Capstone 47

Rolls-Royce Electrical Actuator

Final Report

Andrew Anand Tan (1000963)

Alvee Ahmed (1001130)

Yiran Wang (1000906)

Hezu Ma (1000898)

Kajol Sethia (1000941)

Table of Contents

Executive Summary 6

Chapter 1: Introduction 7

1.1 Background 7

1.2 Problem statement 7

1.3 Client's Needs & Requirements 7

1.4 Precedent Technologies Research 8

Chapter 2: The Concept 8

2.1 Process Breakdown 8

2.2 Concept Generation Methods 9

2.2.1 Mind-Mapping 9

2.2.2 Reverse Engineering Morphological Matrix (REMM) 9

2.3 Computer-Aided Design (CAD) Prototyping and Proof-of-Concept 10

Chapter 3: First Prototype 10

3.1 Ideation & Evaluation 10

3.1.1 Pugh Chart Subsystem 1 Power Transmission Mechanism (PTM) 11

3.1.2 Pugh Chart Subsystem 2 Sensors 11

3.1.3 Calculation 12

3.2 Fail-safe 13

3.2.1 Ideation & Evaluation 13

3.3 Electrical Circuitry and Sensors 16

3.4 Material Selection 17
3.5 Finite Element Analysis (FEA) 18
3.6 Prototype 1 Computer-Aided Design (CAD) 18
Chapter 4: Final Prototype 19
4.1 Lessons learnt from First Prototype 20
4.2 Modifications from First Prototype 20
4.3 Electrical Circuitry and Sensors 21
4.3.1 Sensors 21
4.3.2 Failsafe Circuit 23
4.4 Material Selection 25
4.5 Final Prototype Finite Element Analysis 26
Chapter 5: Motor Control & Experimentation 27
5.1 Motor Control 27
5.1.1 Noise Smoothing Method 27
5.1.2 PID (Proportional-Integral-Derivative) Control 29
5.1.2.1 DC Motor PID 29
5.2.1.2 PMSM (Permanent Magnetic Synchronous Motor) 30
5.2 Experiment Design 31
5.2.1 Accuracy Test 31
5.2.2 Repeatability Test 32
5.2.3 Logistic Regression Model 33

5.2.4 Fail-Safe Mechanism Test 33
5.3 Experiment Results & Analysis 34
5.3.1 Accuracy Logistic Regression Model 34
5.3.2 Repeatability Logit Regression Model 35
Chapter 6: Project Management 36
6.1 Work Breakdown Structure 36
6.2 Responsibility Matrix 37
6.3 Dependency Matrix 37
6.4 Three Point Duration Estimate 38
6.5 Activity on Nodes (AON) & Activity on Arc (AOA) 38
6.6 Gantt Chart 39
6.7 Risk Management 39
6.7.1 Probability and Impact Matrix 40
6.8 Budgeting 41
6.9 Concepts and Theory Involved 41
Chapter 7: Health, Societal & Environmental Concerns 42
Chapter 8: Conclusion 42
References 43
Appendices 45
Annex A - Client's Needs and Requirements 45
Annex B - Interview with IDC Mentor 46

Annex C - Ideation Methodology 48

Annex D - Ideation Pugh Chart Criterion 53

Annex E - Calculations 55

Annex F - Failsafe Pugh Chart Criterion 57

Annex G - FMEA Model 58

Lower Platform 58

Annex H - Work Breakdown Structure 66

Annex I - Three Point Duration Estimation 66

Annex J - Gantt Chart 68

Annex K - Risk Breakdown Structure 76

Annex L 78

Executive Summary

The aim for current aircraft engine makers is to develop more efficient and cost effective engines. Driven by the demand to optimize aircraft performance, decrease operating and maintenance costs, and reduce gas emissions - have underscored the aircraft industry's renewed push toward the concept of more electric aircraft. Current Fueldraulic Actuators used in Variable-Stator Vane actuation have caused uneven fuel distribution within the engine, resulting in undesired loss of engine efficiency. The controllability that currently exists with fueldraulic actuators also seeks further improvement and this can be done through the usage of electrical sensors and control. Thus, our group's solution of the Electric actuator with an in-built fail-safe mechanism hopes to solve these issues.

The concept of using electrical actuators to replace hydraulic or pneumatic actuators is not something new. One example is the Boeing 787's innovative application of switching from hydraulically actuated brakes to electric. Electric brakes significantly reduce the mechanical complexity of the braking system and eliminate the potential for delays associated with leaking brake hydraulic fluid, leaking valves, and other hydraulic failures. This real world example proves that the switch to electrically powered systems is one that is very beneficial.

Thus, our group has designed and fabricated a scaled down prototype of an electrical linear actuator that can be used to replace the current fueldraulic actuators. In addition, we have incorporated various fail-safe mechanism to tackle to potential failure points of the system. The linear actuation would be done by a highly efficient ball screw system that is connected to a Permanent Magnetic Synchronous Motor (PMSM) which allows for high degree of controllability and adjustment of the overall actuation. Linear displacement will be sensed using a highly accurate Linear Variable Displacement Transducer (LVDT) that can measure up to an accuracy of 0.5mm. With the usage of the ball screw, PMSM and LVDT, we can ensure that our linear actuator has a significant advantage over the current fueldraulic actuator

The report provides a detailed breakdown of the task done during different stages of the project i.e. from the ideation to the building of the final prototype. We allocated significant tasks to each teammate and a relevant deadline to finish each task. This method helped us in finishing work on time and be more efficient with our deadlines.

