VIRTUAL RACING: BUILDING A FORMULA STUDENT RACE CAR SIMULATOR

MECH5080M **Team** Project Report
Team 135
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Virtual Racing: Building A Formula Student Race Car Simulator
01/05/2024

SCHOOL OF MECHANICAL ENGINEERING UNIVERSITY OF LEEDS

MECH5080M TEAM PROJECT 45 credits

TITLE OF PROJECT

Virtual Racing: Building A Formula Student Racing Car Simulator

PRESENTED BY

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OBJECTIVES OF PROJECT

To design and manufacture a portable and cost-effective simulator of the Formula Student Race Car for driver training and outreach activities. This included developing an actuated cockpit environment, a virtual environment/game engine to simulate driving conditions, auditory and haptic feedback, and force feedback steering systems.

IF THE PROJECT IS INDUSTRIALLY LINKED TICK THIS BOX AND PROVIDE DETAILS BELOW

X

COMPANY NAME AND ADDRESS:
Formula Student Team, University of Leeds

INDUSTRIAL MENTOR: Krzysztof Kubiak

THIS PROJECT REPORT PRESENTS OUR OWN WORK AND DOES NOT CONTAIN ANY UNACKNOWLEDGED WORK FROM ANY OTHER SOURCES.

SIGNED J.P. A.B. C.L. Q.L. M.F. DATE 01/05/2024

VIRTUAL RACING: BUILDING A FORMULA STUDENT RACE CAR SIMULATOR

A. Bury, C. Lovett, J. Partridge, Q. Liang, M. Fuller

ABSTRACT

This report discusses the design, manufacture, and validation of a portable, cost-effective driving simulator for Leeds Gryphons Racing. A 2 degree of freedom electro-mechanical actuation system was optimised alongside a human machine interface and simulation environment, based upon a single-seat race car. The actuation system is comprised of twin DC servomotors, attached to the motion platform via a crank system, which are controlled by a programmable microcontroller. Inputs in the form of a force-feedback-enabled steering wheel and brake and accelerator pedals are installed, and a simulation environment was developed within rFactor 2. The final implementation demonstrated a reasonable level of performance and was found to generate realistic motion cues despite suffering from excessive mechanical compliance in the roll axis.

Keywords *— Driving Simulator, Control system, Driver-in-loop.*

1. INTRODUCTION

Formula Student (FS) is an international engineering competition that enables students to apply their knowledge to a real-world problem by designing and manufacturing a single-seat race car. This car is then pitched against other teams in both static and dynamic events during a yearly competition at Silverstone. The University of Leeds formula student team, Leeds Gryphons Racing, have outlined a lack of driver experience due to high running costs and fast development cycles, and therefore feel a driving simulator replicating an FS car would be desirable. The team also believe the simulator could be used at outreach events to publicise the team, attracting new members and sponsors.

Driving simulators, widely utilised in the automotive and entertainment sectors, simulate real driving experiences in safe and controlled environments. Often these include an actuated motion platform, with anywhere from one to six degrees of freedom (DoF), which is used to simulate the dynamic forces on the driver.

Among these forces is the load transfer effect, evident during acceleration and braking: as the car accelerates, the load shifts rearward, while braking prompts a forward shift. Moreover, simulators accurately replicate lateral forces during cornering and the tactile feedback of steering wheel resistance, enhancing the overall realism of the experience.

Within this report the design and build of a portable, cost-effective simulator, of a suitable DoF will be explored. The conceptual design will first be introduced, then the focus will shift to the optimisation of the design in the detailed design section. The implementation section will focus on the manufacturing and construction of the simulator, with the validation section testing the simulator against the established requirements.

2. CONCEPTUAL DESIGN

The simulator created in this project consists of 3 main sections: a chassis actuation system, a Human Machine Interface (HMI), and the software that links these systems to the virtual environment. This section will discuss the system requirements and a high-level system design of each of these components.

2.1 Requirements

A list of requirements was established which were deemed crucial to making a realistic simulator within the £500 budget constraint:

- 2 DoF required, with minimum pitch and roll range of ±5°, based on existing simulators' standards.
- A stable closed-loop control system with no overshoot and $< 1^{\circ}$ steady-state error.
- Maximise angular acceleration such that angular velocity reaches a minimum of $2^{\circ}s^{-1}$ with a response time of less than 300ms from movement in the simulation environment to movement of the motion platform.
- A force-feedback steering system capable of providing up to 2Nm of torque with a response time of less than 100ms.
- A pedal box system with an accelerator and brake pedal that feel similar to a real vehicle's.
- Implementation of visual and audio cues, alongside haptic feedback essential for realism.
- Portable, with maximum dimensions of 2000mm × 1000mm × 2200mm (H×W×D) for transport to events.
- Mechanically and electrically safe design, with appropriate warnings and risk assessments.

2.2 High-Level Hardware Design

This section introduces the final simulator design (Figure 2.1), featuring a motion platform constructed from a former formula student chassis, connected to a stationary platform via a ball joint and actuation system. The chassis is equipped with a functional HMI and hardware/software to produce an immersive virtual environment.

Figure 2.1: CAD model of the final concept.

2.3 Actuation System

The simulator operates as a 2 DoF system, featuring two electro-mechanical crank actuators situated at the front corners due to space constraints, with a ball joint situated at the Centre of Mass (CoM). This setup allows for pitch and roll movements, with the motors capable of moving in sync or independently to perform the required motion dynamics.

Each actuator features a 24V brushed DC motor capable of producing 7Nm output torque. This actuation system was selected over other options such as hydraulic or pneumatic due to its compact design, ability to produce quick bursts of acceleration, and availability at the university [1].

As the pitch and roll of the motion platform must be continually variable, it is necessary to include some form of control system which allows measurement, computes error, and acts to reduce this error to achieve the desired angles. For this project a low-cost digital microcontroller, the AtMega2560-powered Arduino Mega, was chosen as the most appropriate system as it has a fast 16MHz processor [2], a mature library base for programming [3], and can communicate with other devices via serial.

2.4 Human Machine Interface

In order to simulate the feeling of driving a real vehicle, a HMI was created that consisted of a force-feedback-enabled steering wheel system and a pedal box with accelerator and brake pedals.

To accurately replicate vehicle dynamics, mathematical models of the vehicle’s powertrain and steering systems were built using MATLAB Simulink. The model outputs the torque on each wheel and their turning angle in response to the steering and pedal inputs. This was integrated with the dynamic model for the tyres and vehicle body to generate theoretical pitch and roll, as well as the feedback torque provided to the steering wheel. All system parameters were measured and calculated from the Formula Student F23 car.

The steering assembly consists of a Maxon 320983 motor, encoder, and gearbox combination for torque maximisation. This motor is powered by a BTS7960 motor driver using Pulse Width Modulation, and the control software is deployed to an Arduino Leonardo.

The pedal box contains an accelerator pedal and a brake pedal which rely on springs to provide realistic pedal motion. The position of each pedal is monitored by a simple 10kΩ potentiometer whose value is monitored by the same Arduino Leonardo.

2.5 High-Level Software Design

With regards to the design approach of the software architecture, it was deemed imperative that each component of the architecture remain independent of the others. This more modular design approach was chosen to enhance the device's versatility, enabling integration of new (or supplantation of existing) software components improving functional flexibility [4]. Safety is also improved in this approach, with user protection against simulation environment crashes since the motion platform remains operational and stable.

The architectural topology of the system is depicted in Figure 2.2, illustrating the simulation software, the standalone motion control application, the Arduino microcontroller, and the motion platform.

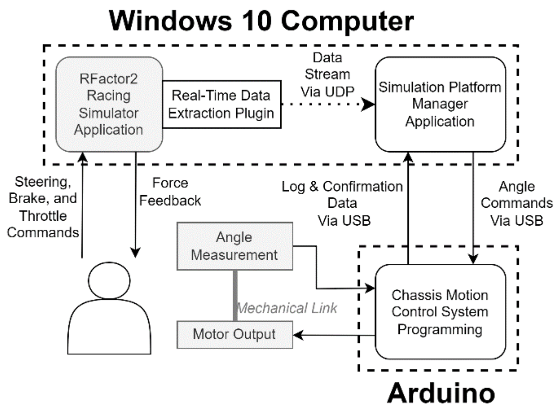

Figure 2.2: Control System Topology

A plugin was created to integrate with the simulation software, rFactor 2 (rF2), facilitating the transmission of telemetry data between rF2, the Motion System software, and the Human Input Software. The plugin extracts telemetry data, recording the live telemetry output to a text file while transmitting the actuation related telemetry data required for the motion cueing process to the motion control software using the User Datagram Protocol (UDP).

A standalone application for motion control was employed to minimise the computational burden on the simulation environment. By offloading the memory-intensive motion cueing tasks, the simulation software can focus on rendering graphics and executing complex physics simulations with the aim of preventing performance and user immersion degradation.

3. DETAILED DESIGN

This section details the optimisation of the actuation system design, focusing on both mechanical and control aspects. It also examines the alignment of the HMI with the real-life formula student car. Finally, it explores the simulation environment and the hardware/software employed for its implementation.

3.1 Actuation Mechanical System

The ball joint was positioned at the CoM of the motion platform, in order to minimise load on the actuators and therefore enhance performance. The CoM was determined be 572mm from the front and calculated by assuming lateral symmetry, taking mass measurements and utilising UK adult weight data. The ball joint was selected due to robustness and having a suitable swivel angle (30°) and flex torque (18Nm), allowing for a strong design, with an appropriate resistance to motion, and capability of providing the required degrees of freedom.

The performance of the actuation system is dependent on the critical dimensions, the crank length (R) and actuation point (C). These are depicted in figure 3.1. The neutral position of the crank is at an angle (θ) of 90°, corresponding to 0° pitch and roll. Consequently, rod length (L) is fixed at 0.16m. Using this schematic, the linear movement, x, is described in Equation 3.1 [5], see appendix H for the derivation.

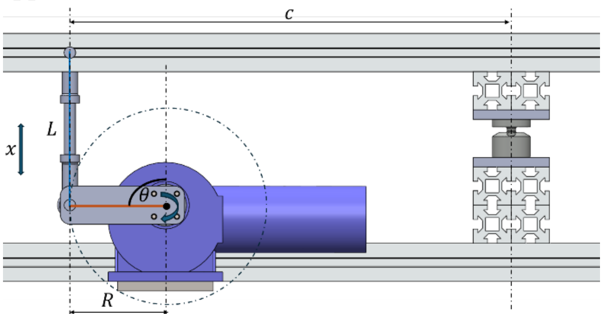

Figure 3.1: *Geometric parameters for the actuation system*

$$x = \left[R\cos\theta + L\sqrt{1 - \left(\frac{R}{L}(1-\sin\theta)\right)^2} \right] \quad (3.1)$$

Utilising Equation 3.1, the motion platform's linear movement can be plotted against the angular displacement of the crank, shown in Figure 3.2. The figure displays a linear relationship between the parameters and therefore the kinematics of the system can be assumed linear.

