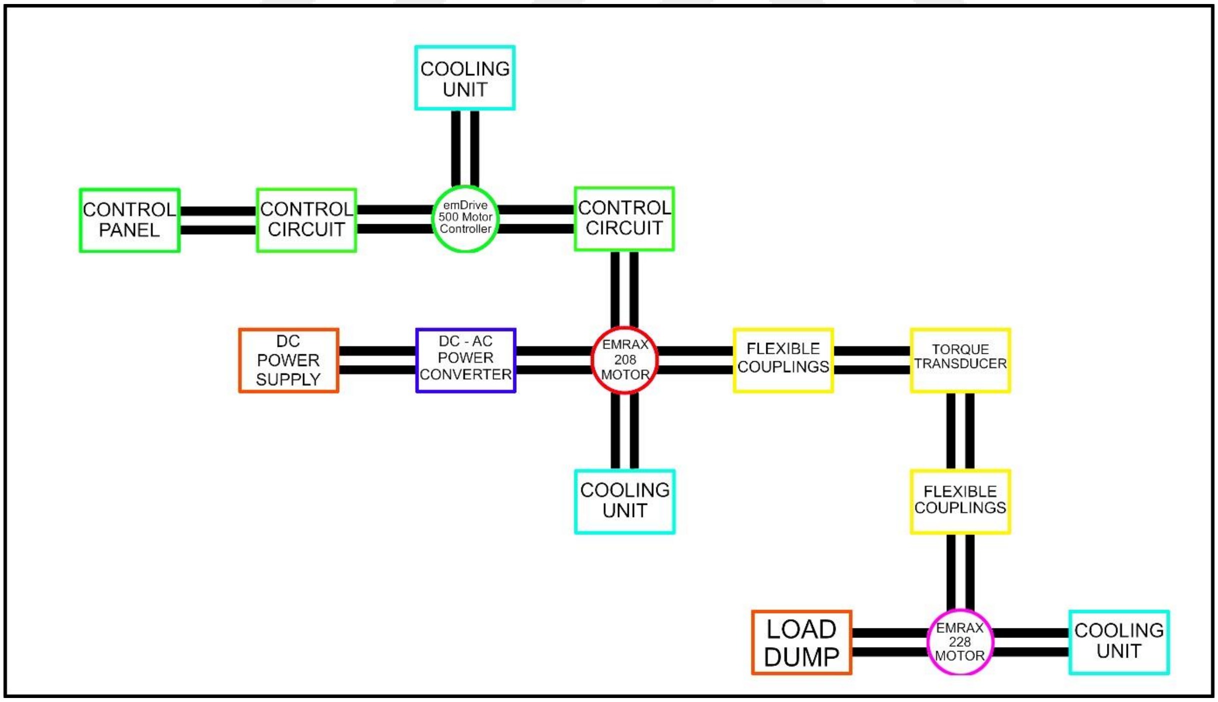
Test Bench Design and Manufacture

Newcastle University

School of Engineering

MEC8095: MSc Project Dissertation

Academic Supervisors: Dr. Iain Evans, Dr. Julian Happian-Smith



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Abstract

The overarching objective of this project was defined as the design and manufacture of a test bench that could perform a series of investigative tests on the motor and motor controller of the Newcastle Racing Formula Student Car. To accomplish this aim, the tasks identified as necessary for project completion were categorised into a number of primary objectives to be completed. These objectives were clearly specified and subjected to critical thinking. Following that, investigation and literature search were conducted to build a foundation of knowledge and understanding to be able to successfully fulfil these objectives. This investigation was conducted for the most prominent test bench components primarily. As for research, internal combustion engines and electric motors were examined and literature review was conduction to control strategies for both kinds of motors but primarily for the electric motors. Afterwards, this foundation was utilised through critical thinking to develop methodologies by the application of which, the primary objectives could be completed. The implementation of the methodologies were done through two primary means. These were design and manufacture work along with acquisition work. Upon the completion of the acquisition, design and manufacturing process, the results obtained from these works were analysed to derive conclusions. The conclusions served as a succinct summary of the achievements attained throughout the course of the project and they were useful in defining future work that could be done to improve the test bench. In the end, all of the components necessary for assembling the test bench were either design and manufactured or simply directly obtained. The assembly of the test bench was relegated to future work.

Declaration

This dissertation was prepared for submission to satisfy the project work requirement of the MSc Mechanical Engineering programme at Newcastle University. This report was specifically prepared to describe and detail all the work that was accomplished for the MEC8095: MSc Project module of Newcastle University. All the work described within the contents of this report with the report itself included was solely the work of Onuralp Yörük, an MSc student at Newcastle University, unless otherwise acknowledged in the writing. The project work described in this report was additionally supported by a Logbook filled with notes of the project development timeline. Also, a project file was provided as well. The author was informed and aware of the penalties for plagiarism and proclaimed this report as free of any such misconduct.

Signed:

Onuralp Yörük

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The completion of this dissertation could only become possible thanks to the invaluable assistance provided by the project supervisors: Dr. Iain Evans and Dr. Julian Happian-Smith. This section was dedicated to acknowledging their support along with that of other sponsors and individuals who assisted in the creation of this work. None of this could have been possible without the valuable advice and guidance of these individuals.

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Iain Evans and Julian Happian-Smith.

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Table of Contents

Table of Figures

Table of Tables

Nomenclature

Abbreviation	Definition
FS	Formula Student
IMechE	Institute of Mechanical Engineers
NR	Newcastle Racing
DC	Direct Current
AC	Alternating Current
kW	Kilowatts
kg	Kilograms
Nm	Newton-metre
rpm	Revolutions per minute
kVA	Kilo-Volt-Ampere
ICE	Internal Combustion Engine
EM	Electric Motor
HIL	Hardware-in-the-Loop
P	Proportional
I	Integral
D	Derivative
RCP	Rapid Control Prototyping
SSI	Steady State Interface
NRX	The Previous Generation of the Formula Student Car
NR11	The Next Generation of the Formula Student Car

1. Introduction

1.1. Formula Student and Newcastle Racing

Formula Student was a prolific, educational engineering competition created by the Institute of Mechanical Engineers (IMechE) with the intention of assisting in the advancement of enterprising engineers [1]. This competition was essentially about the design, development and manufacturing of single seater racing cars by teams of engineering students [2]. These students were encouraged to learn engineering skills as part of a collaborative team effort to produce racing cars which were then put to the test against each other in a race. Newcastle Racing was the title adopted by the team of engineering students assembled by Newcastle University to compete in the Formula Student competition [3]. This team made their first official entry into Formula Student with the appropriately named NR1 in the year 2003. NR1 was the very first racing car created by Newcastle Racing and operated on an internal combustion engine. Newcastle Racing evolved quite far since then and the latest incarnation of their engineering was the NRX, which operated on an electric motor as a fully functional electric vehicle.

Figure 1: The Newcastle Racing Car NRX [3]

Following the NRX, shown in Figure 1, Newcastle Racing started the process of designing the NR11. As a matter of fact, this project was intrinsically linked to the endeavours of Newcastle Racing and was a contribution to further advance the team’s efforts in the development of the NR11. Additional information regarding FS and the Newcastle FS team could be found in the Newcastle Racing Information Booklet produced by the 2018/19 FS team [4].

1.2. Project Specification

The fundamental aim of this project was the design, manufacture and completion of a test bench that could be utilised to perform a series of systematic tests on the motor and motor controller of the NR11.

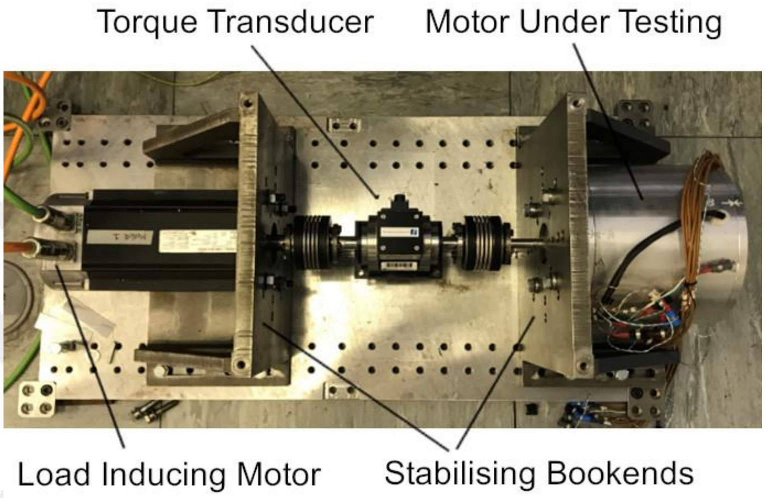


Figure 2: Newcastle University Electrical School Test Bench Design [4]

These tests, conducted by using a test bench as shown in Figure 2, were intended to be performed to understand the interaction between the motor and the controller. The valuable data generated from these tests could be analysed to achieve this understanding. That achievement, in turn, could be used to further improve and develop not only the NR11 but also future Newcastle Racing car designs as well.

Throughout the design process for NR11, the designated priority was the reduction of weight. Newcastle Racing had enjoyed considerable success with the NRX, as that car was the first ever electric vehicle to successfully pass scrutineering in the FS event. Hence, the new objective was to build up on this success by designing a new car with similar specifications but with improved drivability. If the overall weight of the car could be reduced significantly then the performance of the car could be improved greatly with less energy required for operation. To accomplish this goal, research was performed with the intention of determining a motor that was lighter than the EMRAX 228 motor utilised for the NRX. As a result of this research, the EMRAX 208 motor was chosen to be integrated into the newly designed powertrain of the NR11.

The EMRAX 208 motor required a motor controller for smooth, well controlled operation and so, after further research, the emDrive 500 motor controller was chosen for this purpose.

Even though these equipment were acquired, there was no way to test the interaction between the motor and the controller before the NR11 entered the race track. Hence, the goal of this project was originally intended as the utilisation of a test bench in order to perform systematic testing on the chosen motor and motor controller of the NR11. However, the test bench that was necessary for the performance of these tests was not ready in time. Therefore, the fundamental aim of the project shifted from performing tests and analysing data to the design and completion of a test bench that could accomplish those objectives.

1.3. Primary Objectives

The following tasks, designated as the primary objectives, were identified as necessary to be completed for the overarching goal to be successfully attained:

1. Design of a test bench
2. Procurement of a test bed
3. Acquisition of a DC power supply
4. Procurement of a DC – AC power converter
5. Acquisition of the EMRAX 208 motor
6. Procurement of the EMRAX 208 bookend
7. Acquisition of the emDrive 500 motor controller
8. Design and manufacture of a control panel and circuit
9. Acquisition of a torque transducer and flexible couplings
10. Procurement of the EMRAX 228 motor
11. Design and manufacture of the EMRAX 228 bookend
12. Design and manufacture of the shaft adaptors
13. Design or procurement of cooling mechanisms
14. Design or acquisition of a load bank
15. Assembly of the test bench

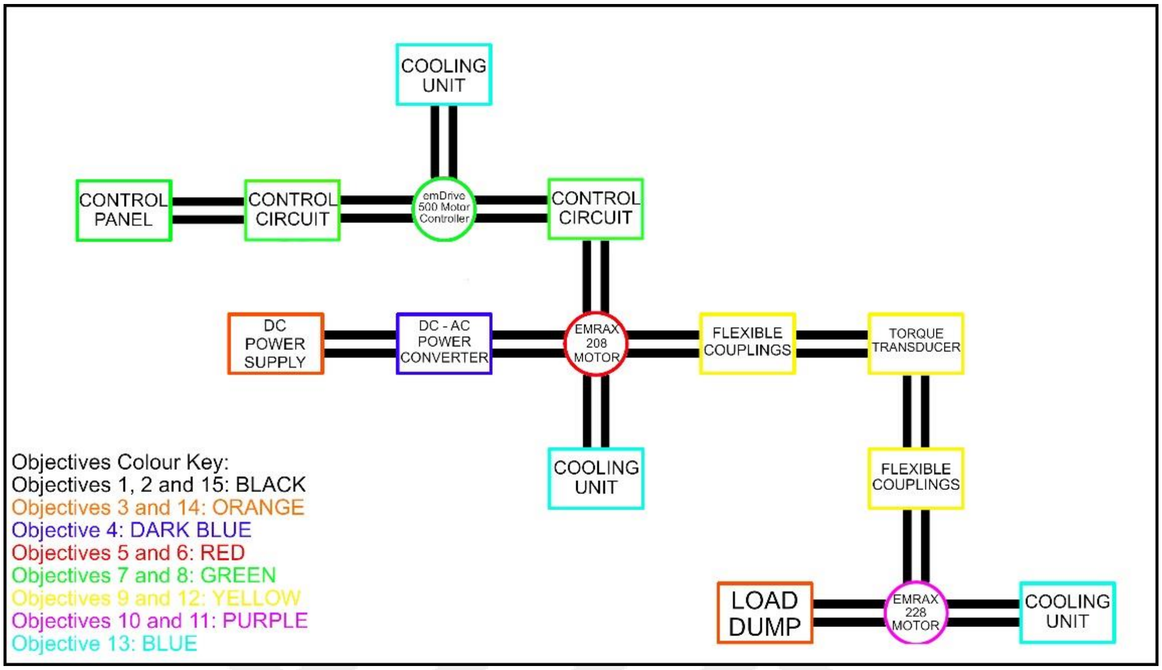


Figure 3: Layout Schematic of the Designed Test Bench with Colour Coded Objectives

The first objective was the completion of a satisfactory test bench design that could then be manufactured and assembled throughout the rest of the project duration. This objective was particularly important because the test bench design was to serve as a guideline to set the direction for the rest of the project work. To accomplish this objective; research, investigation and design work were performed.

Upon the successful definition of the test bench design, the second objective was the procurement of a suitable test bed to build and assemble the test bench upon. This test bed was intended to serve as a foundation for the rest of the test bench. This was completed through investigation.

The third objective was the acquisition of a DC power supply. This power was required to operate the EMRAX 208 motor on the test bench. However, the EMRAX 208 accepted only a 3-phase AC power input. This led to the fourth objective; the procurement of a DC-AC power converter to work in tandem with the DC power supply so that AC power could be provided to the EMRAX 208. Investigation was done to achieve these objectives.

Next, the fifth objective was the obtainment of the EMRAX 208 motor that was to function as the driving motor on the test bench. This motor was purchased previously by Newcastle Racing for use in the drivetrain of the NR11. Hence, the objective was completed by acquiring permission to use the motor. The completion of this objective brought on the sixth objective which was the procurement of a bookend for the EMRAX 208 to be mounted on. This goal was accomplished through investigation.

The seventh objective was the acquisition of the emDrive 500 motor controller. This was necessary to control the EMRAX 208 on the test bench. The emDrive 500 was also bought previously by Newcastle Racing and permission was successfully obtained for the utilisation of it. In order to actually make use of it, however, the design and manufacture of a control panel and circuit was necessary. This was designated as the eighth objective. Fortunately, a suitable control panel and circuit were inherited from the previous Newcastle Racing project that preceded this one. However, the inherited components were not complete for the purposes of this project. Hence, investigation, research and practical work were done to complete this objective.

After that, the ninth objective was the acquisition of an acceptable torque transducer and flexible couplings. The design of the test bench designated the EMRAX 208 as the driving motor and the EMRAX 228 as the driven generator. In accordance with this, the torque output from the EMRAX 208 into the 228 needed to be measured as part of the data generated by the test bench. For this purpose, the use of an appropriately rated torque transducer was decided. Research and investigation was done to determine a suitable product. Also, this torque transducer needed to be properly integrated into the test bench. The utilisation of flexible couplings were decided as a satisfactory means of performing this. Hence, appropriate couplings were acquired through investigation.

The tenth objective was the procurement of the EMRAX 228 motor. Just like the EMRAX 208 motor and the emDrive 500 motor controller, the EMRAX 228 was previously acquired by Newcastle Racing and permission was granted to use it. However, as the EMRAX 228 was the motor of the NRX, it was integrated in the powertrain of the NRX and so had to be removed. The completion of this objective gave rise to the eleventh objective; the design and manufacture of the EMRAX 228 bookend. This bookend was necessary to mount the EMRAX 228 securely on the test bench. The completion of this aim was accomplished through investigation, design and manufacturing work.

Following that, the twelfth objective was the design and manufacture of the shaft adaptors. Even though flexible couplings were obtained to connect the torque transducer to the EMRAX 208 and 228 motors, they alone were not sufficient. To address this issue, shaft adaptors that linked the motors to the flexible couplings were designed and manufactured. Investigative work was necessary to do so.

The thirteenth objective was the design or procurement of cooling mechanisms for the EMRAX 208 and 228 motors as well as the emDrive 500 motor controller. The arrangement of suitable cooling mechanisms was necessary to ensure the safe functionality of the test bench. Malfunction due to overheating was a highly probably result of inappropriate or no cooling and such a situation was desirable to be avoided. Investigative and research as well as some design work was done to decide the most convenient strategy to complete this objective.

The fourteenth objective was the design or acquisition of a load bank. In the test bench design, the EMRAX 208 was designated as the driving motor that applied torque through the torque transducer to the driven generator, EMRAX 228. Hence, the power generated by the EMRAX 228 needed to be dumped securely into a load bank. This was important for the safe sustained operation of the test bench. Thus, research, investigation and design work were done for the completion of this objective.

Finally, the last objective was the assembly of the test bench. All of the other objectives needed to be complete as a pre-requisite before work on this last one could be started. To accomplish the overarching goal of this project, the various tasks necessary for the completion of the test bench were categorised into primary objectives. This last objective entailed the combination of the accomplished results of the previous objectives in a satisfactory manner to create the test bench. Although all the other objectives were completed, this last one was relegated to future work by the end of this project. Even so, investigative and research work was done for the discovery of a suitable strategy for the completion of this aim as well.

2. Investigation and Literature Review

For the completion of the primary objectives of this project, research and literature review was required. To start with, research was done into the most important components involved in the completion of the test bench. These were the EMRAX 208 and 228 motors, the emDrive 500 motor controller and the MAGTROL TM series torque transducer. Following that, literature review into the working principles of internal combustion engines and electric motors was conducted. At the same time, research into control strategies for these motors along with general control strategies was performed. Finally, the working principles of PID controllers were investigated and analysed.

2.1. Test Bench Components

2.1.1. EMRAX 208 Motor

The EMRAX 208 was designed as an axial flux, permanent magnet synchronous motor with a sinusoidal three phase type of input [5]. With a weight of approximately 9 kg, this lightweight motor boasted a high power density value of up to 8.2 kW/kg [5]. Furthermore, the motor possessed an excellent efficiency value of approximately 98% and was highly reliable as it was designed to be utilised primarily in aerospace and electric vehicle applications [5].

