UNIVERSITY OF LEICESTER

SCHOOL OF ENGINEERING

Regenerative Braking in Aircraft Landing Gear

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Summary

With the climate crisis dominating our lifetimes, how will we be able to contribute towards the changes that will save our planet? Aircraft fuel contributes to approximately 5% of global warming [4]. This project proposes a study into the feasibility of using regenerative braking in order to decrease aircraft GHG emissions by approximately 10%. The project aims are to develop and design a regenerative braking system for testing and applying the results to aircraft emission data. It was found that the use of regenerative braking in Aircraft could reduce GHG emissions by as much as 66.2%.

Contents

1 Introduction

1.1 Problem definition

With the climate crisis coming to the forefront of 21st century politics, most industries find themselves under the magnifying glass of public scrutiny. Industries under the most pressure are notably the Automotive and energy industry. However, in response to this we have seen an interest and keen determination by these companies to produce Electric Vehicles (EV's) and clean energy, with even the likes of BP dedicating themselves to an "energy transition" in order to decrease their carbon emissions [4]. Despite this, there has been a considerable lack of action from the aviation industry, a lesser known culprit in this climate crisis.

The aviation Industry is an integral part of the world's economy. The UK's travel and tourism industry is predicted to be worth 257.4 Billion pounds by 2025, making up 9.9% of its GDP and creating 3.7 million jobs (11% of the UK total)[1]. This juggernaut of an industry is supported mainly by the aviation industry. As travel and tourism expands, so does the utilisation of aircraft. There has been a steady increase in the number of commercial flights performed per year, consequently leading to an increase in fuel emissions in the atmosphere. As seen in figure 29 (see appendix A), in just 15 years time the number of flights per year has increased by 15.6 million [2]. Given this trend of approximately 1 million per year increase, the industry shows no signs of slowing, and will continue to grow into the foreseeable future.

Although the increase in air travel may be financially beneficial, its environmental impacts of increases are not. Aircraft contribute to approximately 5% of global warming [4]. With growing concerns about climate change and the recent focus on internal combustion engines contributions to it, it is now time to shine the light on aviation. To ask what we can do in order to decrease or completely stop the pollution they cause.

With the rise Electric Vehicles in the late 2010's, so too came the rise of regenerative braking, a system that is utilised in most Hybrid and EV's. This topic is covered in detail in section 1.2, however its main purpose is to use the wasted energy during braking, to recharge the battery, thus increasing its range. It is this idea, that will be applied to Aviation during this study.

I propose a feasibility study into the use of regenerative braking in aircraft that uses an electric motor for taxiing. Approximately 4% of an aircraft's fuel is used during taxiing [3]. Replacing the taxiing portion of the process with regenerated electricity would allow for a significant decrease in fuel consumption and subsequently GHG emissions. Of the 39.4 million flights set to take place in 2019, this change to the industry would cause a dramatic overall decrease in fuel consumption. The purpose of this is to reduce the amount of GHGs emitted worldwide. Due to this, all objectives are based around the design on such a system, and research into its practicality.

1.2 State of the art literature

The literature review was intended to explore the current and prior research regarding regenerative braking. This took into account any safety or legal constraints. The research was conducted via the use of PhD theses and online sources. All sources were referenced appropriately.

1.2.1 Regenerative Braking

Regenerative braking allows for a vehicle to recover some of its lost kinetic energy when braking, enabling a higher efficiency and increased range. Whilst regenerating, the motor acts as a generator and produces a current via the freewheeling of the vehicle. This negative current is then used to recharge the battery, as discussed in source [11]. This piece of literature illustrates the advantages of regenerative braking whilst explicitly explaining the scientific theory behind it. This is also coupled with a study into why Buck-Boost converters are so important for the system.

1.2.2 Limitations of regenerative braking

There are many limitations that come with regenerative braking. Due to regeneration only functioning on drive wheels (wheels driven by a motor), it means that the vehicle must be all wheel drive in order to fully take advantage of the regeneration. As well as this, Regenerative braking is inadequate when it comes to emergency stopping. Due to this limitation, supplemental dynamic braking must be used, which unfortunately wastes a lot of the energy that the system aims to reclaim. Source [9] covers these issues in detail and provides the reader with basic knowledge on the functionality of regenerative brakes.

Unfortunately this literature lacks the information regarding how to counter these limitation. It also only discusses the limitations in the context of Automotive vehicles. This project aims to fill these gaps.

1.2.3 Power Converters

Power converters are used in order to convert DC energy from one voltage to another DC actuator with a different voltage. This is similar to the way a transformer behaves in an AC/AC application. The simplest form of this can be seen in a voltage divider, however, this is only able to control output voltage and is inefficient, as shown in reference [6].

This method is succeeded by multiple quadrant choppers, which are explored and detailed in the following source:

1.2.4 Aircraft and GHG's

The hand aircraft have to play in the emission of Greenhouse gasses is significant. Due to an increase the popularity of environmentalism, more and more studies are condemning the aviation industry due to the emission of GHG's in our atmosphere. There are studies that date back to 2010 which confirm these claims. This study of the emission of GHG's and Air pollutants in Gihae Airport Korea [20] demonstrates the full scope of the problem, providing precise measurements of emissions, specifying the gases emitted and in which stage of flight they are emitted. More data would have been beneficial as only two years were considered. However, it is a useful study to consider whilst conducting this project.

1.2.5 Electric motors in aviation

The use of electric motors in aviation is a concept that holds a lot of relevance given the current climate crisis. According to source [8], this concept has been explored many times throughout history.

Due to the current climate crisis and our advances in technology, it would be beneficial to use electrical aircraft. This would greatly improve system reliability and improve the weight, volume and complexity of the system. There are many advantages detailed in the document, including the following:

- 50% fewer unexpected delays due to failures in power systems.
- A significant reduction in fuel burn.
- A reduction in maintenance costs.

This source also explores the use of variable speed constant frequency system (VSCF), AC/DC converters and electromechanical actuators in the design of an electrical aircraft. A limitation of this document is that unfortunately it does not discuss the use of regenerative braking within such a system. However, this topic will be discussed in this project.

1.2.6 Limitations of All-Electric Aircraft

With our Automotive industry moving towards electric motors, the use of all electric aircraft seems like the next logical step. In 2015, 276 million tonnes of jet fuel were consumed by aircraft globally, making up 7% of all global oil products. It has been demonstrated that all electric aircraft could eradicate all aircraft associated CO_2 emissions and CO_2 related warming. An annual aviation demand growth of 4.5% makes this an urgent and very pressing subject.

This source [17] provides an in depth analysis of the use of all electric Aircraft, covering the economic, environmental and personal benefits of all electric aircraft. However, most importantly this source confirms that the use of all electric aircraft would not be feasible should battery technology not improve in the foreseeable future, due to the added mass an All-Electric Aircraft battery would bring.

The limitations associated with this literature is its lack of mention of Regenerative braking as a potential method to decrease Aircraft battery sizes and decrease charging and subsequently use of greenhouse gases to provide electricity.

1.3 Technical Background

1.3.1 Early Stages

John Smith Raworth developed the very first of regenerative braking designs for use in his "Demi - Cars" (Trams). Raworth is credited with being the inventor of regenerative braking and his designs were used in his Trams for over 10 years. However, this was up until the Rawtenstall incident that occurred in 1911 [5]. This was an accident involving one of Raworths Trams, and it was determined in a report that the regenerative braking system was to blame for the incident. The shunt windings in the regenerative brakes would fuse when the tram encountered a steep track, causing the motor to accelerate and the tram to crash [5]. This report also suggested that vehicles that used regenerative braking were unsuitable. This led to the banning of regenerative braking by in the UK as it was feared that the technology was imperfect and accident prone.

1.3.2 Modern Regenerative Braking

Fast forward to present day and you'll find that regenerative braking is utilised in almost every Hybrid and Electric Vehicle. It uses the kinetic energy of the motor, converts it into electrical energy and feeds it back to the battery [5]. Whilst in regenerative mode, the motor slows down the car by working in the opposite direction. Whilst doing this, the motor acts as a generator and creates a current that is used to recharge the battery [5].

The use of regenerative braking in vehicles allows for fuel consumption to decrease dramatically in hybrid vehicle, whilst increasing the efficiency and range of electric vehicles. However, despite all this, the limitations of this technology still exist. Regenerative braking is ineffective in an emergency stop, and hence brake pads would be required in the case of an emergency.

1.3.3 Software Skills (Arduino IO & EAGLE)

Despite the hands-on nature of this project, two software platforms were used in order to design and control the circuit. In order to create the PWM pulses used to control the Motor, an Arduino unit was used.

Arduinos are open source microcontroller boards that come with a variety of different functions and capabilities. These boards can be programmed using the Arduino Ide which uses the C programming language. The features and functionality of this device are detailed in source [10], allowing for a greater understanding of its purpose, functions and limitations.

For these purposes, a C program was written using Arduino IDE and used to control the Arduino. Code was also written in order to display certain results from the experiment using the IDE.

In order to create a manufacturable design, the circuit schematic and PCB board were created in Autodesk Eagle, allowing for a manufacturer to recreate the board. This would allow for airlines or any interested parties to mass produce or modify the board. The files cited in the report will be available upon request.

1.4 Equipment

The following equipment were used in this experiment:

- 24V, 0.75KW brushed motor.
- 1200V IGBT.
- Arduino Uno Rev3.
- Resistors (330Ω, 10 Ω).
- Capacitors.
- Breadboard.
- Oscilloscope.
- Soldering Iron.
- Wire cutters.
- Single-Core and Multi-Core wires.

2 Aims and Objectives

This project aims to design and develop a regenerative braking system for testing. Applying the results to aircraft emission data and assessing the real life impacts of using such a system. In order to achieve these goals, an effective and realistic set of objectives needed to be formed

2.1 Objectives

The following objectives were created in order to properly investigate the feasibility of the proposed system. These objectives are as follows:

- Design and manufacture a power converter and regenerative braking system for testing.
- Evaluate and demonstrate the feasibility of using regenerative braking in aircraft landing gear as a means to reduce GHG emission.
- Calculate how much Green House Gas emissions would decrease by.
- Should the said device be deemed to be a success, the amount of landing charges required to power Taxiing would then be calculated in order to demonstrate the systems suitability.

2.2 Requirements

Whilst conducting this investigation, it was important to select an Aircraft to focus on. The Boeing 737 was the chosen aircraft. This is due to it contributing the largest amount in GHG emissions [20]. This is likely due to its popularity within commercial Aviation; the most popular choice amongst Airlines [22].

Table 1 – Boeing 737 Characteristics [27][28]

Boeing 737 Characteristics	
<u>Parameters</u>	<u>Values</u>
M_{v1} – Vehicle Mass (Maximum)	80,000 [kg]
M_{v2} – Vehicle Mass (Minimum)	59,000 [kg]
V – Landing Velocity	155 [knots] or 79.7 [m/s]

<u>Landing</u>

$$E_{Kinetic} = \frac{1}{2} M_v(\Delta V^2) \tag{1}$$

$$E_{Kinetic} = \frac{1}{2} \times 80{,}000(79.7^2 - 0^2)$$

$$E_{Kinetic} = 254{,}083{,}600\ J$$

Taxiing:

Taxi speeds for arrivals and departures differ, and therefore must be considered as separate phases.

Table 2 - Average Aircraft Velocities [29]

Aircraft Characteristics	
Parameters	Values
V_1 – Average Taxi Velocity (Departure)	16.0 [Knots] or 8.23 [m/s]
V_1 – Average Taxi Velocity (Arrival)	21.0 [knots] or 10.8 [m/s]

Kinetic Energy for Departure Taxi:

$$E_{Kinetic} = \frac{1}{2} M_v (\Delta V^2) \quad \textbf{(1)}$$

$$E_{Kinetic} = \frac{1}{2} \times 80{,}000(8.23^2 - 0^2)$$

$$E_{Kinetic} = 2{,}709{,}316\,J$$

Kinetic Energy for Arrival Taxi:

$$E_{Kinetic} = \frac{1}{2} M_v (\Delta V^2) \quad \textbf{(1)}$$

$$E_{Kinetic} = \frac{1}{2} \times 80{,}000(10.8^2 - 0^2)$$

$$E_{Kinetic} = 4{,}665{,}600\,J$$

In order to find out what percentage of energy recovery is necessary to power taxiing, Taxi KE as a percentage of Landing KE must be found.

$$Percentage\ required = \frac{E_{Kinetic}\, for\ Taxi}{E_{Kinetic}\, for\ Landing} \times 100 \quad \textbf{(2)}$$

Departure Taxi:

$$Percentage\ required = \frac{2{,}709{,}316}{254{,}083{,}600} \times 100 = 1.07\%$$

Arrival Taxi:

$$Percentage\ required = \frac{4{,}665{,}600}{254{,}083{,}600} \times 100 = 1.84\%$$

Table 3 - Kinetic Energy of Aircraft in during Taxi stage

Taxi stage	Kinetic Energy [J]	Required Recuperation
Departure	2,709,316	1.07%
Arrival	4,665,600	1.84%
Total	7,374,916	2.91%

Given the above, it can be deduced that the system would need to recuperate at least 2.91% of the kinetic energy produced during landing. Although this amount is small, it must be stressed that losses within the system whilst applying this energy must be taken into account. Hence it would be recommended that a minimum of 5% (1.5 times 3%) recovery would be required of the system.

Following the experiment, the effectivity of the regenerative braking system would be determined by calculating the regenerative ratio.

$$Regenerative\ Ratio = \frac{\sum E_{battery}}{\sum E_{Kinetic}} \times 100 \quad \textbf{(3)}$$

This ratio value will then provide an insight into how effective the system would be at recovering enough energy for taxiing.

3 Methodology

3.1 Work Packages and Timeline

Research into a number of topics was conducted in order to increase understanding of the topic at hand. The following is a step by step breakdown of the key work packages associated with this project. The data and fruits of such work will be demonstrated in later sections of the reports.

3.1.1 Research

- Research Regenerative braking (07-18th October 2019) [WP1]
    - This research was to be completed by: looking at existing regenerative braking patents and applying their functionality to the project objective (aircraft application), using research papers and scientific journals to gain an understanding of the subject.
    - The time needed for this work package was 10 days. This was due to the sheer size and detail of the topic. All other work packages, bar Aircraft fuel consumption, are dependent on the understanding of this topic. As such, no work packages will be able to start unless this task has begun.
    - This work package operates under the assumption that patents and scientific journals are readily available for free online. It also operates under the assumption that the researcher was able to successfully understand the concept and apply it to the work objectives.