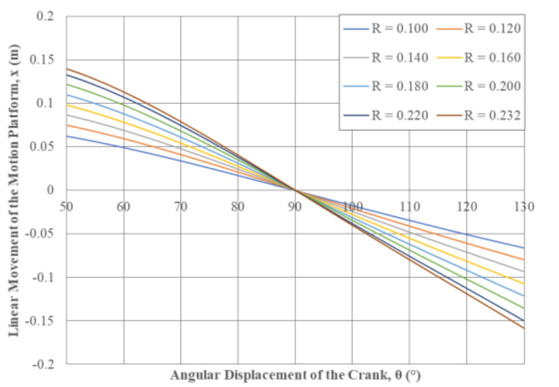

Figure 3.2: *The linear movement of the motion platform against angular displacement of the crank, for a range of different R values.*

To determine the optimal geometry for the actuators, it was necessary to construct a model for angular acceleration in pitch and roll based upon applied force. For the limiting condition this force is assumed to be constant as DC motors have a linear speed/torque relationship [6], and a 1:37.5 ratio gearbox is integral to the motor unit. Consequently, Equation 3.2 was derived by balancing the torques for pitch and roll manoeuvres.

$$I\ddot{\theta} = F_{act}c \quad (3.2)$$

Where I is the angular inertia, $\ddot{\theta}$ is the angular acceleration, and F_{act} is the actuation force.

The inertia of the motion platform is non-trivial as the hand-made nature of LGR's F16 chassis and the large natural variability of the occupant makes mass distribution impossible to characterise precisely. Therefore, an inertial model was created by modelling the motion platform as two concentric cylinders, each with a uniform mass distribution, with their combined CoM coinciding with the measured CoM, and diameter equal to $2h$, as shown in Figure 3.3. The inertia of the motion platform was then evaluated using Equation 3.3 and 3.4 for pitch and roll respectively.

$$I_{pitch} = \sum_{i=1}^{2} \left[\frac{1}{4} m_i r_i^2 + \frac{1}{12} m_i L_i^2 + m_i \sqrt{r_i^2 + \frac{L_i^2}{4}} \right] \quad [7]\,[8] \quad (3.3)$$

$$\Rightarrow \boldsymbol{I_{pitch} = 42.0\ \mathrm{kg\ m^2}}$$

$$I_{roll} = \sum_{i=1}^{2} \left[\frac{1}{2} m_i r_i^2 + m_i r_i^2 \right] \quad [7]\,[8] \quad (3.4)$$

$$\Rightarrow \boldsymbol{I_{roll} = 24.4\ \mathrm{kg\ m^2}}$$

Where m_i, L_i, and r_i are the mass, length, and radius of the cylinder i.

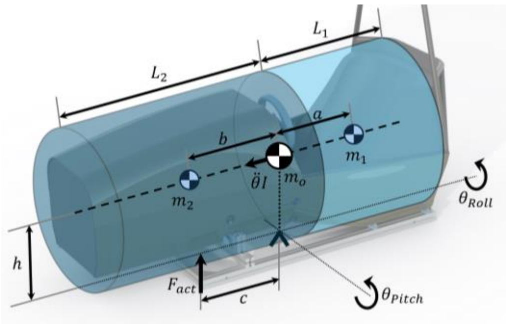

Figure 3.3: *Chassis Inertial Model*

Using linear kinematics and the inertia model, the position of the actuation point, C and the crank length, R were optimised to maximise rotational acceleration and therefore performance. The optimal lengths for C and R were found to be 0.462m and 0.1m respectively, giving a maximum rotational acceleration of 88deg/s^2.

Once the design of the actuation system had been finalised, material selection was the next focus. Areas of high stress were identified and steel selected due to high strength whilst aluminium was selected for the crank due to its lightweight properties and ease of manufacturing [9]. To confirm these materials were suitable, finite element analysis (FEA) was conducted for the worst-case scenario, displayed in figure 3.4 below.

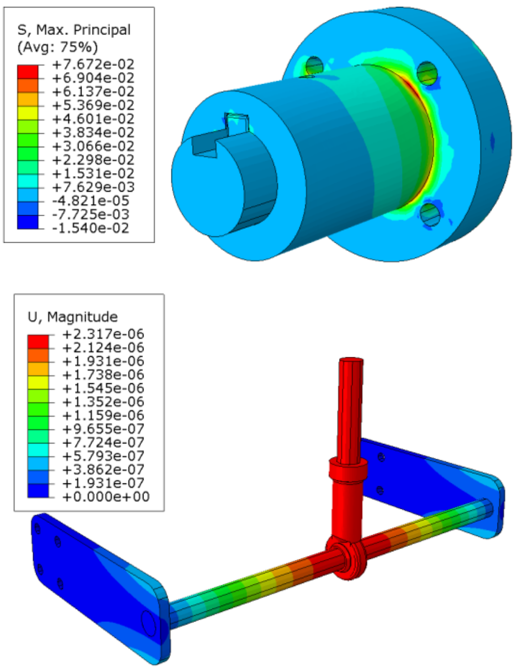

Figure 3.4: *FEA of the circular flange assembly (upper) showing the max principal stress (N/mm^2) and the crank/rod assembly (lower) displaying the displacement (mm).*

3.2 Actuation Control System

To power the motors, two BTS7960B PWM motor controllers were selected, and an enclosure was adapted to provide protection and cooling for the chassis control electronics. A 24V 10A mains power supply was then integrated into a casing and connected via a normally open relay with a direct connection to the emergency stop button in the cockpit.

As the two motors are mechanically connected, it was necessary to have the feedback controllers operating on pitch and roll rather than the motors individually. The outputs of the controllers were then applied to a proportioning function to split the applied power between the two motors along with a bias factor to overcome slight differences in weight distribution and motor performance, as demonstrated by Equations 3.5 and 3.6.

$$P_{m1} = P_{1bias}\left(P_{pitch} + P_{roll}\right) \tag{3.5}$$

$$P_{m2} = P_{2bias}\left(P_{pitch} - P_{roll}\right) \tag{3.6}$$

Where P_i refers to the proportion of power applied to each axis.

Two rotary potentiometers were chosen to be used on the cranks of the motors with inverse kinematics taking place to determine the chassis pitch and roll angles in real-time via linear functions.

A Proportional-Integral-Derivative (PID) controller was implemented on the Arduino for pitch and roll, and an initial tune was achieved using the Ziegler-Nichols method [10] with a 70kg test dummy as the occupant. As this method often results in some oscillation with high gains [11], further tuning was required to eradicate overshoot and minimise steady state error, particularly for the roll axis.

Finally, a desktop application with user interface was then produced using the .NET framework and C# [12], into which an adaption of the classical motion cueing algorithm (MCA), described by Figure 3.5, was implemented.

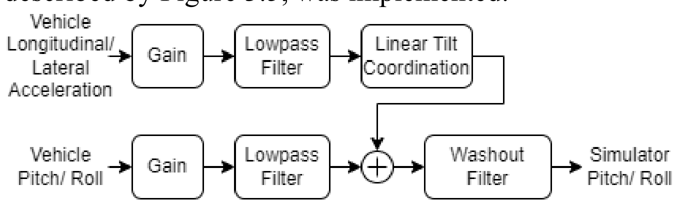

Figure 3.5: *Implemented Motion Cueing Algorithm*

3.3 Vehicle Dynamics

To mathematically model the steering system, the road wheel angles δ_O and δ_i in response to the steering wheel angle θ [13] were considered. δ_O and δ_i are the outer and inner road wheel angles which were used as input parameters to the vehicle body dynamic system.

To calculate the force feedback, the force transmitted to the track rod is given by Equation 3.6, since a rack and pinion system is used.

$$F = \frac{M_{T1}cos\gamma_1}{x_1} + \frac{M_{T2}cos\gamma_2}{x_2} \quad (3.6)$$

Where M_T is the total steering moment of each wheel, given by the sum of the jacking and scrub moments. x and γ are geometrical parameters of the steering system shown in Figure 3.6.

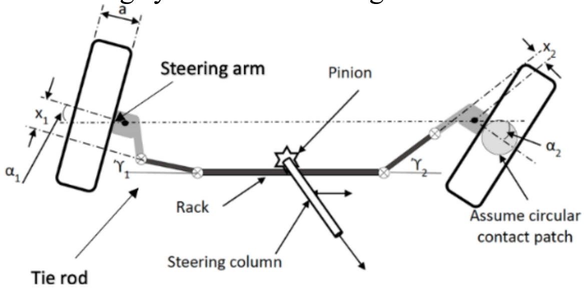

***Figure 3.6:** Rack and pinion steering system* [14]

The torque feedback to the driver is:

$$T = \frac{F \times PCD_{pinion}}{2\eta} \quad (3.7)$$

Where η is the efficiency of transmission and PCD_{pinion} is the pinion diameter. The steering moment is varied by longitudinal and lateral Load Transfer Effects (LTE). This is the weight shifting effect caused by linear and lateral accelerations.

The engine and brake system were modelled based on empirical measurements [15], which gives the relationship between pedal position and wheel torque. The Pacejka tyre model was used to calculate the longitudinal, lateral and vertical forces on each tyre (F_x, F_y and F_z) in response to wheel torques [16], and the IDNGREY vehicle model was used to derive the dynamic equations of longitudinal and lateral accelerations and yaw rate using F_x, F_y, F_z, δ_O and δ_i as inputs [17]. Similarly, the dynamic equations for pitch and roll were derived from longitudinal and lateral accelerations. The response systems for pitch, roll and accelerations were designed using MATLAB Simulink, taking these corresponding dynamic equations into account.

The overall dynamic model is nonlinear, and the subsystems are interdependent, so isolation testing is a useful method to validate each subsystem independently. For example, the roll response is affected by lateral acceleration A_y. When testing roll response, the value of A_y should be controlled. After refining each subsystem, all subsystems were integrated to test and validate against experimental data. The experimental data is the telemetry data of pitch, roll, accelerations, and driver inputs recorded from the Driver-In-Loop testing using the rF2 game engine.

The team finally decided to use the rF2 game engine as the dynamic model due to convenience. This engine is known for realistic physics and provided an excellent testing ground for this project.

3.4 Human Machine Interface

The force-feedback steering wheel system was built from a simple DC motor driven by a BTS7960 motor driver but was first passed through a 15:1 gearbox to increase the torque provided to the user. As the voltage provided to the motor is constant from the implemented power supply, the motor can be controlled via Pulse Width Modulation (PWM), turning the power supply off and on again at a defined rate to control the average power transferred to the motor. In a DC motor the torque provided is directly proportional to the current passing through the motor, which means PWM can be used to effectively control the torque that the motor provides. The relationship between torque and force is shown in Equation 3.8 below:

$$\tau = F \times d \quad (3.8)$$

Where τ is motor torque, F is the tangential force applied, and d is the perpendicular distance from the motor shaft. The Maxon RE 40 motor is capable of providing up to 177mNm of torque, which when fed through the 15:1 planetary gearhead, becomes $0.171 \times 15 = 2.565Nm$ of torque. Since the radius of the wheel is 0.127m, the tangential force felt at the wheel's rim is equal to 20.20N.

