as part of Appendix D. This code is based on available libraries and templates. See Section 3.5.2 for program flow diagram.</td></tr>
<tr><td>Operational Description</td><td colspan="3">The user presses the momentary pushbutton to initiate a forward/reverse sequence of movement. The speed and duration are set in the Arduino programming. Full speed in program is 255 and the speed can be set from 0-255.</td></tr>
<tr><td>Inputs</td><td colspan="3">Momentary pushbutton to digital input 13.</td></tr>
<tr><td>Outputs</td><td colspan="3">Motor outputs through Adafruit motor shield.</td></tr>
<tr><td>Test Procedure</td><td colspan="3">Tested pushbutton functionality with built in LED. Tested program to run one DC motor at a time. Following car assembly tested complete system.</td></tr>
<tr><td>Set Points</td><td colspan="3">Speed = 150
Duration = 15s</td></tr>
<tr><td colspan="4">Modification Record</td></tr>
<tr><td>Date</td><td>Version No.</td><td>Designer</td><td>Modifications/Remarks</td></tr>
<tr><td>23.9.16</td><td>0</td><td>MRC</td><td>Created program for motor control.</td></tr>
<tr><td>25.9.26</td><td>1</td><td>MRC</td><td>Incorporated momentary pushbutton programming.</td></tr>
<tr><td>29.9.16</td><td>2</td><td>MRC</td><td>Updated programming for Adafruit motor shield.</td></tr>
<tr><td>3.10.16</td><td>3</td><td>MRC</td><td>Updated speed and duration settings.</td></tr>
<tr><td>26.4.16</td><td>4</td><td>MRC</td><td>Updated speed and duration settings for different LKAS scenerios.</td></tr>
</table>

Arduino Programming

```
/* This sketch was used as part of ECTE451 to provide the forward and
reverese
 * movement for a Steer-by-Wire demonstration vehicle.
 * The program runs at a specified speed for a specified duration.
 * The movement is initiated by a pushbutton.
 */

// Adafruit motor shield libraries
#include <Wire.h>
#include <Adafruit_MotorShield.h>
#include "utility/Adafruit_MS_PWMServoDriver.h"

// variable declaration
const int buttonPin = 13;
int buttonState=0;

// create the motor shield object with the default I2C address
Adafruit_MotorShield AFMS = Adafruit_MotorShield();

// declare DC motor/ports.
Adafruit_DCMotor *myMotor1 = AFMS.getMotor(1);
Adafruit_DCMotor *myMotor2 = AFMS.getMotor(2);

// setup function for motor shield and pushbutton
void setup() {
  AFMS.begin(); // initialises shield for use with motors
  myMotor1->setSpeed(150); // specify motor 1 speed
  myMotor2->setSpeed(150); // specify motor 2 speed

pinMode(buttonPin, INPUT); // specify the digital I/O as an input at
                              pushbutton
  }

// function to move car forward and reverse
void Car_Forward_Reverse() {

  // move car forward
  myMotor1->run(FORWARD);
  myMotor2->run(FORWARD);
  delay(4000);

  // stop car
  myMotor1->run(RELEASE);
  myMotor2->run(RELEASE);
  delay(1000);

  // move car backward
  myMotor1->run(BACKWARD);
  myMotor2->run(BACKWARD);
  delay(4000);

  // stop car
  myMotor1->run(RELEASE);
  myMotor2->run(RELEASE);
  delay(1000);
}
```

```
void loop() {

  buttonState=digitalRead(buttonPin); // set buttonState as value read
                                         from pin

  if (buttonState == HIGH) // when the pushbutton is pushed start movement
                              function
     Car_Forward_Reverse();
   }
```

Steer-by-Wire Steering Control Modules (Simulink)