- Aircraft GHG Emission research (21st Oct – 08th Nov 19) [WP2]
    - This entailed the selection of a common aircraft to use as a base for the project, as the GHG Emissions and characteristics vary from aircraft to aircraft.
    - Next the fuel consumption of the chosen aircraft was to be researched. This was in line with the objectives which required the results to be applied to fuel consumption data.
    - The time allocated for this task was 15 days as its results will not be applied until Stage 2. Hence, ample time is given to the researcher in order to 5.

    - QII Chopper research (10th Oct – 23rd Oct 19) [WP3]
        - Research Multiple quadrant DC converters (QII) and how they could be used for the project.
        - The time allocated for this task was 13 days.
        - Assumptions made were that there are readily available resources that will allow for such research to take place.

    - Transistor research (25th Oct – 07th Nov 2019) [WP4]
        - Conducted research into the use of transistors in DC converters and which type would be suitable for the motor used to test the circuit. This allowed for the objective of DC converter design to be fulfilled.
        - The time allocated for this task was 10 days

- Assumptions made were that transistors are the optimal switching device for the design of this circuit.

- Arduino and SG3525 Research (11th Nov – 29th Nov 19) [WP5]
  - Conducted research into the two methods for motor controllers and determine which would be most suitable for the project. This allowed for the testing objective to be fulfilled as the motor will be able to accelerate and decelerate.
  - The time allocated for this task was 15 days.
  - Assumptions made were that these two methods were the most superior choices and would work optimally within the circuit.

- QIV Chopper Research (02nd Dec – 13 Dec 19) [WP6]
  - Research into the QIV chopper and its properties were conducted as it may have been better suited to the task than the QII.
  - The time allocated for this task was 10 days as it is a medium task.
  - Assumptions made were that this chopper would be applicable to this project and that a full understanding would be established in order to make an informed decision.

- Regenerative braking Research and documentation (27 Jan – 31 Feb 20) [WP7]
  - More time was given in order to fully grasp regenerative braking in the context of the new design and taking into consideration all the above choices.
  - Due to previous conducted research and an understanding carried throughout the task, the time frame for this work package was only 5 days.
  - As well as this, time was allocated to the creation of graphs and diagrams to demonstrate the circuits modes of operation.

- Optocoupler Research (03 Feb – 14 Feb 20)[WP8]
  - Time was allocated to research optocouplers and their potential uses in this project. This device was necessary to prevent the large volt drop from keeping the IGBT switches shut. The physical connection between the Motor Controller and the Transistor needed to be removed, hence an optocoupler was necessary.
  - The time allocated to this ask was 10 days, as the concept was to be understood and a product needed to be selected.

- Current Transducer and MCB Research (3rd Feb – 14th Feb 20) [WP9]
  - Concerns were raised over the possibility of both T1 and T2 closing at the same time. Although the chances were small, due to the switching of T1 and T2 being controller by the Arduino, the possibility had to be accounted for.
  - Due to this, research was conducted into different types of fuses and which type would be appropriate for this application.

- Due to the need for inductor current to be measured, it was deemed to be necessary to have a Current transducer within the circuit. This would provide the readings for the motor current and a graph would be plotted using the results.

3.1.2 Design

- Regen Circuit Design (13 Jan – 03 Feb 20) [WP10]
  - A preliminary design was drawn up, including all aspects of aforementioned research.
  - A feasibility study was conducted in order to assess whether or not it was fit for purpose.
  - A list of all necessary changes was created in order to improve current design further. These changes were implemented and the process was repeated until all design requirements were met.

3.1.3 Manufacture

- Manufacturing stage 1 - Motor preparations (03 Feb – 07 Feb 20) [WP11]
  - Whilst in the design stage, it was important to ensure that small steps were being taken in regards to the manufacturing.
  - The motor shaft was cleaned of any excess material in order to prevent damage. This was achieved by applying a small voltage across the motor in order to cause a small rotation.
  - During these days it was also important to begin preparations for testing. In order to do this, an M5 hole was drilled into the flywheel shaft.

- Manufacturing stage 2 – PCB construction (17 Feb – 28 Feb 20) [WP12]
  - This entailed the construction of the final circuit design, which incorporated all of the above. This required the ordering of parts and the soldering of all pieces onto a breadboard in a clean and presentable manner.
  - The given time frame for this task was 10 days. This was done in order to account for the delayed delivery of any parts, the possible damage and need to replace any parts or a need to start over due to mistakes.

3.1.4 Testing

- Coding stage 1 – PWM (02 March – 06 March 20) [WP13]
  - As an Arduino was being used to send the PWM signals and read the current, the code needed to be written in order for any testing to take place.
  - The time given for this task was only 5 days as only parts of the code were required in order to complete the first stage of testing.

- Testing Stage 1 – Optocouplers and PWM signals (02 March – 06 March 20) [WP14]

- Prior to the testing of the whole circuit, it was necessary to test the functionality of the Optocouplers and their ability to transmit a PWM signal of the same duty cycle to the output.
- The time allocated for this test was also 5 days, given that this task would be carried out alongside its coding counterpart.
- Testing was to be carried out for each component before using the circuit to run the motor. This would allow for any short circuits or faulty components to be weeded out.
- Initially, testing of the Arduino took place as this was the first component. A sample Arduino program was used in order to blink and LED. This demonstrated the Arduinos functionality and ability to respond to programming, then transmit a signal via its pins.
- Following this, the optocoupler was tested using an oscilloscope. A pulse was sent from the Arduino and measured using the oscilloscope. The signal at pin 6 of the optocoupler was then measured using the oscilloscope.
- Both PWM waves were compared and their duty cycles calculated in order to ensure transmission was successful.
- This process was then repeated but to include the IGBT, measuring and comparing the output wave from the IGBT with the source signal. This was also carried out using an oscilloscope, in order to test the switching functionality of the IGBT.

- Testing Stage 2 – Motor Control (09 March – 13 March 20) [WP15]
  - Following the successful testing of the optocouplers and IGBT, it was necessary to determine the circuits ability to drive the motor. This was conducted using a Wall fed power supply in place of the 24V battery in order to remove the possibility of burning any components should there be a malfunction or short.
  - The speed of the motor was varied using the Arduino in order to demonstrate the functionality of the DC/DC Converter.
  - Following the successful testing of the circuit using the power pack, the 24V battery was used to repeat this test.
  - The time given to this work package was 5 days to allow for any issues to be resolved.

- Testing Stage 3 – Regenerative Braking (16 March - 27 March) [WP16]
  - The time frame allowed for this stage was 10 days. This was done to allow for any issues to be resolved. It would also allow for proper data collection to occur. The regeneration would be tested three times in order to create a fair scientific test.
  - The current leaving the motor and the current leaving the battery would have been measured. This would have allowed for the current graphs to be created and therefore the regeneration to be identified and to which magnitude.
  - The voltage of the battery would have also been measured and recorded.

- Compilation of Results and data interpretation (27 March - 01 May) [WP17]
    - In order to complete the project, the compilation of data and its interpretation must be done in order to articulate any conclusions and their real world impact.
    - This task is assigned the largest time frame as it requires possibly more research, the creation of graphs and tables, interpretation of the results and the articulation of such in this report.

3.2 Design Decisions and Justifications

This section of the report will discuss any uncertainties, justifications of assumptions, simplifications and boundary conditions.

3.2.1 QII Chopper

In order to advance the designs for the regenerative braking, multiple quadrant choppers were researched, as this would be an integral part of the design. It was evident from the research conducted that the design was to be a DC/DC Converter which took advantage of the internal inductance and Back EMF within the Motor.

Multiple Quadrant choppers are used to convert a fixed DC voltage to a pulse width modulated AC voltage or a variable DC voltage [6]. Of the four types of chopper, the Second quadrant chopper was deemed to be suitable for the purposes of this experiment due to its forward regenerating nature.

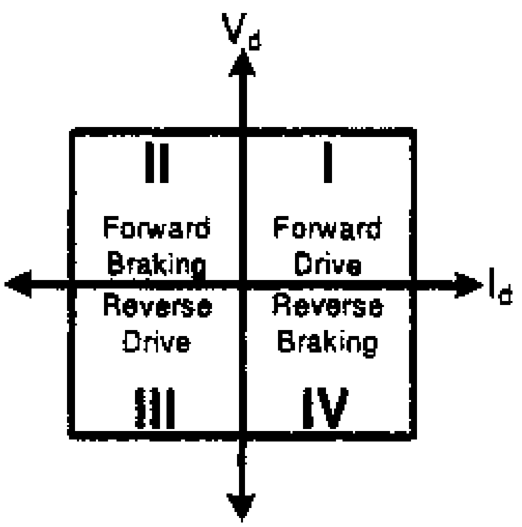

Figure 1 - Four Quadrant Operation [12]

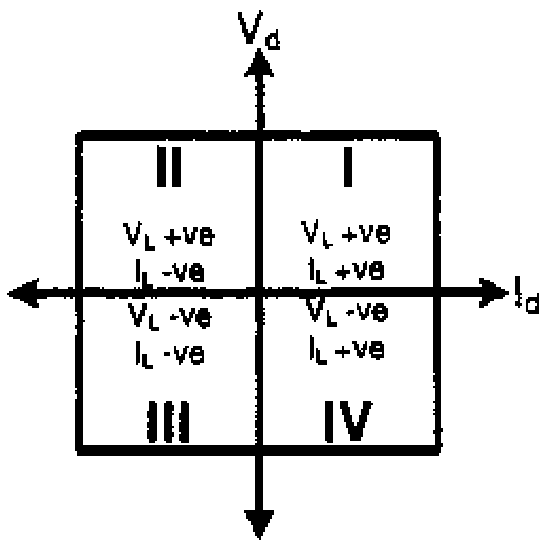

Figure 2 - The polarities [12]

The second Quadrant Chopper was deemed to be the most appropriate for this function due to its negative current, positive voltage and power absorbing properties. These are all the conditions needed for the regeneration.

The second quadrant chopper circuit diagram and its waveforms can be found in figure 3a and 3b below. Using equation 1 it is possible to calculate the output voltage of the circuit.

The QII Chopper operational characteristics are a negative current, positive voltage and forward regeneration. This was deemed perfect for the regenerative braking design that was to be created.

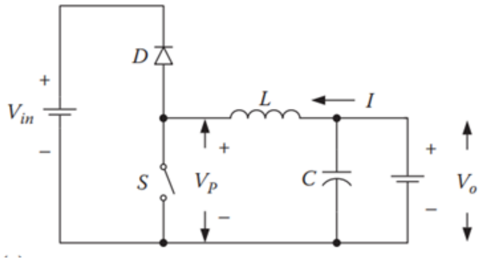

Figure 3a - QII Circuit [6]

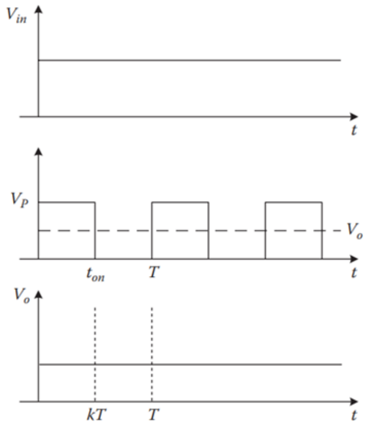

Figure 3b - QII Voltage Graphs [6]

Equations:

- $v_0 = \frac{t_{off}}{T} v_{in} = (1-k)v_{in}$ **(4)**
- $T = \frac{1}{f} = \frac{1}{Chopped\ frequency}$ **(5)**

Where:

- $v_0 = Output\ Voltage$
- $v_{in} = Input\ Voltage$
- $T = Repeating\ period$
- $k = conduction\ duty\ cycle = \frac{t_{on}}{T}$

Once research on the QII chopper was complete, it was implemented into the designs and an initial design was drawn up. This initial design is discussed further in section 3.3 (Technical Design) of the report.

3.2.2 Motor Controller Unit

Table 4 - Selection Matrix

Requirements	Arduino	SG3525 PWM Controller
Able to vary motor speed	1	1
Able to manage and display	1	-1
Simplicity of operation	1	0
Price	0	1
Size	0	1
Versatility	1	0
Total	4	3

Two options were considered to use as a motor controller, an Arduino or an SG3525 chip. A selection matrix was used in order to determine which of the two were more suited to the project.

Given the Arduinos ability to perform other functions and monitor current using the serial monitor within the Arduino IDE, it was deemed to be the superior motor controller for this project.

3.3 Technical Design

As a 24V, 0.75kW motor was being used, the transistor values needed to be calculated. The transistors must have a current rating of at least double the motor. The following calculation was completed in order to determine the minimum current rating of the transistors:

$$P = IV \tag{6}$$

$$0.75 \times 10^3 = 24I$$

$$\therefore I = \frac{0.75 \times 10^3}{24} = 31.25\ A$$

As the transistor must be rated at least double the motors current rating, the minimum current rating would be 62.5 A (2 x 31.25A). Due to the availability of resources in the lab, a 75A, 1200 V IGBT was acquired. These values meet the minimum requirement and so the IGBT was incorporated into the circuit design.