The mechanical design of the wheel assembly was created in SOLIDWORKS (shown in Figure 3.7 below), consisting of the motor, gearbox, and encoder assembly, the Arduino Leonardo, and the BTS7960 motor driver. To hold the components together and attach the assembly to the chassis, a sheet metal L-bracket was designed, along with a 3D-printed enclosure and a spacer component.

***Figure 3.7:** A Render of the Wheel Assembly*

The Arduino Leonardo was loaded with custom software that constantly polls the value of the rotary encoder, converts it to the corresponding wheel angle, and sends the value to the game engine. In response, the bespoke plugin for rF2 outputs a value for the steering wheel torque that should be provided based on steering angle, road conditions, vehicle speed and acceleration, and other external factors, and this value is mapped by the Arduino to provide an appropriate PWM value to the DC motor to drive the wheel back to the neutral position.

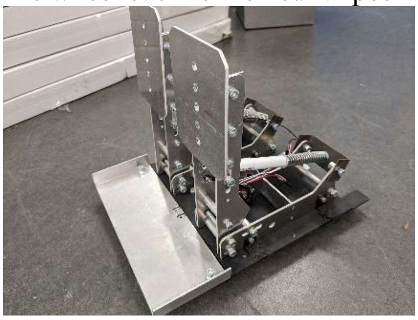

Figure 3.8: *The Pedal Box for the Simulator* [13]

The pedal box used is shown in Figure 3.8 and consists of an accelerator and brake pedal whose depressions are measured via two potentiometers. The accelerator and brake pedals use a singular spring and two springs in serial respectively to mirror the dynamic feel of real pedals. The pedal box was developed by Davidson in 2022 for a previous iteration of this project and was deemed suitable for the simulator without the need for any changes [13].

3.5 Simulation Environment

To create an immersive simulation experience, proper consideration of the hardware and its requirements was required. A 37-inch screen was mounted at a suitable distance from the driver producing a field of vision of 50° horizontally and 40° vertically, which research suggests is the minimum range for an immersive experience [18]. Speakers were also mounted either side of the TV with a subwoofer beneath the seat to allow for surround sound and seat vibrations which further add to driver immersion [19].

In parallel with hardware considerations, the software environment needed to meet criteria to ensure user immersion. The choice of UDP for data transfer was made due to its reputation n for near real-time communication [20], ensuring a seamless link between the simulation software and external hardware components with a response time under 300ms. If this response time is not met, there are risks of visual immersion breakdown due to conflicts with the average racing driver reaction time. This lies in the range of 400ms to 470ms [21].

Additionally, custom-created modifications for rF2 were created to increase user immersion. A racetrack was designed to replicate the characteristics of real-world circuits, while showcasing the full range of features of the simulator. Additionally, an in-game car model resembling the appearance of the physical simulator hardware was created to create a visual similarity between the virtual and physical car features.

4. IMPLEMENTATION

Once the design stage was complete, the necessary parts were acquired, and the design was assembled. Commonly available parts were purchased from external suppliers whilst more complex parts were made in-house. The final build of the simulator, measured at 1530mm × 950mm × 1650mm (H×W×D), is displayed in Figure 4.3 below.

After completion of the main assembly elements, additional safety features such as motor guards and mechanical stoppers were added. To stop unwanted and uncontrollable yaw occurring the rods were angled, effectively locking out the rod end bearings in the yaw direction. Furthermore, dampers were incorporated to mitigate the impact of yaw and to smooth roll operations. Finally, to prevent over-extension of the motors into the non-linear region, flexible, 3D-printed TPU bumpers were added.

Figure 4.1 demonstrates the implemented graphical user interface for the control system, showing how the motion platform can be controlled manually, using an input ('circles') function, or using data from a UDP stream, passed through either a proportional gain system or an adaption of the classical cueing algorithm. A plugin was also created to interface with rF2.

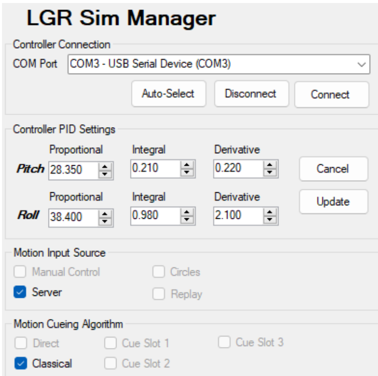

Figure 4.1: *Extract of motion platform GUI, demonstrating the various inputs and processing functions that can be used. Full GUI is presented in Appendix D.*

Figure 4.2: *The Wheel Assembly*

The steering wheel assembly, seen above in Figure 4.2, was constructed from a laser-cut sheet metal L-bracket, a purchased shaft coupling, and

Figure 4.3: *Final implementation of the simulator. Image shows the simulator in use with full driver-in-loop simulation taking place. Peripheral images highlight seatbelt (A), chassis control electronics (B), rear pitch bumpers (C), roll bumpers (D), pedals (E), speakers (F), steering & E-Stop (G), & actuation motors & shields (H).*

several 3D printed parts, and was tested independently of the vehicle. A design error however meant that the completed assembly could not be attached to the simulator chassis due to a shorter motor shaft length than expected. Having verified that the steering wheel would work correctly as an input to the game if not for the connection issues, the assembly was then switched for a Logitech Driving Force Pro wheel and pedals, which were attached to the simulator as a temporary solution for testing.

5. VALIDATION TESTING

Numerous tests were conducted to verify that the performance of the actuation system meets the requirements, using 'George' the test dummy in each case. A high-frequency optical motion capture system, the Optotrack Certus [22], was used to measure the actual pitch and roll of the chassis. Multiple targets were placed on both the moving and stationary platforms with recordings triggered by a pulse from the Arduino.

Once George had been seated within the chassis several preliminary safety tests were performed. It was found that the chassis was able to balance at the approximate neutral position (0° pitch or roll), without requiring any intervention from the motors or stoppers. This validates the CoM calculations.

Additionally, the system safety has been ensured for spectators and users during mounting and dismounting by adding guards and shields to areas with electronics and fast movement components alongside hazard labelling for all pinch/crush areas.

5.1 Motion System: Step Input Testing

To evaluate the transient performance of the actuation system for pitch and roll, step input functions were applied to pitch and roll separately, while holding the other axis at 0^{o}. Figures 5.1 and 5.2 demonstrate these step inputs for pitch and roll respectively.

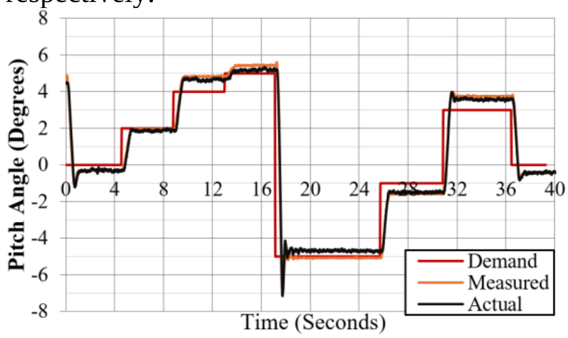

Figure 5.1: *Pure Pitch Step Input.*

From Figure 5.1 it was observed that the simulator performs well in pure-pitch step inputs, completing the maximum step input of $(-)10^{o}$ in

$400ms$, with steady state error at less than 1^{o} for all step conditions.

From Figure 5.2 it was deduced that roll performance is less than ideal as although the maximum step input of $(-)10^{o}$ was achieved in $420ms$, the steady state error in some cases is in excess of 2^{o}. While the roll performance may benefit from some additional PID tuning, it is noted that due to mechanical backlash in the crank system there is a significant free play in the roll and yaw axes which is likely to be the principal cause of this error. It is suggested that this backlash may be somewhat mitigated by installing additional roll dampers, however this possibility is left for future work.

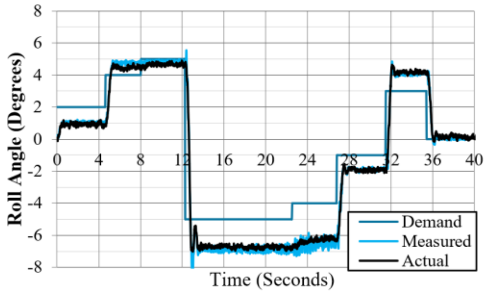

Figure 5.2: *Pure Roll Step Input.*

5.2 Motion System: Dynamic Input Testing

To evaluate the performance of the actuation system in both pitch and roll simultaneously, a sinusoidal function was set as the input to pitch and roll, with a 45° phase offset between the two input functions. Amplitude was increased from an initial 2° up to 5° in the first 36 seconds, and then frequency was increased from 0.25Hz to 0.8Hz in the remaining 24 seconds.

Figure 5.2 contains a plot of demanded, measured, and actual pitch and roll angles for this test. Here it was observed that the measured and actual pitch and roll correlate very closely with only slight over-estimation at the extremities. This is likely due to reaching the limit of the linear region for crank angle against chassis angle.

In addition, it was found that the responsiveness of the motion platform was good, with the leading edge of actual pitch and roll following closely behind that of the demand. However, it was noted that some overshoot does occur, particularly at higher frequencies. This is likely due to the PID controller being overly aggressive and applying too much proportional gain. However, if the proportional gain was reduced, it would likely result in reduced responsiveness and therefore it was determined that this level of overshoot is acceptable.

In addition, it was noted that towards the end of the test as the frequency surpassed 0.8Hz, the motion platform failed to follow the demanded angles and the motors began to stall. This is evident in Figure 5.3 where the amplitude of oscillation reduces below the demand angle for both pitch and roll at around 58 seconds. Therefore, it is suggested that 0.8Hz is an upper limit for this input function.

Ultimately, these tests demonstrate that the implementation is responsive to impulse and continuous input functions, and can achieve angles of up to, including, and in excess of $\pm 5^{o}$.

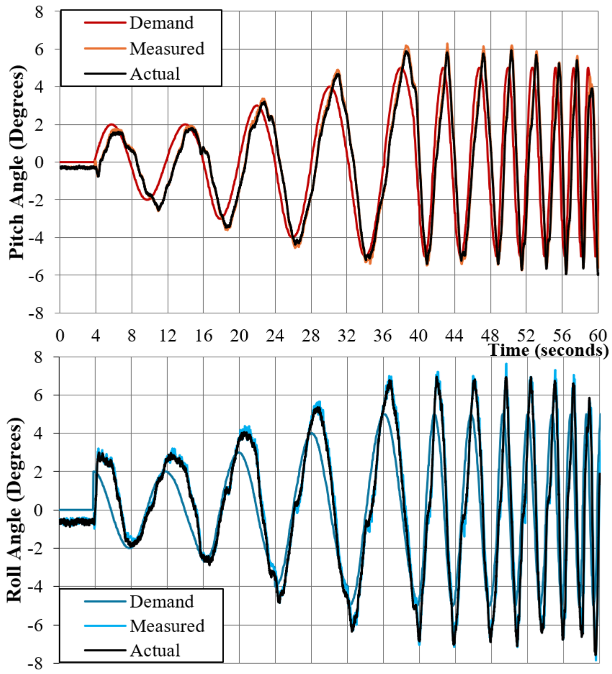

Figure 5.3: *Pitch and Roll angle against time for a 60 second period of sinusoidal input with increasing amplitude, then increasing frequency. Optotrack ('Actual') pitch and roll data overlayed.*

This demonstrates that the simulator is dynamically safe as the controller is stable and has been integrated with an emergency stop to cut power immediately, and the user has a safety harness to maintain control of the simulator.