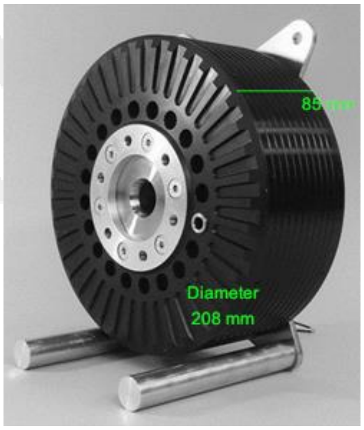
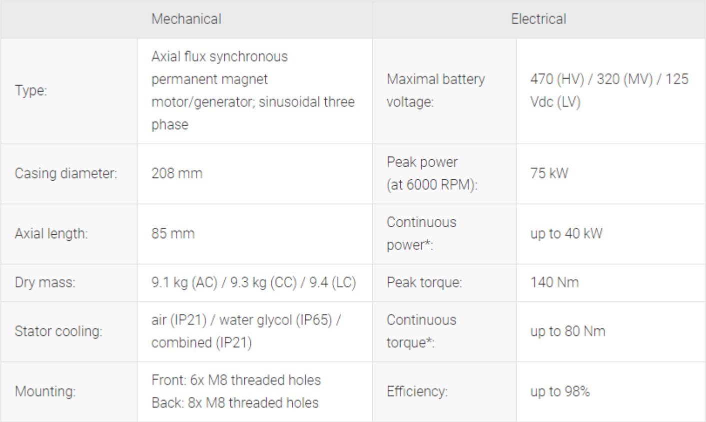


Figure 4: EMRAX 208 Motor [5]

Table 1: EMRAX 208 Motor Specifications [5]



	Mechanical		Electrical
Type:	Axial flux synchronous permanent magnet motor/generator; sinusoidal three phase	Maximal battery voltage:	470 (HV) / 320 (MV) / 125 Vdc (LV)
Casing diameter:	208 mm	Peak power (at 6000 RPM):	75 kW
Axial length:	85 mm	Continuous power*:	up to 40 kW
Dry mass:	9.1 kg (AC) / 9.3 kg (CC) / 9.4 (LC)	Peak torque:	140 Nm
Stator cooling:	air (IP21) / water glycol (IP65) / combined (IP21)	Continuous torque*:	up to 80 Nm
Mounting:	Front: 6x M8 threaded holes Back: 8x M8 threaded holes	Efficiency:	up to 98%

* Depends on the rotation speed and thermal conditions.

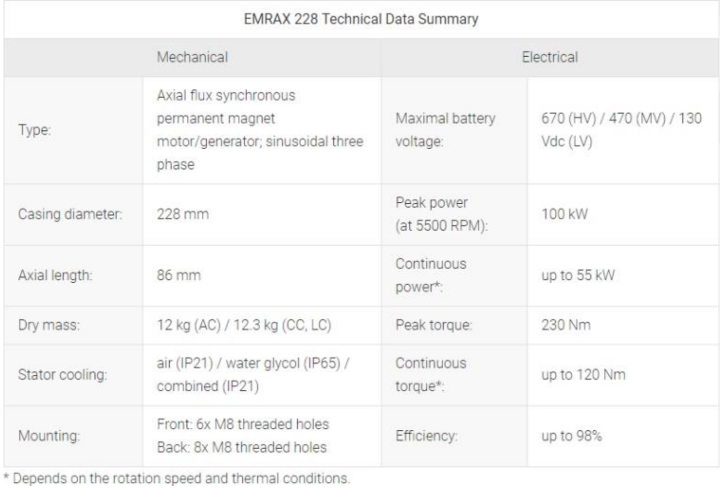
The specifications of the EMRAX 208 motor were shown in Table 1. From this table, the peak power output could be observed at 75 kW with an estimated continuous power output of up to 40 kW. The peak torque was specified as 140 Nm with an approximate continuous torque up to 80 Nm.

2.1.2. EMRAX 228 Motor

The EMRAX 228 motor was created as an axial flux, permanent magnet synchronous motor with a sinusoidal three phase type of input, just like the EMRAX 208 [6]. This motor weighed an approximate 12 kg. The power density of the EMRAX 228 reached up to 8.3 kW/kg. The efficiency of this motor was the same 98% value of the EMRAX 208. In many ways, the motor was a bigger, heavier and stronger version of the EMRAX 208 and similarly was designed for aerospace and EV applications.

Figure 5: EMRAX 228 Motor [36]

Table 2: EMRAX 228 Motor Specifications [36]



EMRAX 228 Technical Data Summary

Mechanical		Electrical	
Type:	Axial flux synchronous permanent magnet motor/generator; sinusoidal three phase	Maximal battery voltage:	670 (HV) / 470 (MV) / 130 Vdc (LV)
Casing diameter:	228 mm	Peak power (at 5500 RPM):	100 kW
Axial length:	86 mm	Continuous power*:	up to 55 kW
Dry mass:	12 kg (AC) / 12.3 kg (CC, LC)	Peak torque:	230 Nm
Stator cooling:	air (IP21) / water glycol (IP65) / combined (IP21)	Continuous torque*:	up to 120 Nm
Mounting:	Front: 6x M8 threaded holes Back: 8x M8 threaded holes	Efficiency:	up to 98%

* Depends on the rotation speed and thermal conditions.

Table 2 showed the specifications of the EMRAX 228 motor. From this table, the peak power output could be seen as 100 kW with a possible continuous power output of 55 kW. The peak torque was designated as 230 Nm with a continuous torque output of up to 120 Nm.

The EMRAX 228 motor was utilised to great success by Newcastle Racing to operate the powertrain of the Formula Student car, NRX. This motor also possessed the ability to function as a generator if needed [6]. However, rather than the EMRAX 228 motor, the EMRAX 208 motor was the driving motor that the test bench was designed to test. The maximum speed of this motor was designated as 6000 to 7000 rpm which was higher than the 5500 to 6500 rpm designation of the EMRAX 228 [7] [8]. The EMRAX 208 was chosen as the motor of choice for the NR11 rather than the more powerful EMRAX 228 in order to reduce the overall weight of the car. By employing the EMRAX 208 over the 228, Newcastle Racing was able to achieve a weight reduction of nearly 20% [4]. The Appendices B1 and B2 showed the dimensions of the EMRAX 208 and 228 motors. Additional specifications for both were in the project file.

2.1.3. emDrive 500 Motor Controller

The emDrive 500 motor controller was chosen by Newcastle Racing as the most suitable controller for the operation of the EMRAX 228 in NR11. This controller boasted relatively lighter weight and lower cost in comparison to other viable alternatives [4]. Additionally, EMRAX and emDrive were known as friendly companies who frequently used the products of each other to test their own.

Figure 6: emDrive 500 Motor Controller [34]

Table 3: emDrive 500 Motor Controller Specifications [9]

emDrive500	500_800/120	unit
Electrical data		
Output continuous current	500	A_{RMS}
Output maximum peak current (one minute)	800	A_{RMS}
Input DC link voltage range	30 to 120	V
Supply voltage range (Ignition voltage)	12 to 30	V
Supply current max. (Ignition current)	750	mA
Output continuous power*	62	kVA
Output maximum peak power (one minute)*	110	kVA
Switching frequency	16	kHz
Operating ambient temperature**	-20 to 65	°C
Coolant temperature (derating point)	60	°C
Operating pressure (pressure drop @ 10 l/min @ 25 °C)	2 (0,3)	bar

* depends on load and cooling
** coolant temperature <60 °C

Table 2 demonstrated the specifications of the emDrive 500 motor controller. From this table, the continuous power output could be observed as approximately 62 kVA with a maximum peak power of 110 kVA for a duration of 1 minute. This power output was sufficient to effectively control the EMRAX 208 motor. As a matter of fact, the power of the controller could be considered to be a little too high for the motor it was chosen to control. Aside from that, the operating ambient temperature was given as the range of -20 to 65 °C. This operating temperature was suitable for the test bench which was intended to operate at room temperature of about 20 to 25 °C. Lastly, the control strategy that was used by the controller was PI control [10]. The utilisation of this strategy rather than the more advanced PID control was highly surprising as advanced controllers such as these were often expected to employ PID controllers. Additional figures demonstrating the dimensions of the controller were given in the Appendix C.

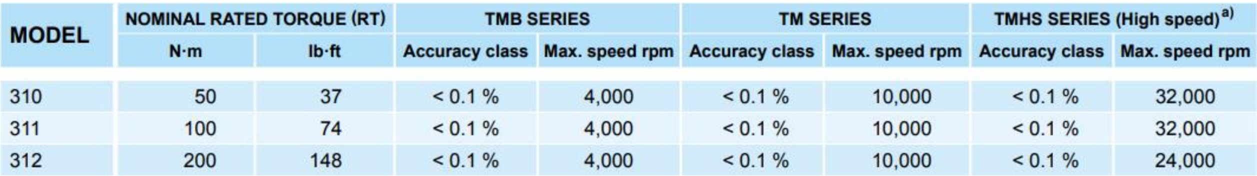
2.1.4. MAGTROL TM Series Torque Transducer

The company MAGTROL manufactured a wide variety of torque transducers for torque and speed measurement. From this catalogue of items, the TM series of torque transducers were identified as suitable for use in the construction of the test bench. The TM series were described as suitable for high speed applications up to 10,000 rpm which is higher than the 6000 to 7000 rpm range maximum speed of the EMRAX 208 motor [11]. Hence, the TM series were usable with the EMRAX 208 motor.

Figure 7: MAGTROL TM Series Torque Transducer [11]

The MAGTROL TM series torque transducers possessed an integrated conditioning electronic module providing 0 VDC to 10 VDC torque output along with an open collector speed output [11]. The equipment was extremely accurate with a less than 0.1% margin for error and boasted high electrical noise immunity [11]. These transducers employed advanced non-contact differential transformer torque measuring technology and they were composed of a number of intricate electro-mechanical components with a hardened steel shaft in the centre [11].

Table 4: MAGTROL Torque Transducer Specifications [11]



MODEL	NOMINAL RATED TORQUE (RT)		TMB SERIES		TM SERIES		TMHS SERIES (High speed)$^{a)}$	
	N·m	lb·ft	Accuracy class	Max. speed rpm	Accuracy class	Max. speed rpm	Accuracy class	Max. speed rpm
310	50	37	< 0.1 %	4,000	< 0.1 %	10,000	< 0.1 %	32,000
311	100	74	< 0.1 %	4,000	< 0.1 %	10,000	< 0.1 %	32,000
312	200	148	< 0.1 %	4,000	< 0.1 %	10,000	< 0.1 %	24,000

Table 4 showed a section from the specifications of MAGTROL torque transducers of various kinds. Here, specifications for the TMB, TM and TMHS series were shown. From this table, the specifications of the TM series of torque transducers were observed as the most suitable for the test bench application. The TMB series was under rated as their maximum speed of 4000 rpm was insufficient to accommodate the EMRAX 208 motor whereas the TMHS series was vastly over rated. From the models available for the TM series, the model 311 was the most suitable choice for this project as the 100 Nm rated torque of that model was above the 80 Nm continuous torque output of the EMRAX 208. However, the rated torque of the 311 model still remained below the 140 Nm peak torque of the EMRAX 208 so caution was advised.

2.2. Internal Combustion Engines and Electric Motors

Motors, or engines, were mechanical constructs designed to convert various forms of energy such as chemical or electrical into mechanical energy. This energy could be used with a powertrain to drive mechanical devices such as automotive vehicles. The most prominent motor varieties were identified to be internal combustion engines and electric motors [12].

2.2.1. Internal Combustion Engines (ICE)

Internal combustion engines used combustible fuel to generate mechanical power. The fuel was compressed and ignited within the ICE to generate a miniature explosion [12]. This was used to produce mechanical power through the pistons of the engine [12]. Essentially, the ICE was a type of heat engine that generated mechanical power from chemical fuel using working fluid composed of fuel-air combustion products [13].

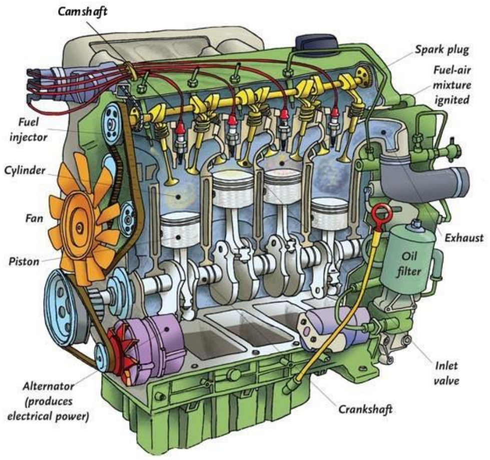


Figure 8: Internal Combustion Engine Schematic [37]

The big problem with the utilisation of the ICE was the unfortunate fact that the vast majority of ICE utilised liquid fuels derived from petroleum [12]. This was a big issue as petrol was a limited non-renewable resource the utilisation of which generated highly environmentally damaging emissions. For this reason, the decision was made to move away from ICE and look for more environmentally friendly alternatives moving forward with the development of automotive technologies. This led to the popularisation of electric motors.

2.2.2. Electric Motors

Electric motors operated by transforming electrical energy to mechanical energy. Electric motors could provide a mechanical power output that was sufficient enough to substitute for ICE without using petroleum derived fuels [14]. Hence, they were a powerful, efficient and environmentally friendly alternative to ICE. Automotive vehicles that utilised EM were called electric vehicles. These existed as early as the year 1890 when the first electric vehicle was designed [14]. However, electric motors only achieved considerable prominence in the previous decade as rising concerns regarding the environment and fossil fuel reserves made them quite popular [14].

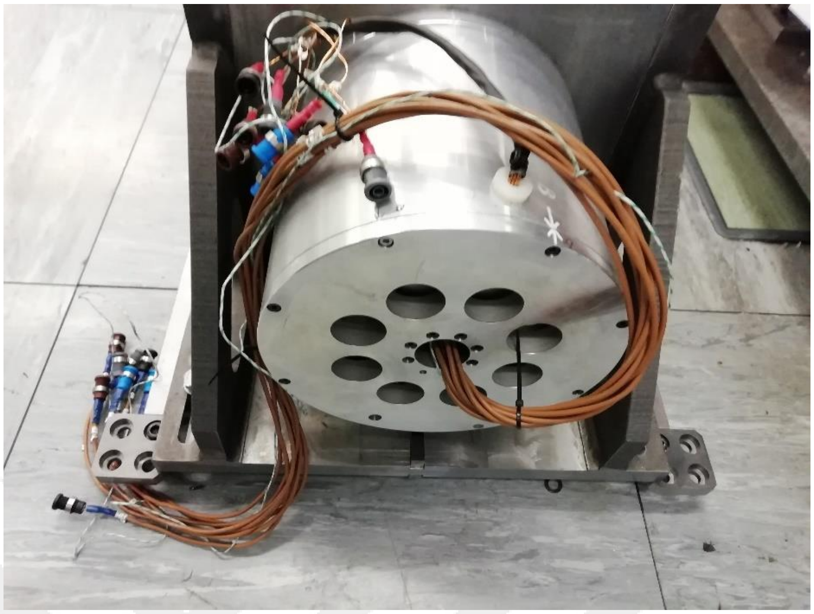


Figure 9: Electrical Motor from Newcastle University Electrical School

Figure 9 showed an electrical motor attached to a test bench situated at the Newcastle University Electrical School. Electrical motors were highly robust and could be strong enough to effectively power the operation of even motor sports vehicles. The electrical vehicles developed by Newcastle Racing for the Formula Student event, NRX and NR11, were examples of such vehicles. As a matter of fact, the high potential power output and the green technology status of electric vehicles made them a very attractive choice for transportation.

However, the storage of the electricity necessary utilise electric motors was a problematic issue. Electric motors required electricity to function and electric vehicles, due to their mobile nature, could not be simply attached to the power grid. The utilisation of batteries to store the necessary electricity was the chosen solution to this problem. Batteries, unfortunately, were not perfectly efficient storage devices and batteries utilised in electric vehicles had long charge times [15]. As an example, electric vehicle batteries had charge times of a range between 4 to 8 hours whereas ICE could be filled up with fuel in mere minutes [15].

These were the difficulties of utilising electric vehicles. Fortunately, these complications did not make for significant obstacles in motor sports applications as the operation time was minimal with a generous amount of preparation period provided. Therefore, the utilisation of the EMRAX 208 motor electric motor in the Formula Student car rather than an ICE was fully acceptable.

2.3. Control and Testing Strategies for ICE and Electric Motors

Internal combustion engines and electric motors were highly powerful and efficient means of generating mechanical power in comparison to other alternatives of similar size and weight [12] [14]. However, even though these devices were capable of generating great mechanical power, their power output had to be controlled for most applications, automotive or otherwise. For automotive applications, if the power output could not be controlled then there could not be any means to manage the motion of the vehicle powered by the motor. To elaborate, without fine control only no power and maximum power settings could exist for the vehicle. Vehicles such as these could not be allowed to exist due substantial safety risks. Hence, to ensure a sufficiently safe motion control of the vehicle, motor controllers were designed and utilised.

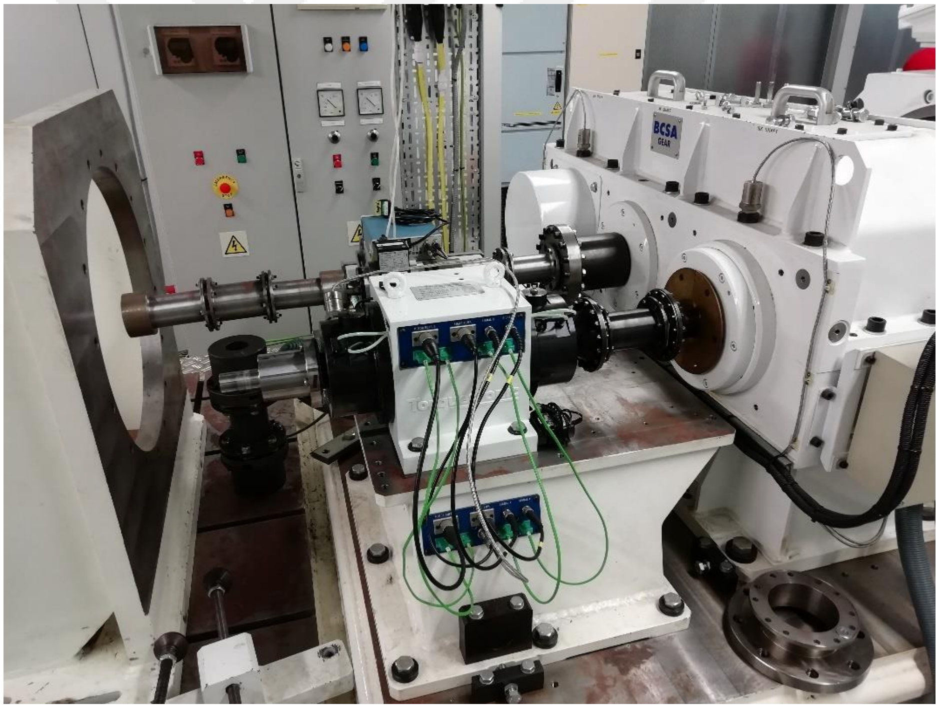


Figure 10: Advanced Electric Motor and Controller Test Bed from the Electrical School

These motors controllers required testing to develop further and improve their accuracy, precision and overall functionality. Figure 10 demonstrated a highly advanced test rig for electric motor and controller testing. The overarching goal of this project was to design and manufacture a test bench such this although a much more simple one. Hence, this section was an exploration of the control and testing strategies available for ICE and electric motors.

2.3.1. Strategies for Internal Combustion Engines

Internal combustion engines played a significant role in the development of automotive technologies. [13]. Even though this project utilised the EMRAX 208 electric motor rather than an ICE, there was still merit in examining testing methods for ICE and their controllers to achieve valuable insight into the nature of motor controllers.

To start with, the most obvious means of testing ICE was through the performance of road tests. However, the high cost of road testing in terms of both time and money made it infeasible for repeated use. Therefore, a powerful strategy was to transfer these tests from the road to a virtual environment constructed in a laboratory. To accomplish this, test benches which could perform this function were designed and manufactured. In a particular study, a dynamometer was used as the means of applying the engine load [16]. In addition, a torque regulator was employed to reduce deviations from the nominal load of the combustion engine as well as to mitigate the excessive vibration of the combustion engine [16]. Through the use of these components among others, the design of a basic dynamic ICE test stand which was intended to facilitate ICE optimisation was described. This design was given in the Appendix D.

Secondly, instead of using a physical controller for the testing of an ICE another strategy was to create and utilise a virtual controller. In a certain study, an ICE was taken and its relevant parameters were transferred into a virtual control and monitoring environment developed in the software Labview [17]. Here, Labview was utilised to develop a control and testing interface for the ICE where accurate measurements could be taken and engine parameters adjusted precisely. Once again, a dynamometer was made use of to apply load to the engine while the Labview interface functioned as the controller during testing [17]. This was shown in Appendix E.