Regen braking system design 1:

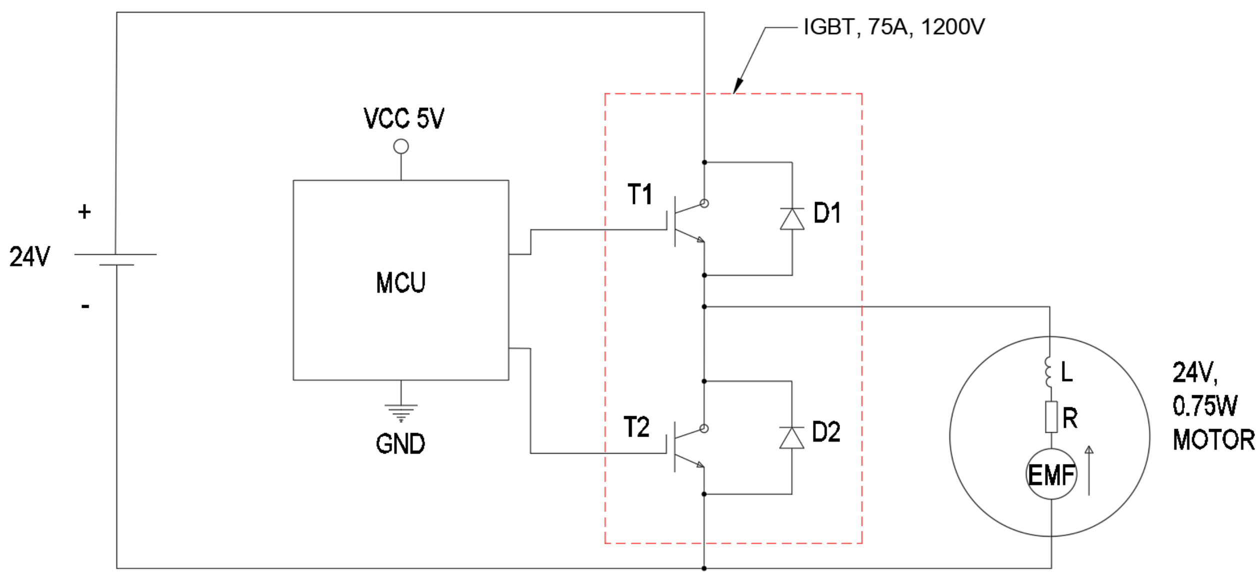

Figure 4 - AutoCAD Initial Circuit Design

This circuit has three modes of operation. The "running" mode in which the motor is running up to speed, a braking mode in which the motor is freewheeling and the inductance is increasing within the motor, and a regenerating mode in which the motor is allowed to push negative current back up into the battery. Each mode is explored in more detail below.

Where:

- MCU = Motor controller.
- Transistor 1 = T2, Transistor 2 = T2.
- Diode 1 = D1.
- Diode 2 = D2.

3.3.1 Phase 1: Motoring

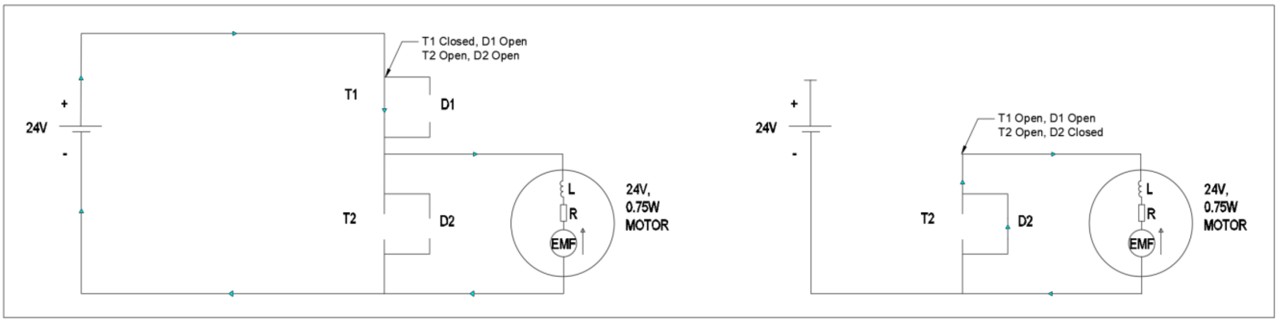

Figure 5 - AutoCAD Phase 1: Motoring

T1 = ON/OFF, T2 = OFF

Whilst the bridge output is high, (T1 is closed and T2 is open), the motor accelerates to the desired speeds. This is due to the path allowing for the Line current to flow through the motor.

This model is equivalent to a series circuit containing an inductance, resistor and a voltage source, (Back EMF). A PWM signal is used to control the speed of the motor. The switch T1 is turned on and off at the required duty cycle to reach the desired speeds. Whilst T1 is off, the inductor current continues to flow through the motor in the same direction as the motor continues to run. This is short lived as Back EMF will eventually reverse the current.

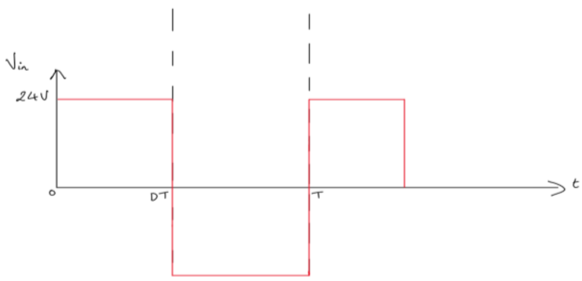

Figure 6 - Phase 1 Voltage Graph

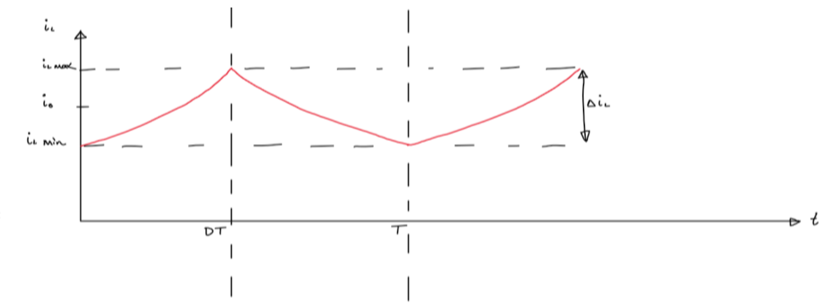

Figure 7 - Phase 1 Current Graph

3.3.2 Phase 2: Regenerating

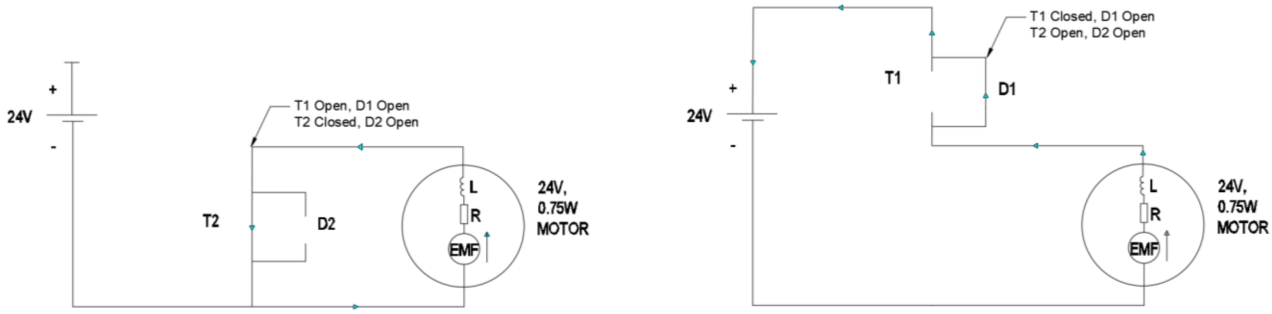

Figure 8 - AutoCAD Phase 2: Regenerating

T1 = OFF, T2 = ON/OFF

During Phase 2, T1 is turned off whilst T2 is being controlled. Whilst T2 is on, there is a high negative current flow. The motors torque is proportional to the average current, so now rather than applying a clockwise force, a strong anticlockwise force is applied to the clockwise rotating motor. This causes the motor to decelerate. As the current subsequently decreases, back EMF decreases. This energy is recovered before it is wasted, by switching T2 off and forcing the current up D1, back into the battery, replenishing its charge in the process, as seen in figure 8.

3.3.3 Optocoupler and Current Transducer

Due to the 24V across both transistors, it was a concern that the physical connection between the Arduino PWM signal and the transistor would cause the appearance of a constant signal being sent. This would lead to both T1 and T2 being closed at the same time, causing the battery to short circuit. This could be very hazardous for both the Engineer and the equipment. The windings within the motor may burn or fuse together, or the battery may spark and cause a fire. In order to avoid this, there should be no physical connection between the Arduino and the Transistor, avoiding the voltage drop entirely.

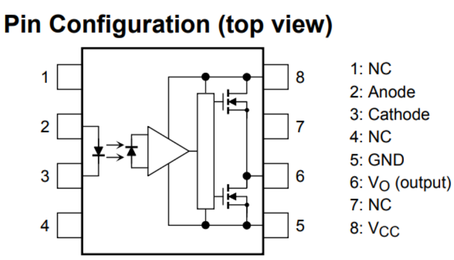

Figure 9 Optocoupler Pin configuration [23]

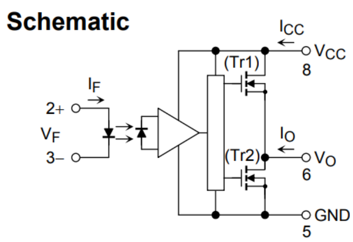

Figure 10 Optocoupler Schematic [23]

It was found that optocouplers allow for signals to be sent between two points without a physical connection. A TLP351 Toshiba opto-coupler was selected for this as its power supply voltage was up to 30V. This device uses an infrared LED and a photo IC to send signals. As can be seen in figures 9 and 10, the PWM signal would be sent as a 5V signal in pin 2. This would then cause the LED to emit light. This light is then picked up by the LDR opposite, which allows a pulse of its own to pass through the opto-coupler and into the gate of the transistor.

The LED within the Opto-driver is in need of 2V in order to operate effectively. In order to achieve this, the values for a resistor at Pin 2 was calculated.

The maximum current that can be drawn from an Arduino IO pin is 40mA.

According to the datasheet, the current drawn by the TLP351 will be a maximum of 10mA and a minimum of 7.5 mA.

$$V_R = V_{Arduino} - V_{LED} = IR \tag{7}$$

$$V_{Arduino} - V_{LED} = I \times R$$

$$R_{max} = \frac{5V - 2V}{7.5\ mA} = 400\Omega$$

$$R_{min} = \frac{5V - 2V}{10\ mA} = 300\Omega$$

Given these results, a 330Ω resistor was used as the current drawn from the LED would be approximately 10mA. A 0.1µF ceramic capacitor was connected from pin 8 to 5 (Source to GND) in order to stabilise the high gain linear amplifier within the opto-coupler. This would prevent damage to the switching properties of the device.

Given that the results of the tests would be primarily focused on a change in current direction and magnitude, it was important to ensure it could be monitored. A current meter could have been used, however it was necessary to include the current measuring property as a part of the final PCB Design. This is why the decision was made to include a current transducer (CT). This would allow for testing to be completed and for the results to be recorded. As well as this, it would allow for any potential pilots or engineers to see how much regeneration is occurring per flight. An image of the chosen CT (LTS 6-NP) can be found below:

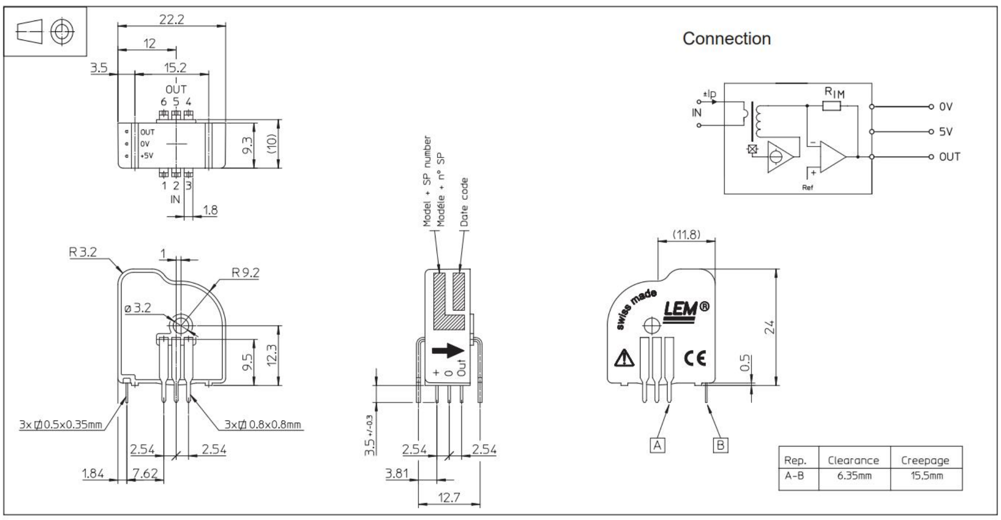

Figure 11 – LTS 6NP Current Transducer [24]

3.3.4 New Circuit including Optocoupler:

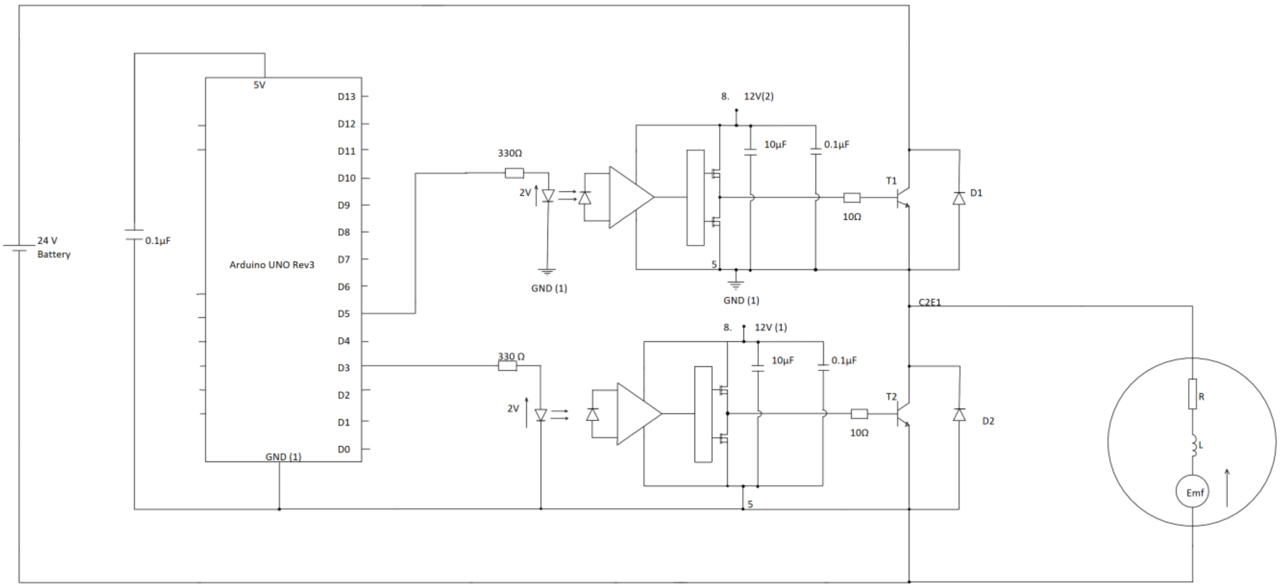

Figure 12

As can be seen in the new graph, the optocoupler and the capacitors have been added to the design, along with 10Ω resistors for the gate of each transistor.