After months of ideation and close consultation with our academic and industry mentor, we built our first prototype using 3D printing materials i.e. ABS/PLA. Hence, after the review on our first prototype, we made significant changes for the final prototype. High strength material were used, more metallic components were incorporated and sensors such as optical sensor were added after receiving feedbacks

from our mentors. Finally, with the use of PMSM, LVDT and ball screw, we can ensure high functionality of our product fulfilling the client's need and concerns.

Chapter 1: Introduction

1.1 Background

The move towards more electric aircraft demands the development of electrical actuators to replace hydraulic actuators which currently are widely used. Moreover, most requirements are limited to linear type of actuations. One such linear actuator is required to control the Variable Stator Vanes (VSV) to improve engine performance. The typical electrical actuator consists of an electrical motor employed to produce rotational motion and mechanical transmission which can convert it to linear motion and provide sufficient output force.

1.2 Problem statement

High safety standards and high efficiency are required for aerospace applications. Current Variable Stator Vanes (VSV) Actuation are done by fueldraulic actuators which receive pressurized fuel from the engine’s fuel pump. These fuel pumps are required to be oversized to fulfil the fuel pressure requirements of both the VSV and the engine. Activation of the VSV draws pressure from the fuel system to power the fueldraulic actuator, causing a period of uneven distribution of fuel pressure. This would lead to uneven distribution of fuel flow to the engine, causing inefficiency. Fueldraulic Actuators are also susceptible to leakage which could pose a threat to safety. Our project is intended to design and prototype a scaled model of a VSV Actuator that proposes a new solution to resolve the existing problems faced by the fueldraulic VSV, using lightweight materials to ultimately save fuel and operational cost.

1.3 Client's Needs & Requirements

The project needs and constraints are vital before entering the concept generation phase. We need to ensure that our concepts are focused on our clients’ needs and constraints or it will not fulfill its requirements and ultimately not function as required. After analysis of our clients’ needs statements and constraints with consultation from our industry mentors, we formulated a ranking table based on the importance of each need (*Figure 1-1*). Detailed requirements can be found in Annex A.

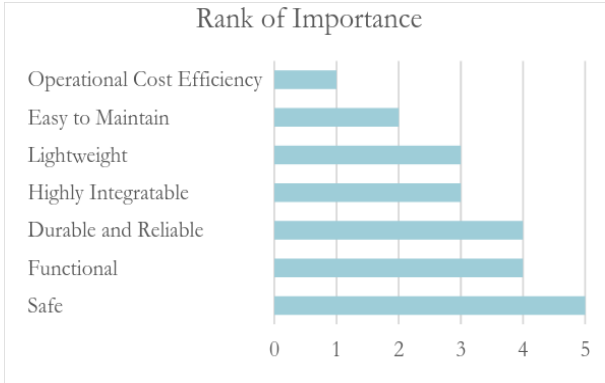


Figure 1-1. Ranking of Importance table

1.4 Precedent Technologies Research

To understand the current situation in actuation technology, our group embarked on research on precedent technologies. Majority of our precedent technology analysis was done through secondary research. This consist the usage patents and research papers to analyse the current technologies available in the current market. We also had an avenue for our primary research interview with Mr James Tan from IDC. Minutes of the interview can be found in Annex B. From our research, we were able to identify the potential technologies that we could use in our concept generation. From the four aspects of our project, we narrowed down the types of actuation that we could research further on and possibly utilize technology from.

Chapter 2: The Concept

Our precedent research allowed our team to streamline our ideation phase, giving us a clearer direction as to which technologies would be best suited to work to meet our project requirements. Thus, our concept generation phase will be a progression from our research analysis phase, where we utilize different methods to analyze the current state-of-art and generate new concepts that adapt or modify these products and technologies for our project.

2.1 Process Breakdown

Before starting the concept generation phase, our group broke down the process into three main stages as seen in *Figure 2-1*. This is to provide focus on each stage and be able to generate concepts with quality.

Figure 2-1. Concept Generation Flow

At the end of the three stages, we would then move on to concept collaboration where we utilize the concepts generated at each phase and try to generate a new integrated concept. The three stages are derived from the four main subsystems that are found in actuation systems: Power Transmission Mechanism, Sensor, Fail-safe mechanism and Structure. We decided to group the Power Transmission Mechanism and Sensor concept generation into one phase as we believe that it would be vital to have a sensor that is able to integrate well with the power transmission mechanism.

2.2 Concept Generation Methods

For the first phase of our concept generation, we used two different methods to structure our concept generation. The methods we used were "Mind-Mapping", "Reverse Engineering Morphological Matrix(REMM)". The reason we chose these two was because the limitation of one method is being addressed in another. For example, Mind-Mapping does not favor ideation from people with highly logical mindsets. Hence, we use REMM to allow the members in our team with logical thinking to analyze and draw inspiration from precedent technologies to generate new concepts. As we move on to the next stage of concept generation after the first phase power transmission mechanism concept selection, we will be moving towards other types of concept generation methods that we feel are more suitable for that aspect. Diagrams can be found in Annex C.