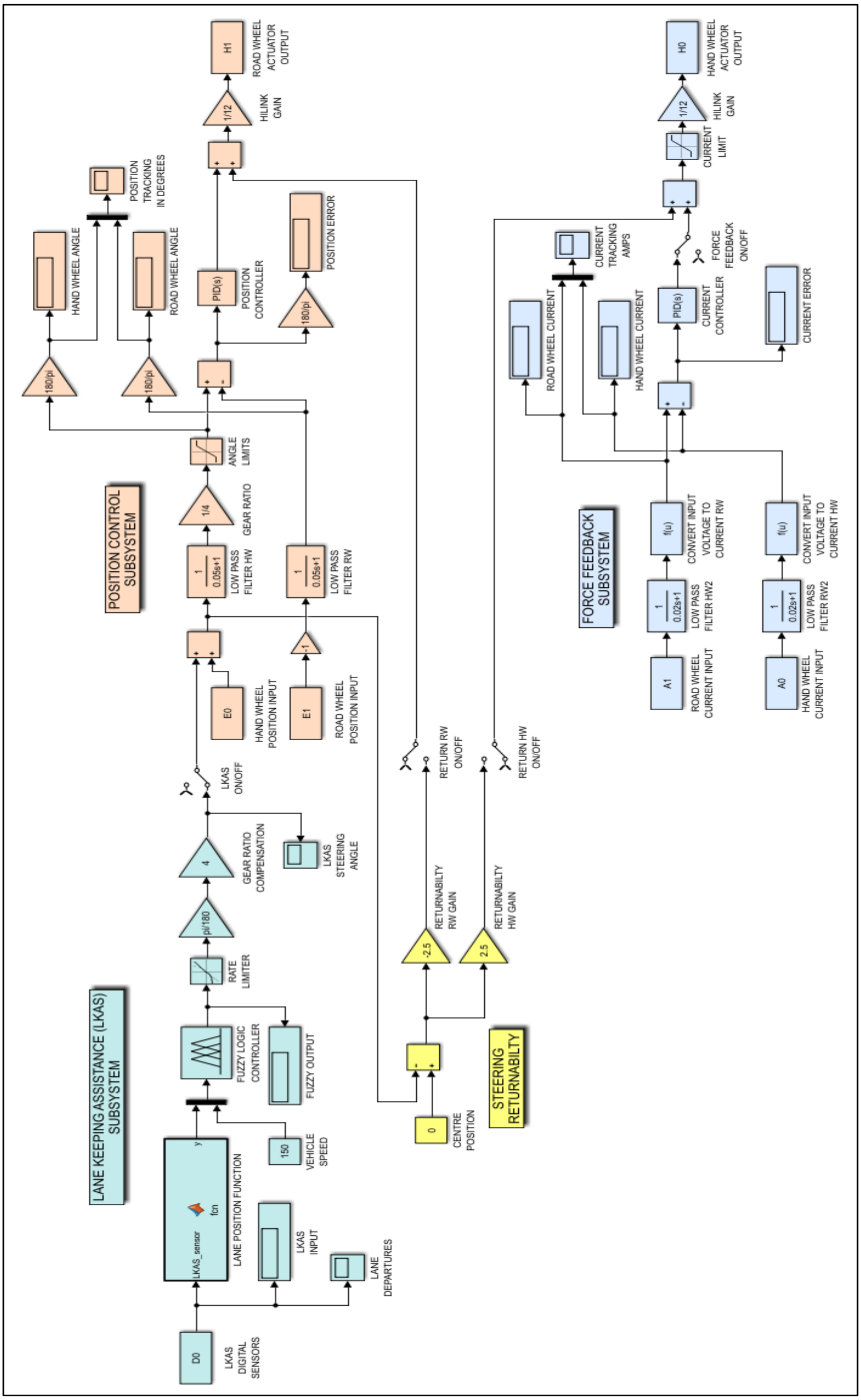
Module Name: Position Control			
Coding	See Section 3.5.1.1 for the Simulink programming used for position control. The full Simulink block diagram can also be found in Appendix D.		
Operational Description	The user inputs a steering angle through the hand wheel, which is translated to the road wheel. This is a closed loop system with the road wheel steering angle as the feedback.		
Inputs	Encoder inputs E0 and E1 to provide road wheel and hand wheel motor position.		
Outputs	H-bridge output H1 to road wheel motor to transfer the desired steering angle to the road wheel actuator.		
Test Procedure	Tested position following capability of the two DC motors. Tested position control of demonstration vehicle.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
3.10.16	0	MRC	Created program for position control.
5.10.26	1	MRC	Added low pass filters and angle limits on encoder inputs in program.
6.10.16	2	MRC	Added PID controller in program.
7.10.16	3	MRC	Tuned PID control.
22.3.17	4	MRC	Updated model to work on Matlab/Simulink 2016.
1.4.17	5	MRC	Retuned PID controller using Ziegler Nichols method. Added gear ratio and returnability feature.

Module Name: Force Feedback			
Coding	See Section 3.5.1.2 for the Simulink programming used for force feedback. The full Simulink block diagram can also be found in Appendix D.		
Operational Description	The current is measured at the road wheel. This current increases as the required torque increases depending on the road surface. The current at the hand wheel is measured as to provide negative feedback.		
Inputs	Analogue inputs A0 and A1 provide road wheel and hand wheel current inputs.		
Outputs	H-bridge output H0 to the hand wheel motor to transfer the force at the road wheels to the driver.		
Test Procedure	Tested current sensing ability of program of individual sensors. Test force feedback created by different road surfaces.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
3.10.16	0	MRC	Created program for motor control.
5.10.26	1	MRC	Added low pass filters on analogue inputs in program.
6.10.16	2	MRC	Added PID block to set force

			feedback correctly.
22.3.17	3	MRC	Updated model to work on Matlab/Simulink 2016.
1.4.17	5	MRC	Adjusted PID controller proportional gain.

Module Name: Lane Keeping Assistance (LKAS)			
Coding	See section 3.5.1.3 for the Simulink programming used for LKAS. The full Simulink block diagram can also be found in Appendix D.		
Operational Description	The lane detecting digital inputs, attached to the demonstration vehicle, are read into the Simulink program and through a Matlab function block the vehicles lane deviation is determined. Based on the vehicle's speed and deviation the vehicles steering angle is adjusted through a fuzzy logic controller and the existing SBW system.		
Inputs	Digital inputs D0/d4-D0/d7 provide the vehicle's lane position.		
Outputs	H-bridge output H1 to road wheel motor to transfer the desired steering angle to the road wheel actuator.		
Test Procedure	Tested the values read into the system when the various sensors were activated.		
Modification Record			
Date	Version No.	Designer	Modifications/Remarks
17.4.17	0	MRC	Created subsystem for LKAS.
27.4.17	1	MRC	Updated the fuzzy logic membership functions.

Simulink Steer-by-Wire Block Diagram



Matlab Lane Position Function Block (LKAS Deviation)

LANE POSITION FUNCTION*

```
function y = fcn(LKAS_sensor)
% big right case
if(LKAS_sensor==112)
    y=2;
% medium right case
elseif(LKAS_sensor==96)
    y=1.5;
% small right case
elseif(LKAS_sensor==224)
    y=1;
% big left case
elseif(LKAS_sensor==208)
    y=-2;
% medium right case
elseif(LKAS_sensor==144)
    y=-1.5;
% small left case
elseif(LKAS_sensor==176)
    y=-1;
% centre of lane case
else
    y=0;
end
```