5.3 Driver-In-Loop Testing

The Logitech steering and pedals were mounted into the chassis to enable full driver-in-loop (DIL) testing to take place along with visual, aural, and haptic feedback via the TV, sound system and subwoofer respectively. A 70kg occupant was seated in the simulator and the environment was set up to drive a McLaren M23 around the Mount Panorama Racing circuit with MCA settings shown in Appendix D.

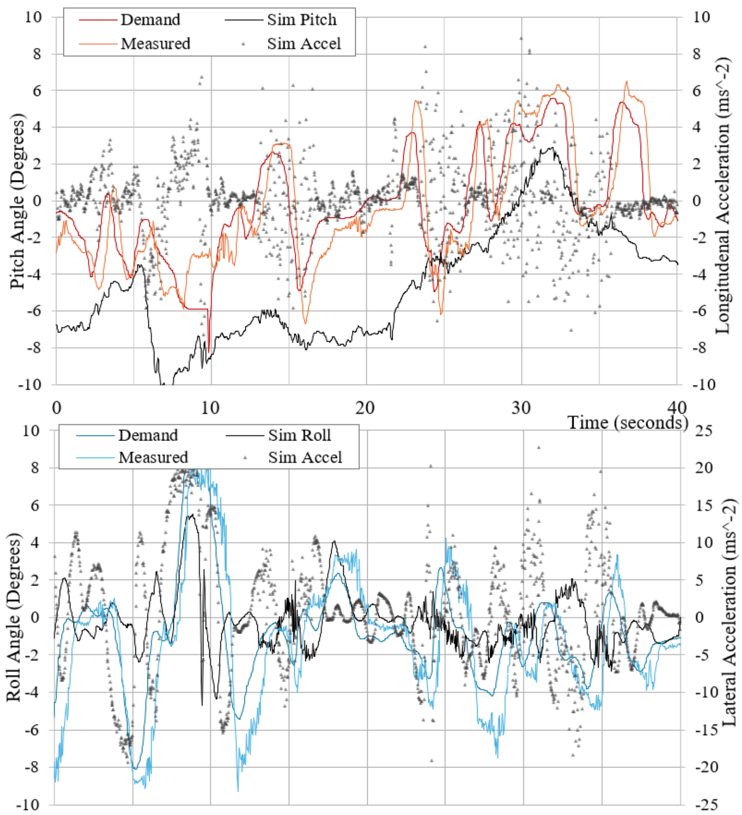

Figure 5.4: *Pitch and roll demand against time for full DIL simulation using Logitech steering and pedals. Pitch, Roll, longitudinal acceleration, and lateral acceleration (i.e. inputs to MCA) from the simulation environment plotted on same grids.*

Figure 5.4 demonstrates the pitch and roll performance of the simulator. Here it is shown that measured pitch and roll of the simulator follows that of the demand, albeit with some delay. It is clear that the MCA is effectively attenuating high-frequency acceleration inputs where sudden large changes in acceleration result in small movements of the platform. It is also observed that the washout filter is attenuating low-frequency inputs as the vehicle is descending a steep hill in the first 25 seconds, resulting in a large input pitch angle, but the MCA effectively avoids saturation of the platform's pitch axis. In addition, it was noted that from the driver's perspective the motion cues are believable and do add a significant element of immersion to the simulator, although a degree of bias is recognised as ethical approval was not returned in suitable time to conduct unbiased 3rd party testing despite being submitted well in advance.

However, while the motion platform responds to pitch demand with a reasonable level of accuracy and relatively little lag, roll response is less than ideal. It can be seen to suffer from large ($\approx 2^{o}$) overshoots, for example at 27 seconds, and struggles to effectively simulate small displacements, for example at 22 seconds. This is most likely a symptom of the mechanical compliance discussed in section 5.1.

In addition, as to be expected with the classical MCA, there is a degree of error between the simulated environment and the demanded pitch and roll angles. For example, at 13 seconds the vehicle begins a low-speed (50kmh^{-1}) right-hand bend on a banked section of track. The roll of the simulated vehicle is negated by the banking, and so the platform's roll opposes lateral acceleration. This is problematic for the classical MCA applied to a 2-DoF simulator as opposing roll and acceleration vectors could result in attenuation of feedback to the driver. Even for simulators with a greater number of DoFs this is likely to be tricky as sustained acceleration must be achieved in the vertical axis which would require either a very large range of motion or even employ a human centrifuge.

6. CONCLUSION

Literature informed a suitable design concept for a 2 DoF system, which led to detailed hardware and software designs. Relevant vehicle dynamic analyses were conducted to identify design targets for accurate replication of motion. An electro-mechanical crank actuation system was designed, optimised, and implemented with a control system capable of producing real-time feedback. An immersive simulation environment was collated, and in conjunction with a motion platform control software and plugin, enables the acquisition and real-time transmission of the appropriate Telemetry and HMI data.

The designs were realised within the £500 budget and assembled to form the finished product. Difficulties mounting the custom steering wheel led to the use of a temporary Logitech wheel that was mounted on the chassis and was used to facilitate validation testing.

The performance of the actuation system was critically evaluated based upon response characteristics and speed, and was found to be adequate in pitch manoeuvres but demonstrated excessive steady-state error in some roll manoeuvres. Full DIL testing was completed, and drivers reported that the motion cues were believable, if a bit slow in some cases.

The simulator's footprint falls within the design requirements, enabling the simulator to be used for outreach events such as the LGR F24 unveiling event, demonstrating its portability.

6.1 Future Work

Several areas that would benefit from further work have been identified. These include:

- Redesign the steering assembly's mechanical connection to factor in the shorter motor shaft.
- Configure pedal box as rFactor 2 input rather than using the Logitech pedals.
- Reduce mechanical compliance of roll axis by either adding dampers or adjusting the motor arrangement.
- Perform non-biased validation of simulator based around 3rd-party testing.

ACKNOWLEDGEMENTS

The authors of this report would like to thank Dr Andrew Jackson for his guidance and support throughout the duration of this project. They also thank Leeds Cares for funding George the Test Dummy who was used for validation testing, and Leeds Gryphon Racing for use of their laboratory.

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APPENDIX A – CONTRACT PERFORMANCE PLAN

Virtual Racing: Building a Formula Student Race Car Simulator

MECH5080M Contract Performance Plan

MECH5080M – Team Project
Virtual Racing: Building a Formula Student Race Car Simulator

***Students**:*
Curtis Lovett - 201321318
Jordan Partridge - 201301826
Alex Bury - 201324944
Mathew Fuller - 201289335
Qianli Liang - 201438295

Supervisor: Andrew Jackson

Industrial Mentor: University of Leeds – Formula Student 'Gryphons Racing'

Date: 07/11/2023

Table of Contents

Introduction and Background

Formula Student (FS) is an annual engineering competition run by student teams from over 100 universities all over the world, in which the aim is for students to create a fully functional racecar using their engineering expertise. This car is then raced against other teams as a competitve way to demonstrate the practical engineering and project management skills that the students have learned [1].

Just like with professional racing teams in competitions like Formula One, an accurate driving simulator is an invaluable tool for FS teams to help train their drivers, especially when the real vehicle is undergoing work, damaged, or unavailable to be driven on a real track (i.e. track unavailability). Simulators can also be used as a safe enviornment to perform both training and research, and, when implemented correctly, can be easily configured to different settings to simulate different road conditions, different vehicle configurations, vibration, noise, and plenty of other variables [2]. A further use is as an outreach tool to demonstrate what the FS team does and recruit more members to join the team and share their engineering expertise. This is important to improve the overall competency of the team.

One key area in simulator creation is the inclusion of data acquisition systems built into the device [3]. These not only allow the device to more accurately portray real motion to the driver, but also allow for real-time driving data to be collected (for example how a particular driver slows down before an upcoming turn), which can be useful for strategy analysis. This data can also be compared to data from the real vehicle if available, which can aid in iterative improvement of the simulator over time.

Other notable areas of importance for the simulator are realistic emulations of steering wheel resistance, visual and auditory cues, vibration, and pedal resistance. These systems work in tandem to create a more natural and immersive experience, with the steering wheel and pedals being the most important, since they are the primary ways that the driver interacts with both simulator and vehicle [4].

Previous projects have aimed to create a similar device for the University of Leeds' Formula Student team, but currently there is no functioning device that the team can use for training or data acquisition. This project aims to build upon the previous work carried out by these students, resulting in a fully realised simulator.

Aim

To design and manufacture a portable and cost-effective simulator of the Formula Student Race Car for driver training and outreach activities.

Objectives

1. Determine a suitable approach for the simulation encompassing both hardware and software aspects.
2. Design and develop an actuated cockpit environment to simulate the dynamics of vehicle including functional feedback system.
3. Adapt pedal and steering arrangements to mimic functionality of the real formula student car.
4. Implement a virtual environment containing an immersive graphical representation of the formula student car and external surroundings.
5. Implement auditory and haptic feedback systems to deliver a highly immersive driving experience to the user.
6. Ensure a feasible level of portability to aid with outreach events such as university open days and formula student events.
7. Minimise simulator discomfort and ensure ergonomic experience for a wide range of users.
8. Deliver the aforementioned objectives alongside a critical assessment of safety with adequate mitigation in place.
9. **Stretch Objective:** Improve the immersive experience by enhancing the actuation system, implementing a virtual-reality headset, and replicating racing-condition features.

Activities and Deliverables

For Objective 1:

a) Literature review of existing software to determine a suitable package for the application.

b) Detailed analysis of existing hardware with research into additional appropriate hardware.

For Objective 2:

2a) Suitable actuators found and purchased capable of producing the required forces.

2b) A lightweight chassis mounted upon a 2 DoF actuated rig capable of simulating pitch and roll.

2c) An accurate dynamic model to mimic the real life feel of a race car.

For Objective 3:

3a) A steering system capable of providing realistic force feedback.

3b) A communications network for transferring information from both the steering and peddles into the game engine.

For Objective 4:

4a) An in-simulation representation of the formula student car within the simulation software that can be tweaked through the use of software modification.

4b) A custom racetrack that can be loaded into the simulation software.

4c) A stream of data output from the game engine to the simulator hardware to enable seamless communication between the hardware and software components.

For Objective 5:

5a) A sound system that can accurately portray engine and ambient noise.

5b) A vibration system with game engine synchronization

For Objective 6:

6a) A relatively lightweight and compact device, that can fit in the school's lift.

6b) An aesthetically pleasing design that upholds engineering quality.

For Objective 7:

7a) A suitable choice of hardware and software to reduce motion sickness.

7b) An adjustable design that can accommodate a wide range of users.

For Objective 8:

8a) An electrically and mechanically safe simulator with an emergency stop and other risk mitigation.

For Objective 9 (Stretch):

9a) An integrated virtual reality system and lower latency actuators for a more immersive experience.

Resources and Expenditure

Table 1 contains the expected expenditure based upon required components. Note that most of these values are estimates as market fluctuations results in price variability.