2.2.1 Mind-Mapping

Mind mapping is simply a diagram used to visually represent or outline information. This method allows us to categorize and organize the ideas that our group has brainstormed and identified their relationships mind maps are used to generate, visualize, structure, and classify ideas. It is also used as an aid in study, organization, problem solving, decision making, and writing. A more detailed analysis can be found in Annex C.

2.2.2 Reverse Engineering Morphological Matrix (REMM)

To reverse engineer is to disassemble and examine or analyze in detail (a product or device) to discover the concepts involved in manufacturing. Using this concept, our group considered the precedent research and reverse engineered the current types of actuation technologies in the market. By doing this, we dissected the individual technologies into their different subsystems and made them into block diagrams for ease of understanding. All the Block diagrams can be found in Annex C.

2.3 Computer-Aided Design (CAD) Prototyping and Proof-of-Concept

To understand our selected concept better, we employed the method of "Throw-Away Prototyping" where we use readily available materials to construct our concept and prove if it is a viable option. This gave us a better understanding and a more hands-on experience with regards to our concept generation.

Chapter 3: First Prototype

Our mechanism for the first prototype was inspired by precedent linear actuation technologies as shown in *Figure 3-1*. The mechanism utilizes two stepper motors which are connected to lead screws. The lead screw is connected to a platform that moves to and from the stepper motors, depending on the direction of rotation of the motors. An aluminum shaft is then connected to the platform and held in place using a pin. A shaft cover is placed on top, which also allows the connection of the spring from the top of the shaft to the platform. This then forms the basis of the mechanical failsafe mechanism.‘

Figure 3-1. First Prototype Mechanism Model

3.1 Ideation & Evaluation

The concept selection for each of the four aspects were done using the “Pugh Chart” method, as well as through Numerical Theoretical Analysis. The “Pugh Chart” analysis made use of the client’s needs and constraints to generate a list of requirements. The concepts generated will be compared against each other, judging by the level at which each concept is able to satisfy the predetermined requirements. The Numerical Theoretical Analysis also allowed us to utilize simple mathematical models to quickly identify the feasibility of a concept and if it was possible for it to be further developed.

3.1.1 Pugh Chart Subsystem 1 Power Transmission Mechanism (PTM)

This subsystem is responsible for converting input power to output linear motion. There are the various concepts generated and evaluated based on set of criteria derived from the client’s needs and constraints. We have selected 3 concepts that we will look into further.

	Weightage	Fueldraulic	Lead Screw	Harmonic linear	Electromagnetic	Piezo Electric	Electro-Hydrostat	Magnetostrictive	NiTi Material
Safety	5	0	-1	-1	-1	0	1	0	1
Durability	4	0	-1	1	0	1	0	-1	-1
Reliability	4	0	1	-1	0	0	1	0	1
Weight	3	0	1	1	0	-1	1	-1	1
Repeatability	4	0	0	0	1	1	0	-1	-1
Accuracy	4	0	1	1	-1	1	0	0	-1
Maintenance	2	0	0	0	1	0	0	0	-1
Sum		**0**	**2**	**2**	**-3**	**9**	**12**	**-11**	**-4**

Table 3-1. Pugh Chart for Mechanism Evaluation

From the Pugh chart analysis of the first subsystem(*Table 3-1*), our group has narrowed down to three potential concepts that we will further develop in the next phase. These three are: “Lead-Screw”, “Harmonic Linear Drive” and “Electro-hydrostatic.” Pugh Chart Criterion can be found in Annex D.

3.1.2 Pugh Chart Subsystem 2 Sensors

This subsystem is responsible for sensing and providing feedback on the position of the actuator. There are the various concepts generated and evaluated based on set of criteria derived from the client’s needs and constraints. As the current sensor is highly suitable for our application, we will continue to develop our concepts based on the existing Linear Variable Differential Transducer (LVDT) as well as an additional concept that we will look into further. Pugh Chart of Sensors Criterion can be found in Annex D.

	Weightage	LVDT	Eddie Current	Optical Image Encoder	Potentio meter Sensor	Capacitive Element	Inductive Encoders /
Safety	5	0	0	0	0	0	0
Durability	4	0	-1	-1	-1	-1	-1
Reliability	4	0	0	-1	-1	-1	1
Resolution	4	0	-1	-1	0	0	0
Repeatability	4	0	0	1	1	0	1
Accuracy	4	0	0	0	0	0	0
S		**0**	**-8**	**-8**	**-4**	**-4**	**4**

Table 3-2. Pugh Chart of Sensors

From the Pugh chart analysis of the second subsystem (*Table 3-2*), we have only identified one other sensor that could potentially be used for our project and that is the "Inductive Encoders." However, our team has realized that the current sensor also is a viable option for us as it fulfils all the criteria and does not have any major flaws. We will be considering both to see how we can improve and integrate it into our prototypes.

3.1.3 Calculation

To support the results of the Pugh Chart, we used simplified numerical analysis with hypothesized values and components that we could find in the current market. Doing this will allow us to have an idea of whether the concept that is selected is feasible to continue developing in our next stages of prototyping and analysis. A simple calculation shows that for the nut to linearly travel 100 mm along the screw it must do 10 complete rotations. Moreover, since the nut must travel linearly at a speed of 100mm/s, we end up with 600 revolutions per minute for the nut. For a motor with 600 rpm the output torque is 31.8 Nm which sufficient, in theory, to provide an axial force of 20,000 N. Detailed formulas and explanation of the numerical Analysis for all the concepts funneled from the Pugh chart can be found in Annex E.