Lastly, a testing strategy could be implemented from a different perspective than dynamic motor behaviour analysis. To elaborate, rather than performing dynamic testing on the ICE, the engine could be analysed during start-up instead. In another study, the start-up of an ICE was controlled to perform emission tests [18]. This was done by using a model based vehicle start-up control simulation in a virtual environment [18]. The simplified mechanic model utilised for the control simulation was delivered in the Appendix F.

2.3.2. Strategies for Electric Motors

For the purposes of this project, the test bench was intended to be built to test the emDrive 500 motor controller and the EMRAX 208 electric motor. As such, the main focus of the research was placed on analysing strategies for electric motors.

To start with, the most common means of controller testing for electric motors was through the utilisation of a test bench. In one particular study, the design and development of a test bench intended to study and monitor the performance of the propulsion driver of an electric vehicle was documented [19]. Here, by utilising induction machines, specifically the squirrel cage induction motor, along with an AC/DC current converter, a remote console and various other specialist equipment; the test bench was assembled [19]. In addition to these components, the test bench was also equipped with a foot pedal to imitate the driver's input into the vehicle [19]. The resulting test bench was capable of measuring the functionality and durability of the propulsion drive by performing speed control, torque control and even driving simulation tests among others [19]. The schematic of the test bench circuit was given in Appendix G.

Rather than utilising test rigs, electric motor control strategies could be considered as well. In one research, the most popular strategies for the control of induction type electric motors were identified to be the indirect field oriented control (IFOC) and direct torque control (DTC) [20]. The IFOC method was a control scheme that was intended to adjust the speed of the electric motor [20]. This scheme was used to decouple the torque and the flux currents [20]. By doing so, this strategy aimed to achieve control of the electric motor through manipulating the torque and flux components independently of each other within a synchronous reference frame [20]. In contrast, DTC was a control strategy intended for electric machines that was a relatively simpler method in comparison to IFOC [20]. The strategy for DTC implementation was built upon assuming direct control of the torque and currents [20]. This was done with the utilisation of double hysteresis controllers and a switching table [20]. Look at Appendix H.

To conclude, various strategies existed both for the testing of the electric motor controller and the implementation of electric motor control. Research into these topics provided knowledge that was helpful to the design of the test bench and the development of testing methodologies.

2.3.3. General Control Strategies

Certain strategies for the control of the motor and testing of the motor controller could be effectively applied to both ICE and EM. Unlike the highly specialised techniques described in the earlier sections, these general control strategies boasted a high degree of flexibility and robustness that made them applicable to both kinds of motors.

To start with, hardware in the loop simulation (HIL) was a powerful, flexible and robust method both for the design and testing of controller and motor systems. The hardware in the loop simulation technique attempted to side step the loss of time and money that was to be spent on tests through digitisation [21]. To explain further, certain parts of the system were replaced by simulations of these parts instead of real components. Sophisticated software was utilised to model and simulate components of the system under testing wherever possible, achieving resource conservation [21]. In a typical HIL application, the controller and perhaps the actuators of the system were to be the only real components whereas the rest would be simulated [21]. Hence, the sufficiently precise simulation of these components was necessary [21]. This often involved the creation and use of mathematical models for these components [21]. On the other hand, as certain other components were real, testing with this method could only be performed in real time [21]. More information was given in Appendix I.

Secondly, although internal combustion engines and electric motors were normally separate entities, certain systems designed and built to incorporate aspects of both existed [22]. For a significant time interval, internal combustion engines were the most common motor utilised in the automotive industry. Over this time period, numerous improvements have been made to ICE to improve them. Often, these enhancements were electronic components [22]. Hence, over time certain ICE transformed from purely mechanical devices to highly complex electro-mechanical hybrid systems [22]. For this reason, a mechatronic approach could be taken both for the testing of electro-mechanical engines such as these and regular electric motors. This strategy aimed to integrate the engine with computer based information systems that utilised rapid control prototyping (RCP) on a test bench [22]. RCP was a powerful process that was meant to be used for the swift testing and iteration of engineering strategies.

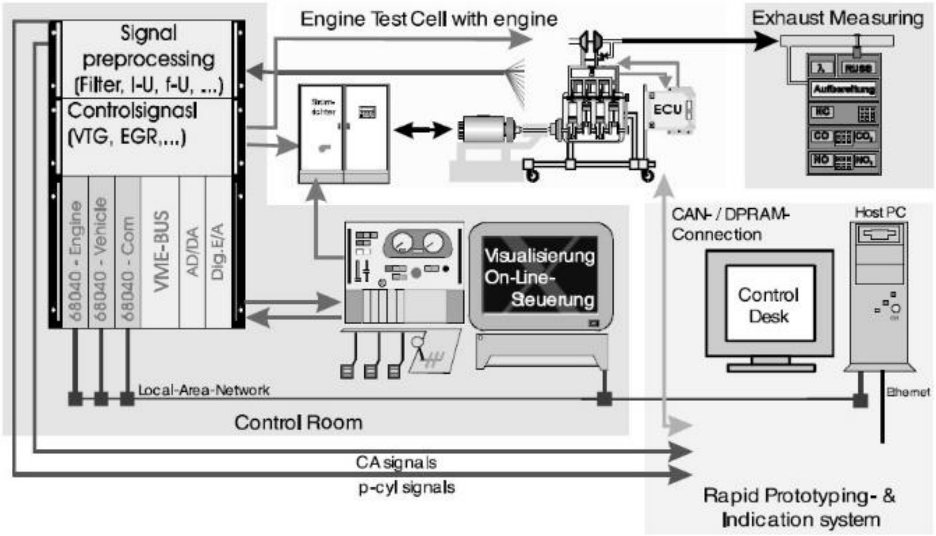


Figure 11: Dynamic Test Bench with RCP System [22]

To facilitate the use of RCP, a digital signal processor system was implanted into the test bench. [22] Figure 10 showed the schematic of this test bench. A test rig such as this could be utilised for the robust testing of both mechatronic ICE and electric motors [22].

2.4. Proportional-Integral-Derivative (PID) Controllers

Proportional-Integral-Derivative, abbreviated as PID, control was a closed loop control system that was implemented by PID controllers. Closed loop control systems operated by constantly monitoring and attempting to correct a specific parameter of the system they were implemented on. Essentially, for a specific parameter of the system under a closed loop control, a desired target value could be specified. Once such a specification had been made, the closed loop control system continuously monitored and changed the chosen parameter until it matched the selected value. One of the most popular closed loop control systems was the PID control [23]. Through the seamless integration of three different kinds of control responses, PID controllers worked to control a wide variety of systems with minimal overshoot from the desired value [23].

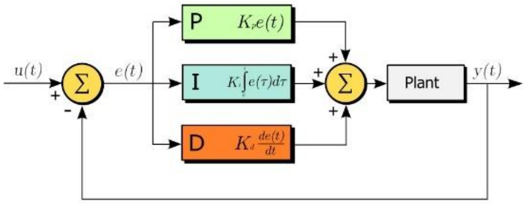


Figure 12: Typical PID Controller [24]

In Figure 12, a typical PID controller was shown. From this figure, the 3 different sorts of control responses that were integrated within can be observed. These responses were proportional, integral and derivative represented in the figure by P, I and D respectively [23]. These responses together formed the basis of the PID.

The 3 distinct controller responses that were combined together to form the PID controller could be separated and put together as necessary to form different kinds of controllers [23]. These derivatives of the PID controller possessed only some of the complete functions of the PID controller depending on the type of controller responses they incorporated. For example, the emDrive 500 motor controller that was utilised as the controller of choice for the test bench employed a PI controller, a derivative of the PID controller [9].

2.4.1. Proportional (P) Controller

The proportional (P) response was the foundation upon which the PID controller was built upon. The P control response received the output of a chosen parameter of the system and compared it with the desired value that was specified [23]. If these did not match then the P control returned a proportional response to the system which was intended to shift the current value closer to the desired value [23].

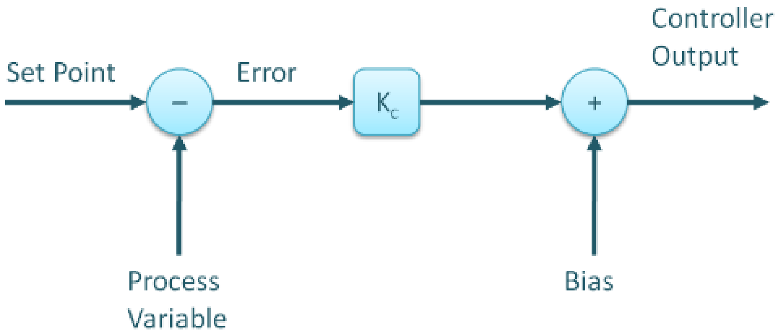


Figure 13: Depiction of a P Controller [25]

As shown in Figure 13, the P control response alone could be utilised in a closed loop controller to form the proportional controller. Unfortunately, as the response of the P controller was proportional to the value of the deviation from the desired value, error could never be eliminated and the output value eventually settled into a steady state of fluctuation instead [23].

2.4.2. Proportional-Integral (PI) Controller

The shortcoming of the P controller could be resolved with the addition of an integral (I) element.

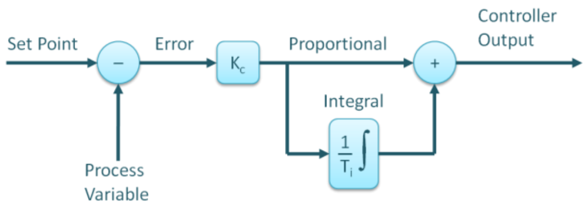


Figure 14: Depiction of a PI Controller [25]

In the proportional-integral (PI) controller, shown in Figure 14, the integral element addressed the fluctuation issue by integrating the error over time and modifying the proportional response accordingly [23]. As a result, over time the present error could be completely eliminated.

2.4.3. Proportional-Integral-Derivative (PID) Controller

The proportional-integral (PI) controller was capable of monitoring the chosen system parameter and adjusting it as necessary to reduce the error to 0. For this reason, the PI controller appeared to have no shortcomings and so no need for improvement.

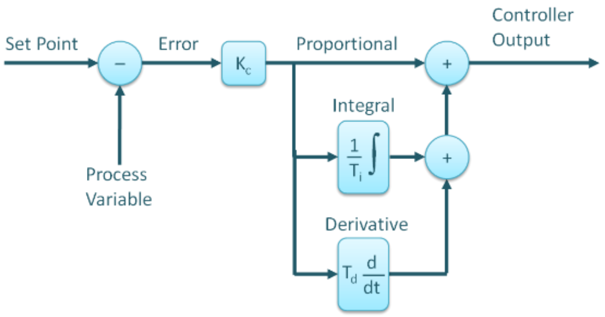


Figure 15: Depiction of a PID Controller [25]

However, while the P response monitored present errors and the I response compensated for past errors in the PI controller, there was no means to account for future errors that were liable to occur. This weakness in the design could be resolved with the introduction of the derivative (D) element to the closed loop control structure as demonstrated in Figure 13 [23].

The D response attempted to predict and prepare for possible future errors that could occur in the system. In addition, it functioned to stabilise the system and decrease potential overshoot. With the introduction of the D response, the PID controller was fully assembled and complete.

3. Methodology

Methodologies needed to be conceived to satisfactorily utilise the research performed for the accomplishment of the primary objectives. The research and investigation done formed a foundation for the concoction of the appropriate methodologies to complete the primary objectives. These methodologies were categorised according to the nature of the work involved for their implementation.

3.1 Methodologies for Design, Manufacture and Assembly

For the completion of a suitable test bench, the test bench first needed to be designed. Then, the design and manufacture of some test bench components was required. Furthermore, the test bench needed to be assembled from the various manufactured or acquired components at the end of the project. Hence, this section detailed the methodologies that were created for the design and manufacture of certain components as well as the test bench assembly.

3.1.1 Methodology for Test Bench Design

The methodology for the test bench design was developed to ensure satisfactory functionality and safety in the end product. First of all, priority was given to make sure that the designed test bench could fulfil the fundamental aim of this project. This could only be accomplished if the test bench could successfully accommodate the EMRAX 208 motor and the emDrive 500 motor controller while allowing for a series of investigative tests to be performed on them. Hence, research was done to understand the specifications of the various powerful electronic equipment and engineering principles involved so that proper functionality could be ensured and appropriate safety measures taken. In addition, further research was done into existing designs for test benches intended for motors and controllers to acquire innovative ideas some of which were implemented in the test bench design. Furthermore, investigation was conducted into the test rigs for motor testing that were already present in the Electrical School in order to learn about robust test bench design from all these realised examples. There were 3 different test rigs present in the Electrical School. The first one was a miniature test rig formed out of the most basic of components. The second one was a more advanced version of the first one and the third one was a massive test rig simply amazing in scope. The first test rig was given in Figure 2 and the third rig was given in Figure 10. Inspiration was taken from both of these for the test bench design.

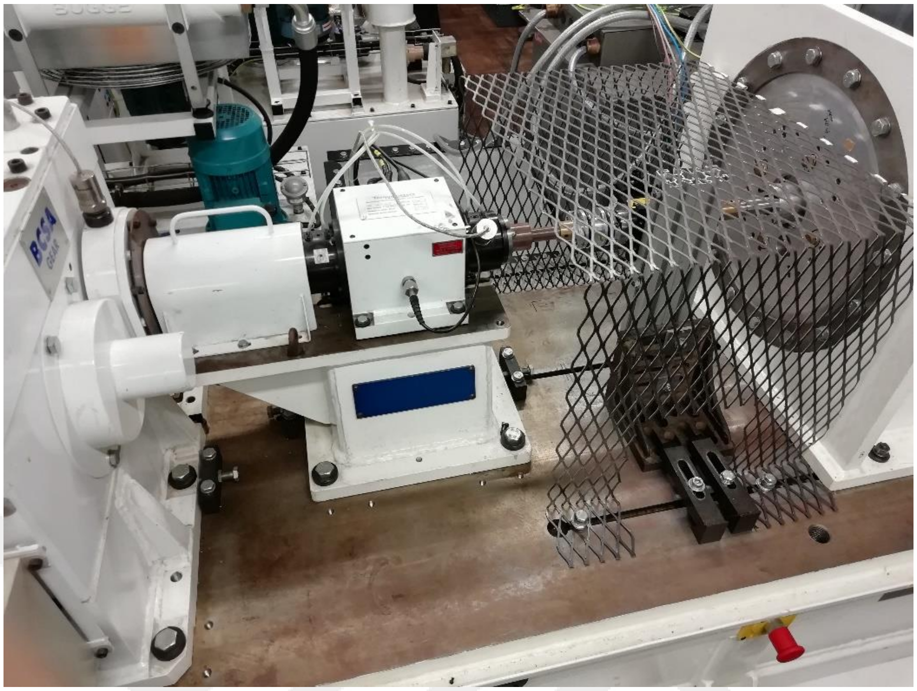


Figure 16: Advanced Test Rig from the Electrical School

The second test rig is shown in Figure 16. This highly advanced test bench was relatively easier to understand compared to the others and the design of it assisted the development of the design methodology. Lastly, the issues of resource, time and space availability and limitations were considered before proceeding with the test bench design. All of these together formed the methodology through which the test bench was designed.

3.1.2 Methodology for EMRAX 208 Motor Mounting

The EMRAX 208 motor was to be mounted on the EMRAX 208 bookend that was acquired from the Electrical School. However, that bookend was not specifically made to accommodate the EMRAX 208 motor and was not suitable for direct mounting [26]. Therefore, a methodology to accomplish the mounting of the EMRAX 208 motor on the bookend had to be concocted. After some consideration, the chosen methodology was to design and manufacture a component that could function as a connector. This connector was to be designed to facilitate the mounting of the EMRAX 208 motor on the bookend. Furthermore, this connector could be manufactured in house by the Mechanical Workshop located in the Stevenson Building of Newcastle University. The design and manufacture of this connector, which was labelled the motor mount plate, was the methodology decided for mounting the EMRAX 208 motor on the bookend.

3.1.3 Methodology for Control Panel and Circuit Rewiring

The control panel and circuit utilised in the test bench were inherited from a previous Newcastle Racing project. In that project, the methodology used to make the control panel and circuit was to first design them, then to manufacture some of the components while purchasing others and lastly to assemble these together [4] [27]. The methodology for the control circuit was to design it based on the SSI Motor Response circuit given in the manual of the emDrive 500 motor controller while also making modifications as necessary [4]. On the other hand, the method for designing the control panel was to come up with a robust and simplistic design that prioritised easy operation of the test bench from a safe distance.

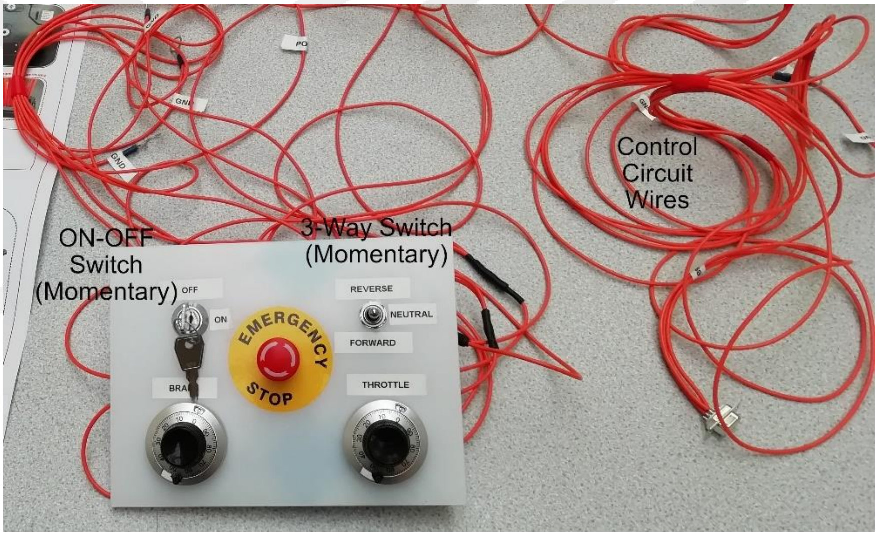


Figure 17: Inherited Control Panel and Circuit with Momentary Switches

Even though these methodologies were implemented to design, manufacture and assemble the control panel and circuit together in the previous project as shown in Figure 17, the inherited components were not completely suitable for use in the test bench. To elaborate, the switches utilised in them were momentary switches that snapped back into their original positions after activation [28]. This rendered the operation of the control panel by a single person alone infeasible and dangerous. Therefore, the inherited control panel and circuit needed to be improved for use in the test bench. The methodology for accomplishing this was decided to be the replacement of the momentary switches with non-momentary ones. This could be done by locating the new switches, acquiring them and replacing the old switches with them after learning the practical skills needed for their implementation.

3.1.4 Methodology for EMRAX 228 Bookend Design and Manufacture

The methodology for the obtainment of the EMRAX 228 bookend considered the ideas of designing and manufacturing it or simply purchasing it instead. Investigative work was performed to determine if a satisfactory bookend could be successfully bought or borrowed. However, such a bookend that could accommodate the EMRAX 228 motor could not be found. Therefore, a suitable bookend was chosen to be designed and manufactured instead. The methodology for the bookend design had to take the high power of the motor into consideration to minimise safety risks. Furthermore, the bookend needed to be designed to ensure that the EMRAX 208 could be appropriately connected to the EMRAX 228 to facilitate proper functionality of the test bench. Once all of the design elements were decided, the bookend could be manufactured in house in the Mechanical Workshop [29]. These specifications formed the basis of the methodology for the EMRAX 228 bookend design and manufacture.