Table 1: Details of required components and anticipated expenditure to meet base and stretch objectives.

To Meet Base Objectives			
Item	**Description**	**Expenditure**	**Comment**
Chassis	Formula Student 2017 Chassis.	N/A	Existing from previous project.
High-Performance Computer	Re-configuration of existing workstation (GPU/SSD upgrade).	£200 (est)	For running the simulation software.
Chassis Actuation Motors	Output speed: 80rpm, Output torque: 7nm, 24v DC, Quantity: 2.	N/A	Existing from previous project.
Chassis Motor Controllers	Used to control motors that actuate the chassis.	£150 (est)	Including Limit Switches
Steering wheel	Formula Student steering wheel.	N/A	Provided by FS team.
Steering Wheel Electronics	Arduino & Electrical Components (buttons, resistors, transistors etc)	£40 (est)	Available from the University.
Pedal box – Mechanical	Existing pedal box from previous project with appropriate upgrades.	£20 (est)	Provisions for replacement springs..
Pedal box – Electrical	2 x Rotary Encoders, Arduino, Cables, etc.	£40 (est)	
Simulation Software	rFactor 2.	£10 (est)	From re-seller.
Existing engines/ packages/ modules	Open Source tools to interface with rFactor 2.	N/A	Open Source, freely available.
3D printing	3D Printed Components.	£40 (est)	
	Total	**£500**	

To Meet Stretch Objectives			
Item	**Description**	**Expenditure**	**Comment**
VR Headset	Oculus Quest 2 or similar.	£299.99 [7]	Personal item available for testing.
Upgraded actuators	Fast-response linear actuators or DC Motors.	£1600 (est)	
Vibration system	Motor with eccentric weight and motor controller.	£100 (est)	
	Total	**£1999.99**	

Project Management

Team Structure

The team is made up of 5 students with Andrew Jackson as the main supervisor. The team has opted for an Agile Flat Hierarchy management approach, with Curtis as lead and is the main go between with the module leader. The competencies of the group members are below:

Curtis Lovett

Curtis is a L4 Mechanical Engineering at the University of Leeds. Having just returned from a year in industry working as a Design Engineer at Eaton Corporation, Curtis' knowledge of design and the surrounding areas is profound. Curtis has a keen interest in the automotive industry, having briefly worked as a part of the Formula Student team before and studying modules based around 'Vehicle Design', 'Automotive Chassis' and 'Electrical and Hybrid Drivetrain'.

Alex Bury

Alex is a L4 Mechanical Engineering student at the University of Leeds who has a wealth of experience within the formula student team, previously leading the drivetrain development of both internal combustion and electric vehicles. With a strong interest in manufacturing and automation, Alex also has a part-time job at PepsiCo following his placement year and continues to leverage his programming skills to develop digital applications for manufacturing facilities.

Jordan Partridge

Jordan is a L4 Mechatronics and Robotics student at the University of Leeds. He recently completed a year-long placement at Solid Solutions and is therefore an expert in using the SOLIDWORKS suite of software, including mechanical design, simulation, animations and rendering. He has also undertaken modules in circuit design, programming in C++, MATLAB, and Python, and has a wealth of knowledge about Embedded Systems and signal processing.

Mathew Fuller

Mathew is a Level 4 Mechatronics & Robotics student at the University of Leeds. He has gained experience during extracurricular activities such as the Leeds University Rocketry Association where he built a rocket as a member of the avionics team, as well as personal projects such as a voice-controlled prosthetic arm. He has experience in multiple coding languages (C++, Python, R, Rust etc.), SOLIDWORKS, and several other pieces of software, as well as experience in manufacturing and simulation.

Albert (Qianli Liang)

Albert is a Level 4 Mechanical Engineering student at the University of Leeds. His recent internship in China gives him experience in developing the control system of autonomous vehicles and the remote sensing system. He has developed his skills in MATLAB, Python, SOLIDWORKS and computer vision. He has also taken modules in automotive propulsion systems, vehicle design, automotive chassis and Electrical & hybrid drivetrain.

Risk Assessment

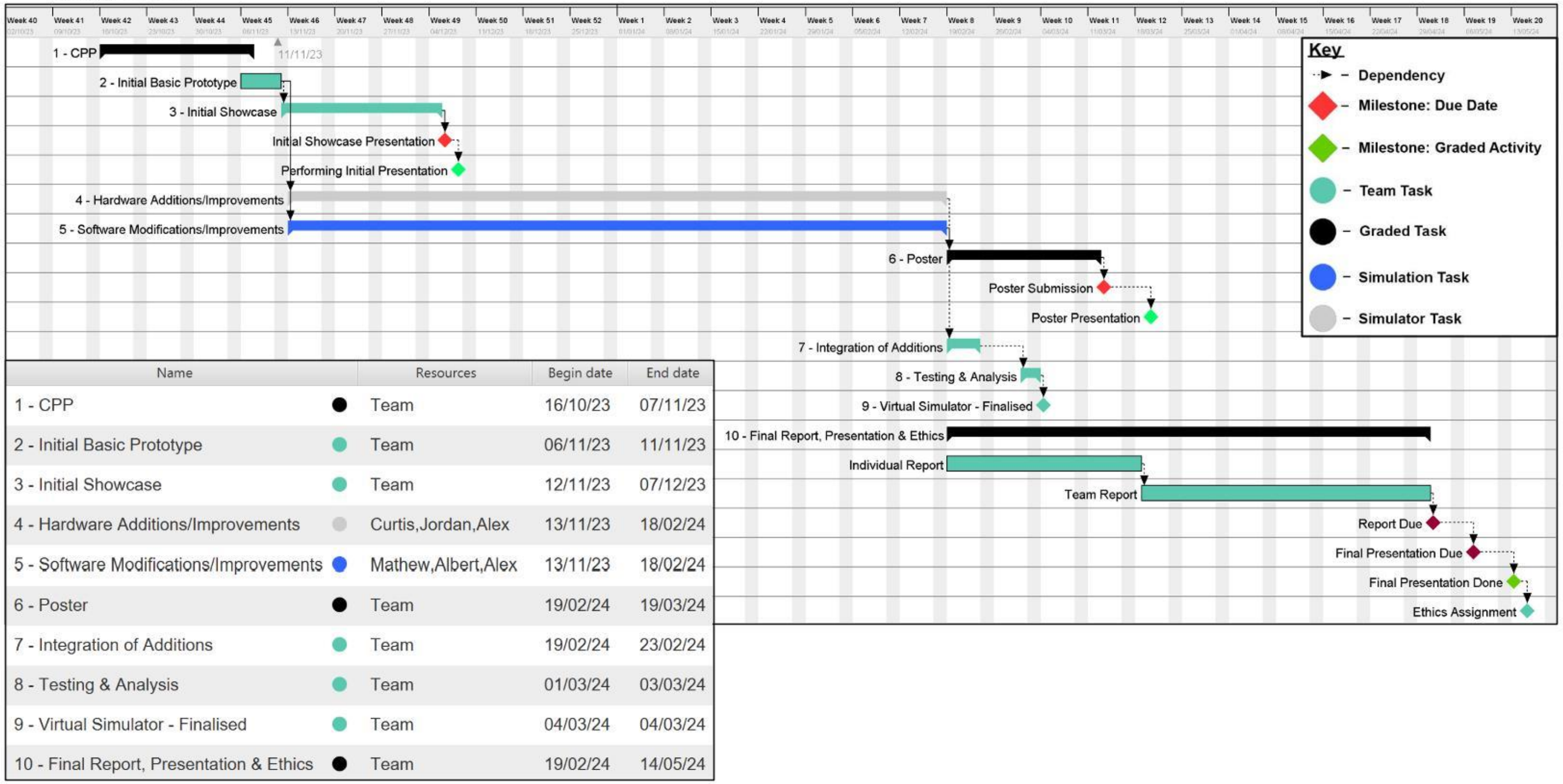
Table 2 details the identified risk, mitigations, and contingencies specified.

Table 2: Risk Management Table.

Risk	(Before Mitg.)		Mitigation	Contingency	(After Mitg.)
	Proba-bility	Impact			Severity
Damage of key components such as the chassis or steering wheel during assembly	Low	High	Resources are available to repair components in workshop	Repair parts	Low
Delay in arrival of purchased components/good	Med	High	Order all parts with a 20% buffer on lead time	Use alternative suppliers	Med
Final simulator is unsafe for testing	Low	High	Consider all aspects of safety throughout the design process	Redesign unsafe components	Med
Unavailability of team member (Illness or health problem)	Low	High	Add safety margins into the plan	Contact the module leader and supervisor to discuss further actions	Low
Inadequate budget	Low	Med	Use resources readily available at the university	Contact the formula student team to discuss further budget	Low

Unavailability of workshop	Low	Med	Complete lab induction in the early stages of the project and book time in, in advance	Use alternative design where less time in the workshop is required	Low
Documentation loss	Low	High	Store all key documents in shared online databases e.g., OneDrive	Recover most recent back up	Low
Limited access to software due to licensing issues	Low	High	Use software in which the university already has a shared license or that does not require a license	Use other available software	Low
Poor time management leading to incomplete objectives	Med	High	Objectives split into primary and stretch, hence prioritise the primary objectives	Agree a new scope with formula student team	Med
Rejection of ethical approval for testing	Low	High	Apply for approval in the early stages in the project	Do not include testing in final report	Med

Gantt Chart



Name	Resources	Begin date	End date
1 - CPP	Team	16/10/23	07/11/23
2 - Initial Basic Prototype	Team	06/11/23	11/11/23
3 - Initial Showcase	Team	12/11/23	07/12/23
4 - Hardware Additions/Improvements	Curtis,Jordan,Alex	13/11/23	18/02/24
5 - Software Modifications/Improvements	Mathew,Albert,Alex	13/11/23	18/02/24
6 - Poster	Team	19/02/24	19/03/24
7 - Integration of Additions	Team	19/02/24	23/02/24
8 - Testing & Analysis	Team	01/03/24	03/03/24
9 - Virtual Simulator - Finalised	Team	04/03/24	04/03/24
10 - Final Report, Presentation & Ethics	Team	19/02/24	14/05/24

Figure 1 Project Gantt Chart

Ethical Considerations

The simulator is designed to seat a human who will be subjected to stimuli in the form of video, sound, motion, and force feedback through the controls. While the aim is to replicate the feedback an individual feels when driving a vehicle, it is virtually impossible to identically replicate this due to limited motion, computational power, and modelling accuracy [5] [6]. Consequently, it is likely that some participants will feel motion sickness when using the simulator, and therefore they may become uncomfortable. It is therefore advised that any participants should be made aware of the risks associated with using the simulator, and that they can immediately and safely stop the stimuli if they desire.

In addition, to properly evaluate the efficacy of the project, it will be necessary to conduct a study with participants from the industrial sponsor, in this case the formula student team, and request them to complete a survey for feedback. As they will be reporting on their experience in an *active* environment (IE one with stimuli that respond to their input), this aspect of the project does not fall within the MECH5080M block ethical approval and therefore requires separate approval.