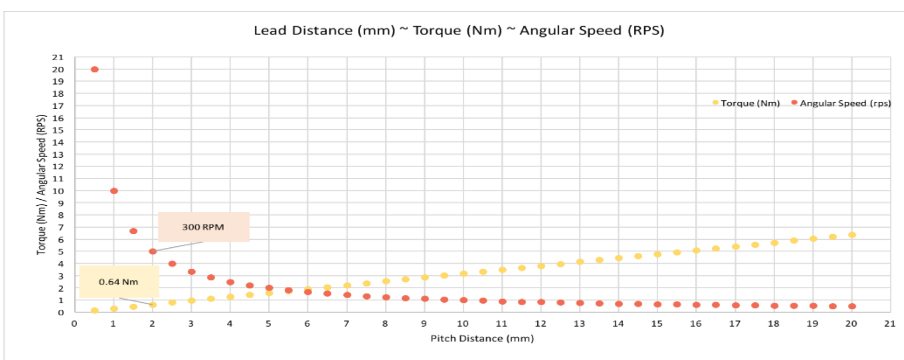


Figure 3-2.Motor Parameters Calculations Graph

3.2 Fail-safe

A failsafe is a mechanism or a process put in place to allow the system to revert to a safe condition in the event of an equipment breakdown and malfunction. Based on our failure mode analysis (*Table 3-3*), there were three areas which required a failsafe design. This is to ensure that the actuator will be able to revert to a safe position and allow the engine to function safely till the next chance of repair.

No.	Item / Function	Potential Failure Mode(s)	Potential Effect(s)of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Lik	RPN	**Risk Mitigation Action**
c	DC Motor	Motor stops rotating	Leadscrew does not rotate, preventing actuation	3	Main Power Supply Failure, Wiring Damaged	2	6	**Require additional failsafe method**
d	DC Motor	Motor fails mechanically	Leadscrew does not rotate, preventing actuation	3	Motor Jammed	2	6	**Require additional failsafe method**
h	Lead Screw Nut	Jamming	Motor rotates leadscrew but no linear motion	4	Foreign debris, misalignment of nut	2	8	**Require additional failsafe method**

Table 3-3. Failure Mode Analysis

3.2.1 Ideation & Evaluation

Overall, our team had four main ideas for potential mechanical failsafe:

1. Pin-locked Spring Release (*Figure 3-3)*

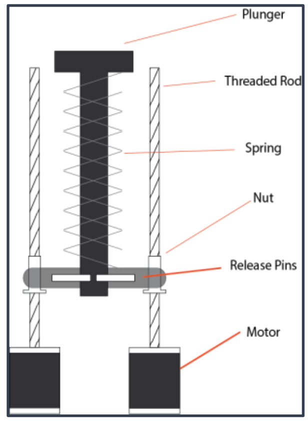


Figure 3-3. Failsafe Idea 1

A plunger is held in place by a pin while a preloaded spring is extended and set in place on the shaft. Upon the activation of failsafe, the pin is pulled out and spring retracts the plunger to neutral position.

2. Redundant Actuator on Platform (*Figure 3-4)*

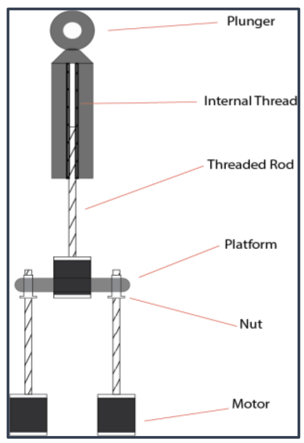


Figure 3-4. Failsafe Idea 2

This idea utilizes and additional actuator on the moving platform. When the failsafe is activated, the third actuator, which will be powered by an external capacitor will retract the plunger to a neutral position

3. External Support Actuation (*Figure 3-5)*

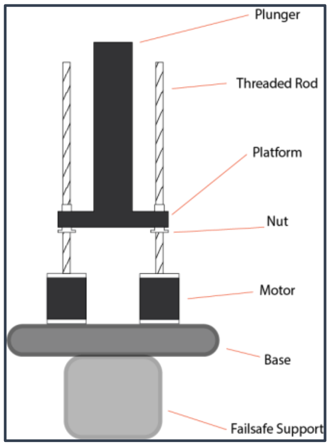


Figure 3-5. Failsafe Idea 3

This failsafe will also utilize another external actuator. When the failsafe is actuated, the whole actuation system gets retracted and moves back to neutral position.

4. Breakable Platform with Magnetic Dampener (*Figure 3-6)*

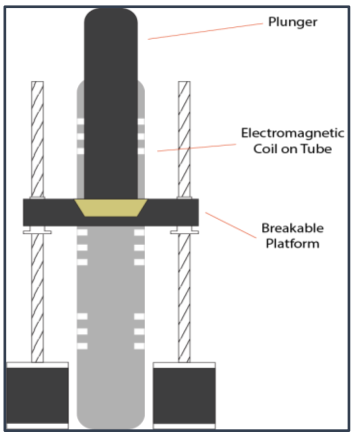


Figure 3-6. Failsafe Idea 4

The design of this failsafe requires the platform to be designed with a weak material in the middle that breaks when the load exceeds a certain value. When it is broken, the electromagnetic coil will reduce the acceleration of the plunger and hence dampen the force.