3.1.5 Methodology for Shaft Adaptor Design and Manufacture

The methodology for the obtainment of the shaft adaptors was developed through investigation. Investigation was performed to determine suitable shaft adaptors for purchase.

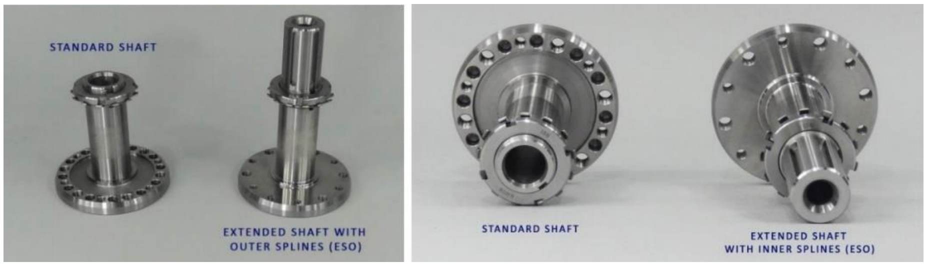


Figure 18: EMRAX Shaft Adaptors Available for Purchase [6]

Figure 18 showed the EMRAX shafts adaptors available for purchase. However, as the adaptors for this project had to be specifically for the EMRAX 208 and 228 motors as well the flexible couplings obtained from the Electric School, these were not satisfactory.

Hence, the methodology for their acquisition was determined to be to design and manufacture them. The adaptors had to be designed to be able to withstand the large amounts of torque that the EMRAX 208 was intended to output through them. This concern was considered as the priority for the methodology of the shaft adaptor design. The completed design could then be manufactured in house in the Mechanical Workshop.

3.1.6 Methodology for Test Bench Assembly

The methodology for the test bench assembly was intended to realise the test bench design into reality by combining the various components prepared for this purpose. Essentially, all the pieces that were prepared for the project needed to be connected together in accordance with the test bench design. The method to accomplish this was chosen to be simply bolting the components together. To start with, the bookends for the EMRAX 208 and 228 were intended to be bolted onto the test bed by using M12 bolts. Next, the motor mount plate could be mounted and bolted onto the EMRAX 208 bookend using M14 bolts and special spacers. After that, the EMRAX 208 and 228 motors were to be mounted and bolted on their respective bookends. Following this, the flexible couplings were to be attached and bolted to the torque transducer. Then, the transducer along with the couplings could be fitted in between the EMRAX 208 and 228 motors with the assistance of the shaft adaptors which were to be bolted to the surfaces of the two motors and the ends of the flexible couplings. The next step was the integration of the control circuit. The EMRAX 208 motor was to be connected to the emDrive 500 motor controller and that controller was to be linked to the control panel through the 32-pin connector. After that, the cooling systems were to be implemented. Chiller units were to be attached to the EMRAX 208 and 228 motors as well as the emDrive 500 motor controller. Then, the load dump was to be connected to the EMRAX 228 motor. Lastly, the DC power supply was to be linked through the DC – AC power converter and the output of that fed as the input to the EMRAX 208 motor. The implementation of all these steps in a logical, sequential order was decided as the methodology for the test bench assembly.

3.2 Methodologies for Investigation and Acquisition

There were certain components of the test bench that could not be designed and manufactured, they needed to be acquired instead. To facilitate their acquisition, investigation needed to be performed to locate them and determine suitable means for their obtainment whether though purchase, borrowing or inheritance. Methodologies to accomplish this for the various components that needed to be obtained were categorised here.

3.2.1 Methodology for Test Bed Procurement

The methodology for test bed procurement initially included two different possibilities. The first one was the manufacture of an appropriate test bed whereas the second one was to find a test bed. After some consideration, the manufacture of a sufficiently large and sturdy metal bed to build the test bench on was deemed an unnecessary waste of time and resources compared to the alternative method. Hence, the most suitable methodology for procuring the test bed was decided to be the investigation of the available test beds that could accommodate a test bench.

3.2.2 Methodology for DC Power Supply Acquisition

Investigation was performed to find a DC power supply strong enough to operate the EMRAX 208 motor. The research done into the EMRAX 208 revealed that the power supply had to be rated at 120 V and 400 A and be able to provide 48 kW of power continuously during the operation interval of the test bench [7]. Hence, the methodology for DC power supply acquisition was to satisfy these specifications while searching for a suitable power supply.

3.2.3 Methodology for DC – AC Power Converter Procurement

The power generated by the DC power supply had to be converted into a 3-phase AC input for the EMRAX 208 motor. Therefore, the DC – AC power converter that was to be acquired had to be rated high enough to accommodate the 48 kW of power provided by the DC power supply. The methodology for the procurement of the DC – AC power converter was to investigate and determine a fitting power converter while ensuring this condition was satisfied.

3.2.4 Methodology for EMRAX 208 Motor Acquisition

The EMRAX 208 motor was purchased by Newcastle Racing prior to this project for the NR11.

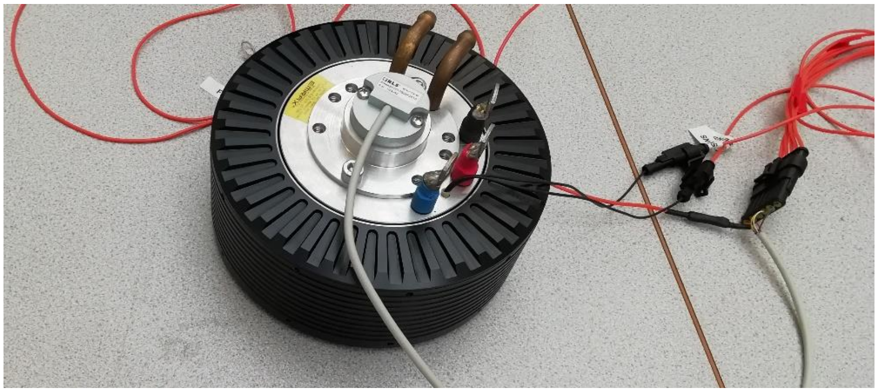


Figure 19: The EMRAX 208 Motor of Newcastle Racing

The availability of this motor for use in the test bench was investigated. As a result of this investigation, permission was acquired to make use of it. This investigation and the inheritance of the motor from Newcastle Racing could be identified as the methodology for the EMRAX 208 motor acquisition.

3.2.5 Methodology for EMRAX 208 Bookend Procurement

The methodology for the obtainment of the EMRAX 208 bookend was limited to the possibilities of either designing and manufacturing the bookend or simply finding one. Before going ahead with designing the bookend, investigation was performed to determine if a satisfactory one could be found. The results of the investigation revealed that during a previous Newcastle Racing project, an applicable bookend was borrowed from the Newcastle University Electrical School. Therefore, communication was established with the Electrical School and it was determined that to continue lending the bookend for use in this project. Thus, the procurement of the bookend from the Electrical School was the chosen methodology.

3.2.6 Methodology for emDrive 500 Motor Controller Acquisition

The emDrive 500 motor controller was bought by Newcastle Racing before the advent of this project for use in the NR11. The availability of this controller for utilisation in the test bench was investigated. This investigation and the inheritance of the controller from Newcastle Racing could be identified as the methodology for the emDrive 500 motor controller acquisition.

3.2.7 Methodology for Torque Transducer and Flexible Couplings Acquisition

The methodology of the torque transducer and flexible couplings acquisition involved investigation both into the purchase of them and the borrowing of them. The first step was to identify the type of torque transducer that was satisfactory for use in the test bench. Then, communication could be established to determine the price of purchasing such a transducer and the flexible couplings for mounting it. Because the price was revealed to be quite high, the decision was made to conduct investigative work to determine if borrowing a transducer, along with the flexible couplings necessary for mounting it, could be possible before proceeding with the purchase. All of this investigative work was decided as the methodology for this task.

3.2.8 Methodology for EMRAX 228 Motor Procurement

The EMRAX 228 motor was procured by Newcastle Racing before the start of this project and used in the drivetrain of the NRX. Investigation was performed to determine the availability of this motor for use in the test bench as a generator. An additional concern was the fact that the EMRAX 228 motor was still firmly mounted in the drivetrain of the NRX. Even if the motor was determined to be available for use in the test bench, the removal of the motor from that contraption was required first before it could be mounted on the test bench. The investigation, this work and the inheritance of the EMRAX 228 motor were the methodology for the procurement of the EMRAX 228 motor.

3.2.9 Methodology for Cooling Mechanism Procurement

The methodology for cooling mechanism procurement was determined through investigation and research. From research, the EMRAX 208 and 228 motors as well as the emDrive 500 motor controller were all discovered to require sufficiently powerful cooling mechanism for safe operation. The possibility of designing an applicable cooling mechanism was first considered. However, implementing a satisfactory design proved to be challenging because of the necessity to arrange for a large water supply to be present in the test bench location. Hence, investigation was performed to procure the cooling mechanism instead. This whole process could be considered as the methodology for the procurement of the cooling mechanism.

3.2.10 Methodology for Load Bank Acquisition

The methodology for load bank acquisition was determined through research and investigation. Initially, the design of a load bank that used an electric circuit to dump the power generated by the EMRAX 228 motor into a series of large floodlights through the use of mosfets was deemed to be the most appropriate methodology. Research and investigation was conducted into this concept to proceed with the implementation of this method. Evaluation of the results of these endeavours revealed that designing a load bank was not the optimal means of completing this task. Hence, investigative efforts were focused to determine a suitable load bank that could be acquired instead. These endeavours together formed the methodology for the acquisition of the load bank for the test bench.

3.3 Methodology for Test Bench Testing and Data Analysis

The completion of the acquisition, design and manufacture of the various test bench components was intended to follow with the assembly of the test bench. Once this final primary objective was complete, the overarching aim of the project was to be accomplished as well. Hence, the utilisation of the test bench to test the motor and motor controller as well as the analysis of the data acquired from this process were relegated to future work. Nevertheless, methodologies for testing and analysis were developed and detailed in this section.

3.3.1 Methodology for Test Bench Testing

The testing of the motor and controller were intended to begin with a small amount of power provided to the EMRAX 208 motor using the potentiometers on the control panel. The magnitude of the power delivered to the motor was intended to start small to avoid unnecessary risks and facilitate safe operation. Once this initial start was complete, the power was intended to be increased in small intervals. This process was to be done slowly but surely until the motor could be made to operate on a reasonable amount of power and speed. The key point of importance throughout this process was to avoid inducing excessive vibration in the motor as that could prove to be quite dangerous. Through this method, how the motor reacted to slow increments in power until stabilisation could be tested. This test could be considered similar to the start-up process of the motor in the Formula Student car, only occurring through-out a larger timeframe.

Upon the stabilisation of the power provided to the motor, another form of testing could be carried out. To simulate the breaking and turning of the Formula Student car, the power could be increased and then decreased suddenly in small jolts. The occurrence of sudden increments and decrements in the power allotted to the motor by the controller was often the case when the Formula Student car was breaking or turning. Testing of the motor under such sudden changes in the power input could provide valuable data to understand and improve the breaking and turning processes of the Formula Student car.

Finally, once basic tests such as these were accomplished, a more advanced form of testing could be the allowance of large power inputs into the motor in short time intervals. To elaborate, the start-up process of the motor for example could be more accurately simulated by inputting high power in a short timeframe. Another example could be the introduction of large leaps in the power input into the motor already running at steady speed and power to better simulate turning and breaking events. Introducing power input changes of large magnitude to the motor in a short period of time was inherently a dangerous task. Hence, testing methods such as these were classified as advanced testing methodology that were only to be attempted with the proper safety measures and precautions in place. Despite the inherent risks however, these advanced testing methods were more accurate simulations of the Formula Student car in operation and were expected to produce better, more clear data for analysis.

3.3.2 Methodology for Data Analysis

The data obtained from the testing had to be analysed to derive meaningful results and conclusions. These conclusions were intended to provide insight to the intricacies of the EMRAX 208 motor and emDrive 500 motor controller operations and their interaction together. The achievement of this understanding was intended to facilitate the development and improvement of the Formula Student car in terms of controlled operation. Hence, methodologies for data analysis were developed.

There were two main types of data analysis methods that were commonly accepted to produce useful results. These were known as qualitative and quantitative data analysis methods. Qualitative data analysis was generally concerned with more subjective forms of data such as information acquired from focus groups or interviews. On the other hand, quantitative data analysis was about the interpretation of figures and numbers acquired from experimentation. Hence, the data acquired from the test bench was intended to be analysed using quantitative data analysis methods. Through the application of pattern identification and critical thinking to the test bench data, meaningful conclusions were intended to be derived. For example, after repeating a series of tests on the motor and controller where the power input is steadily incremented until stability, the data obtained could be analysed for patterns and other points of interest. This method was intended as the starting point for the development of the data analysis methodology. Further improvements and refinements to achieve greater success were relegated to future work.

4. Acquisition, Design and Manufacture

The successful completion of the test bench required the finalisation of the test bench design and the obtainment of various test bench components before proceeding to the assembly process. To accomplish this, the test bench design methodology was developed first. Then, methodologies for the obtainment of these equipment were developed specifically for each individual part. After careful consideration, these methodologies were developed to be subcategories of either design and manufacture or direct acquisition. The results obtained from the application of these methodologies were categorised and detailed in this section.

4.1 Design and Manufacture

The design and manufacture of the test bench was the overarching goal of this project. Therefore, the starting point was the application of the methodology to generate a satisfactory test bench design. Once that was accomplished, the other components necessary for the completion of the test bench were designed and manufactured in accordance with the methodologies developed for each of them. All the manufacturing processes were successfully completed in house in the Mechanical Workshop located in the Stevenson Building of Newcastle University.

4.1.1 Test Bench Design

The design of the test bench was based on the principles of safety, robustness and simplicity while ensuring proper functionality in accordance with the established test bench design methodology. The design methodology was kept in consideration throughout the development of the test bench design until it was finalised.

To start with, the decision was made to build the test bench on top of a large, long and sturdy metal bed with mounting holes built into it. This bed had to able to accommodate having a test bench built on top of it as it was intended to serve as the foundation.

With the test bed ready, the next step was to choose the motor that the test bench was to be utilised to test. The EMRAX 208 motor that was intended by Newcastle Racing to be used in the drivetrain of the NR11 was chosen for this purpose.

Next, the choice was made to utilise a strong, metal bookend to secure the EMRAX 208 motor on the test bed. During this design process, the fact that the available bookend for the EMRAX 208 motor required a motor mount plate was known. Hence, this motor mount plate was also incorporated into the design of the test bench as one of the components necessary for securing the EMRAX 208 motor on the test bed.

Although the EMRAX 208 was chosen as the motor that was to be tested, there was a requirement to attach a load onto it to ensure the proper functionality of the EMRAX 208. If this load was not present then the EMRAX 208 was likely to vibrate excessively and dangerously during operation. Therefore, the EMRAX 228 motor, which was utilised in the drivetrain of the NRX, was chosen for this purpose.

According to the research done on the EMRAX 228, the motor could also be operated as a generator. As such, the following step was to use another bookend to secure the EMRAX 228 onto the test bench. This bookend was designed specifically to accommodate the EMRAX 228 and so did not need a motor mount plate unlike the EMRAX 208.

After that, the EMRAX 208 and 228 had to be connected to each other so that the EMRAX 208 could act as the driving motor and the EMRAX 228 as the driven generator respectively. To facilitate this, first of all, the bookends that the two motors were mounted on were arranged to face each other. This made it possible to connect the two motors with a shaft. However, the choice was made to measure the torque output from the EMRAX 208 that was to be input to the EMRAX 228. Therefore, the implementation of a suitably high rated torque transducer onto the connection between the two motors was decided.

With the acquisition of a satisfactory torque transducer, the decision was made to use two flexible couplings at each end of the transducer to mount it in between the two motors. To facilitate this, the decision was made to use shaft adaptors. These adaptors were intended to be attached to the face of the two motors and their other ends were meant to be connected to the flexible couplings. As a result, EMRAX 208 and 228 motors were intended to be connected through this assembly to facilitate secure torque transmission between the motors that could also be measured with the torque transducer in between.

Following that, the next step was to choose a controller for the controlled operation of the EMRAX 208 and implement it to the test bench. The emDrive 500 controller that was bought by

Newcastle Racing for use in the NR11 was chosen for this purpose. The integration of this controller into the test bench was decided to be done with the implementation of a control circuit and panel.

With that decided, the following step was to determine suitable cooling mechanisms for the EMRAX 208 and 228 motors as well as the emDrive 500 motor controller. Chiller units, procured from the Electrical School, were decided to be used for this purpose.

Next, because the EMRAX 228 was chosen to operate as a generator, the integration of a load bank into the test bench to dump the load was required. This load bank was acquired from the Electrical School and integrated into the test bench for the safe operation of the EMRAX 228 as the driven generator.

Lastly, there needed to be some controlled way to feed power into the EMRAX 208 so that the test bench could be activated as necessary. For this purpose, the decision was made to acquire a DC power supply. This power supply was procured from the Electrical School. However, the EMRAX 208 was a motor that only accepted a 3-phase AC power input. Hence, a DC – AC power converter was obtained from the Electrical School to convert the power from the DC supply to a 3-phase AC input. The DC power supply and the DC – AC power converter were implemented together into the test bench. They were designed to serve as the means of providing power to operate the EMRAX 208 and through that motor, the test bench.

With all of these components in place, the test bench that was to result from this design was deemed likely to be functional and safe to operate. The test bench design formed a guideline that was followed throughout the rest of the project. Once the design was completed, the remaining project time was dedicated to acquiring, designing and manufacturing the various components of the test bench design. Ultimately, these components were intended to be brought together and assembled to form the designed test bench to fulfil the overarching goal of this project.

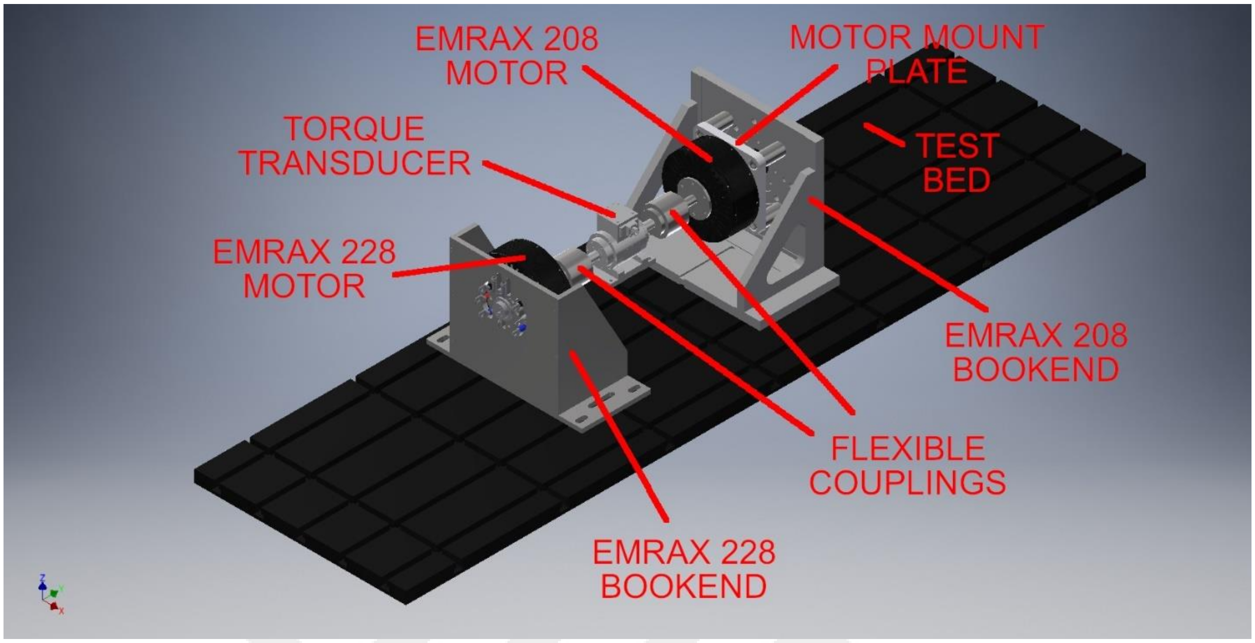


Figure 20: Completed Test Bench Design as Drawn in Inventor

The completed test bench design was drawn in Autodesk INVENTOR as shown in Figure 20. This simplified drawing of the test bench evolved through many iterations until reaching this final point. There was no need to incorporate all of the numerous components of the test bench design into this CAD drawing. The components involved in this drawing were placed accordingly to convey the design methodology behind the test bench.