3.3.5 MCB

An issue with the above design would arise should there be an Arduino malfunction. Having both transistors close simultaneously would cause the circuit to short circuit. This may be prevented by the use of a fuse, however, that would leave the system unusable following an error.

A circuit breaker was necessary to protect the motor and circuit in the event of an overcurrent. In this case a domestic Miniature Circuit Breaker (MCB) was chosen instead of a traditional fuse. There are many advantages to using an MCB in place of a fuse. When using a fuse, in the event of an overcurrent they must be replaced, whilst MCBs are reusable. In the event of an overcurrent, the circuit may be restored by switching the MCB back on again. MCBs are a lot more sensitive to overcurrent than a fuse and will trip in cases of fault conditions.

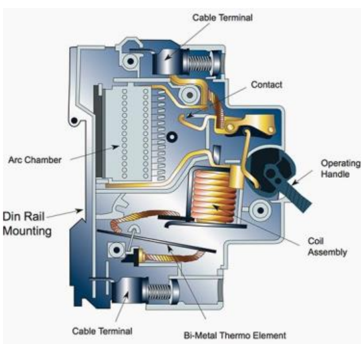

Figure 13 – MCB Internals [25]

Figure 14 – MCB Diagram [26]

An MCB has three main traits: The Tripping curve, Overload Current Rating (Amperes) and Short Circuit Rating (Kilo Amperes)[16].

Traditionally used for domestic applications, an overload current would occur when there were too many appliances are connected to the ring circuit. This causes them to draw more current than the circuit and cable are rated for. In such an event, the MCB trips due to the deformation of the bimetallic strip[15]. This prevents fires and damage to electrical appliances[16]. For the application we are using, this would occur in the event that the motor and circuit components draw too much current from the battery.

Short circuits are quite possibly more dangerous than over currents. A short circuit occurs when there is a direct connection between the live and neutral, without the resistance, the current could increase by a thousand times in a millisecond [16]. In any circuit this is a problem, however in an aviation application this can be problematic as it may cause fires and for the motor to be damaged severely before landing is completed. This is why an MCB is necessary for this application.

Due to the aircraft approaching the runway at high speed, the electric motor touching down at such a speed would cause a surge in current. This surge current must be allowed for when choosing an MCB. If the MCB were to trip as soon as the landing gear made contact with the runway, the circuit would not regenerate. In order to determine which MCB would be suitable for this application, we can analyse the tripping curves and MCB types shown in figure 15.

There are three types of MCB's used domestically, Type B, C and D. The following are their tripping curves:

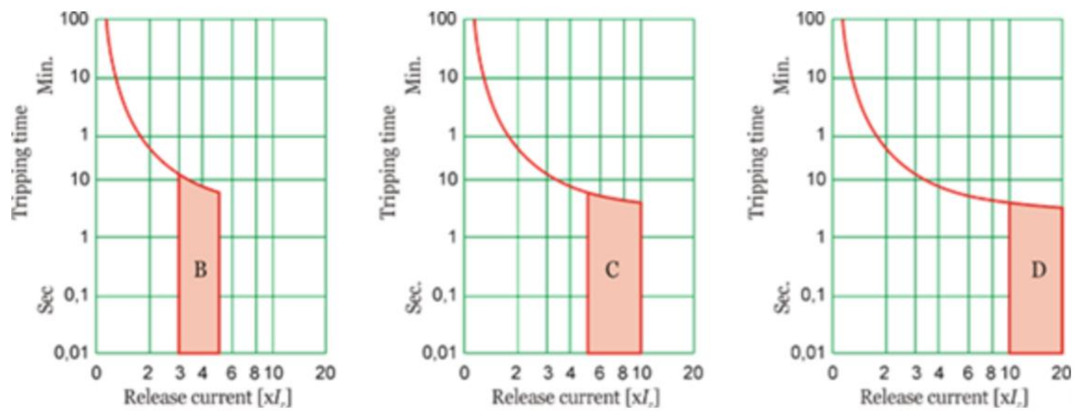

Figure 15 - MCB Tripping Curves [16]

From the above curves, we can deduce that all three types trip within 0.1 seconds. It can also be seen that D type MCBs trip at the highest number above the load current. D type MCBs are used industrially for large motors and X-ray machines. These applications have a large potential surge, hence D types trip at 20 times the load current. This would mean that a 32A D types would trip at 6400A. It would be suggested that for the real life application, a D type MCB would be most suitable. This is due to the size of the motor required to move the aircraft and the sheer size of overcurrent that would be caused by turning the motor at such great speeds. However, for our testing purposes, a C type would be better suited to this project as it trips between 5-10 times load current[16].

Due to this, a 32A Type C MCB was chosen for the project. This would prevent short circuits damaging the circuit components and the motor.

3.3.6 Lockout circuit:

As discussed above, the purpose of the MCB would be to protect the circuit from overcurrent. One cause of this would be both transistors closing at the same time. However, an MCB will not suffice as a primary solution to this. This is due to the application of this circuit. A short due to signal malfunction should not occur at all during the landing sequence as this may cause damage to the motor. Any damage or complications could therefore cause a risk to life as they may malfunction completely during the next flight.

In order to ensure there was no signal malfunction, a "lockout circuit" was designed in order to prevent both transistors from receiving the same signal.

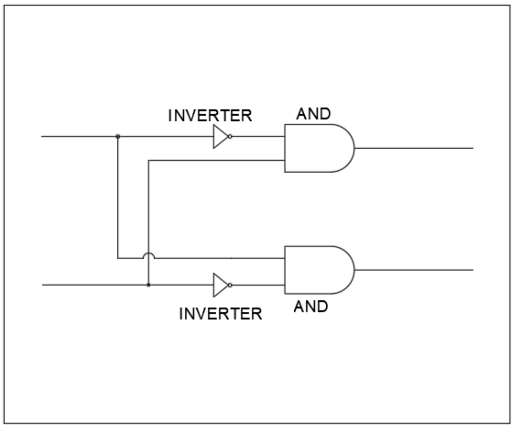

Figure 16 – AutoCAD DWG Lockout

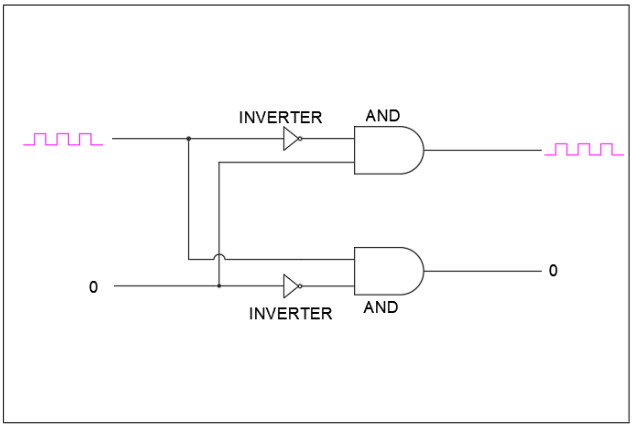

Figure 17 – AutoCAD DWG Lockout

As seen above, AutoCAD was used in order to create a schematic for this design. All figures in this section are taken from this drawing. This particular circuit DWG will be available to view alongside this report.

Through the use of AND gates and Inverters, a circuit was designed in which only one input could be true. For the output of an AND gate to be true, both inputs must be true. However, due to the inverter, the AND output can only be true if its inputs are different. This means that the AND output will never be true if the circuit inputs are the same. This can be seen in the figure 18.

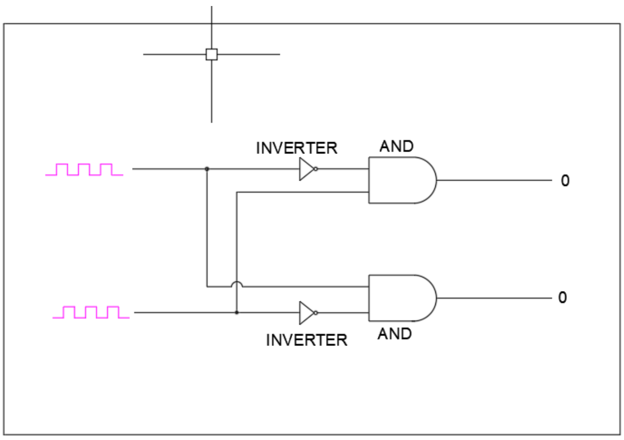

Figure 18

In order to manufacture this circuit, the following components were chosen for the AND gate and the buffer:

- SN74LS08N - AND Gate, 74LS08, 2 Input, 8 mA, 4.75 V to 5.25 V, DIP-14
- SN74LS06N - Buffer / Driver, 74LS06, 4.75 V to 5.25 V, DIP-14

The above chips then had their inputs and outputs connected in the desired configuration on a PCB.

3.3.7 Final circuit including Lockout & MCB:

A final circuit design was completed, incorporating all of the above components and research. The purpose of the design in figure 19 is to allow for replication of the circuit in industry.

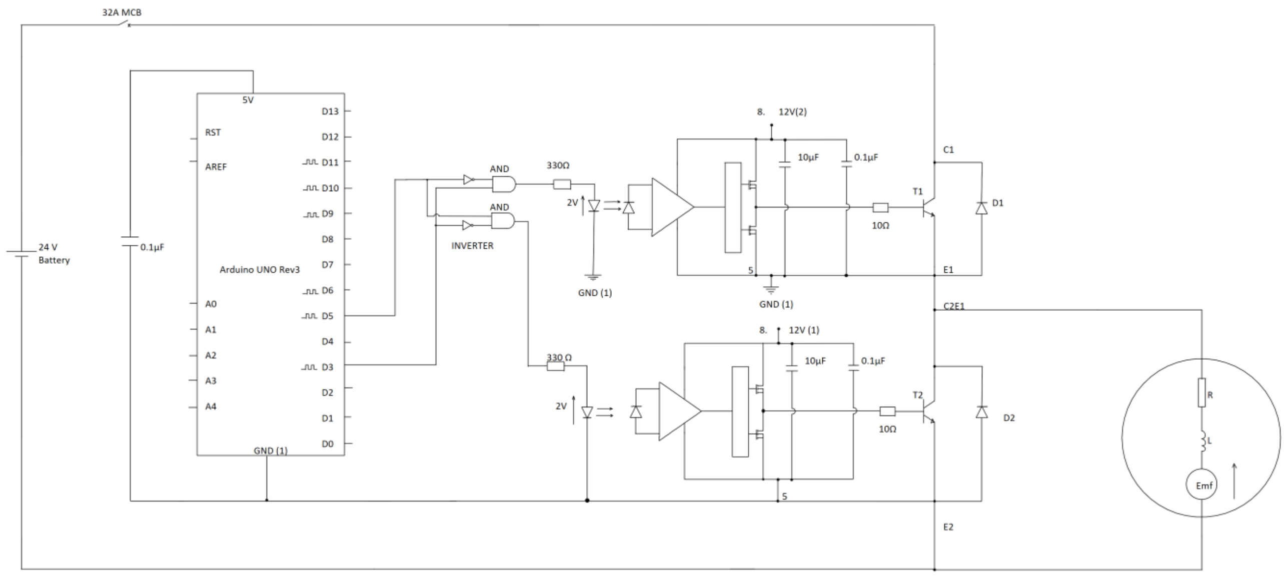

Figure 19 – Final Circuit Diagram

3.4 PCB and Circuit Schematic Design

In order to ensure the designs were manufacturable and applicable in a real world, a PCB schematic was created using Autodesk eagle. This schematic would be sent to a manufacturer who would then use this file to create a Printed Circuit Board. Due to the project budget, the circuit for this project was created using a breadboard. However, a printed circuit board would be necessary for mass production. Please find the schematics for these PCB design in Figure 28, Appendix A.

3.5 Manufacturing

Following the completion of the design (see figure 20), all necessary components were gathered and the design was recreated on bread board. These connections were soldered and made permanent in order to create something that would resemble the actual system.

As seen in the figure below, the lockout circuit, optocoupler circuit and arduino were all made on separate detachable breadboards. This was done in order to enable the replacement or customisation of any circuit in the event of failure. Allowing for ease of replacement would significantly reduce costs in the case of a malfuntion.

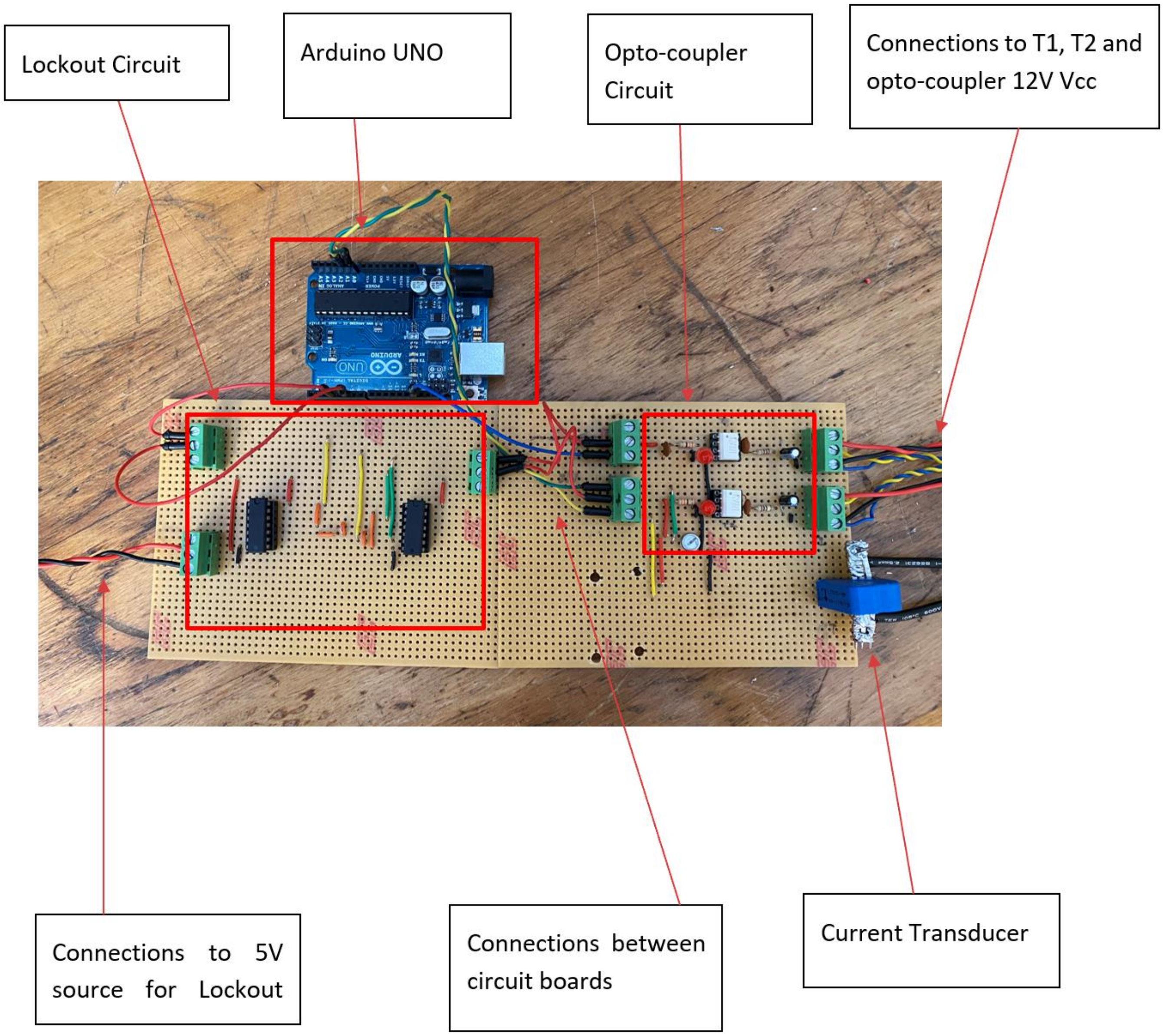

Figure 20 - Manufactured PCB

For use in the real-world system, the protection of this circuit is imperative as the damage of such a system would result in a motor failure. In order to mitigate any external inputs, each individual circuit board would be stacked in an insulated IP66 rated enclosure. This would protect the circuit from any water or heat damage.