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Appendix A – Ethical Submission Form

MECH5080M ethical approval form

Don't forget to save your answers in the next screen (you can ask for it to be emailed to you) - you need to include the file as appendix of your scoping and planning document. Once completed, if more information is required, you will be contacted by the module leader

1. What is your team number? (this is the PID number given to you at allocation) *

   135

2. who is your team lead? *

   Curtis Lovett: mn19cl@leeds.ac.uk

3. Does your project involve human participants or their data (eg interviews, questionnaire, focus group, measurement) *

   ◉ yes

   ○ no

4. Is it a clinical trial or an investigation of a medicinal product?

   ○ Yes

   ◉ No

5. Are participants NHS patients (including deceased), or identified as participants because they are relatives of or carer of NHS patients (not including existing PPI groups)?

   - ( ) Yes
   - (•) No

6. Are NHS staff involved as participants, because of their role in the NHS?

   - ( ) Yes
   - (•) No

7. Is this project already covered by the school low risk block ethical approval?

   - ( ) Yes
   - (•) No

8. Confirm that you know that your project requires University ethical approval

   Yes

APPENDIX B – RISK ASSESSMENT

Faculties of Environment and EPS

Risk Assessment Form

UNIVERSITY OF LEEDS

School(s):	Mechanical Engineering	Group/PI:	
Risk Assessment Title:	Formula Student Driving Simulator	Assessment No:	
Location of Activity:	G.52	Name of Assessor:	Andrew Jackson
Details of Activity:	Testing of an actuated driving simulator		
Other assessments or documents which might also be required, X if needed:			
Manual Handling ☐	COSHH ☐	Noise ☐	Other (please specify)

Signature of Assessor	
Signature:	Date:
Signature of Manager(s) "The risks identified in this assessment are controlled so far as is reasonably practicable"	
Signature:	Date:

Date of Reassessment (Every two years minimum)	Are There Any Changes To The Activity Since The Last Assessment?	Signature of Manager

Name of Person Undertaking the Activity	School	Role	Signature	Date

LIKELIHOOD (L)	
5	Inevitable
4	Highly Likely
3	Possible
2	Unlikely
1	Remote Possibility

SEVERITY (S)	
5	Very High –Death or permanent disability
4	High – Serious injury (hospital admission)
3	Moderate - RIDDOR over 7 days
2	Slight - First Aid treatment
1	Nil - Very Minor

RISK RATING	ACTION
1 – 4	Broadly Acceptable - No action required
5 – 9	Moderate - Reduce risks if reasonably practicable
10 – 15	High Risk - Priority Action to be undertaken
16 – 25	**Unacceptable - Action must be taken IMMEDIATELY**

RISK RATING = LIKELIHOOD X SEVERITY						
SEVERITY (S)	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5
		1	2	3	4	5
		LIKELIHOOD (L)				

PROCESS / ACTIVITY NO.	HAZARD e.g. Falling Objects, Fire, Explosion, Noise, Violence etc.	PERSONS AT RISK e.g. Employees, Contractors, Members of the public	POSSIBLE OUTCOME	RISK RATING WITHOUT CONTROLS (LXS)	CONTROL MEASURES e.g. Guards, Safe Systems of Work, Training, Instruction, Authorised Users, Competent Persons, Personal Protective Equipment (PPE)	RISK RATING WITH CONTROLS (LXS)	FURTHER ACTION REQUIRED? Yes/No
	Moving Parts	Users/Bystanders	Pinching or entrapment	6	Warning Stickers, Shielding of moving parts, emergency stop button	4	No
	Sharp Corners	Users/Bystanders	Cuts, scrapes, and puncture wounds	6	Sanded metal surfaces, removal of protruding edges	4	No
	Flashing Images	Users	Epileptic fit	3	Verbal warning about epilepsy risks, emergency stop button	3	No
	Motion Sickness	Users	Nausea, vomiting, imbalance	6	Verbal warning, limited range of motion, emergency stop button	4	No
	Tripping	Users/Bystanders	Blunt Force Injuries	1	Gated-off perimeter around device, operator present at all times	1	No
	Strong Vibration	Users	Blunt Force Injuries, Concussion	12	Emergency Stop Button, Harness, Mechanical end stops	4	No

ACTION If further action has been identified above, describe what needs to be done, by whom with agreed timescales for completion			
Description	**Who**	**Target Date**	**Completed On**

COMMENTS AND INFORMATION Use this section to record any additional information, comments, dynamic risk assessment comments etc.

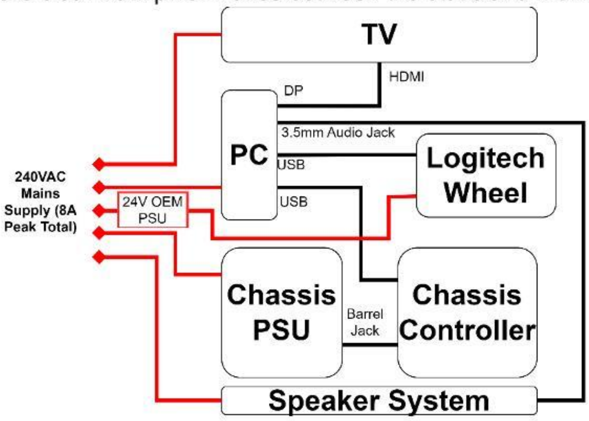
Process / Activity Log

PROCESS / ACTIVITY	PROTOCOL REF. NO. e.g. SOP, COSHH, OOH/LONE WORKING
1.	
2.	
3.	
4.	
5.	
6.	
7.	
8.	
9.	
10.	
11.	
12.	
13.	
14.	
15.	

APPENDIX C – STANDARD OPERATING PROCEDURES

LGR Simulator Standard Operating Procedures

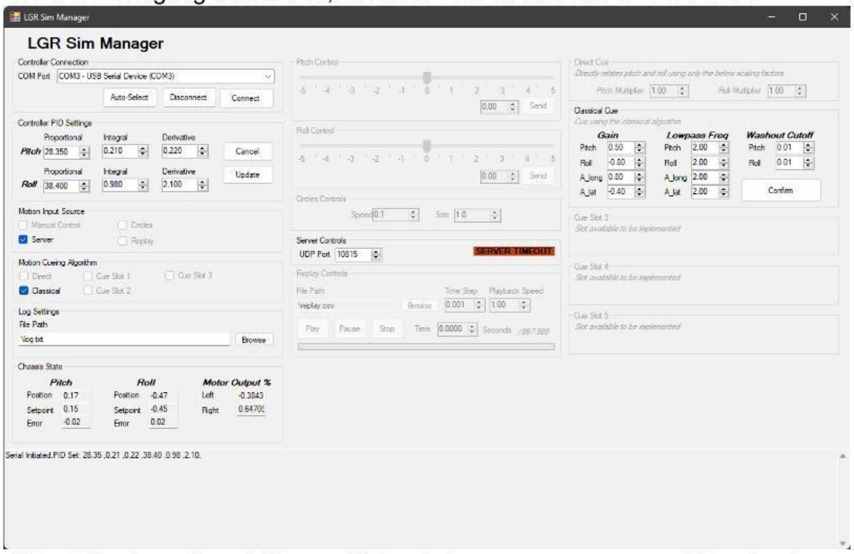
1. Ensure the frame is locked using the locking pins as shown in the picture below.
2. Find a suitable test location away from highly trafficked areas and ensure that the test area is clear from trip hazards. Lock the wheels of the simulator.
3. Perform a visual inspection of the simulator components to check for loose fixings and damaged components. **If any issues are found, do not proceed until rectified.**
4. Ensure the emergency stop button is depressed to prevent powering at this stage.
5. Connect the various components of the simulator as shown in the diagram below. Ensure all wires are clear from pinch zones between the static and moving platform.



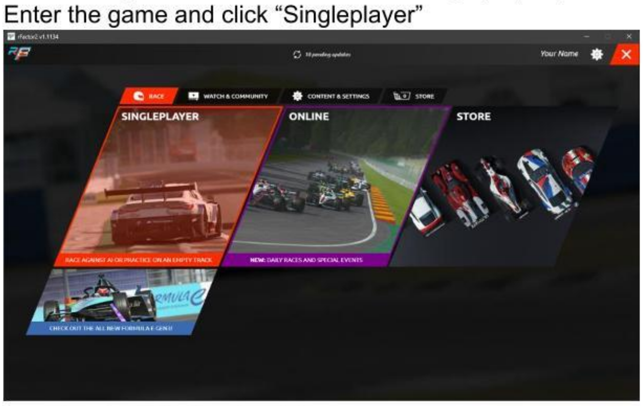
6. Turn on the simulation computer and login to windows. The password is “AndrewJackson”.
7. Get the occupant seated in the simulator, ensuring the harness is tight but comfortable. Make sure they are familiar with the controls and the emergency stop positioned to the right of the steering wheel.

8. On the desktop, open the “LGR Sim Manager Folder” and click on “LGR Sim Manager.exe”. The following application will open.
    a. The application should connect to the chassis controller automatically. If not, you will receive a warning on launch, and you will need to manually connect using the “Controller Connection” area of the GUI.
        i. To do this, first select the appropriate COM port in the drop down using the auto-select function.
        ii. Then click “connect”. If successful, you should see “Serial Initiated.” In the console window at the bottom directly followed by the saved PID settings from the microcontroller.
    b. By default, the program is configured to move the chassis manually using the GUI controls and the direct cueing function. For simulation use, you must uncheck “Manual Control” within the “Motion Input Source” box, check “Server” within the same box, and similarly in the

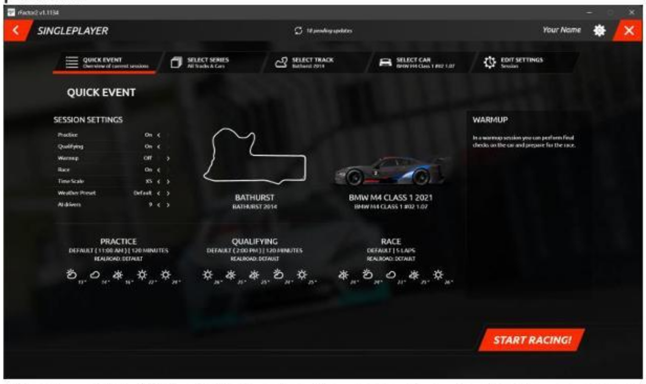
“Motion Cueing Algorithm” box, uncheck “Direct” and check “Classical”.