4.1.2 Motor Mount Plate Design and Manufacture

The design of the motor mount plate went through a development phase before being finalised. The initial design was created as part of another Newcastle Racing project that preceded this one. In that previous project, the manufacture of this design was undertaken in-house in the Mechanical Workshop using the Denford CNC machine [27]. However, there was a power outage during the manufacturing process. This power outage interrupted the machining process of the motor mount plate and as a result the plate was only partially machined and unfinished [27].

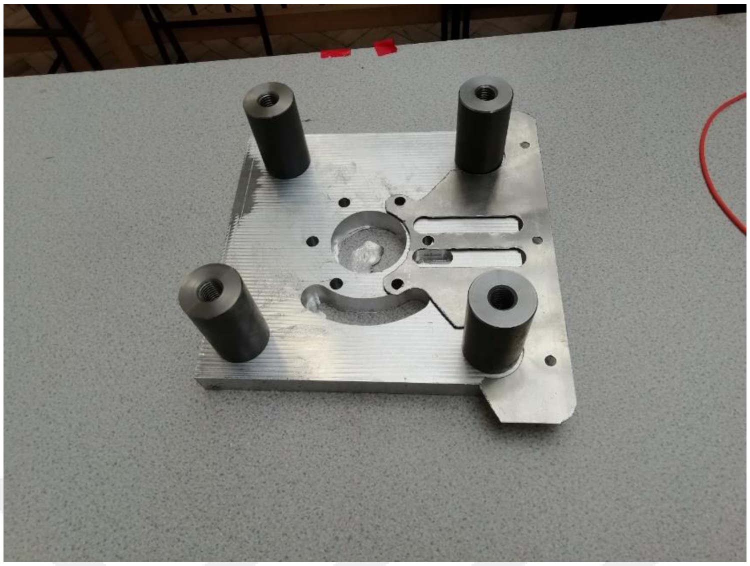


Figure 21: Incomplete Motor Mount Plate with Windshield and Spacers

Figure 21 demonstrated the partially machined motor mount plate, this was inherited for utilisation in this project. The initial design of the motor mount plate was decided to be modified for better functionality on the test bench. The initial design was created in the form of a 3D model by using the CAD software Autodesk INVENTOR. Hence, this software was decided to be utilised to modify the design. To start with, a new 3D model of the current design was created.

The design was then modified into the following form:

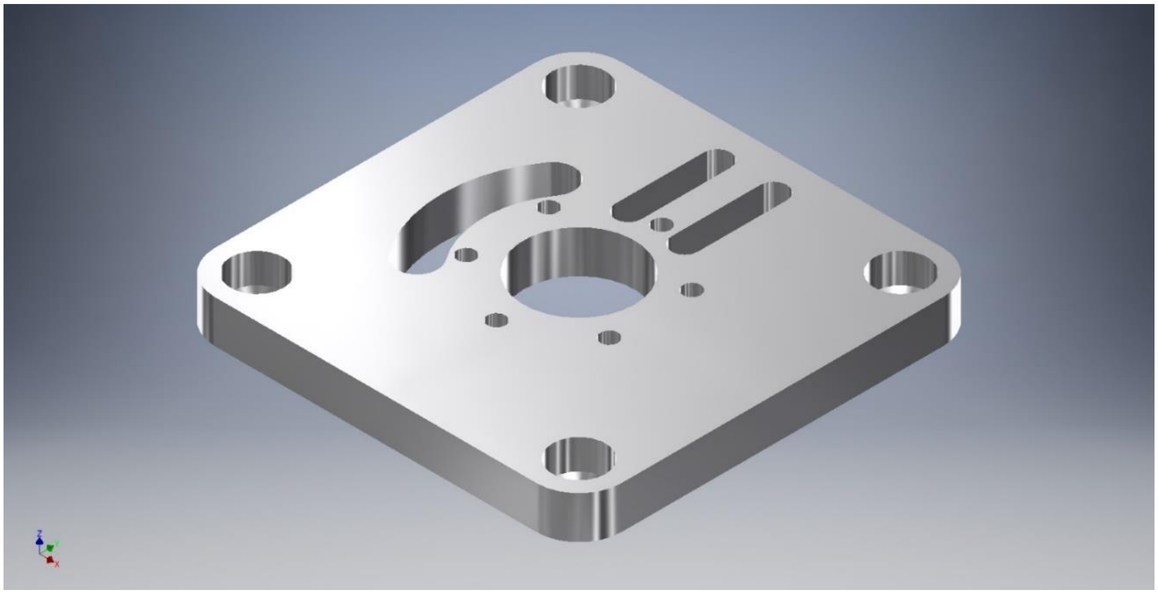


Figure 22: Motor Mount Plate Design Final

Figure 22 showed the final design of the modified motor mount plate. Here, the motor mount plate was designed as a square plate with a length of 192 mm, width of 192 mm and thickness of 20 mm. The design included slots and holes to accommodate the various features of the EMRAX 208 motor that were intended to protrude out of it. Additionally, mounting holes were placed in the design to allow the motor to be mounted on the plate and the plate on the EMRAX 208 bookend. The details of the plate dimensions were shown with an engineering drawing in the project file.

The final design of the motor mount plate was very similar to the initial design, the manufacture of which was unfinished. This decision was made because the initial motor mount plate design was considered quite suitable for use in the test bench. Furthermore, keeping the design similar allowed the manufacture of the motor mount plate to be completed by making use of the incomplete plate. The benefit of this was the saving of time, material and manpower. However, the chamfers in the upper slots were removed due to concerns of weakening the material around the mounting holes. This was the key difference between the initial and final mount plate designs.

Following this final modification, the design of the motor mount plate was completed. Therefore, the decision was made to get it manufactured in the Mechanical Workshop. After communicating with the workshop personnel, the manufacture of the plate was accepted.

Figure 23: Manufactured Motor Mount Plate

Figure 23 displayed the manufactured motor mount plate as placed on the EMRAX 208 motor. The manufacturing of the plate was expediently completed in only a few days and the completed plate was acquired. With the successful design and manufacture of the mount plate, the next step was to test mounting the EMRAX 208 motor on the bookend by utilising it as a connector.

Figure 24: EMRAX 208 Cooling Pipe Protrusions on Motor Mount Plate

Figure 24 demonstrated the protrusion of the cooling pipes during the mounting test. This testing attempt was successful. However, during the testing it was discovered that the upper slots for the cooling pipes were not wide enough for proper operation as shown in the figure.

Figure 25: Additional Machining

Hence, the decision was made to have an additional operation performed to machine off a small portion of the upper plate. Communication was established with the Mechanical Workshop personnel and this machining operation of the mount plate was completed. Figure 25 demonstrated the final machining operation performed to finalise the mount plate. Upon the completion of the machining operation, the functionality of the mount plate was once again tested. This was done by mounting the EMRAX 208 on the bookend with the plate serving as the connector again.

Figure 26: EMRAX 208 Mount Testing

As a result of this testing, the plate was discovered to be safely able to accommodate the proper operation of the cooling pipes. Hence, the decision was made to accept this state of the mount plate as the final state. Although the plate was not exactly as designed, modifications to the manufactured product for the purpose of correcting an unexpected difficulty was perfectly acceptable. The project file had the 3D and engineering drawings.

4.1.3 Control Panel and Circuit Rewiring

The control panel and circuit for the test bench were inherited from the Newcastle Racing project preceding this one. However, those equipment utilised momentary switches that snapped back to their original position upon activation.

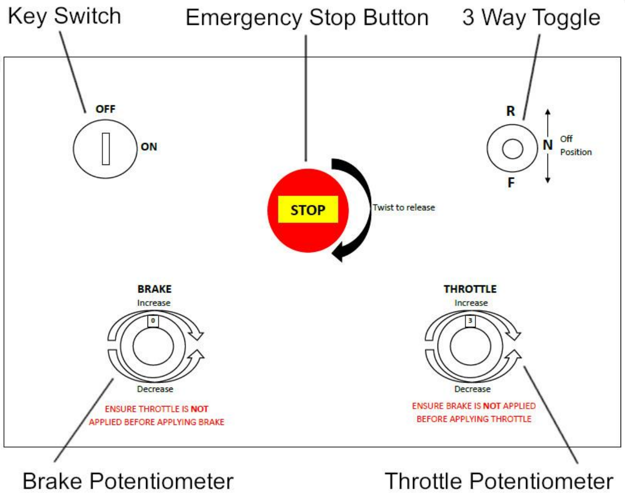


Figure 27: Design of the Control Panel [4]

Figure 27 showed the design of the control panel. Here, the key switch and the 3-way toggle switches were implemented as momentary switches [30] [28]. These momentary switches made the utilisation of the control panel by a single person alone very difficult and dangerous. Hence, the inherited control panel was deemed unsuitable for the operation of the test bench. Therefore, the decision was made to modify this panel by replacing the momentary switches with non-momentary ones.

For the accomplishment of this task, investigation was first conducted to determine suitable non-momentary switches for purchase. During this process, it was important to make sure that the dimensions of the new switches matched those of the old ones. The reason for this was the fact that the control panel was already manufactured to accommodate the old switches. If the new, non-momentary switches had different dimensions compared to the old ones then the manufacture of a new control panel was to be necessary. Therefore, new switches with the same dimensions as the old ones were found. This was done by looking up the products offered by the manufacturers of the old switches and simply buying new, non-momentary versions of the old, momentary switches [28] [30].

With the acquisition of the new switches successfully accomplished, the following step was to integrate them into the control circuit and panel in place of the old switches. To accomplish this process, the control circuit and panel needed to be disassembled to remove the old switches and then reassembled with the new switches integrated in. As such, the control circuit and panel were disassembled and the switches removed.

Figure 28: Replacing the Switches

Then, as shown in Figure 28, the new switches were soldered in to the proper locations on the control panel and shrink wrapped with a heat gun for safety purposes. Finally, the control circuit was reassembled through soldering and shrink wrapping.

Figure 29: Final State of the Control Panel

These endeavours resulted in the formation of a control circuit and panel with non-momentary switches as shown in Figure 29. These improved equipment were now suitable for implementation into the test bench to facilitate the operation of the emDrive 500 motor controller for controlling the EMRAX 208 motor.

4.1.4 EMRAX 228 Bookend Design and Manufacture

The design of the EMRAX 228 bookend underwent numerous iterations until reaching a final design. Unlike the EMRAX 208 bookend, which was chosen to be borrowed from the Electrical School, the EMRAX 228 bookend was decided to be designed specifically to accommodate the EMRAX 228 alone. The reason behind this was that the EMRAX 228 was intended to remain as the generator on the test bench in the future after the conclusion of this project as well. Even though the motor that was to be tested on the test bench was subject to change with future generations of the Formula Student car, the EMRAX 228 was planned to persist as the generator on the test bench. This situation also meant that the EMRAX 228 bookend was intended to persist alongside the EMRAX 228 motor for a significant time frame as well. Hence, the development, finalisation and manufacture of a satisfactory design for this bookend was of high importance. Furthermore, the EMRAX 228 bookend was the most complicated component that was design and manufactured in this project and so was highly significant in that regard.

The initial design for the EMRAX 228 bookend took inspiration from the windshield of the NRX drivetrain. This design was intended to encircle the power motor top to bottom for safe operation.

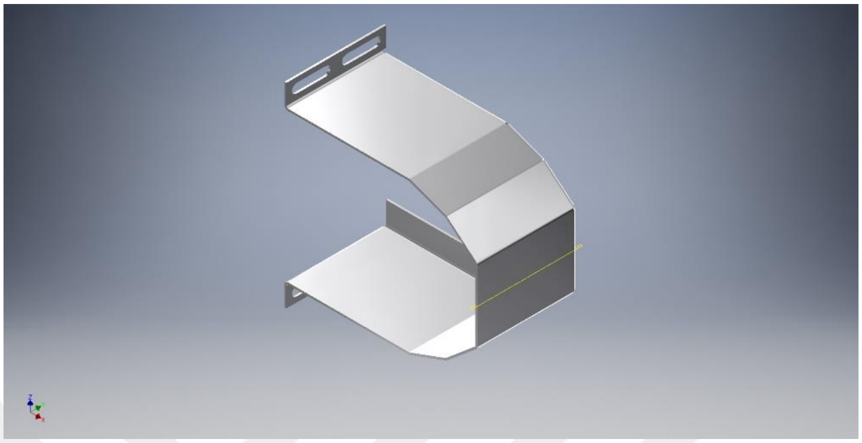


Figure 30: EMRAX 228 Bookend Initial Design

Figure 30 showed the initial design of the EMRAX 228 bookend. This design was quickly abandoned and left incomplete because the choice was made to make the design more similar to the EMRAX 208 bookend. Even so, this initial design served as a good starting point for the development of the EMRAX 228 bookend design.

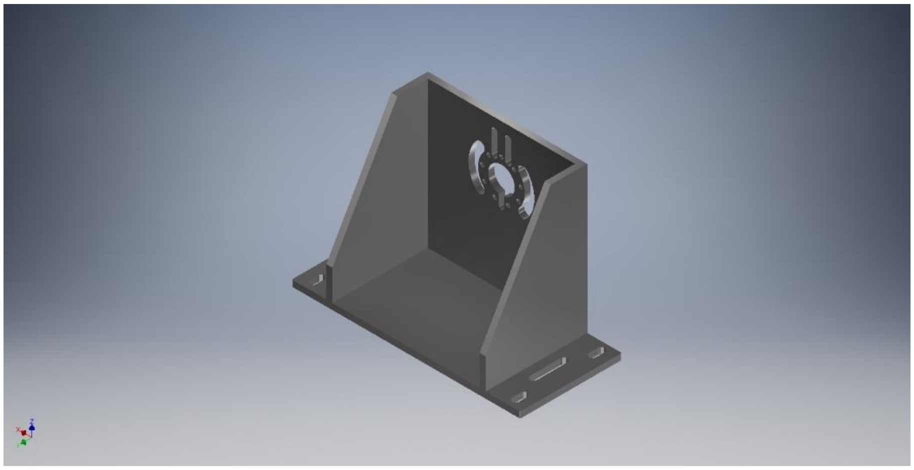


Figure 31: EMRAX 228 Bookend Final Design

Next, inspiration was taken from the EMRAX 208 bookend to change and develop the EMRAX 228 bookend design. The new design incorporated a bottom plate, two side plates and a back plate shaped specifically to accommodate the mounting of the EMRAX 228 motor. The final design of the EMRAX 208 bookend was shown in Figure 31.

There were numerous different iterations between the initial design shown in Figure 30 and the final design of the EMRAX 228 motor demonstrated in Figure 31. After the first design, the EMRAX 228 bookend was first designed to similar to the EMRAX 208 bookend. During this design process, an important point of consideration was the elevation of the centre of the EMRAX 228 motor [29]. The centres of the EMRAX 208 and 228 motors had to align to a high degree of accuracy to avoid disrupting the readings taken by the torque transducer between them. To accomplish this, the elevation of the centre of the EMRAX 208 motor was measured in the INVENTOR CAD drawing. The elevation was determined to be 200 mm and the EMRAX 208 bookend was designed to place the centre at that elevation.

Another important point of consideration was the weight of the bookend. Even though the bookend was to be bolted onto the test bench, the weight was still important for transportation purposes. The transportability of the EMRAX 228 bookend was important as there were two viable test beds that the designed test bench could be built upon. These were the test beds at the Formula Student bay and the Electrical School respectively. Both of these test beds were attractive options for utilisation. Therefore, a novel idea was to design the test bench such that it could be transported between the two test beds as necessary [31]. For this reason, the design of the EMRAX 228 bookend was attempted to be kept as light as possible. To accomplish this, the bookend was initially designed out of 6 mm thick stainless steel. Additionally, support plates that could be bolted and removed from the bottom of the bookend as needed were introduced to the design to allow the bookend to be transported between the two test beds.

However, the design had to be changed during the manufacturing process. The manufacturing of the design was decided to take place in house in the Mechanical Workshop of the Stevenson Building of Newcastle University. Communication was made with the technicians in that workshop to manufacture the design of the bookend. Unfortunately, 6 mm steel plates were not available to facilitate the manufacture of the EMRAX 228 bookend. The available plates were 12 mm thick and so the bookend had to be manufactured out of those [29]. Additionally, the design was changed to remove the support plates and remodel the bottom plate of the EMRAX 228 bookend to be able to accommodate the two test beds. These modifications, among other minor ones, were implemented to obtain the design shown in Figure 31.

Before the manufacture of the EMRAX 228 bookend could commence, another point of contention was the assembly methods of the bookend. The bookend was designed out of several components to make the manufacturing process easier and more feasible. Rather than just manufacturing the bookend as a whole, the pieces of the bookends could be manufactured with much more ease [31]. However, these pieces then had to be put together to from the bookend. Initially, the means of accomplishing this was envisioned to be through welding. In one of the design iterations, the bookend was designed to accommodate welding during assembly by moving the back plate further in from the edge of the bottom plate. Even so, during the manufacturing process, welding the bookend together was decided to be difficult as distortion was liable to occur [29]. This distortion was predicted to disrupt the 90 degrees of angle between the back plate and the bottom plate [29]. If this angle was disrupted, then the connection between the EMRAX 208 and 228 motors could not be a straight line and the readings acquired by the torque transducer could not be accurate. Hence, the decision was made to bolt the EMRAX 228 bookend together rather than welding it.

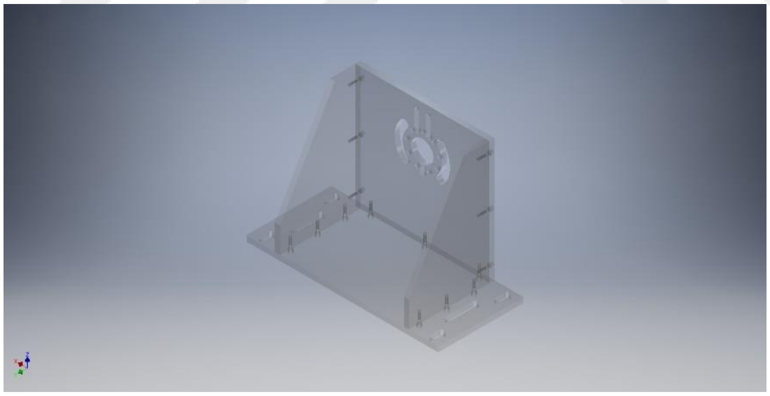


Figure 32: EMRAX 228 Bookend Final Design Transparent

Figure 32 showed the final design of the EMRAX 228 bookend made transparent in INVENTOR. Here, the screws utilised to bolt the bookend together could be observed. These screws were designed as M6 counterbored bolts and so were intended to function without disturbing the elevation level of the bookend. The final changes to the EMRAX 228 bookend design in accordance with this decision to bolt it together were made. These changes were implemented in the CAD drawings and engineering drawings made in INVENTOR. Lastly, these final drawings were submitted for manufacture in the Mechanical Workshop. These were in the project file.