From the evaluation of the four ideas, we utilized two methods; a) Single Point of Failure Analysis (SPOF) and b) Pugh chart.

a. SPOF (Table 3-4)

A single point of failure is a part of a system that, if it fails, will stop the entire system from functioning

		Idea 1	Idea 2	Idea 3	Idea 4
Failure Points	Motor Controller	✔	✖	✔	✔
	DC Motor	✔	✔	✖	✔
	Lead Screw	✔	✔	✔	✔
	Lead Screw Nut	✔	✔	✔	✔
	Power Source	✔	✖	✖	✖

Table 3-4. SPOF Analysis

b. Pugh Chart (*Table 3-5*)

The Pugh chart is used to provide a more thorough selection process on the idea we will be using for the failsafe mechanism. It acts as a second line of evaluation for the ideas. PUGH Chart Criterion can be found in Annex F.

	Idea 1	Idea 2	Idea 3	Idea 4
Functionality	0	0	0	-1
Reactivity	0	-1	0	0
Maintenance	0	-1	-1	0
Weight	0	-1	-1	-1
Size Requirement	0	-1	-1	0
Total	0	-4	-3	-2

Table 3-5. Failsafe Ideation PUGH Chart

After complete analysis using the SPOF and Pugh Charts, we came to a conclusion to develop Idea 1 and utilized that idea for our mechanical failsafe.

3.3 Electrical Circuitry and Sensors

The electric circuitry for our first prototype consisted of an arduino controller, a motor driver and capacitors (*Figure 3-7*). This circuit was used to control and deliver instructions to the stepper motors and release pins for the fail-safe mechanism.

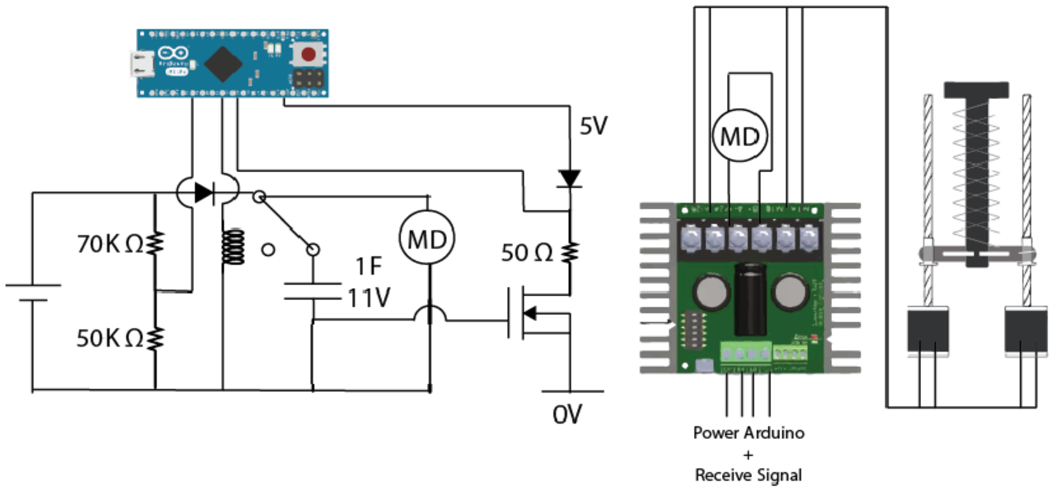


Figure 3-7. Electrical Circuit Diagram

3.4 Material Selection

For our first prototype, we used a couple of materials for fabrication. This was to allow for quick prototyping as well as for budgeting reasons. Despite this, our FEA will show that the materials used are still able to withstand the forces that it will experience. *Figure 3-8* shows the materials used for each component and *Table 3-6*shows its properties and reasons for using them.

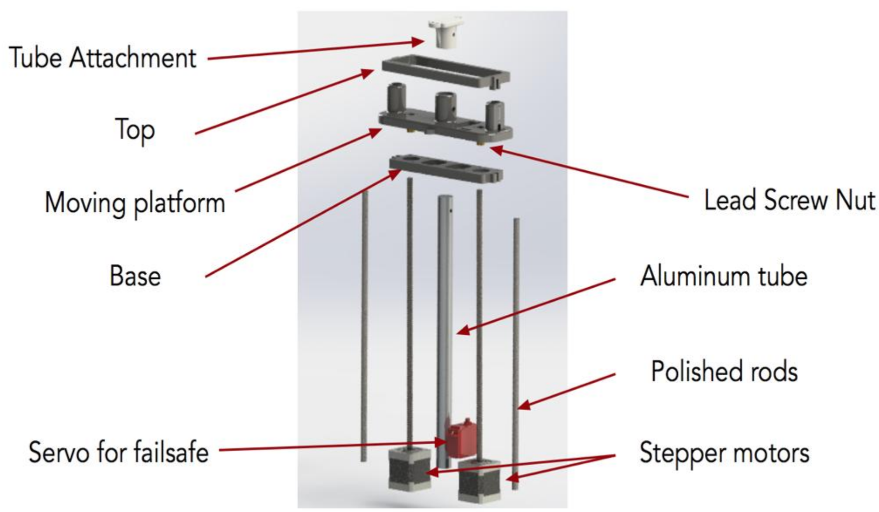


Figure 3-8. Exploded view of first prototype

Components	Material	Properties	Reason
Top, Moving Platform, Base	PLA	**Density:**	• Cheaper for fabrication
		1.3 g/cm3 (81 lb/ft3)	• Easily accessible
		Elastic Modulus: 3.5 GPa (0.51 x 10^6 psi)	• Good for prototyping
Shaft	Aluminium	**Density:**	• Cheaper for fabrication
		2.7 g/cm3 (169 lb/ft3)	• Easily accessible
		Elastic Modulus:	• Good for prototyping
		69 GPa (10 x 10^6 psi)	