4 Results and project findings

This section of the report endeavours to present all results and data whilst providing an insightful and detailed discussion as to their meaning. As well as this, the section will also explore the ramifications of these results in industry. The methodologies are also discussed in order to allow for replication of the project by others.

4.1 Optocoupler Testing

In order to test the functionality of the optocoupler circuit, a PWM signal was sent via the Arduino and its output measured with an oscilloscope. This input PWM signal had a duty cycle of 50% and was created using the Arduino code sequence found below:

```
//PWM 50% Duty Cycle T1

digitalWrite(T1, HIGH);
delay(50);
digitalWrite(T1, LOW);
delay(50);
```

For the purposes of testing, a small LED was attached between the optocoupler input pin and ground. This LED would flash at the rate of the PWM frequency and be seen by the tester, allowing for the confirmation of input signal throughout the test. This technique is only valid for frequencies up to 40Hz as any higher would be indistinguishable from a constant signal.

Input signal:

- Frequency = 10Hz
- Duty Cycle = 50%

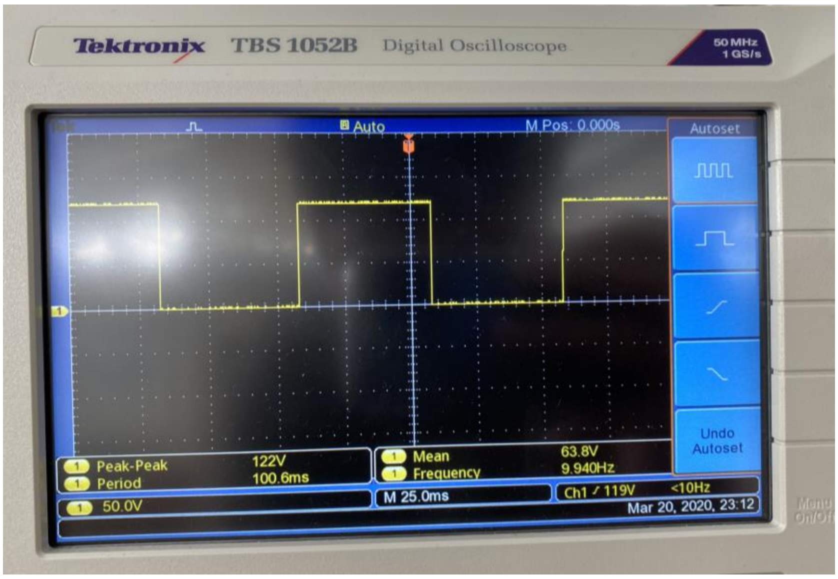

Figure 21 – Optocoupler output PWM 1

Figure 26 illustrates the optocoupler output signal measured with the oscilloscope. In order to confirm that the duty cycle of the pulse has been maintained, a calculation must be done. As can be seen from the above diagram, the period of the measured wave is 100.6ms, and the time division for this diagram is 25ms. From this, the T_{ON} can be derived as 50ms.

Output Duty Cycle Calcualtion.

$$Duty\ Cycle = \frac{T_{ON}}{T_{Period}} \quad \textbf{(8)}$$

$$Duty\ Cycle(\%) = \frac{50ms}{100.6ms} \times 100$$

$$Duty\ Cycle(\%) = 49.7\%$$

Output Frequency Calcualtion.

$$Frequency = \frac{1}{T_{Period}} \quad \textbf{(9)}$$

$$Frequency = \frac{1}{100.6ms} = 9.94Hz$$

As shown in the above calculations, the output frequency and duty cycle match that of the input. However, there is some error present in the result. This was calculated as percentage error in order to determine the source.

Frequency error:

$$Error = \left|\frac{f_{output} - f_{input}}{f_{input}}\right| \times 100 \quad \textbf{(10)}$$

$$Percentage\ Error = \left|\frac{9.94 - 10}{10}\right| \times 100$$

$$Percentage\ Error = 0.6\%$$

Duty Cycle error:

$$Error = \left|\frac{D_{output} - D_{input}}{D_{input}}\right| \times 100 \quad \textbf{(11)}$$

$$Percentage\ Error = \left|\frac{49.7 - 50}{50}\right| \times 100$$

$$Percentage\ Error = 0.6\%$$

4.2 IGBT Testing and Motor running

In order to test the functionality of the IGBT, a PWM signal was sent via the Arduino and its output measured between the positive and negative of T1. This input PWM signal had a duty cycle of 70% and was created using the Arduino code sequence found below:

```
//PWM 70% Duty Cycle T1

digitalWrite(T1, HIGH);
delay(0.0014);
digitalWrite(T1, LOW);
delay(0.0006);
```

As well as this, the IGBT was also connected to the motor via T1. This allowed the operation of both the motor and the IGBT to be tested simultaneously. The frequency of this input signal was increased to 50kHz as it would emulate smooth operation of the motor. At this stage, the motor was powered using a power pack. This was done in order to avoid damaging the equipment in the event of a short.

Input signal:

- Frequency = 50kHz

- Duty Cycle = 70%

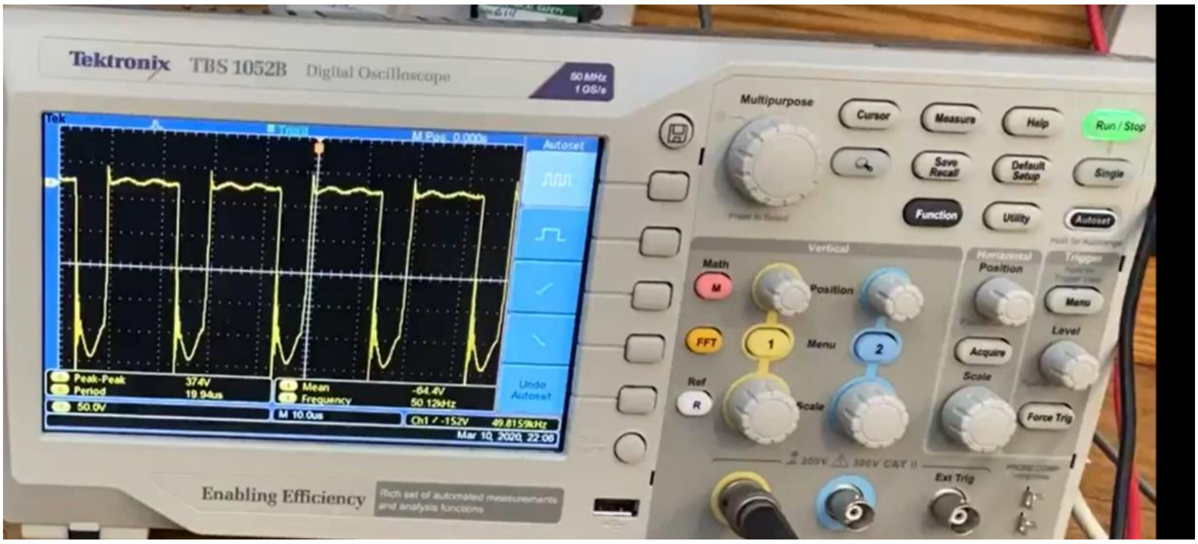

Figure 22 - IGBT Switching

Output Duty Cycle Calcualtion.

$$Duty\ Cycle = \frac{T_{ON}}{T_{Period}} \quad \textbf{(8)}$$

$$Duty\ Cycle(\%) = \frac{14\mu s}{20\mu s} \times 100$$

$$Duty\ Cycle(\%) = 70\%$$

Output Frequency Calcualtion.

$$Frequency = \frac{1}{T_{Period}} \quad \textbf{(9)}$$

$$Frequency = \frac{1}{19.94\mu s} = 50.15Hz$$

As shown in the above calculations, the output frequency and duty cycle match that of the input. However, there is some error present in the result. This was calculated as percentage error in order to determine the source.

Frequency error:

$$Error = \left|\frac{f_{output} - f_{input}}{f_{input}}\right| \times 100 \quad \textbf{(10)}$$

$$Error = \left|\frac{50kHz - 50.15kHz}{50kHz}\right| \times 100$$

$$Percentage\ Error = 0.24\%$$

Duty Cycle error:

$$Error = \left|\frac{D_{output} - D_{input}}{D_{input}}\right| \times 100 \quad \textbf{(11)}$$

$$Percentage\ Error = \left|\frac{70 - 70}{70}\right| \times 100$$

$$Percentage\ Error = 0.00\%$$

Motor operation was also successful at this stage, as the motor demonstrated the ability to run under the direct control of the regenerative braking circuit. A video of this demonstration can be provided if upon request.

4.3 COVID -19 Impacts

Unfortunately, testing of circuit components with the motor was delayed a week as it was found that the provided motor had been damaged. This in turn delayed the testing of the regenerative circuit by a week. However, due to the early closure caused by COVID-19, the regenerative functionality of the circuit was unable to be tested. In order to complete the project, indicative data was used to calculate the effects that a successful regenerative braking circuit would have on the industry.

4.4 Aircraft Data and interpretation

In order to calculate the desired outcome of the regenerative braking circuit, GHG emission data must be examined. The data for GHG emissions will come from the 2010 study on air pollutant emissions in GIA, Korea. This study was chosen as it provides an accurate breakdown of the emission of GHGs and for which mode of operation they are emitted. This study also provides details of air pollutants released, however these will not be considered as they are not related to the main objectives.

Extracted data is as follows:

Table 5 - Emission of GHG's for Boeing 737 at the GIA in 2010 (in kg/yr) [17]

Type	N_2O	CO_2	CH_4
Boeing 737	950	51,739,284	-32

Table 6 - Emission of GHG's for aircraft operational mode at the GIA in 2010 (in kg/yr) [17]

Operation	N_2O	CO_2	CH_4
Approach	361	20,333,105	-329
Climb-out	231	31,624,254	-582
Start-up	4	70,124	7
Take-off	78	12,235,769	-229
Taxi-in	356	12,613,560	264
Taxi-out	967	34,236,805	717
Total	1,998	111,113,617	-151

For tables containing the full data set from the study, including other aircraft and pollutants, please see Appendix A. Using the data above, the percentage of emissions contributed by the concerned modes of operation could be calculated.

Calculations for CO_2:

$$\% \ CO_2 \ emitted: Take \ off = \frac{Take \ off \ CO_2}{Total \ CO_2} \times 100 \tag{12}$$

$$\% \ CO_2 \ emitted: Take \ off = \frac{12{,}235{,}769}{111{,}113{,}617} \times 100 = 11.01\%$$

$$\% \ CO_2 \ emitted: Taxi \ in \ and \ Taxi \ out = \frac{Taxi_{in} + Taxi_{out}}{Total \ CO_2} \times 100 \tag{13}$$

$$= \frac{12{,}613{,}560 + 34{,}236{,}805}{111{,}113{,}617} \times 100 = 42\%$$

Calculations for N_2O:

$$\% \ N_2O \ emitted: Take \ off = \frac{Take \ off \ N_2O}{Total \ N_2O} \times 100 \tag{14}$$

$$\% \ N_2O \ emitted: Take \ off = \frac{78}{1{,}998} \times 100 = 3.\dot{9}0\dot{3}\%$$

$$\% \ N_2O \ emitted: Taxi \ in \ and \ Taxi \ out = \frac{Taxi_{in} + Taxi_{out}}{Total \ N_2O} \times 100 \tag{15}$$

$$= \frac{356 + 967}{1{,}998} \times 100 = 66.2\%$$

Calculations for CH_4 were not carried out due to its net contribution being a negative.

Table 7 - Emission of GHG's for aircraft operational mode at the GIA in 2010 (%)

Operation	N_2O	CO_2
Take off	3.90	11.0
Taxiing (in and out)	66.2	42.0
Total	70.1	53

As can be seen in the table above, the contribution of take-off and taxiing are both above 50%. This suggests that using an electric motor that utilises regenerative braking for taxiing and take-off would significantly reduce GHG emissions.

4.4.1 Assumptions

It is assumed that that weight of an electric motor and battery would not increase the weight of the aircraft significantly enough to negate the decrease in fuel consumption/GHG emission.

It is also assumed that such a method of operation would be approved by aviation authorities such as the European Aviation Authority (EASA).

4.4.2 Regeneration Calculations

Despite the unfortunate set back caused by COVID-19, the impacts of a reduction of Greenhouse gases and Energy recovered can be calculated using some estimated values. These calculations will provide an indication of what impacts the system would have had, had it been successful.