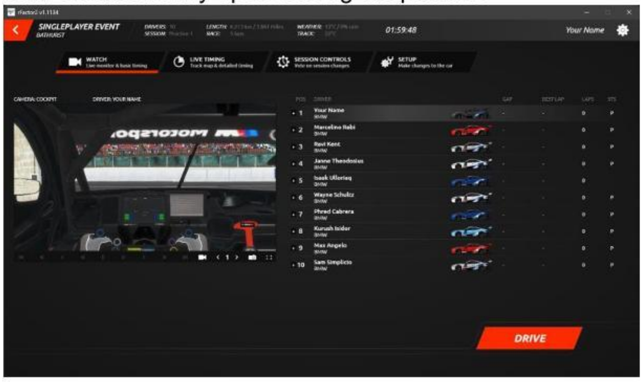
9. **NOTE: After this stage the platform will begin to move, so ensure all bystanders are clear of the motion platform.** Remove the motion platform locks from the simulator and ask the occupant to reset the stop button (Twist clockwise). The motion platform will move to the neutral position. You may need to reset the chassis controller by removing and re-plugging the chassis controller USB into the computer as the lack of response when unpowered can ‘confuse’ the PID controller. If you do this you may need to reconnect the sim manager to the controller too.
10. Open “Steam” on the simulation computer. You may need to login using the following credentials:
    Username: fs_sim_leeds
    Password: AndrewJackson123
    The account is associated with the Gmail account fs.sim.leeds@gmail.com, the password for which is: “AndrewJackson”. You may need to login to Gmail to authenticate the Steam account.
11. Navigate to “Library” and select “rFactor2”. Click play, select the “Play rFactor 2” option and click “Play”. Note rFactor2 can be very slow to load and sometimes crashes.
12. Depending on the preference of the driver, rFactor 2 can be configured to provide various driving experiences. This guide details how to enter a singleplayer practice race.
    a. Enter the game and click “Singleplayer”



    b. **NOTE: At the following stage the UDP Server plugin will begin sending commands to the simulation platform, so ensure all bystanders are clear of the simulation rig.** In the “Quick Event” tab, click “Start Racing!”. The game may take some time to load so please be patient.



c. Finally, click “Drive” to begin. By default autopilot is enabled in the pits so the driver will gain control immediately upon leaving the pit lane.

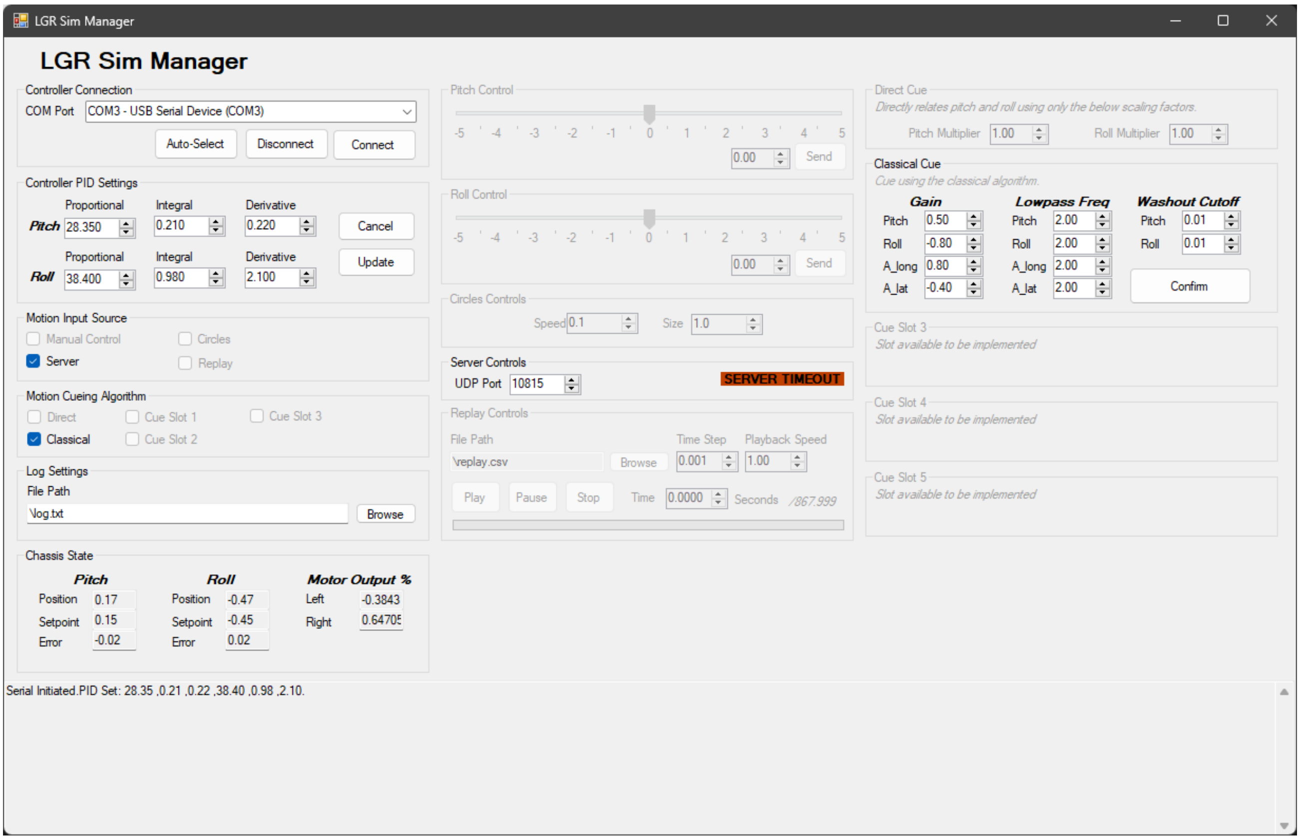


d. The occupant can now drive the vehicle within the simulator using the pedals and steering and experiences motion from the actuation platform.

13. To stop the simulation, press “Escape” on the keyboard and the motion platform will remain at it’s current position.
14. To exit the simulator, first press the emergency-stop button, move both locks and ensure pins are in place. The chassis is now secure for exiting.

APPENDIX D – DEFAULT SETTINGS

The simulator was tested using the following settings. These are recommended for best performance.



APPENDIX E –BILL OF MATERIALS

Item	Subsystem	Purpose	Qty	Responsible	Link	Cost (per item)	Total cost	Notes
24v 10 Power Supply	Chassis Actuation	Motor Power	1	Alex	https://uk.rs-online.com/web/p/switching-power-supplies/1618226?gb=s	74.47	74.47	Wrong PSU Ordered
DC Connector (Female)	Chassis Actuation	Motor Power	2	Alex	https://uk.rs-online.com/web/p/dc-power-connectors/8785257	12.76	25.52	0
DC Connector (Male)	Chassis Actuation	Motor Power	2	Alex	https://uk.rs-online.com/web/p/dc-power-connectors/8104573	8.29	16.58	0
Chassis Control Enclosure	Chassis Actuation	To house the Arduino and motor controllers	1	Alex	https://cpc.farnell.com/spelsberg/111-007/poly-enc-with-trans-lid-182x180x90mm/dp/EN81955?st=abs%20enclosure	22.5	22.5	Discussed making one but found this one for £22.50 which saves lots of time
Chassis Control Enclosure Fan	Chassis Actuation	To cool motor controllers	1	Alex	https://uk.rs-online.com/web/p/axial-fans/2025391?gb=s	7.21	7.21	0
Pinch Warning Sign	Safety	Warning Sign	1	Alex	https://uk.rs-online.com/web/p/warning-signs/3058298?gb=s	5.71	5.71	0
Crush Warning Sign	Safety	Warning Sign	4	Alex	https://uk.rs-online.com/web/p/safety-labels/8134454?gb=s	2.35	9.4	0
Rexroth 40x40mm Aluminium Extrusion 3m Length	Frame	Frame	1	Curtis	https://uk.rs-online.com/web/p/tubing-and-profile-struts/4597211?gb=a	83.88	83.88	0
12mm Rod End Bearing	Chassis Actuation	Rods connecting motor to frame	4	Curtis	https://uk.rs-online.com/web/p/rod-ends/1852512?gb=s	15.04	60.16	0
Thread steel rod (12mm)	Chassis Actuation	Crank connectors	**2**	Curtis	N/A	Internal Sourcing	Internal Sourcing	
E-stop	Safety	Emergency Stop	1	Alex	N/A	Inherited	Inherited	
FS Chassis	Motion platform	Chassis Motion platform	1	Curtis	N/A	Inherited	Inherited	
Motion platform	Motion platform	Motion platform	1	Curtis	N/A	Inherited	Inherited	
Stationary platform	Stationary platform	Stationary platform	1	Curtis	N/A	Inherited	Inherited	
Crank	Chassis Actuation	Crankshaft	4	Curtis	N/A	Internal Sourcing	Internal Sourcing	Manufactured in house
37" TV	Tv assmebly	TV	1	Curtis	https://www.lg.com/ca_en/tv-soundbars/lcd-tvs/37ld450/	Internal Sourcing	Internal Sourcing	
Logitech Speakers	Sound system	Speakers	2	Curtis	https://www.amazon.co.uk/Logitech-Surround-Sound-Speakers-System/dp/B003WJR482	Internal Sourcing	Internal Sourcing	
Logitech subwoofer	Sound system	Subwoofer	1	Curtis	https://www.amazon.co.uk/Logitech-Surround-Sound-Speakers-System/dp/B003WJR482	Internal Sourcing	Internal Sourcing	
Speaker Holder	Sound system	Hold Speakers	2	Curtis	N/A	Internal Sourcing	Internal Sourcing	3D printed
Circular flange	Chassis Actuation	Attach crank to motor	4	Curtis	N/A	Internal Sourcing	Internal Sourcing	Manufactured in house
General fixings	Whole system	Whole system	N/A	All	N/A	Internal Sourcing	Internal Sourcing	
5v Power Supply	General	Provides low voltage DC for control systems	1	Alex	N/A	0	0	
Power Supply Casing (fits both PSUs)	General	Casing to house power systems.	1	Alex	N/A	£0	0	Need to get certified
10k Potentiometer	Chassis Actuation	Measure Chassis Position	2	Alex	N/A	£0	0	Need 1x more if possible
1.5mm^2 flex cable	Chassis Actuation	Supplies power to Motors	1	Alex	N/A	£0	0	Have enough lying around to work with - going to need some cable for E-Stop though
12v 6A Power Supply	Steering	Force Feedback Motor Power	1	Jordan	N/A	£0	0	Inherited
IBT_2 Motor Driver	Chassis Actuation	Motor Power	2	Alex	N/A	0	0	Inherited
Arduino Mega	Chassis Actuation	Actuation Controller	1	Alex	N/A	0	0	Inherited
Desktop Computer	Chassis Actuation	To run simulation environment & Motion System	1	Alex	N/A	0	0	Inherited
Potentiometer Bracket	Chassis Actuation	To hold potentiometers concentric to motors	2	Alex	N/A	0	0	Manufactured
Driver Harness	Safety	Harness	1	Alex	N/A	0	0	Using Borrowed Harness
Motor Guard	Safety	Minimise Crush Risk	2	Curtis	N/A	0	0	Manufactured
Front Bump Stop	Chassis Actuation	Prevent over-extension	2	Alex	N/A	0	0	Manufactured (3D Print)
Rear Bump Stop	Chassis Actuation	Prevent over-extension	2	Alex	N/A	0	0	Manufactured (3D Print)
Lateral Bump Stop Upper	Chassis Actuation	Prevent over-extension	2	Alex	N/A	0	0	Manufactured (3D Print)
Lateral Bump Stop Lower	Chassis Actuation	Prevent over-extension	2	Alex	N/A	0	0	Manufactured (3D Print)
Chassis Electronics Support Frame	Chassis Actuation	Supports electronics within enclosure	1	Alex	N/A	0	0	Manufactured (3D Print)
5V Power Distribution Breadboard	Chassis Actuation	Distributes low-power DC current	1	Alex	N/A	0	0	Inherited
Control Enclosure Mounting Brackets	Chassis Actuation	Mounts Control enclosure to chassis	3	Alex	N/A	0	0	Manufactured
7NM Brushed DC Motor with Integral Gearbox	Chassis Actuation	Actuates chassis	2	Curtis	N/A	0	0	Inherited
Power Supply Mounting Tray	Chassis Actuation	Holds the high-power power supply for the actuation system	1	Alex	N/A	0	0	Manufactured
Logitech Steering wheel and Pedals	Steering	Temporary solution for HMI	1	Alex	N/A	0	0	Inherited
Logitech wheel mounting bracket	Steering	Holds logitech steering wheel in chassis	1	Alex	N/A	0	0	Manufactured
Logitech wheel extender	Steering	Extends wheel closer to driver	1	Alex	N/A	0	0	Manufactured (3D Print)
Display Port to HDMI Cable	Tv assmebly	Display Cable	1	Alex	N/A	0	0	Inherited
Maxon RE40 Motor	Steering	Provides Force Feedback	1	Jordan	N/A	0	0	Inherited
Maxon Planetary Gearhead GP 42 C	Steering	Increases Force Feedback Torque	1	Jordan	N/A	0	0	Inherited
Maxon Encoder MR, Type L	Steering	Measures Motor Position	1	Jordan	N/A	0	0	Inherited
BTS9760 Motor Driver	Steering	Drives the Maxon motor	1	Jordan	N/A	0	0	Inherited
Arduino Leonardo	Steering	Controls the Steering and Pedals	1	Jordan	https://uk.rs-online.com/web/p/arduino/7617324	18.35	18.35	0
Steering Assembly Enclosure	Steering	Holds the Steering Electronics in Place	1	Jordan	N/A	Internal Sourcing	Internal Sourcing	3D printed
Motor L-Bracket	Steering	Prevents Motor Rotation	1	Jordan	N/A	Internal Sourcing	Internal Sourcing	Manufactured in house
Motor Shaft Coupling	Steering	Attaches Motor Shaft to Steering Wheel Spacer	1	Jordan	https://uk.robotshop.com/products/12mm-shaft-universal-stainless-mounting-key-hub	20.26	20.26	0
Steering Wheel	Steering	For the Driver to Steer With	1	Jordan	N/A	0	0	Inherited