Table 3-6. Material Properties

3.5 Finite Element Analysis (FEA)

For the first prototype, the main component that was undergoing the most stresses was the moving platform. Hence, we conducted the FEA stress analysis for the critical parts of our actuator (Figure 3-9). The simulation shows an exaggerated deformation of the platform. The materials during the simulation is Stainless steels and force applied is 20 kN under the real world application. Based on the simulation, the overall platform is safe under the load, except for the parts that are marked red. We will be enhancing these parts in the final prototype.

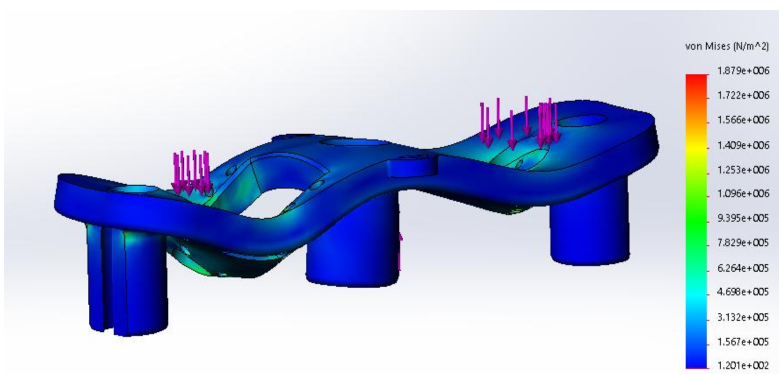


Figure 3-9. FEA of Platform

3.6 Prototype 1 Computer-Aided Design (CAD)

Figure 3-10. shows the render of our first prototype. It consist of two stepper motors connected to a lead screw at the base, a servo motor for the release pin, guide rods, linear bearings, an aluminum shaft and the shaft cover.

Figure 3-10. CAD Render of First Prototype

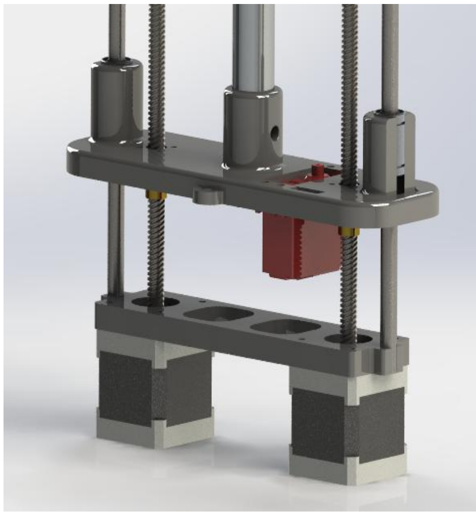


Figure 3-11. Close up view on failsafe mechanism

This is a close look of our fail safe mechanism. When jamming is being experienced in the system, the servo in red color will be triggered and this will cause it to pull-out a pin that holds the central shaft in position. This will then release the shaft to drop to its neutral position.

Chapter 4: Final Prototype

4.1 Lessons learnt from First Prototype

After building and testing our first prototype, we encountered certain issues that might potentially affect the operation of our actuator. Firstly, we realized that using a stepper motor would not be ideal for our case as stepper motors might encounter a slip in steps that would alter the accuracy of the system. Secondly, the usage of two stepper motors increases the chances of jamming. Thirdly, the failsafe mechanism was restricted by the length of the central shaft and so the failsafe could not be activated at a very close distance to the bottom structure connecting the two stepper motors as the impact force of the shaft on the platform when it is being released would break it. Lastly, the usage of lead screws proved to be inefficient as the friction experienced by the platform was quite high. Hence, we will aim to improve that for our final prototype.

4.2 Modifications from First Prototype

As seen in *Table 4-1*, our final prototype has been modified to improve its performance and efficiency, as well as to meet the requirements of our clients. *Figure 4-1* provides the rendered model of our final prototype after assembly.