The regenerative ration would have been used to gauge the effectivity of the designed regenerative braking system.

$$Regenerative\ Ratio = \frac{\sum E_{battery}}{\sum E_{Kinetic}} \times 100 \tag{3}$$

There are many sources in which model recovery rates for calculation may be taken, however the stated percentage of recovery by many automotive manufacturers is not necessarily reliable as these claims require “optimal conditions”. In order to use a more accurate and realistic figure, it will be assumed that 32% of kinetic energy would be recovered. This value is the percentage of energy recovered in source [18] in a Tesla model S.

Table 8 - Boeing 737 Characteristics

Boeing 737 Characteristics	
Parameters	Values
M_{v1} – Vehicle Mass (Maximum)	80,000 [kg]
M_{v2} – Vehicle Mass (Minimum)	59,000 [kg]
C_{ω} – Drag Coefficient	0.019
V – Landing Velocity	155 [knots] or 79.7 [m/s]

Landing

$$E_{Kinetic} = \frac{1}{2} M_v (\Delta V^2) \tag{1}$$

$$E_{Kinetic} = \frac{1}{2} \times 80{,}000(79.7^2 - 0^2)$$

$$E_{Kinetic} = 254{,}083{,}600\ J$$

Table 9 - Kinetic Energy present in Flight Stages

Given an assumed regeneration ratio of 32%, this would yield the following recovery of kinetic energy from landing.

Stage	**Kinetic Energy [J]**	**Recovered Energy [J]**
Taxi Departure	2,709,316	N/A
Taxi Arrival	4665600	N/A
Total Taxi	7,374,916	N/A
Landing	254,083,600	794,011,250

$$E_{Recovered} = E_{Kinetic} \times \frac{\sum E_{battery}}{\sum E_{Kinetic}} \quad \textbf{(16)}$$

$$E_{Recovered} = 254{,}083{,}600\,J \times 0.32 = 81{,}306{,}752\,J$$

This calculated value immediately suggests that it is possible to power Taxiing with his recovered Kinetic Energy. This energy will be subject to the various inefficiencies that are present in source to wheel transmission. However, the amount of energy recovered is large enough that these losses will not impede or diminish its ability to reuse the energy.

In order to calculate the number of Taxis that could be powered using this kinetic energy, the following calculation was done:

$$\frac{81{,}306{,}752}{7{,}374{,}916} = 11.02$$

This shows that the recovered Kinetic Energy amounts to that of 11.02 Taxi journeys.

Taking the above into account, it can be assumed that all CO_2 and N_2O emissions that would occur during taxiing would become 0 whilst utilising this method. Calculations were conducted in order to discover the amount that CO_2 and N_2O would reduce by on an annual basis. These calculations are done using data from the 2010 study referred to in section 5.1.

Table 10

Operation	N_2O [%]	CO_2 [%]
Taxiing (in and out)	66.2	42.0

Given the above information, the annual reduction in GHG emissions for the Boeing 737 can be calculated using the data in section 4.4.

Table 11

Type	N_2O reduction	CO_2 reduction
Boeing 737	628.9 [kg/yr]	21,730,499 [kg/yr]

4.5 Discussion

Given the aforementioned regenerative assumptions, it was found that the use of an electric motor and regenerative braking in aircraft landing gear would decrease the CO_2 and N_2O emissions of a Boeing 737 by 42% (22M kg/yr) and 66.2% (628.9 kg/yr) respectively. As the kinetic energy recovery was found to be 81MJ, this would translate to enough recovered energy for 11.02 Taxi journeys, both arrival and departure. The implications of this are profound, as they provide not just environmental but also financial relief. The replacement of Taxiing as a whole using recovered energy to power an electric motor, would also significantly reduce the fuel consumption, and subsequently Airline running costs. Considering the above, all objectives laid out in section 2.1 were met.

However, the limitations of such a technology must be discussed. This study was conducted under the assumption that the weight of a battery powerful enough to Taxi an aircraft would not add so much weight that the recovered energy would be obsolete. Tests would need to be conducted by airlines to assess the validity of such an argument. If it were found to have such a significant impact as to negate the energy recovery, battery technology would need to improve in order to utilise this method. Further recommendations would be to run the motor up to desired speeds before touching down. This would not only reduce the costs of tyre replacement, but would also reduce the spike in current produced by the abrupt rise in RPM.

If the experiment were to be repeat, a number of changes would be recommended. The week delay caused by the motor damage caused testing to be scarified due to early university closure (see section 4.3 regarding COVID-19). As a result, data from other experiments had to be used in order to calculate the impact of the device. It would be recommended to allow two weeks more for the testing of the regenerative circuit, in order to mitigate the damage inflicted by unforeseen circumstances such as these. Another change would be to calculate the size of the battery necessary to Taxi the Boeing 737 and calculate if the added weight would negate any energy saved, (through increased fuel consumption).This would therefore remove this assumption and provide a more comprehensive study of the topic.

5 Conclusions

In conclusion, the use of regenerative braking within aircraft was found to be a feasible and successful way to decrease the GHG emissions. A regenerative braking circuit and power converter were successfully designed and constructed and although regenerative functionality tests were not completed, calculations were still made using estimated values. Using these values, the decrease in GHG emissions was successfully calculated, given the assumptions stated within the report.

6 Project Evaluation

6.1 External Factors

6.1.1 Environmental Constraints

There are no environmental constraints to be considered regarding the project in its current form. All tests were performed within the engineering project lab and no fuel was used during these tests. In theory, large amounts of aircraft fuel would be used in real life testing of such a device, however no fuel was used in this case as it was a feasibility study.

6.1.2 Sustainability Constraints

The ability of the device to withstand the forces of a landing would be called into question. In order to avoid this, the motor controller unit and circuit board would be housed in a container strong enough to withstand these forces.

6.1.3 Ethical Constraints

There were no ethical constraints associated with this project.

6.1.4 Risk Issues

- The heavy flywheel may have fallen or have been dropped whilst being transported from A to B. This would cause a direct risk to the feet of the carrier. In order to avoid this, a minimum of two people would move the flywheel. Risk could also be decreased by asking the carriers to wear steel toe safety boots in the lab.
- The use of a battery would increase the risk of a fire in the event of a crash.
- The large 24V motor to be used for testing must be handled with care as any sharp or stray parts of the rotor may cut the skin during contact.
- The flywheel used for testing may have disconnected from the motor if secured incorrectly.
- Regenerative brakes are not ideal for emergency stops as they are unable to cause the car to come to a complete stop. Therefore, brake pads would be used in the case of an emergency stop.

6.1.5 Health Constraints

- Bodily harm may have been incurred should the whole flywheel have come loose from the motor whilst at full speed.
- The participants eyes may have been damaged had any pieces of the flywheel broken away during testing. In order to reduce the risk of this, safety glasses would have been worn during testing.

6.1.6 Security Constraints

- There were no security constraints associated with this project.

6.1.7 Intellectual Property

- Some variations of regenerative braking have been patented, fortunately the core design and concept has not. However, intellectual property is irrelevant as this experiment seeks to prove its use and not market a new device/design that may be someone's intellectual property.

6.1.8 Relevant legal and contractual Issues

- The type of design that was used for this experiment is not protected by any IP laws.

6.1.9 Codes of Practice

- There are no codes of practice associated with this project.

6.1.10 Standards

- It is assumed that such a method of operation would be approved by aviation authorities such as the European Aviation Authority (EASA) for use on Commercial Aircraft.

6.1.11 Availability of resources

- All the necessary equipment was acquired.

6.2 Management Outline

This project contains two key stages of work: "Requirements and Research" (stage 1) and "Development and Testing"(stage 2). These two stages have been split up, with stage 1 dominating semester 1 and stage 2 dominating semester 2.

6.2.1 Requirements and Research

The research aspect of this project begins with determining the requirements. Requirement were necessary as they would allow for the In order to do this, research was conducted into which regenerative braking methods would be used. This consisted of looking at existing patents for regenerative braking systems, analysing what their key similarities were and determining what components and features would be required for this project. As well as this, many scientific journals and research documents were taken into consideration, allowing more knowledge and understanding of the regenerative braking systems to be gained. All of this would allow for the nature of the design to be understood, and as such the component requirements could be determined.

Following this the aircraft GHG Emission data was researched in order to provide context for the project, allowing the performance requirements of the design to be determined. In order to do this, an aircraft was chosen to act as a research base point to refer to, as the data varies from aircraft to aircraft. It was found that the Boeing 737 Commercial aircraft was the most popular commercial aircraft, and was therefore the most suited to being the model for this project. Following this, the GHG Emission data for this aircraft was found, alongside general statistics detailing the economic and environmental impacts of the aviation industry.

As the components had been determined, research into each component was conducted. One such component was a DC/DC converter. The project required a converter that would regenerate and operate under negative current. Due to this, multiple quadrant DC converters were researched, bringing to light the suitability of the second quadrant chopper and they were thus implemented into the circuit design as a result of this. This would then be followed by the research of transistors to be used in the converter, using the motors values to calculate its required current rating.

During the research it was determined that a motor controller unit would be required to control the transistor switches, hence research was then conducted into the different options for motor control, the Arduino and the SG2535. Following the development of an initial design, research was conducted into the feasibility of using a QIV chopper to negate the risk of the circuit shorting out in the case of a switching error.

From this research the following requirements were discovered:

- Circuit design must be able to recover energy from the freewheeling motor
- The design must contain a DC/DC converter in order to allow for the building of inductance during freewheeling and passage of negative current to the battery.
- The circuit must contain a motor controller in order to control the motor speed and the switching speeds.
- The circuit must contain transistors to act as switches in the QII converter
- The system must allow for the control of the motor speed.

6.2.2 Development and Testing

The development and testing aspect of the project included a wide range of tasks. This included the design, manufacture and testing of the circuit as well as data interpretation of results. The first task was to draw up a preliminary design including all aspects of aforementioned research. A feasibility study was conducted in order to assess whether or not this design was fit for purpose. Following this, a list of all necessary changes in order to improve current design was created and all changes were implemented. Given that the designs were suitable, manufacturing would begin, shortly followed by the testing of all created circuits.

Following all testing, the data and research would be compared against the results and calculations would be completed to assess the success of the design. These calculations and results would then be interpreted and applied to a real-life context.

6.3 Work Packages

The following is an evaluation of the work packages specified in the methodology. An assessment was made as to whether the work packages were completed on time and using the planned resources.

Table 12 - Work Packages

Work Package	Name	Resources	Complete on time?	Comments
WP1	Research Regenerative braking	Patents and Online	Yes	N/A
WP2	GHG Emission Research	Research Papers	Yes	N/A
WP3	QII Chopper Research	Books and online	Yes	N/A
WP4	Transistor Research	Online sources	Yes	N/A
WP5	Arduino/SG3525 Research	Online sources	Yes	N/A
WP6	QIV chopper Research	Books and online	Yes	N/A
WP7	Regenerative braking 2	Online sources	Yes	N/A
WP8	Opto-Coupler Research	Online sources	Yes	N/A
WP9	Current Transducer/MCB	Online sources	Yes	N/A
WP10	Initial Regen Circuit Design	AutoCAD	Yes	N/A
WP11	Manufacture stage 1 - Motor	Project Lab	Yes	N/A
WP12	Manufacture stage 2 - PCB	Project Lab	Yes	N/A
WP13	Coding Stage 1 - PWM	Arduino IDE	Yes	N/A
WP14	Testing Opto-Couplers	Project Lab	Yes	N/A
WP15	Testing Motor Control	Project Lab	Late	Delayed by 1 week
WP16	Testing Regeneration	N/A	No	See 4.3 COVID-19
WP17	Final Report	MS Office	Yes	N/A

All work packages were completed in the assigned time frames and with the assigned resources, bar WP15 and WP16. Please refer to section 5.4 – COVID19 for further detail regarding these delays.

All work packages were included in the following Gantt chart. This Gantt chart can be used as an indication to compare planned project progress to actual project progress.