APPENDIX F – MEETING LOG

Date	Attendees	Apologies	Absent	Purpose	Key Outcomes	Supervisor Signed
17/10/2023	AB, CL, JP, QL	MF		To discuss division of work	Determine areas of interest & review literature	
25/10/2023	AB, AJ, CL, JP, MF, QL			Agree on division of work	Begin planning work	
01/11/2023	AB, AJ, CL, JP, MF, QL			Planning & Ethics	Review ethics and arrange meeting with client	
06/11/2023	AB, AJ, CL, JP, MF, QL, George Ganiford [LGR], Kris Kubiak [LGR]			Client Requirements meeting	Collect Logitech and computer equipment & set up. Define Requirements.	
15/11/2023	AB, AJ, CL, JP, MF, QL			Update on plans	Begin designs	
29/11/2023	AB, AJ, CL, JP, MF, QL			Individual Sub-Project Updates	Fill in ethics forms, update CAD and render. Finish presentation slides	
06/12/2023	AB, AJ, CL, JP, MF, QL			Planning	Review presentation, prioritise ethics submission	
30/01/2024	AB, AJ, CL, JP, MF, QL			Planning	Detail Designs, focus on dependent tasks	
31/01/2024	AB, AJ, CL, JP, MF, QL			Manufacturing planning	Get purchase list prepared for following week.	
07/02/2024	AB, AJ, CL, JP, MF, QL			Manufacturing planning/order review	Update pricing on BOMs	
14/02/2024	AB, AJ, CL, QL	JP	MF	Report Planning and Updates	Continue designs & implementation	
05/03/2024	AB, CL, JP, MF, QL			Report Planning and Updates	Agreed on focus areas	
06/03/2024	AB, AJ, JP, MF		CL, QL	Updates (Note: Short notice meeting)	Check g52 Availability for manufacturing, make sure all parts are correct	
11/03/2024	AB, CL, JP, MF, QL			Poster Planning	Update relevant poster sections	
16/03/2024	AB, CL, JP, MF, QL			Finalising Poster	Finalise poster areas	
25/03/2024	AB, CL, JP, QL		MF	Group Report Planning	Start report sections, agreed on intensive manufacturing periods	
27/03/2024	AB, AJ, CL, JP, MF, QL			Group Report Structure Meeting	Agreed to finalise group report by 19/04/2024	
08/04/2024	AB, CL, JP, MF, QL			Project Updates	Agreed to assemble wheel to chassis by 12/04/2024 and Optotrack on 11/04/2024	
19/04/2024	AB, CL, MF, QL	JP		Group Report Review	Review structure & content	
22/04/2024	AB, AJ, CL, MF, QL	JP		Group Report questions & Plan moving forward	Agreed to mount Logitech steering and pedals	
26/04/2024	AB, CL, JP, MF, QL			Group Report Review	Review structure & content	
26/04/2024	AB, AJ, CL, JP, MF, QL			Final questions & Structure check	Review structure & content	

APPENDIX G – MANUFACTURING SCHEDULE

Activity	Details	Atendees (hours spent)
Mount chassis on motion platfrom	Ensuring the chassis was sucurely mounted onto the motion platform	Alex (4) Curtis (4)
modications to chassis	Removing impact attenuator and any scrap/sharp metal & adding seat belt	Alex (2 hour) Curtis (2 hour) jordan (4 hours) and albert (1 hours
stationary platform	Crank manufacturing, assemblying actuation system and attaching to stationary platform	Alex (12 hour) Curtis (12 hour) jordan (2 hours)
Ball joint	Mounting the stationary on the motion platform	Alex (2 Hour) Curtis (2 hour)jordan (1 hours)
Electronics	Adding tv, speakers, sub woofer, mounting eletronics for system	Alex (12 hour) Curtis (12 hour)
add saftey features	adding guards and mechanical stopper	Alex (8 hour) Curtis (8 hour)
Steering	steering sub assmebly, including adding motor and wiring	Jordan (10 hours)
Steering & Pedals	Mounting logitech pedal and wheels	Alex (3 hour) Mat (3 hour)

APPENDIX H – DERIVATION OF EQUATION 3.1

Using the schematic below, a simplified version of Figure 3.1, the equation for linear movement of the crankshaft can be derived:

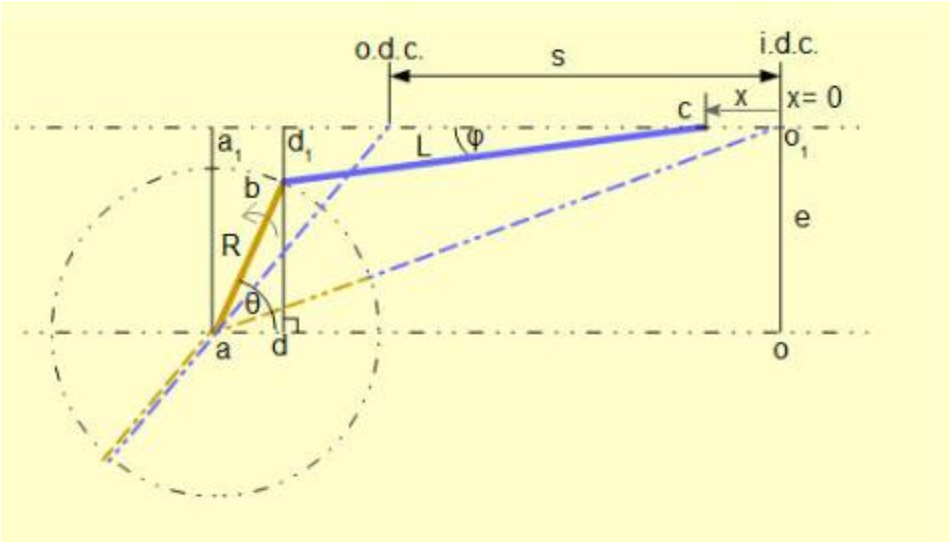


Figure H.1: A geometric diagram outlining the important dimensions witihn an offset crankshaft [5]

Figure H.1 is the same schematic as figure 3.2 but rotated 90° anti-clockwise. This schematic will be used to derive the equation.

$$\text{Note that } x = a_1o_1 - (a_1d_1 + d_1c) \;\&\; ao = \sqrt{(R+L)^2 - (e)^2}$$

$$\text{also, } \quad ao = a_1o_1 \quad a_1d_1 = ad = Rcos\theta \quad d_1c = Lcos\varphi$$

$$\text{Note that in the actuation system: } e = R$$

$$\text{Therefore for any angle } \theta, \varphi \quad X = \sqrt{(R+L)^2 - R^2} - [R\cos\theta - \text{L}\cos\varphi]$$

Therefore, we need to find Lcosφ in terms of θ:

$$\text{Note that } \quad e = (db + bd_1) = (Rsin\theta + Lsin\varphi) \quad \text{thus} \quad Lsin\varphi = (R - Rsin\theta)$$

$$\text{gives: } \sin\varphi = \frac{R}{L} - \frac{R}{L}\sin\theta = \frac{R}{L}(1 - \sin\theta)$$

$$\text{Using identity: } cos^2\varphi = 1 - sin^2\varphi \;\therefore\; cos^2\varphi = 1 - \left(\frac{R}{L}(1 - \sin\theta)\right)^2$$

$$\therefore \cos\varphi = \sqrt{1 - \left(\frac{R}{L}(1 - \sin\theta)\right)^2}$$

$$\therefore X = \sqrt{(R+L)^2 - R^2} - \left[R\cos\theta + L\sqrt{1 - \left(\frac{R}{L}(1 - \sin\theta)\right)^2}\right]$$

Since the equation gives displacement from the top of the slider, the equation must be calibrated to give the movement about 90°. To do this, an equation for the displacement at a crank angle of 90° was found and subtracted from the equation for X:

$$X_{90} = \sqrt{(R+L)^2 - R^2} - \left[R\cos 90 + L\sqrt{1 - \left(\frac{R}{L}(1 - 90)\right)^2}\right]$$

$$X_{90} = \sqrt{(R+L)^2 - R^2} - L$$

$$x = X - X_{90}$$

$$x = \left(\sqrt{(R+L)^2 - R^2} - \left[R\cos\theta + L\sqrt{1 - \left(\frac{R}{L}(1 - \sin\theta)\right)^2}\right]\right) - \left(\sqrt{(R+L)^2 - R^2} - L\right)$$

$$= L - \left[R\cos\theta + L\sqrt{1 - \left(\frac{R}{L}(1 - \sin\theta)\right)^2} \right]$$

Inverted direction to ensure upward displacement is positive and downward displacement negative.

$$\therefore\ x = \left[R\cos\theta + L\sqrt{1 - \left(\frac{R}{L}(1 - \sin\theta)\right)^2} \right] - L$$