Issues	Modifications
Stepper Motor not a suitable option	Change to Permanent Magnetic Synchronous Motor (PMSM)
Two Stepper motors increases the chances of jamming	Change to single direct drive motor
Lead screw experiences high friction	Change to ball-screw

Table 4-1 Modifications made for final prototype

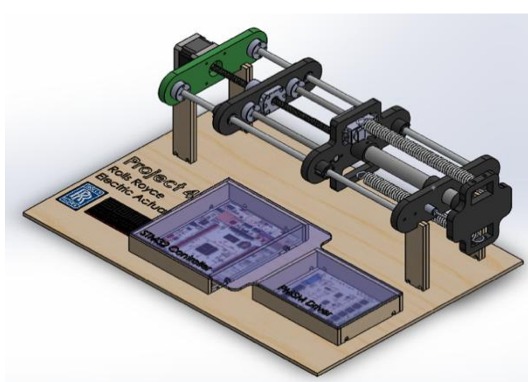


Figure 4-1 Final Prototype Render

4.3 Electrical Circuitry and Sensors

The electrical circuitry for the final prototype remained relatively similar with respect to the failsafe circuitry. However, the modification to the usage of a PMSM for the final prototype meant that a new controller (STM32) and motor driver had to be used. On top of that, during testing of our Linear Variable Displacement Transducer (LVDT), the sensor malfunctioned, requiring us to use a backup Light Detection and Ranging (LIDAR) sensor. This required us to use re-programmed the sensor into the new controller.

4.3.1 Sensors

Linear Variable Displacement Transducer (LVDT) (*Figure 4-2*)

Figure 4-2. LVDT and display

It is a common type of electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electrical signal. LVDT linear position sensors are readily available that can measure movements as small as a few millionths of an inch up to several inches.

To use with a microcontroller, we used the voltage output from the LVDT as the voltage input for a potential divider with resistors such that the max voltage output of the potential divider was 5V as shown below. This way we could protect the micro-controller from over voltage.

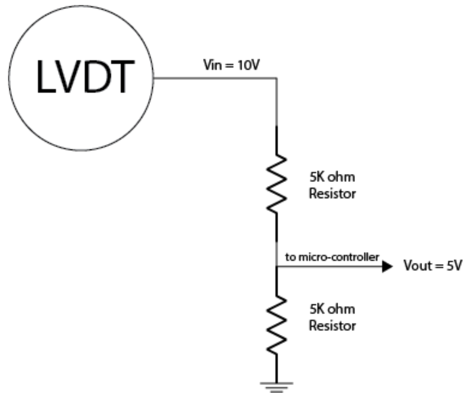


Figure 4-3. LVDT connection

Light Detection and Ranging (*Figure 4-4)*

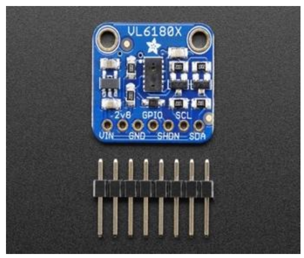


Figure 4-4. VL6180X LIDAR

To integrate the LIDAR with the STM32 micro-controller we used the I2C interface. I2C (Inter-Integrated Circuit) or sometimes called TWI (Two Wire Interface) is a synchronous serial protocol that only require 2 wires for communication. The two pins for the two wires are SCL (serial clock) and SDA (serial data). We connected the LIDAR using the I2C bus.For accessing the LIDAR, we used addresses that were specific to the device and the device register. The STM32 micro-controller was the Master device and the LIDAR was the slave device. To communicate with the LIDAR, STM32sends clock signal to the slave device. Clock signal is always generated by the master. I2C drivers are open-drain, therefore, in each signal line there must be a pull up resistor to pull the signal high (as in the image below) when there is no communication between the devices. The master device initiates the communication with a START signal that is a rising age in the SDA line simultaneously with a rising edge in the SCL line.Followed by START condition the master sends the slave address and the R/W bit. Then the slave device generates an ACK to acknowledge. ACK is defined as low logic on SDA line.

For our application, we only read from the slave. Two addresses are required, the slave address and the register address (this is where the required data is obtained). The

VL6180X datasheet contains more information on the I2C protocol specific to the sensor.

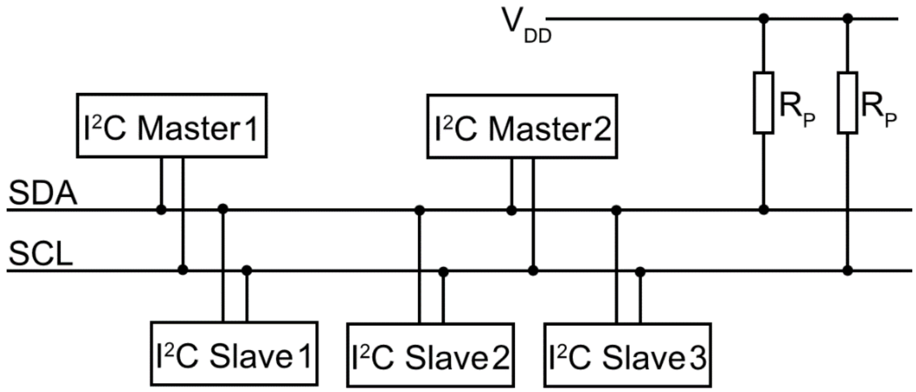


Figure 4-5. VL6180X LIDAR

4.3.2 Failsafe Circuit

The failsafe circuit is designed for emergency power supply in case the main power supply fails. The failsafe circuit consists of supercapacitors and switching components to turn circuit loops ON/OFF depending on whether we want to charge the capacitor or discharge it.