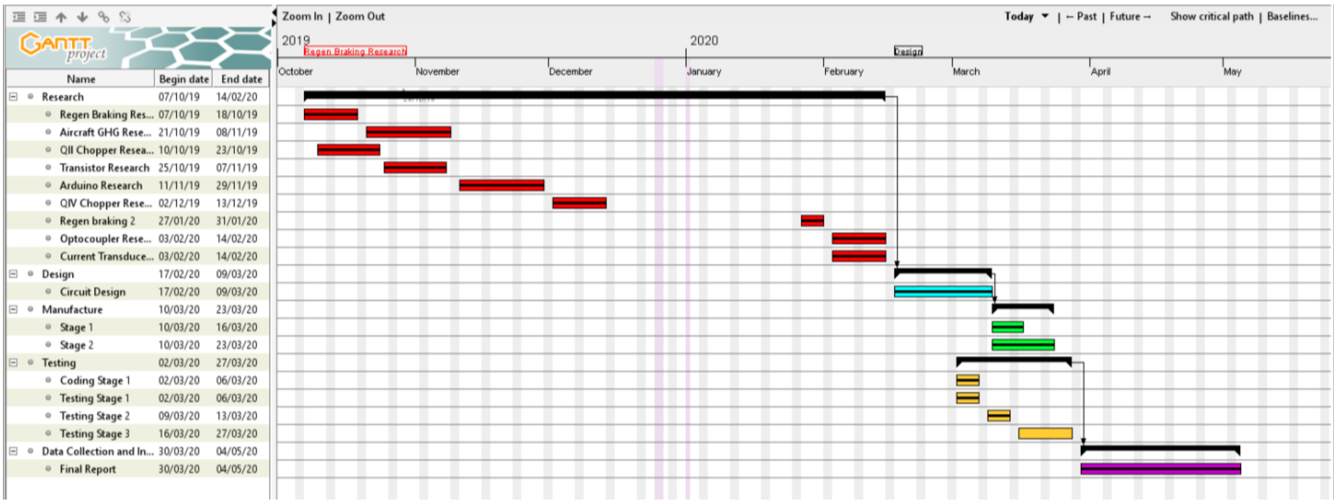

Figure 23 – Gantt Chart of Planned Progress

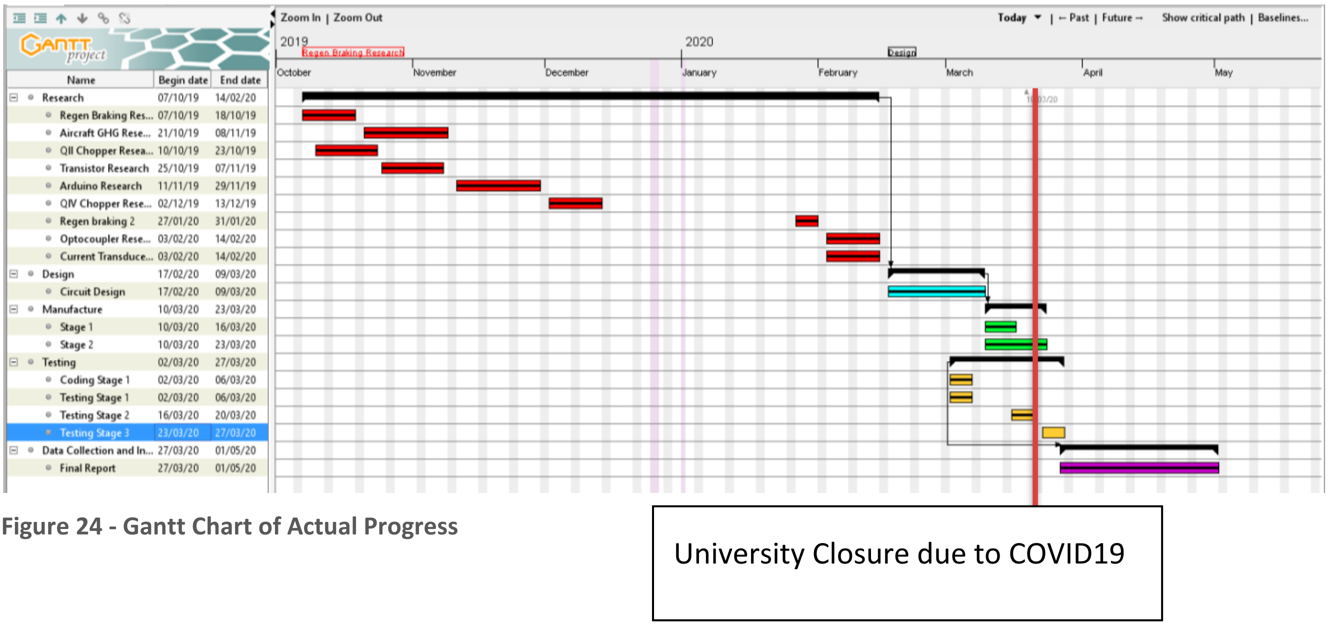

Figure 24 - Gantt Chart of Actual Progress

6.3.1 Gantt Interdependencies and Interpretation

- As shown above, the delay caused by the motor damage had delayed the Regen testing by a week. Due to the University closure as a result of COVID 19, this task was not completed.
- All Circuit design work packages are dependent upon the completion of their corresponding research work package. For example, there is interdependency between WP3 and developing the DC/DC converter into the design (WP10).
- All work packages are interdependent with WP1 as this is the first event, and without it there would be no project.
- Development and testing is interdependent with Circuit design as this cannot begin without the designs.
- Data collection and interpretation is interdependent on testing as this cannot be done without any results.

6.4 Risk Management

Table 13 – Risk Management

Risk	Risk Description	Risk Impact	Risk probability (1-5)	Severity (1-5)	Mitigating Action	Risk Contingency
1	Project deadlines are missed	All following tasks with interdependencies would also miss their deadlines	3	2	The end date of the project, 20th March 2020 is 7 days earlier than necessary in order to allow for this.	Allow ample time before beginning tasks and work packages in the project.
2	Health and Safety: Eyes damaged when testing motor	Victim may experience some pain or permanent damage.	1	5	Ensure the participant receives medical attention.	All participants must wear eye protection during testing.
3	Battery puncture	Victim may inhale dangerous gases	2	3	Evacuate the Area as soon as possible.	All batteries will be housed in a housing.
4	Project objectives are not achieved	Regenerative braking system fails and the concept is misunderstood	1	5	Report why the objectives were not achieved and what could have been done to prevent this.	Spend more time conducting research

Unfortunately, early closure was not considered when completing Risk Management. As stated previously, this led to an inability to complete testing. However, this was mitigated by using example data to make the necessary calculations. No other risks came to fruition.

6.5 Cost analysis

6.5.1 Equipment Costs

Table 14 - Equipment Costs

Equipment	Source	Quantity	Cost (£)
Arduino Uno Rev 3	University of Leicester	1	0.00
24V, 0.75kW Motor	University of Leicester	1	0.00
Oscilloscope	University of Leicester	1	0.00
Bread board	University of Leicester	2	0.00
Cables	University of Leicester	5 Meters	0.00
Soldering Iron	University of Leicester	1	0.00
Solder	University of Leicester	30 cm	0.00

Toolbox and provided Tools	University of Leicester	1	0.00
Voltmeter and Ammeter	University of Leicester	1	0.00
75A, 1200V IGBT	University of Leicester	1	0.00
32A MCB	University of Leicester	1	0.00
Capacitors	University of Leicester	4	0.00
Resistors	University of Leicester	4	0.00
AutoCAD License	University of Leicester	1	0.00
Autodesk EAGLE License	University of Leicester	1	0.00
Opto-coupler	Farnell	2	1.67
AND Gate	Farnell	1	0.506
Buffer/Inverter	Farnell	1	0.721
Current Transducer	Farnell	1	13.81
		Total Cost	16.80

All items sourced from the University of Leicester were provided free of charge. This was due to the items being readily available for no extra cost. The case may be different in an industry context as all components must be acquired from scratch. The costs would also vary depending on the scale of the repeated project.

6.5.2 Staff and Location Costs

Table 15 - Staff Costs

Staff Position	Quantity	Grade	Spine Point	Gross Salary p.a. (£)	Salary p.a (£) with NI (14%) and Pension (8%)
Trainee Engineer	1	5	16	22,017	26,860.74
Dr of Engineering	1	8	39	43,267	52,785.74
Technical and Support Staff	2	6	24	27,830	33,952.60
Total	4	-	-	120,944	147,551.68

This would give a total project cost of 147,551.68 + 16.80 = £147,568.48

These numbers and costs are reflective of this project and the scale at which it was conducted, however costs may differ by manufacturer/researcher depending on cots of utilities and amount of pre-existing equipment.

Appendix A

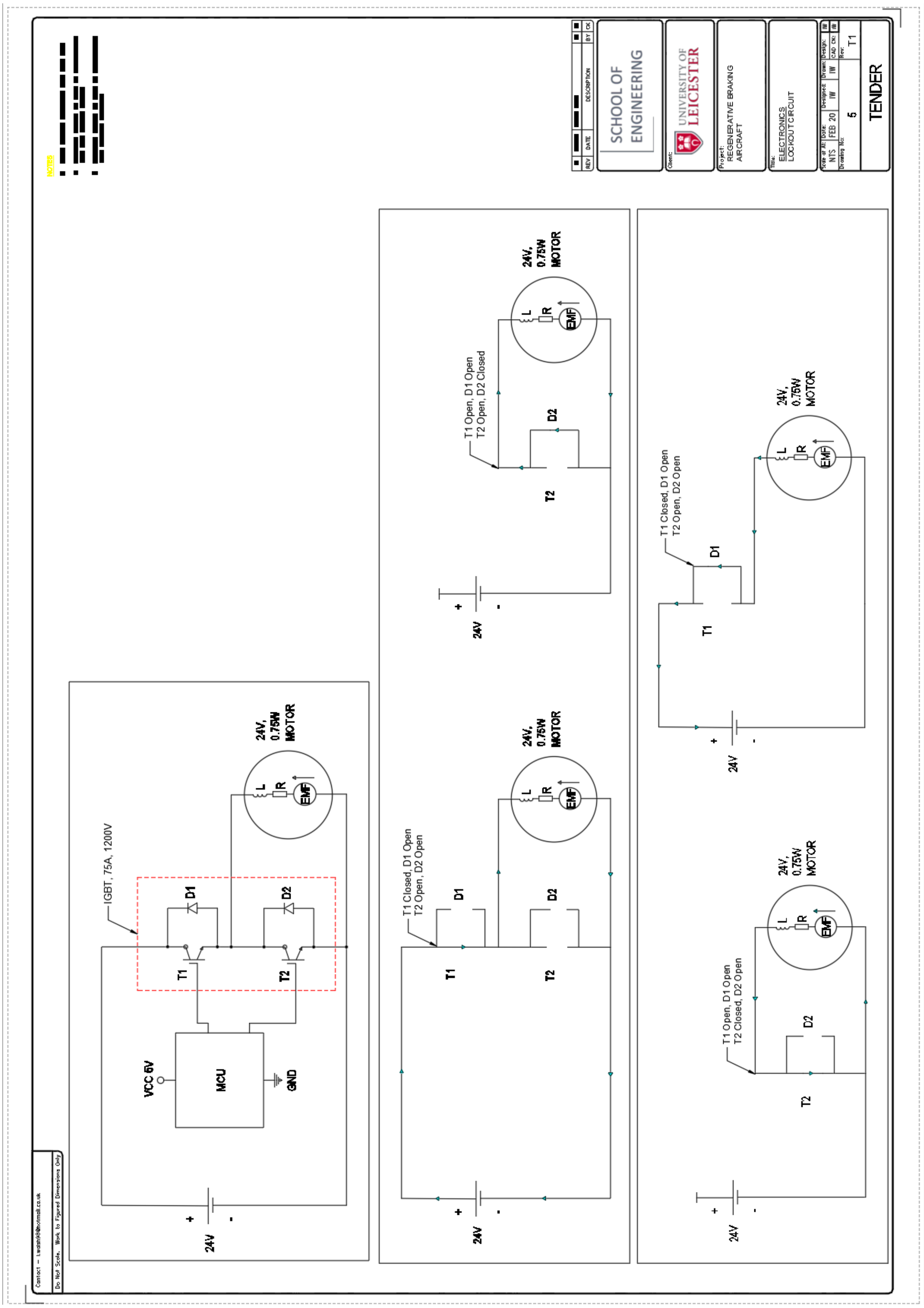

Figure 25 - Initial Circuit Design Full AutoCAD

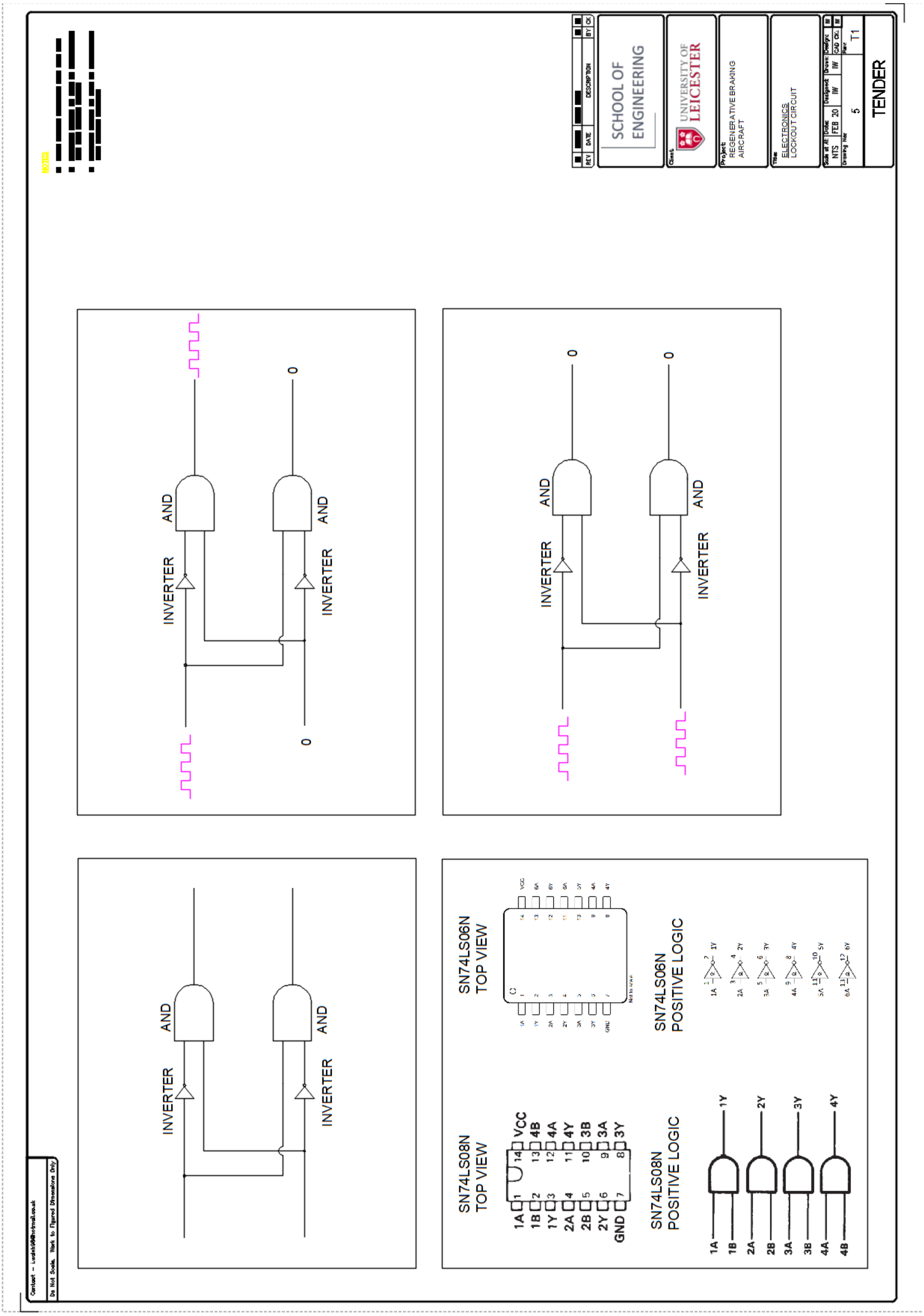

Figure 26 - Lockout Circuit full AutoCAD DWG

Table 3. Emissions of air pollutants and GHGs for aircraft type at the GIA in 2009 and 2010. (in kg/yr)

	Type	CO	NO_x	VOCs	SO_x	PM_{10}	CO_2	CH_4	N_2O
2009	B737	444,334	127,473	93,181	19,223	2,140	51,739,284	−32	950
	B747	1	69	6	5	0.4	13,486	−0.04	0.2
	B767	8,676	13,700	2,709	990	88	2,663,750	−12	44
	B777	95	331	19	15	0.4	39,891	−0.14	0.7
	A300	104,929	180,602	16,659	14,136	887	38,019,053	−83	668
	A330	28,425	58,075	2,485	4,968	207	13,361,822	−28	235
	TU154	305	30	296	6	3	14,932	0.04	0.3
	Others	8,208	23,953	1,117	1,838	262	4,942,676	−2	91
	All	594,974	404,233	116,472	41,181	3,588	110,794,894	−157	1,989
	GSE*	379,151	42,367	1,299	13,183	1,496	N/A**	–	–
	Total	974,130	446,600	117,771	54,364	5,084	110,794,894	−157	1,989
2010	B737	480,233	137,772	100,709	20,776	2,313	55,919,384	−35	1,027
	B747	0.5	27	3	2	0.2	5,394	−0.02	0.1
	B767	567	895	177	65	6	174,038	−1	3
	B777	123	430	24	19	1	51,859	−0.19	0.9
	A300	112,077	192,906	17,794	15,099	948	40,609,180	−89	713
	A330	26,182	53,492	2,289	4,576	191	12,307,475	−26	217
	TU154	0	0	0	0	0	0	0	0
	Others	3,398	9,917	462	761	108	2,046,288	−1	38
	All	622,581	395,439	121,458	41,298	3,566	111,113,617	−151	1,998
	GSE*	345,077	37,867	931	11,927	1,320	N/A**	–	–
	Total	967,658	433,306	122,389	53,225	4,886	111,113,617	−151	1,998

*Ground Support Equipment. **N/A=Not available.