4.1.5 Shaft Adaptor Design and Manufacture

Shaft adaptors were necessary to connect the torque transducer on the flexible couplings to the EMRAX 208 and 228 motors. These adaptors were intended to be connected to the faces of the two motors while the other end interfaced with the flexible couplings attached to the torque transducer. This assembly was intended to facilitate the smooth transfer of torque output from the EMRAX 208 driving motor to the EMRAX 228 driven generator.

Figure 33: EMRAX Transmission Shafts [6]

To start with, investigation was conducted to determine if suitable shaft adaptors could be purchased instead of designing and manufacturing them. Figure 33 showed various EMRAX brand transmission shafts that were. Even though many varieties of these shafts were available, shafts that could suit the flexible couplings could not be procured through purchase [6]. Hence, the decision was made to design and manufacture them instead.

Even so, inspiration was acquired from investigating and analysing these shaft designs shown in Figures 33 and 18. After consulting the technicians in the Mechanical Workshop, the design of the shaft adaptors was finalised [29]. The project file contained the 3D and engineering drawings.

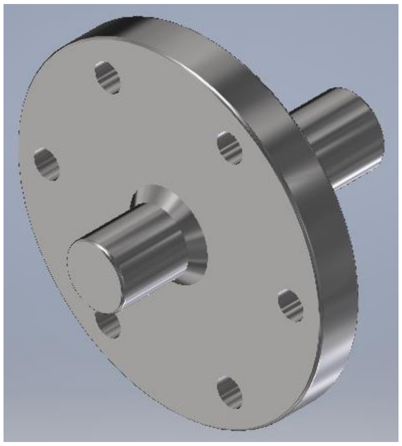


Figure 34:Shaft Adaptor Final Design

Figure 34 demonstrated the final design of the shaft adaptors. The adaptor was to be made out of stainless steel and bolted on to the EMRAX 208 and 228 motors through the utilisation of M8 bolts. The adaptors were designed to fit onto and cover the circular mounting protrusions on the surfaces of the EMRAX 208 and 228 motors. This feature was inspired by the EMRAX transmission shafts as any slight misalignment in the interfacing surfaces was to be a tell-tale sign of the existence of a problem.

4.2 Acquisition of Components

For the assembly and completion of the test bench, the methodologies for the obtainment of certain components was chosen to be through direct acquisition. These equipment were procured through the application of the methodologies formed specifically for them and the results of these endeavours were documented in this section.

4.2.1 Test Bed Procurement

The investigation of the available test beds in the immediate vicinity that could successfully allow for a test bench to be built upon them resulted in the discovery of two satisfactory test beds. The first one was discovered in the Formula Student Bay located in the Multifunction Lab 2 of Newcastle University's Stevenson Building. The second one was detected in the Electrical School of Newcastle University.

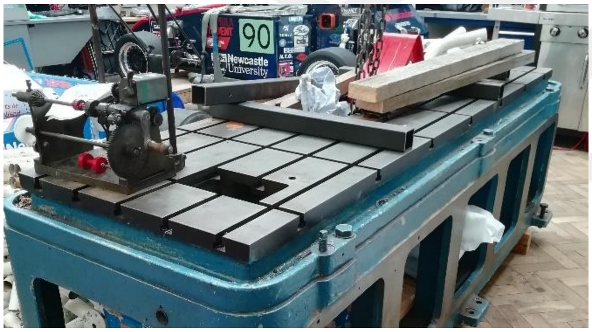


Figure 35: Formula Student Bay Test Bed

Figure 35 shows the first test bed found in the Formula Student Bay and Figure 2 demonstrated the second bed located in the Electrical School. With the possibilities identified, the remaining task was to choose which one was more convenient for utilisation.

To start with, investigation to determine the availability of the two test beds was conducted. The bed in the Formula Student Bay was revealed to be available throughout the project duration and perhaps available for some time afterwards. On the other hand, the bed in the Electrical School was not currently available but the possibility of availability in the future was feasible. Therefore, the decision was made to use the test bed in the Formula Student Bay as the foundation for the test bench assembly. Even so, the option of using the Electrical School test bed was also taken into consideration by designing the test bench with the flexibility to change test beds as necessary. This was done as while the test bed in the Formula Student Bay was readily available for project use, the bed in the Electrical School was in a much more convenient location because of the proximity it had to the various useful electronic equipment in the Electric School.

4.2.2 DC Power Supply Acquisition

The possibility of acquiring a DC power supply that was rated at 120 V and 400 A and could supply 42 kW of power stably for the operation of the EMRAX 208 motor in the test bench was investigated. The most likely location to find such a power supply was determined to be the Electrical School. After some communication regarding this issue, permission was obtained from the Electrical School to make use of their DC power supply for the test bench.

4.2.3 DC – AC Power Converter Procurement

Investigation was conducted to determine if a DC – AC power converter that was suitable for use with the DC power supply could be procured. The power converter needed to be rated high enough to be utilised in tandem with the 42 kW DC power supply. Because of this intrinsic relationship between the DC power supply and the DC – AC power converter, the most likely place to procure the converter was decided to be the Electrical School. Communication was made with the Electric School personnel regarding this issue. As a result, permission to make use of a suitable DC – AC power converter from the Electric School was acquired.

4.2.4 EMRAX 208 Motor Acquisition

The EMRAX 208 motor was previously purchased by Newcastle Racing and was situated in the Formula Student Bay for the use in new Newcastle Racing projects. Investigation was performed to learn if the motor was available for use in the test bench. This investigation yielded the results that the EMRAX 208 motor was indeed accessible for use in the test bench throughout the project duration. Hence, permission was subsequently obtained to make use of the motor in this project.

4.2.5 EMRAX 208 Bookend Procurement

Prior to designing and manufacturing a suitable bookend for the EMRAX 208 motor, investigation was conducted to determine if such a bookend could be directly acquired instead. This investigation revealed that a bookend was previously borrowed from the Electrical School and was located at the Formula Student Bay. The bookend was examined to determine if it could be utilised to accommodate the EMRAX 208 motor in the test bench.

Figure 36: EMRAX 208 Bookend

After careful evaluation, the bookend was confirmed to be usable for the EMRAX 208 motor if a motor mount plate was utilised as a connector. Hence, an inquiry was made to the Electric School regarding the availability of the bookend for the project duration and permission was obtained to keep borrowing it throughout this time period for use in the test bench.

4.2.6 emDrive 500 Motor Controller Acquisition

Figure 37: emDrive 500 Motor Controller

The emDrive 500 motor controller was acquired by Newcastle Racing prior to the start of this project and awaited use in the Formula Student Bay. Therefore, an investigation was initiated to determine if the motor controller was available for use in the test bench for the project duration. In the end, permission was obtained to make use of the emDrive 500 motor controller in the test bench until the end of the project.

4.2.7 Torque Transducer and Flexible Couplings Acquisition

The acquisition of a satisfactory torque transducer for the test bench and the flexible couplings that could be used to mount it began with an investigation to determine a suitably high rated transducer. Out of all the numerous transducers in the market, the TM series of transducers produced by the company MAGTROL and rated at 100 Nm was identified as a fitting choice. Hence, communication was established with official MAGTROL personnel so that the cost of buying this transducer and the flexible couplings could be determined. Unfortunately, the price for the transducer alone was revealed to be quite high at an approximate 4000 GBP. Due to this high cost, investigative work was done to ascertain if a fitting transducer could be borrowed instead prior to the purchase. This investigation revealed that a 100 Nm TM series torque transducer from MAGTROL along with the flexible couplings were indeed available for borrowing from the Electrical School.

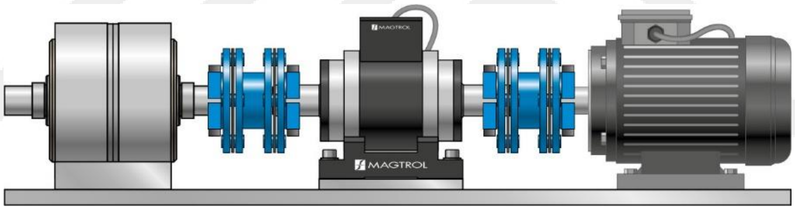


Figure 38: MAGTROL Torque Transducer Mounting [11]

Figure 38 showed how to mount the transducer with the flexible couplings. For high speed applications such as usage with the EMRAX 208 motor, there was a suggestion to use a base plate to secure the transducer as well. Just like the flexible couplings, permission was obtained to borrow the base plate from the Electrical School as well. In the end, the decision was made not to go ahead with the purchase but instead to borrow the transducer and the couplings from the Electric School for use in the test bench.

4.2.8 EMRAX 228 Motor Procurement

The EMRAX 228 motor was previously acquired by Newcastle Racing long before the start of this project and utilised as the motor for the drivetrain of the NRX. Hence, investigation was conducted so that the availability of the EMRAX 228 motor for use in the test bench could be determined.

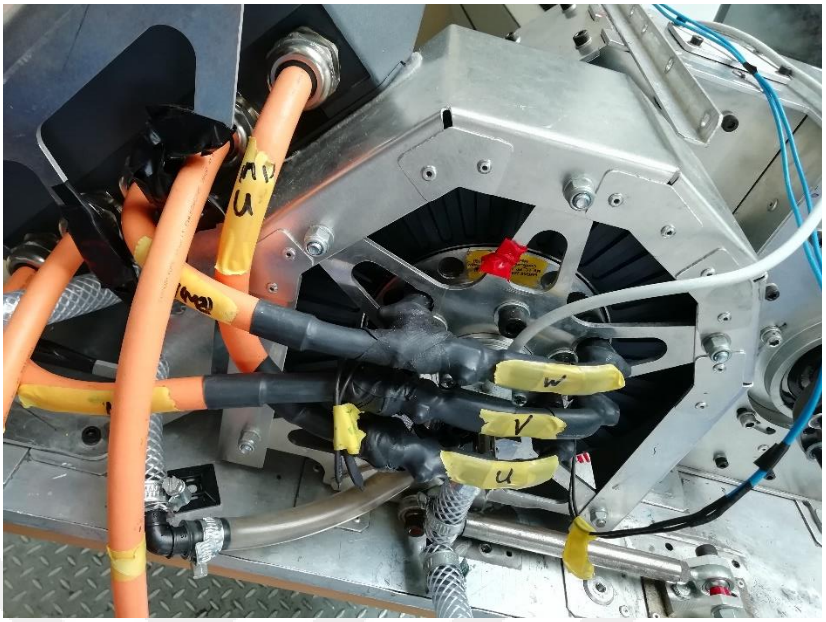


Figure 39: EMRAX 228 Motor in the Drivetrain of the NRX

This investigation revealed that the motor was available for utilisation throughout the project duration and permission was obtained to make use of it in the test bench. Despite this, however, the motor was securely mounted on the drivetrain of the NRX as seen in Figure 39. The removal of the EMRAX 208 motor from this drivetrain was necessary to implement it on the test bench.

4.2.9 Cooling Mechanism Procurement

The implementation of suitable cooling mechanisms for the EMRAX 208 and 228 motors as well as the emDrive 500 motor controller on the test bench was initially thought to be accomplished through design work. Throughout the development of the design process, investigation was performed to test different types of cooling pipes until a suitable type was found. Even so, concocting a satisfactory design proved to be challenging due to the necessity to have a large supply of water present in the test bench location. Permitting the presence of a water reservoir in either the Formula Student bay or the Electric School laboratory was a risky preposition for the sensitive electronic equipment situated in these places. Therefore, the decision was made to conduct an investigation to determine if suitable cooling mechanisms could be acquired instead. As a result of this work, chiller units that could satisfactorily serve as cooling mechanisms for the EMRAX 208, 228 motors as well as the emDrive 500 motor controller were found in the Electrical School. After some communication, permission was obtained for their use in this project.

4.2.10 Load Bank Acquisition

The acquisition of the load bank was at first decided to be done through the design of a circuit to dump the power generated by the EMRAX 228 motor into a number of sizable floodlights. This circuit was planned to integrate mosfets and other electronic components in its composition to successfully dump the power to the floodlights. Research was performed to evaluate the feasibility of this method and investigation was conducted to determine suitable electronic components for the effective implementation of it. Unfortunately, the results showed that designing and producing a load bank powerful enough to accommodate the 40 kW power of the EMRAX 228 motor was infeasibly high in resource consumption. Therefore, investigation was performed to locate a satisfactory load bank for use in the test bench instead. As a result of this endeavour, a fitting load bank was discovered in the possession of the Electrical School. Thus, communication was established with the Electrical School personnel and permission was obtained for the use of the load bank in this project.

5. Analysis and Discussion

Analysis and discussion of the experiences acquired throughout the course of this project as well as the results achieved were necessary to derive meaningful conclusions to learn and improve from. As a starting point, an analysis of the project as a whole was conducted. Then specific tasks were analysed. These analyses and discussions were categorised and documented in this section.

5.1 Overall Analysis of the Project

The fundamental goal of this project was to design and manufacture a test bench that could safely perform a series of investigative tests to understand the nature of the interaction between the motor and motor controller of the Formula Student car, NR11. Initially, this project was intended to utilise a finished test bench to conduct these tests and analyse the results. This was because it was estimated that a test bench was to be designed and constructed before the bulk of the project work period began. Unfortunately, the test bench was not ready for that time. Hence, the goal of the project shifted from performing tests using the test bench to designing and completing the test bench. The evolution of the project throughout the year to accommodate the demands and limitations of reality proved to be very satisfying and educational.

5.2 Analysis of Design and Manufacture

Following the overall analysis of the project, the design and manufacture efforts performed for the various components of the test bench were analysed.

5.2.1 Analysis of Test Bench Design

The design of the test bench emphasised the principles of safety and functionality primarily. The design took inspiration from the test rigs already present in the Electrical School as well as the test rigs discovered in literature review. Critical thinking was involved in the design and a number of revisions were gone through in an effort to give the proper consideration to the resources and time available for the design and manufacture of the components. Ultimately, the test design of the test bench could only be complete once all of the components necessary for assembly were brought together. Before that time, the design of the test bench was a constantly evolving idea that was shaped by research, investigation and the limitation of the resources in reality.

5.2.2 Analysis of Motor Mount Plate Design and Manufacture

The initial design of the motor mount plate was inherited from a previous Newcastle Racing project. This inherited design was refined and manufactured using the incomplete mount plate. Unfortunately, the cooling pipes of the EMRAX 208 were found to be unable to function as necessary due to the high thickness of the mount plate obstructing access to them. As such, an additional machining operation was necessary before the mount plate could be completed. This additional work could have been avoided if the plate was design as a little less thick.

5.2.3 Analysis of Control Panel and Circuit Rewiring

The control circuit and panel were inherited from a previous Newcastle Racing project. These equipment were functional but used momentary switches in the control circuit and panel. These switches snapped back upon operation if not kept pressed down. This quality of the switches made the control panel dangerous and difficult to use by a single person alone. Hence, the replacement of these momentary switches with non-momentary ones had to be done. This work could have been avoided if the non-momentary switches were implemented into the control circuit and panel from the very beginning. The work required some practical skills such as soldering and could have been done better if these practical skills were acquired and developed prior to the advent of this project.

5.2.4 Analysis of EMRAX 228 Bookend Design and Manufacture

The design of the EMRAX 228 bookend underwent numerous revisions before reaching a final conclusion. The initial design resembled the windshield of the drivetrain of the NRX. This designed evolved to resemble the EMRAX 208 bookend from the Electrical School. Many further revisions to the design were done until a final design was settled upon. However, even this final design had to undergo a number of revisions once communication was established with the manufacturers. This large number of revisions could have been avoided if communication was established with the manufacturers at an early stage. Throughout the design process, many ideas were considered only to be discarded. The idea of welding the bookend together was one of them. The establishment of communications with the Mechanical Workshop at an earlier stage could have prevented spending time and energy on these paths that were actually infeasible to implement.

5.2.5 Analysis of Shaft Adaptor Design and Manufacture

The shaft adaptors were designed to be incorporated into the connection between the EMRAX 208 driving motor and the EMRAX 228 driven generator. This pathway was to be utilised to transmit torque. The idea of buying the adaptors was considered but discarded as suitable adaptors could not be found. Even so, inspiration was taken to design the adaptors such that any misalignment on the connecting faces was to be a tell-tale sign of an unexpected problem. The design of the adaptors went through revision only once. Consideration of this fact marks this task as one of the more successful ones in this project.

5.3 Analysis of Acquisition

Lastly, analysis of the work done to acquire components for the completion of the project was performed.

5.3.1 Analysis of Test Bed Procurement

The test bed procurement process resulted in the determining of two suitable test beds; one in the FS bad and the other in the Electrical School. These choices were both attractive for a multitude of reasons. Hence, the decision was made to design the test bench with the flexibility to be transported between these two test beds as necessary.

5.3.2 Analysis of DC Power Supply Acquisition

The acquisition of the DC power supply rated at 120 V and 400 A and able to provide 48 kW of power continuously was accomplished through establishing communications with the Electrical School and asking to borrow a suitable one.

5.3.3 Analysis of DC – AC Power Converter Procurement

The procurement of the DC – AC power converter was done by requesting a suitable converter from the Electrical School.

5.3.4 Analysis of EMRAX 208 Motor Acquisition

The EMRAX 208 motor was inherited for utilisation in this project. The EMRAX 208 motor was one of the two components that this project revolved around. This powerful asynchronous motor was one of the two main objects that the test bench was built around. The entirety of the project could be stated as designing and manufacturing a means to understand how this motor interacted with the emDrive 500 motor controller.

5.3.5 Analysis of EMRAX 208 Bookend Procurement

The EMRAX 208 bookend was essentially a repurposed generic bookend borrowed from the Electrical School. The bookend was not specifically designed to accommodate the EMRAX 208 motor. Hence, the bookend was not suitable for directly mounting the motor onto. This problem was resolved by the design and manufacture of a motor mount plate to serve as a connector. Essentially, repurposing the borrowed bookend from the Electrical School as the EMRAX 208 bookend reduced the task of designing and manufacturing a specifically made bookend into simply designing and manufacturing a motor mount plate instead.

5.3.6 Analysis of emDrive 500 Motor Controller Acquisition

The emDrive 500 motor controller was inherited from Newcastle Racing. This robust controller could be set up with the emDrive configuration software and was intended to control the EMRAX 208 motor. This component along with that motor were of high important to this project as they were essentially the two equipment that building the test bench revolved around. The purpose of building the test bench was essentially to analyse the relationship between this motor controller and the EMRAX 208 motor. Therefore, this motor controller had a great and subtle influence over the direction of project development.

5.3.7 Analysis of Torque Transducer and Flexible Couplings Acquisition

The initial plan was to purchase a suitable torque transducer along with the couplings. This plan was abandoned when the rather sizable, approximately 4000 GBP price of the torque transducer was revealed. The torque transducer, flexible couplings and even a base to mount the transducer were arranged to be borrowed from the Electrical School instead. Throughout this process, the TM series of torque transducers rated at 100 Nm were chosen as the most suitable option for the test bench. In addition, the opportunity arose to examine the structure of one of the borrowed flexible couplings and design shaft adaptors to accommodate them. Ultimately, the existence of a suitable transducer in the Electrical School was quite fortunate. Obtaining a high price equipment like this was likely to be very difficult otherwise.

5.3.8 Analysis of EMRAX 228 Motor Procurement

The EMRAX 228 motor was inherited from Newcastle Racing. The EMRAX 228 was used to power the NRX and was situated in the drivetrain of that car at the advent of this project. Research revealed that this motor could also function as a generator if necessary. Hence, the decision was made to utilise the EMRAX 228 motor as a driven generator serving as the load on the EMRAX 208 driving motor on the test bench. However, actually implementing the EMRAX 228 as a generator on the test bench proved to be a challenging endeavour. There was some information to be found in the manual of the motor but ultimately that was insufficient.