Table 4. Emissions of air pollutants and GHGs for aircraft operational mode at the GIA in 2009 and 2010. (in kg/yr)

	Operational mode	CO	NO_x	VOCs	SO_x	PM_{10}	CO_2	CH_4	N_2O
2009	Approach	98,222	60,282	21,085	7,552	1,403	20,311,345	−329	361
	Climb-out	21,864	186,584	757	11,763	754	31,636,968	−583	231
	Start-up	–	–	21,941	12	–	69,477	7	4
	Take-off	8,373	91,607	291	4,551	297	12,239,825	−229	78
	Taxi-in	125,600	17,704	19,492	4,659	305	12,529,268	263	354
	Taxi-out	340,915	48,055	52,906	12,645	828	34,008,012	713	961
	All	594,974	404,233	116,472	41,181	3,588	110,794,894	−157	1,989
2010	Approach	104,993	59,428	22,679	7,560	1,456	20,333,105	−329	361
	Climb-out	23,152	180,855	695	11,758	701	31,624,254	−582	231
	Start-up	–	–	22,146	11	–	70,124	7	4
	Take-off	8,866	89,231	268	4,549	282	12,235,769	−229	78
	Taxi-in	130,730	17,749	20,373	4,690	303	12,613,560	264	356
	Taxi-out	354,840	48,176	55,298	12,730	823	34,236,805	717	967
	All	622,581	395,439	121,458	41,298	3,566	111,113,617	−151	1,998

Figure 27 - Full table of GHG Emissions from source [20]

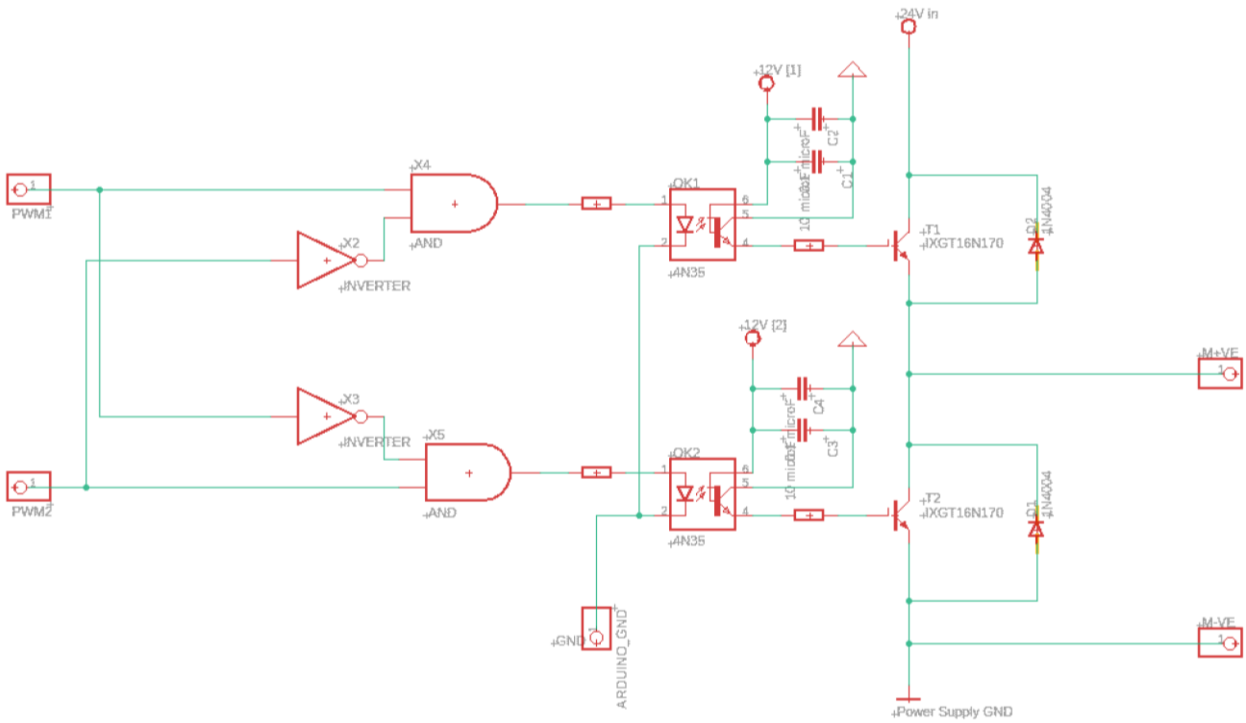

Figure 28 - AutoDesk EAGLE PCB Schematic

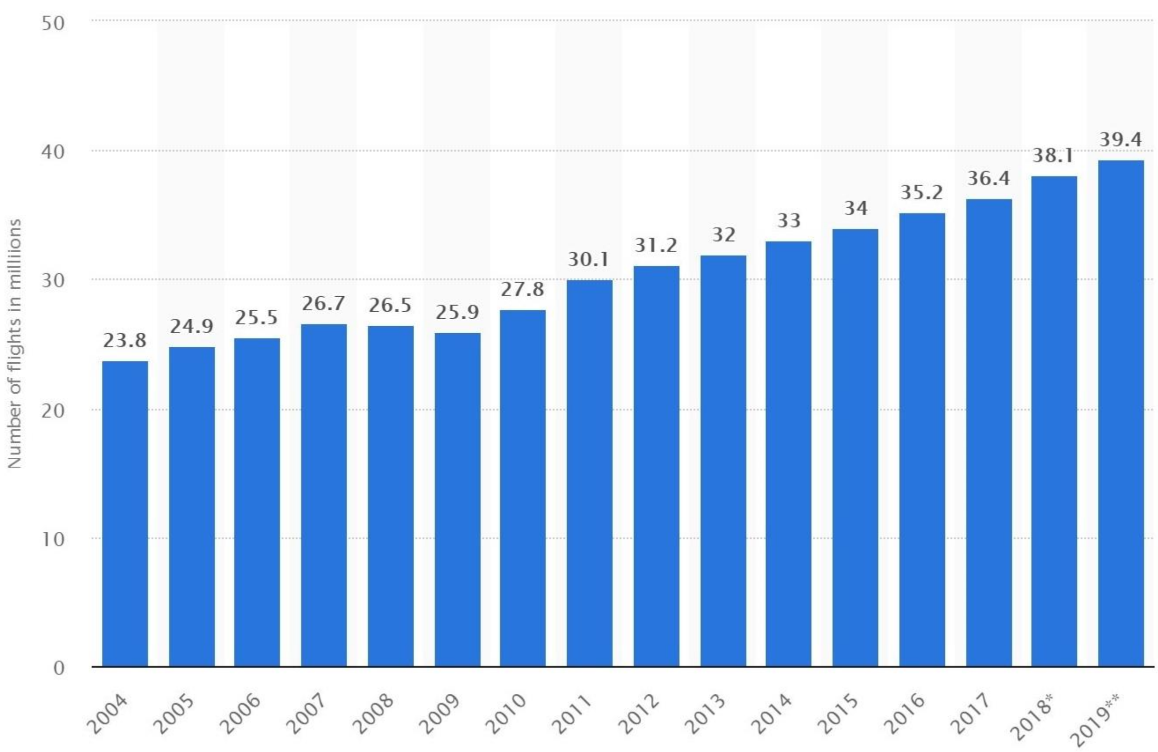

Figure 29 - Number of Flights Worldwide per Year [2]

References

[1] https://www.visitbritain.org/visitor-economy-facts (Accessed 15:33 18/11/19).

[2] https://www.statista.com/statistics/564769/airline-industry-number-of-flights/ (Accessed 15:36 18/11/19).

[3] https://www.safran-landing-systems.com/systems-equipment/electric-taxiing-0 (Accessed 17:07 05/12/19)

[4] https://www.newscientist.com/article/2207886-it-turns-out-planes-are-even-worse-for-the-climate-than-we-thought/ (Accessed 17:15, 05/12/19)

[5] Modeling and demonstrating regenerative braking of a squirrel cage induction motor with various deceleration rates using V by F control - Nytko, Billy J. 2010

[6] Advanced DC/DC Converters – Fang Lin Luo 2017

[7] Aircraft power systems: technology, state of the art, and future trends - K. Emadi ; M. Ehsani, 2000 https://ieeexplore.ieee.org/document/821660

[8] Moving Towards a More Electric Aircraft J.A. - Rosero, J.A. Ortega, E. Aldabas, & L. Romeral, 2007 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4145070

[9] https://www.lifewire.com/can-regenerative-braking-recover-lost-energy-534816 (Accessed 16:24 07/12/19)

[10] The Working Principle of an Arduino - Yusuf Abudullahi Badamasi 2014 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6997578

[11] Studies of Regenerative Braking in Electric Vehicle - Faculty of Engineering, Kuala Lumpur, Malaysia, 20 & 21 November 2010

[12] https://www.spellmanhv.com/-/media/en/Images/Technical-Resources/Application-Notes-HVPS/four_quadrant_operation.gif?la=en&hash=FC5ECB68235A628D702D3CA92A5C1440 (Accessed 18/11/19, 17:03)

[13] https://www.robotshop.com/uk/arduino-uno-r3-usb-microcontroller.html (Accessed 13/12/19, 04:00)

[14] http://tahmidmc.blogspot.com/2013/01/using-sg3525-pwm-controller-explanation.html (Accessed 13/12/19, 04:00)

[15] https://www.electronicsforu.com/resources/learn-electronics/miniature-circuit-board-mcb (Accessed 17:23 18/02/20).

[16] https://www.consumerunitworld.co.uk/what-is-an-mcb-and-how-does-it-work-328-c.asp (Accessed 17:31 18/02/20).

[17] https://www.nature.com/articles/s41560-018-0294-x.epdf?sharing_token=9SV_ZGnDhg_2w9RBf5O1_9RgN0jAjWel9jnR3ZoTv0MvL99qj__pt1SyURdgvkJVyAmHv9BR87sqNGGSc1qNaEJZRy3tJJfEsmRAc3IyL_5-kXMNGdSrraXSSjLc2vUGK0GTT0Y4tuYvnWs1G5o4YhonmCZpbXGjfXwht_VHTvMFq_A9SASCLpgyVdE7sgQAByp wrcptog60-C5CoL173wDRvyGt6OVtOjH5zjw-kK0uwvAXh5jwC1cC0-UiWmz4PPjPk7-KTQwSMrEP6wNfkf3CiKdIc-U-uc9nu042jtkApOn42EPcM6_w6UlR6_DKCRlNxrAT2o_Odn7oqreCUw%3D%3D&tracking_referrer=www.technologyreview.com (Accessed 14:43 17/12/19).

[18] https://www.youtube.com/watch?v=KnOwWyUsJlE&feature=youtu.be (Accessed 13:16 26/04/20).

[19] http://www.b737.org.uk/techspecsdetailed.htm (Accessed 10:02 07/01/20).

[20] https://www.sciencedirect.com/science/article/abs/pii/S1352231012007078 (Accessed 10:45 07/01/20).

[21] https://www.tramwayinfo.com/tramways/Download/Raworth.pdf (Accessed 15:09 18/10/19).

[22] https://simpleflying.com/best-selling-commercial-aircraft/ (Accessed 10:02 07/01/20).

[23] Toshiba TLP351 Photocoupler Data Sheet - Inverter for Air Conditioner IGBT/Power MOS FET Gate Drive Industrial Inverter - http://www.farnell.com/datasheets/461004.pdf

[24] LEM Current Transducer LTS-6NP Data Sheet - http://www.farnell.com/datasheets/1639891.pdf?_ga=2.122896907.1445201110.1588209629-4559534.1580746717

[25] https://electrical-engineering-portal.com/things-about-mcbs-that-every-low-voltage-electrician-should-know (Accessed 23:47 27/04/20).

[26] https://www.se.com/uk/en/product/A9F54132/acti9-ic60h-1p-32a-c-miniature-circuit-breaker/ (Accessed 00:05 28/04/20).

[27] https://howthingsfly.si.edu/ask-an-explainer/how-much-weight-can-average-size-airplane-hold (Accessed 00:12 28/04/20).

[28] https://www.aircraftcompare.com/blog/how-fast-do-airplanes-go/ (Accessed 00:27 28/04/20).

[29] KARI-NASA ATM Research Collaboration Korea Aerospace Research Institute: Comparison of Taxi Time Prediction Performance Using Different Taxi Speed Decision Trees - Hanbong Lee, Korea May 23-25, 2017

Student Self-reflection on performance

All students must complete the following sections for every piece of work they submit using this template. The aim of this is to help you use feedback more effectively to improve your marks and your skills as a professional engineer. This section is not formally marked, but your tutor may use it when discussing your work with you.

Describe how you have used AT LEAST ONE of the following sources of information to improve this piece of work: **1.) (PREFERRED) Feedback from previous assignment(s). This can be from the same module or from a previous module or previous year of study (e.g. comments from 1st year lab formal reports should be used to help improve your 2nd year lab formal reports).** **2.) The marking criteria or rubric provided for this assignment.** **3.) The Department Technical Writing Handbook for Students.**
Student to add text here…
Are there any aspects of this work that you would specifically like the marker to comment/or advise on? For example: "I wasn't sure if my figure formatting looked professional and would appreciate feedback on this aspect"
Student to add text here…