5.3.9 Analysis of Cooling Mechanism Procurement

The procurement of the cooling mechanism was accomplished by borrowing the chiller units present in the Electrical School. Prior to that, an attempt was made to design and create an independent cooling mechanism. However, this could not be carried out due to the necessity to involve a water reservoir to assist with the cooling process.

5.3.10 Analysis of Load Bank Acquisition

The load bank was initially intended to be designed and built using an electronic circuit incorporating mosfets and large, strong floodlights. However, the design and manufacture of such a load bank proved more challenged and resource consuming than anticipated. Hence, the load bank acquisition was completed through procuring a suitably high rated load bank from the Electrical School. Actually building such a load bank was thought to be a very challenging task.

6. Conclusions and Summary

The conclusions derived as a result of the analyses of the numerous endeavours undertaken through the course of this project were detailed in this section. These was intended to provide a clear summation of the project achievements.

6.1 Conclusions of the Design and Manufacture Work

To start with, the test bench design was satisfactorily completed. Even so, further improvement was always possible. Following that, the incomplete motor mount plate was success finished and tested as ready for implementation. Next, the momentary switches in the control panel and circuit were successfully replaced with non-momentary ones. Even so, the control panel still required some more work before implementation into the test bench. After that, engineering drawings for the EMRAX 228 bookend were successfully delivered in the Mechanical Workshop for manufacturing. Also, the engineering drawings for the shaft adaptors were accepted as well. Finally, the methodology for test bench assembly was developed through critical thinking and was ready for application.

6.2 Conclusions of the Acquisition Work

First of all, the procurement of the test bed was successfully accomplished with the utilisation of the test bed located in the Formula Student bay. Next, the DC power supply acquisition was completed by arranging for it to be borrowed from the Electrical School. To make use of the DC power supply, a DC – AC power converted also had to be procured. This was accomplished through the assistance of the Electrical School. Next, the EMRAX 208 and 228 motors along with the emDrive 500 motor controller were inherited from Newcastle Racing for utilisation in this project. Following that, the procurement of the EMRAX 208 bookend was completed by repurposing the generic bookend borrowed from the Electrical School through the use of a motor mount plate. Afterwards, the torque transducer and the flexible couplings necessary for mounting it along with the base plate for high speed applications were arranged for acquisition through borrowing from the Electrical School. To continue, a solution to the cooling mechanism procurement problem was discovered through the borrowing of some of the numerous chiller units located in the Electrical School. Lastly, the load bank acquisition was completed by arranging to borrow a suitably high rated load bank again from the Electrical School.

7. Future Work

Future work that could be done to further develop and improve the test bench were categorised and documented in this section. To start with, the means that could be utilised to evolve the functionality of the test bench were explained. Secondly, the feasible means of developing the testing and analysis methods that were to be used in the operation of the test bench were explored. Finally, the possibilities of testing motors other than the EMRAX 208 motor and controllers other the emDrive 500 controller were examined.

7.1 Evolution of the Test Bench

Throughout the course of this project, a test bench that could successfully perform a series of the investigation tests on the motor and motor controller on the Formula Student car was designed, developed and manufactured. All of the components necessary for the completion of the test bench as designed were arranged to be gathered together either through direct acquisition or design and manufacture. The final remaining step of assembling the test bench together from these components was relegated to future work. The accomplishment of that final step was to mean that the test bench was completed in accordance with the final design. However, that design was concocted with due consideration given to the realities of time and resources limitations for the project duration. Therefore, the design was not as ambitious as it could have been if these limitations did not exist. In that sense, the assembled test bench from that design could be considered a good starting point for the further development of the test bench. For example, temperature sensors can be implemented as a means of improving the test bench. Even though in-built temperature sensors exist in the EMRAX 208 and 228 motors along with the emDrive 500 motors controller, additional sensors could be integrated to the test bench to acquire more valuable data. Furthermore, the implementation of strain gauges into the test bench to obtain data on the strain endured by the shaft adaptors and flexible couplings was also a possibility. The torque transducer and the in-built temperature sensors were the only sensors. Additionally, the bookends on the test bench could be re-designed and manufactured to be lighter to facilitate better transportability.

7.2 Development of Testing and Analysis Methods

After the completion of the test bench the next step was to utilise the test bench to actually perform investigative testing into the motor and the motor controller. These tests needed to be conducted in an orderly, structured manner and the data obtained from them documented. This data could then be analysed to acquire insight to the workings of the motor, motor controller and the interaction between them. Methodology for testing was in fact developed throughout the course of this project. However, as the assembly of the test bench was relegated to future work, the application of that methodology to utilise the test bench was also assigned to future work. In that sense, the methodology for testing that was developed for this project could be utilised as a starting point. After the successful assembly of the test bench from all the acquired, designed and manufactured components gathered together for the duration of this project, the methodology developed for testing could be implemented as an initial means of testing. Through research and investigation along with potentially trial and error, the testing and analysis methodology could be improved and refined.

7.3 Testing Future Electric Motors and Controller for the Formula Student Car

The test bench was designed and developed with the intention of testing the operation of the EMRAX 208 motor in tandem with the emDrive 500 motor controller. The test bench, once assembled, was likely to be able to perform the testing of these two particular equipment satisfactorily as it was designed to do. However, the possibility remained that the need to test motors and controller other than these two could arise in the future. Newcastle Racing as an organisation was intended to continuously develop new cars for the Formula Student competition. As such, the possibility that new motors and controller were to be chosen for implementation into the newer generations of Formula Student cars was more than likely. When designing the test bench, this possibility was accounted for. The EMRAX 208 bookend was not designed and manufactured specifically for the EMRAX 208 motor. The motor mount plate was the specifically made equipment rather than the bookend. This allowed the test bench the flexibility of being able to switch out the motor under testing as necessary.

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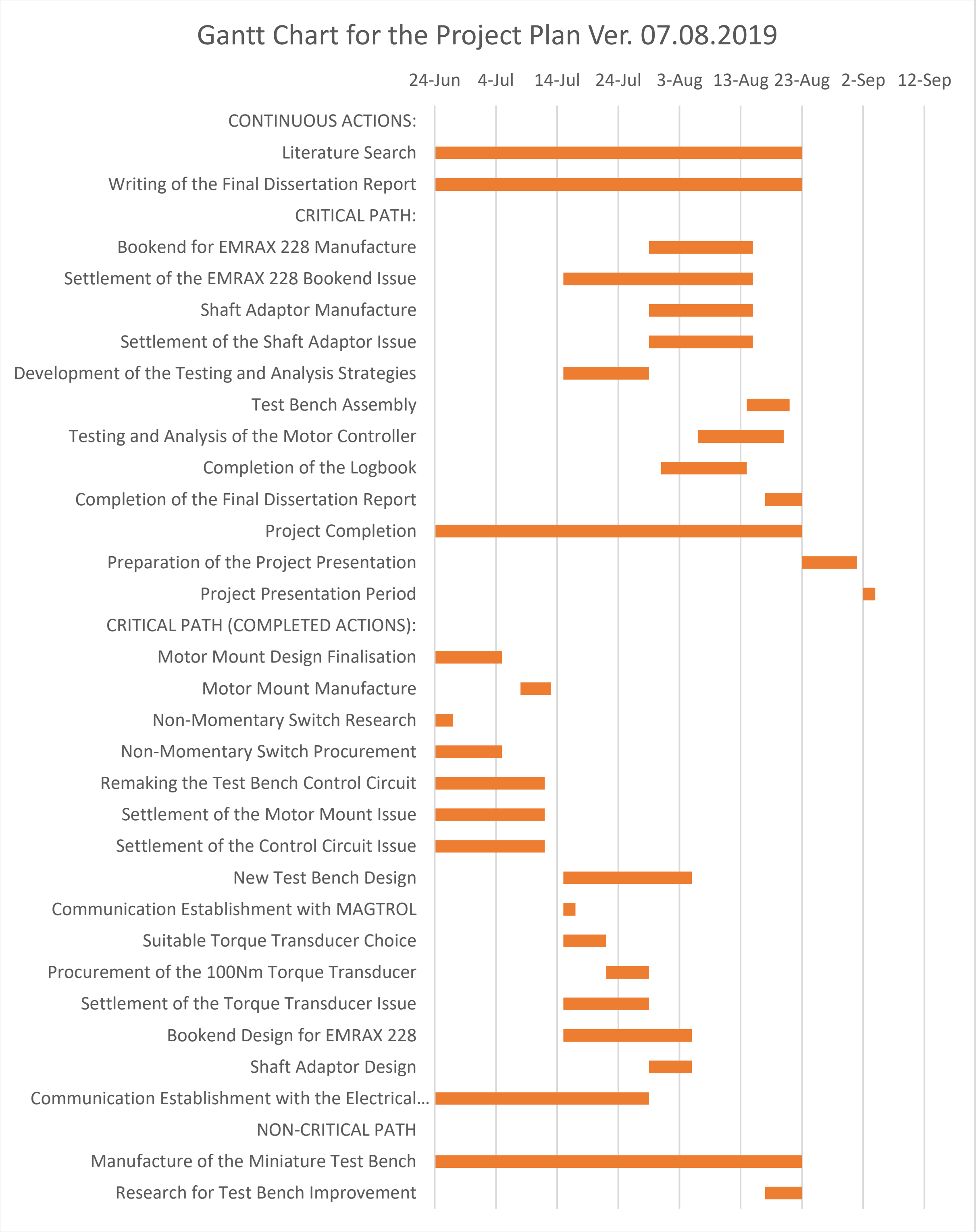
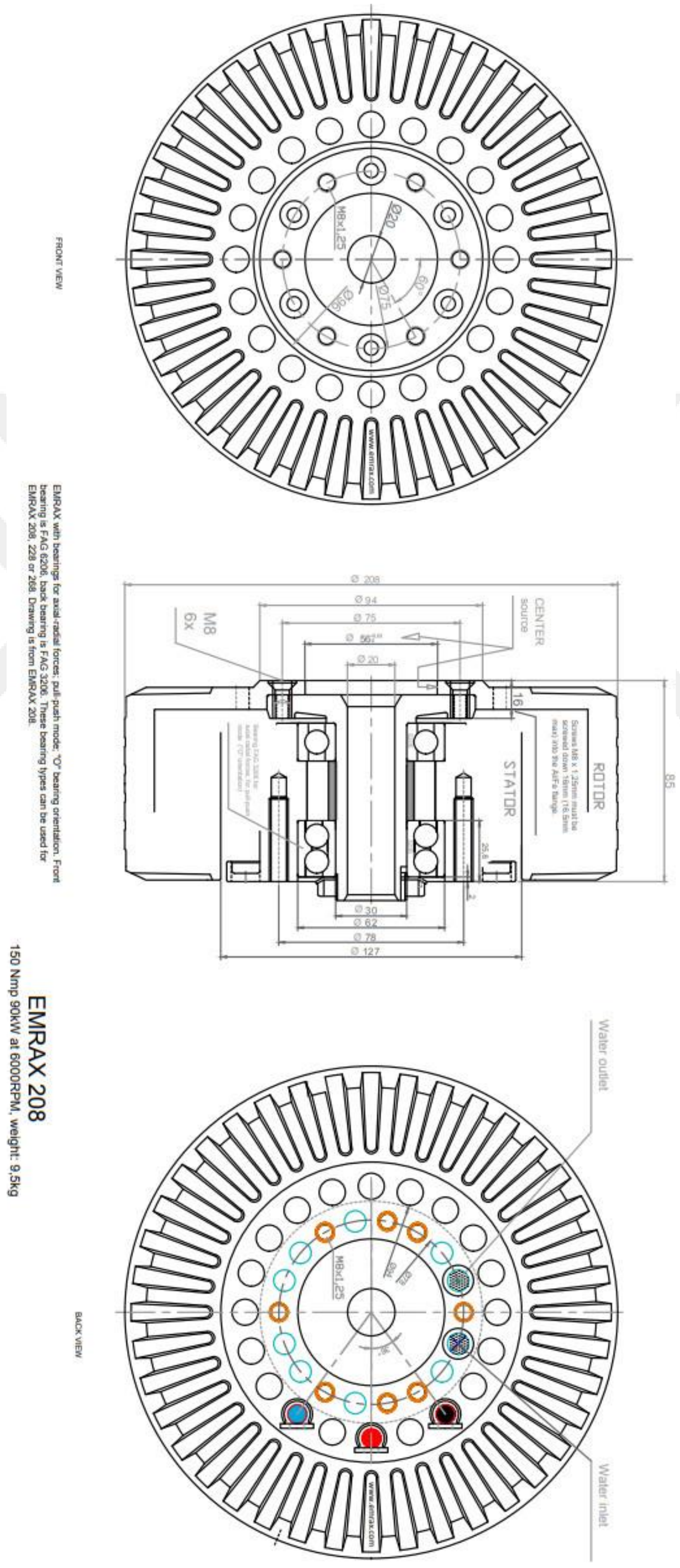
9. Appendix

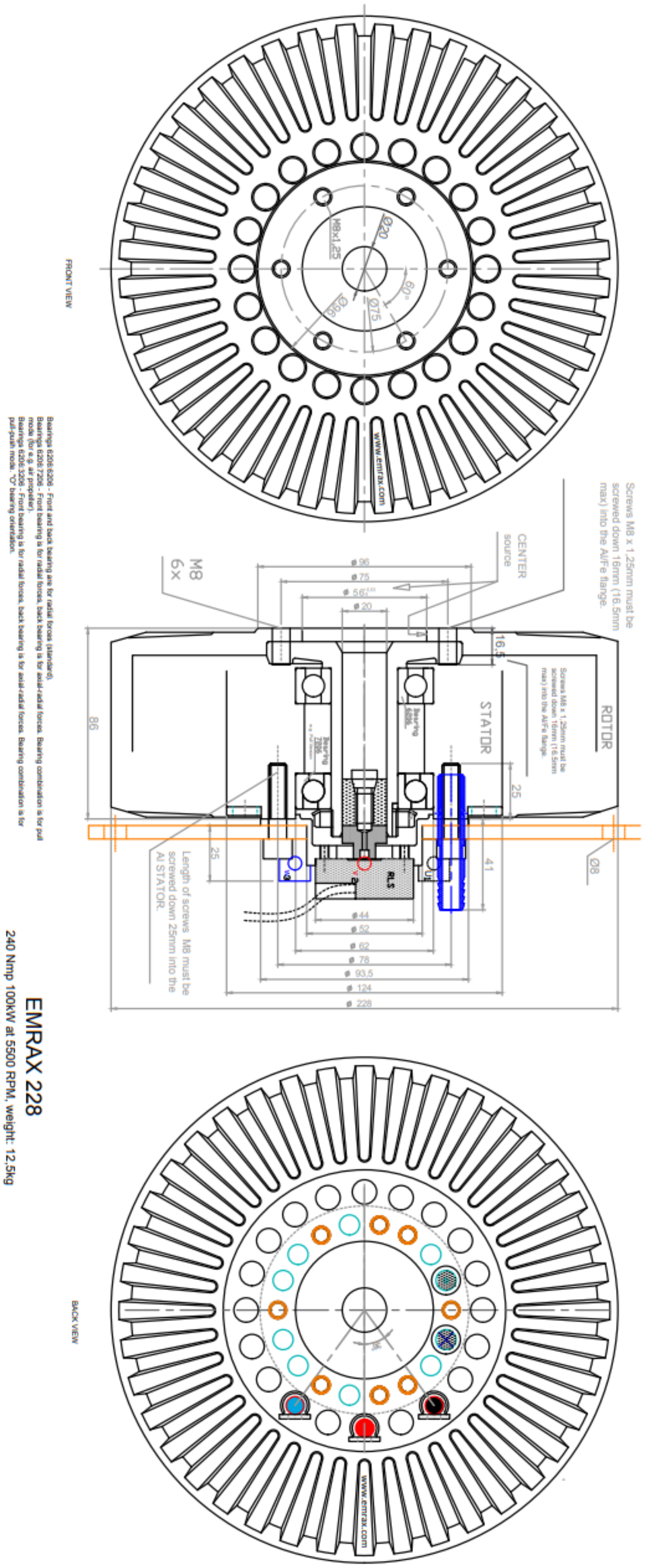
Appendix A – Final Gantt Chart



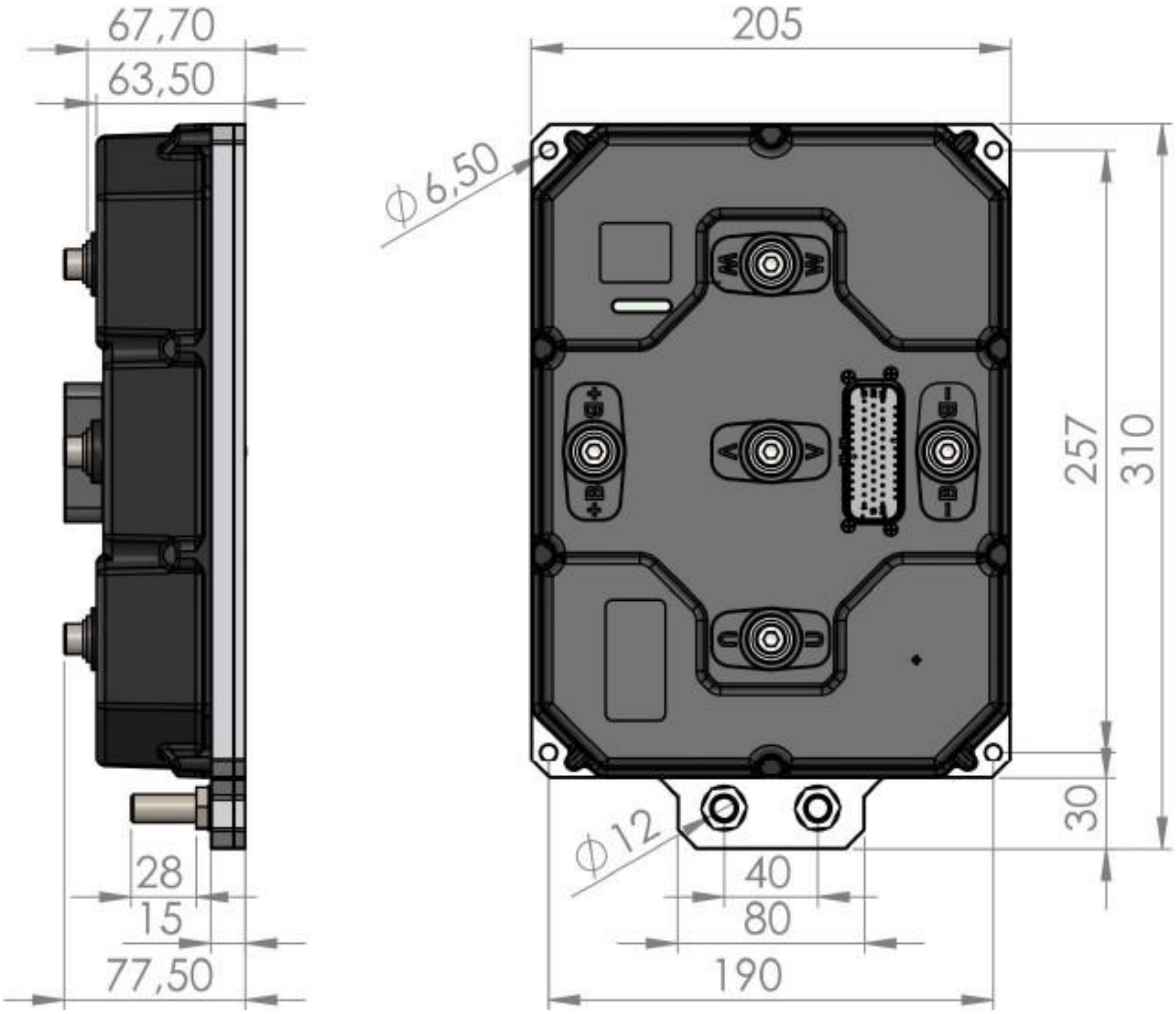
Appendix B1 – EMRAX 208 Motor Detailed Dimensions [32]



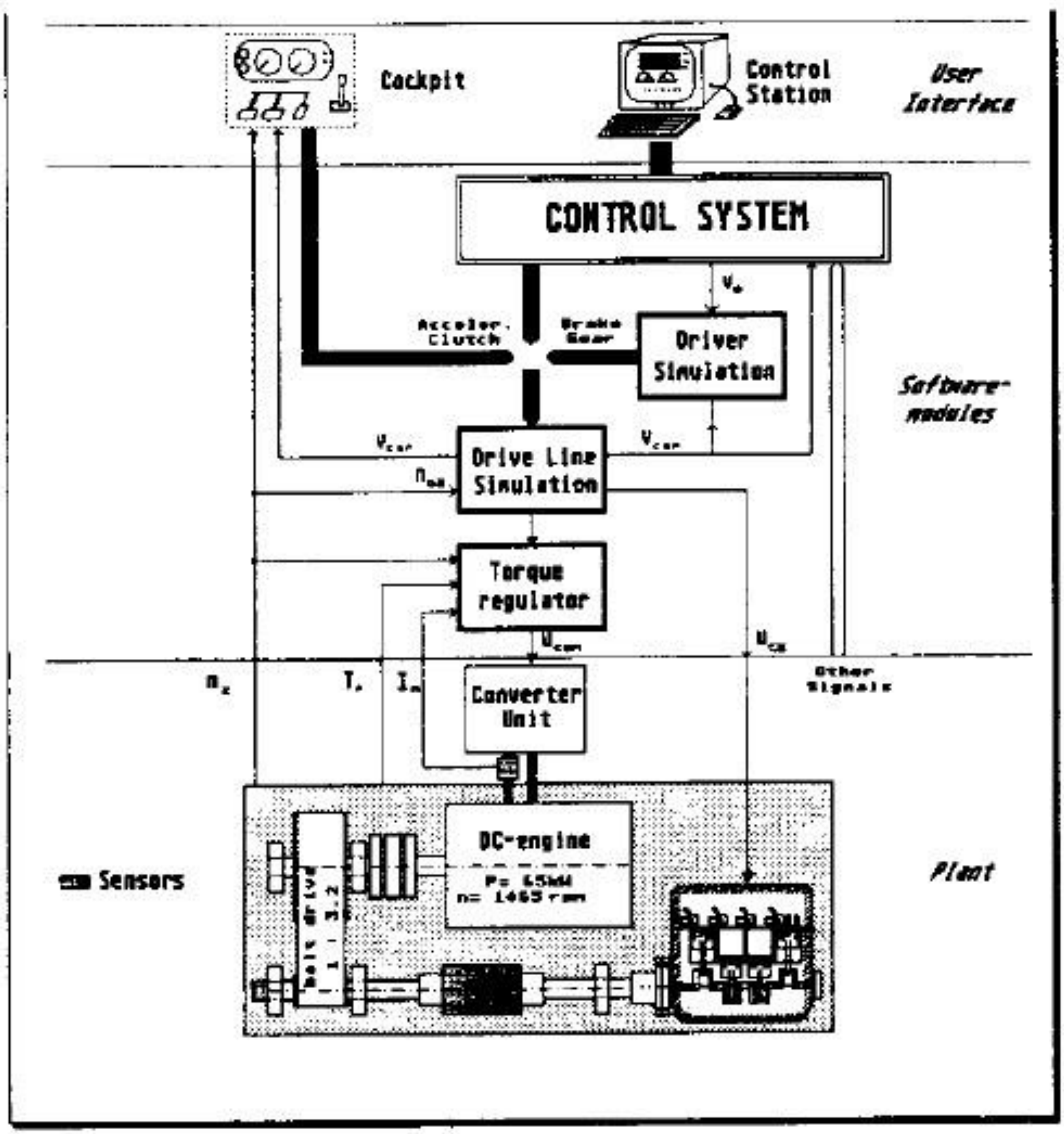
Appendix B2 – EMRAX 228 Motor Detailed Dimensions [33]



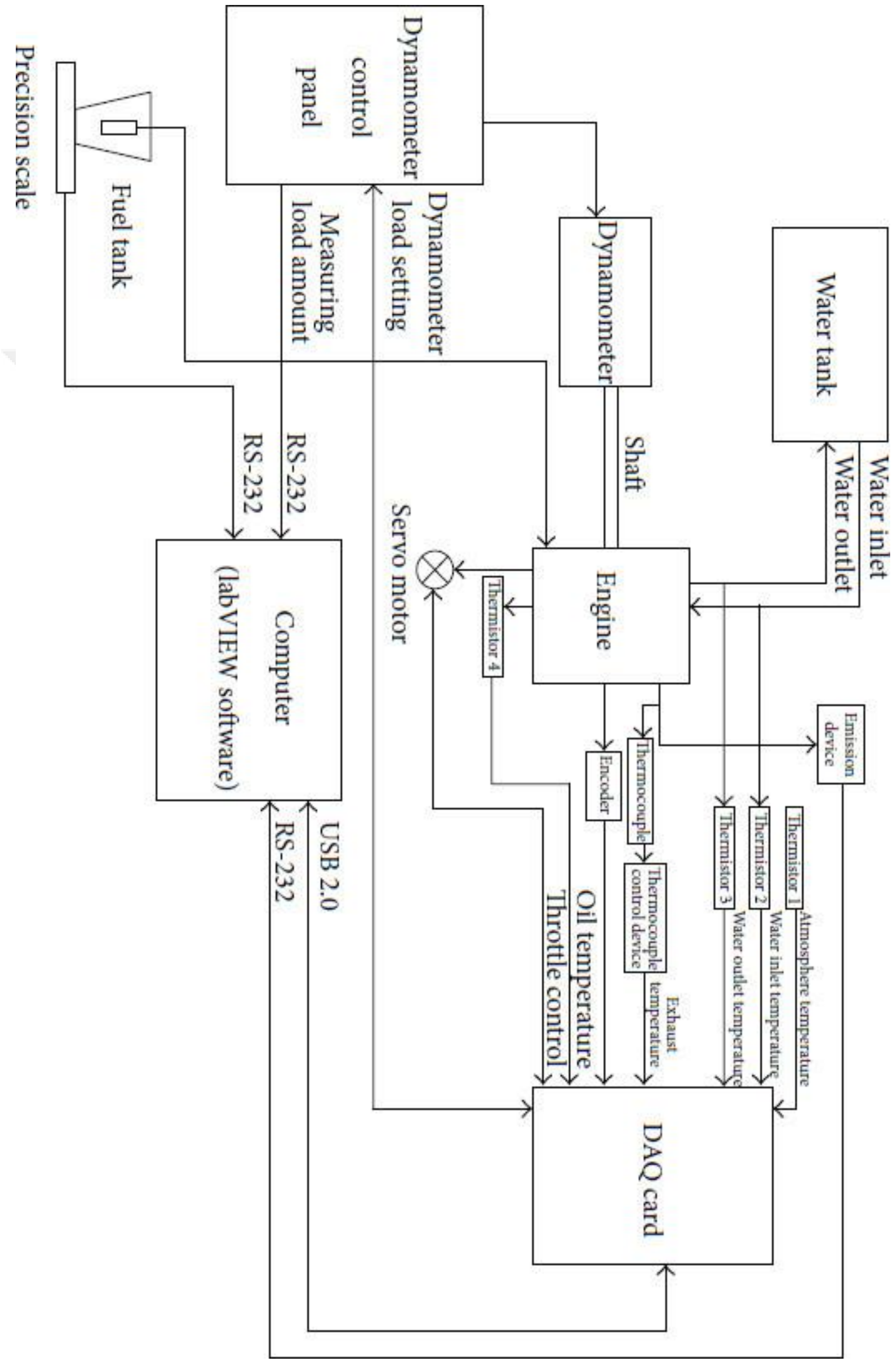
Appendix C – emDrive 500 Motor Controller Detailed Dimensions [34]



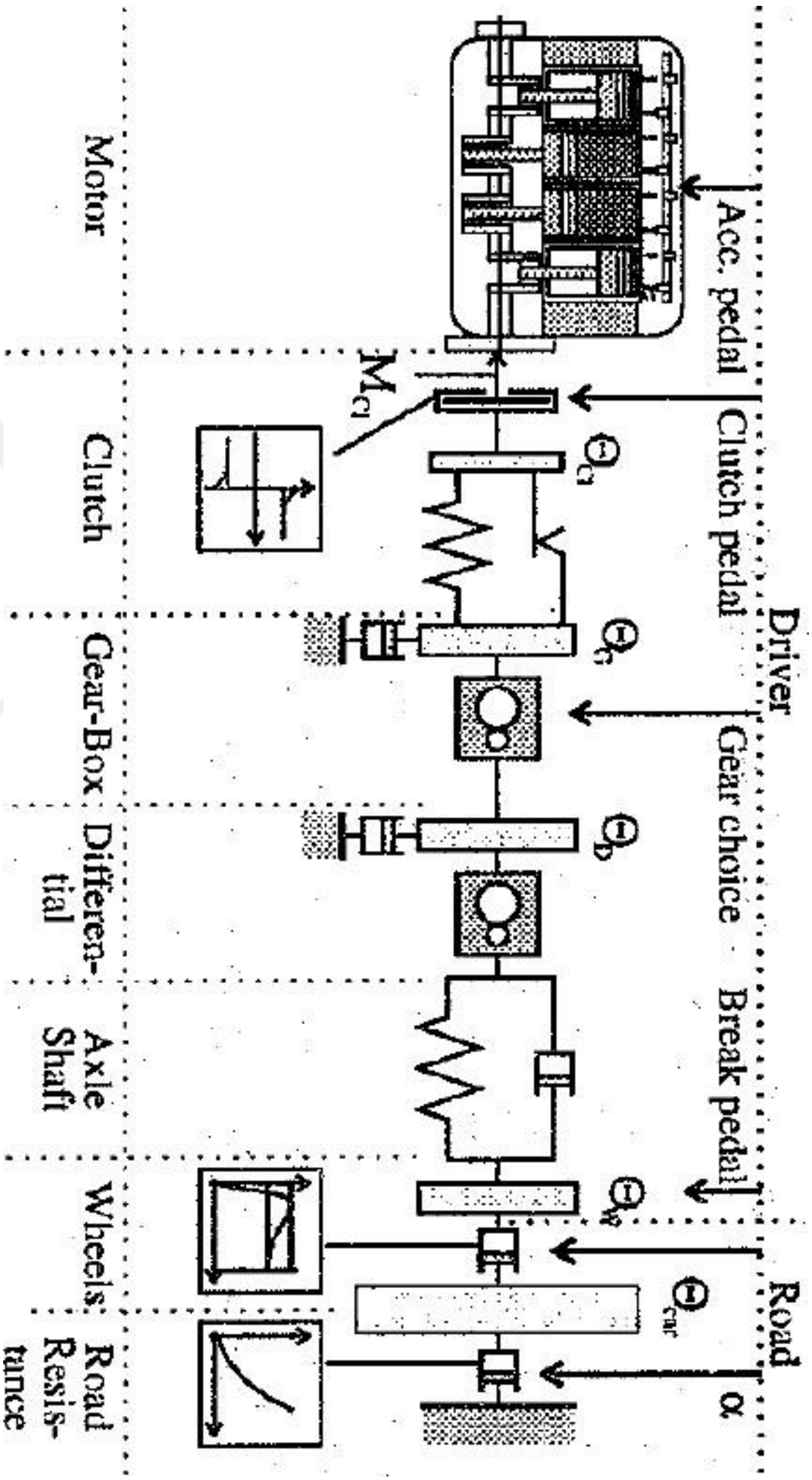
Appendix D – Dynamic Testing Stand Design [16]



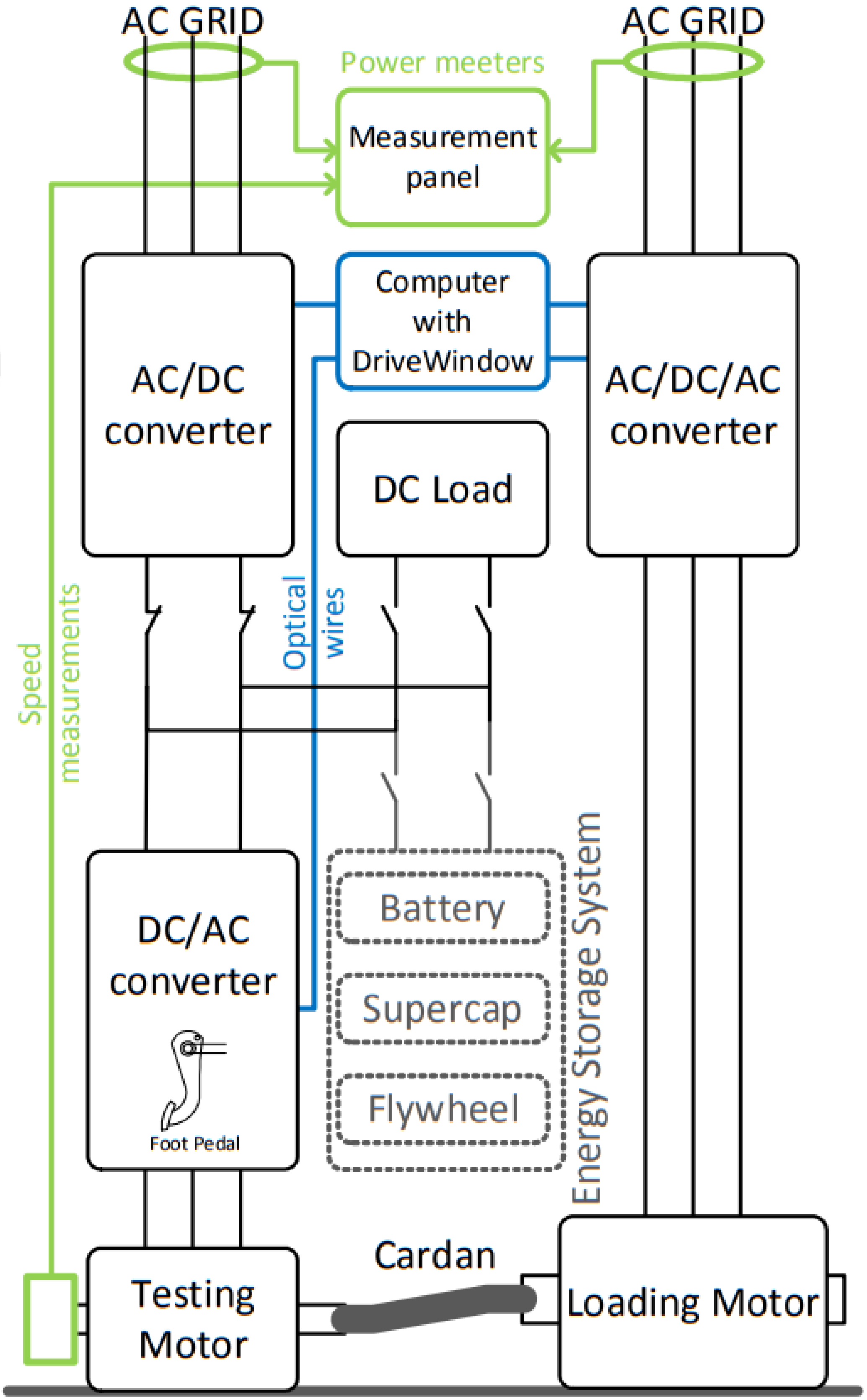
Appendix E – Experimental Setup Diagram with Labview Interface [17]



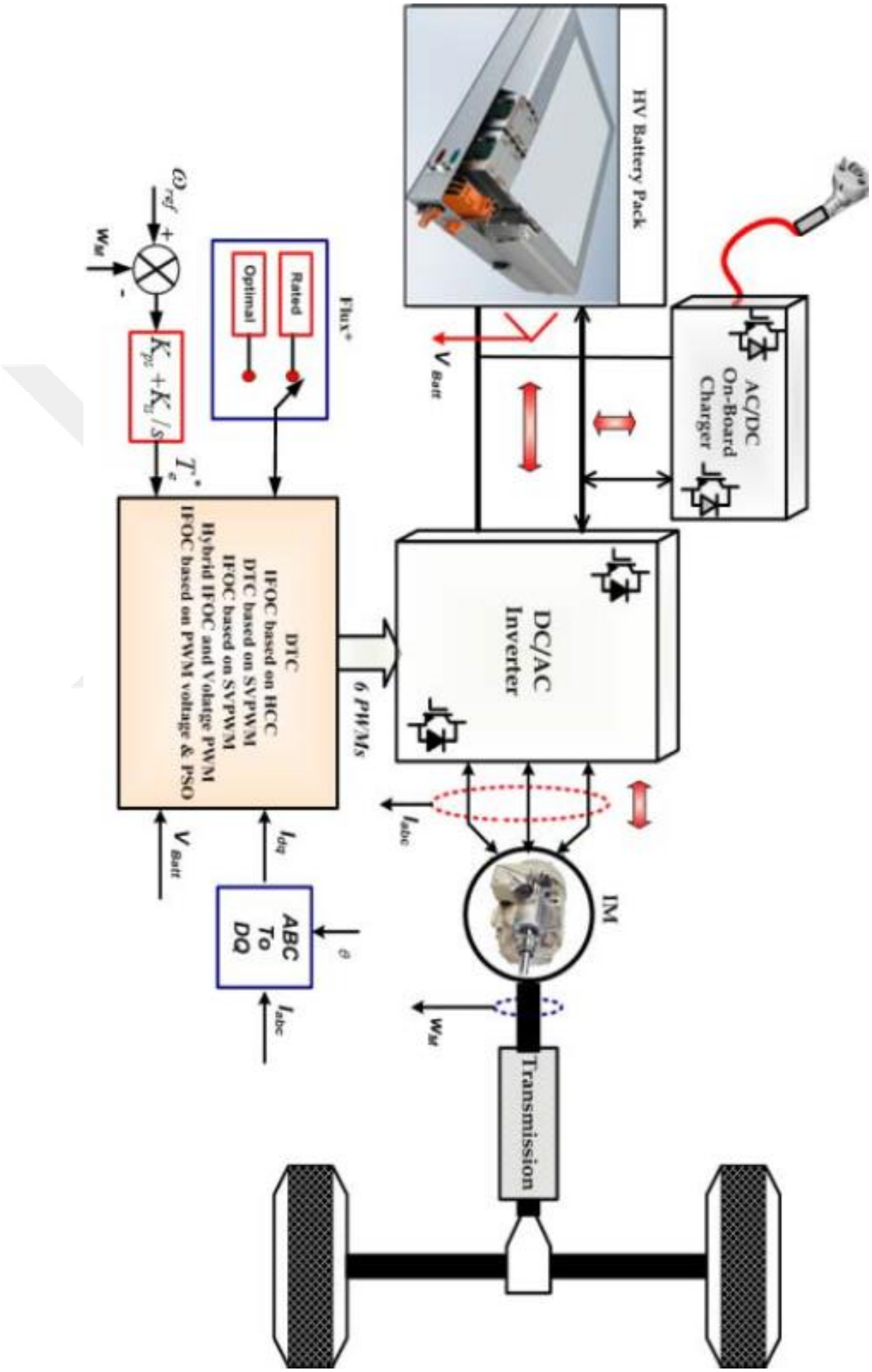
Appendix F – Simplified Mechanic Model of the Driveline of a FWD Vehicle [18]



Appendix G – Test Bench Circuit Schematic [19]



Appendix H – Schematic of Different Electric Motor Control Strategies [20]



Appendix I – Classification of Simulation Methods for Testing Applications [21]