The specifications of the supercapacitor depend on the amount of current that must be supplied, the amount of time the device has to be powered and the allowable voltage drop. In the example below the capacitor can deliver current of 1A for 11s with voltage dropping from 12Volts to 10Volts.

$$\int_{0}^{11} i\,dt = \int_{10}^{12} C\,dV$$

$$1A * 11s = C * (12 - 10)$$

$$C = 5.5F$$

Figure 4-6. Zener Diode Circuit Diagram

With Zener Diode:

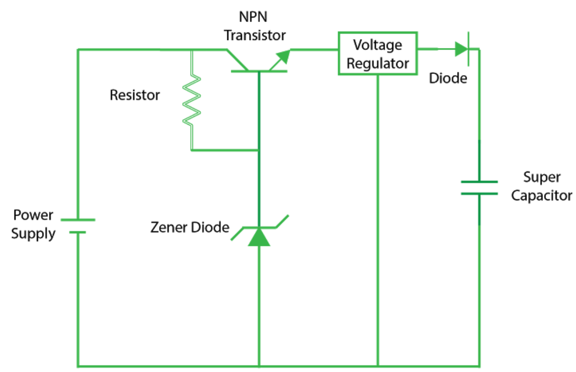


Figure 4-7. Zener Diode Circuit Diagram

We can use an NPN Transistor to act as switch. As the Capacitor draws less current when it reaches the max voltage the potential drop across the resistor increases and reaches the Zener Diode voltage at which the Zener Diode draws less current and switches the NPN transistor OFF.

With Mosfets:

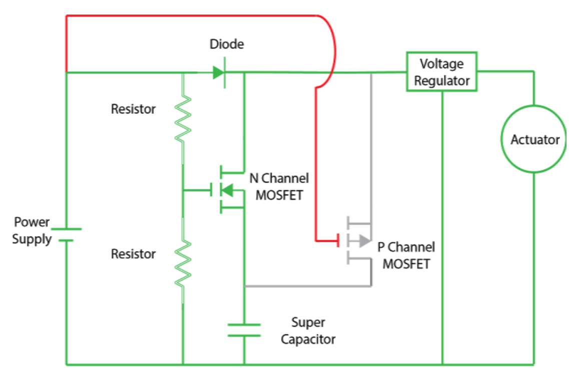


Figure 4-8. Mosfet Diagram

Figure 4-4. When the power supply is ON the N-Channel MOSFET operates as a closed switch until the capacitor charges up to the desired voltage.

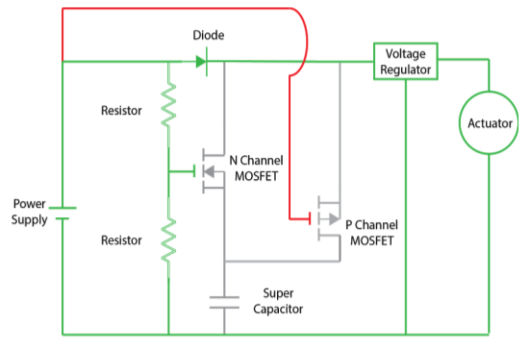


Figure 4-9. Open MOSFET Circuit diagram

Figure 4-5. When the capacitor is fully charged, the N-Channel MOSFET operates as an open switch turning OFF capacitor charging circuit.

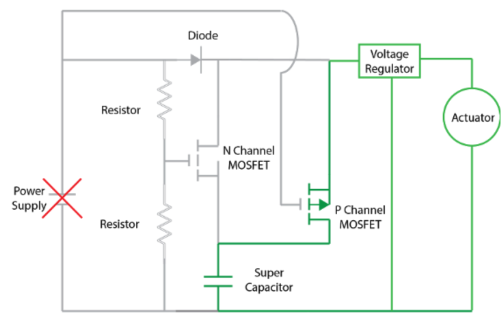


Figure 4-10. Closed MOSFET Diagram

*Figure 4-6.*When the power supply fails, the P-Channel MOSFET operates as a closed switch and the capacitor discharges through the actuator.

4.4 Material Selection

For the final prototype, we used materials that are much stronger and durable as compared with our first prototype. This ensured that the materials for the final prototype could meet the required temperature and load stresses.

*Table 4-1*shows the materials used for our final prototype and its respective properties.

Components	Material	Properties	Reason
Top,	Vero Black	**Density:**	• Relatively cheaper than metal
Moving Platform, Base		1.3 g/cm3 (81 lb/ft3)	• Good for non critical parts
		Elastic Modulus: 1.4 - 2.0 GPa	• Higher strength than PLA/ABS
Shaft	1060 Aluminium	**Density:**	• Cheaper for fabrication
		2.7 g/cm3 (169 lb/ft3)	• Good for critical parts
		Elastic Modulus:	• Higher strength
		69 GPa	

Table 4-1. Materials Used for Final Prototype

On top of the existing materials being used, we researched and found out a different material, CarbonMide, that could be 3D printed in-house. Due to its lightweight property, we thought it would be a better material for non-critical parts. However, due to its brittle nature, we didn't proceed with this material.

CarbonMide :

- Extreme stiffness and brittle causing fractures.
- Density : 1040 g/m^3

4.5 Final Prototype Finite Element Analysis

We conducted a systematic Finite Element Analysis in Solidworks for the five critical parts of the actuator system (*Figure 4-7)*. The simulation materials is Aluminum 1060. After analyzed the stress and compared the displacement caused by the stress, we draw the conclusion that our system is safe and could perform welcome in the 20KN requirements set by our clients and remain stable. The full FEA results can be found in Annex G

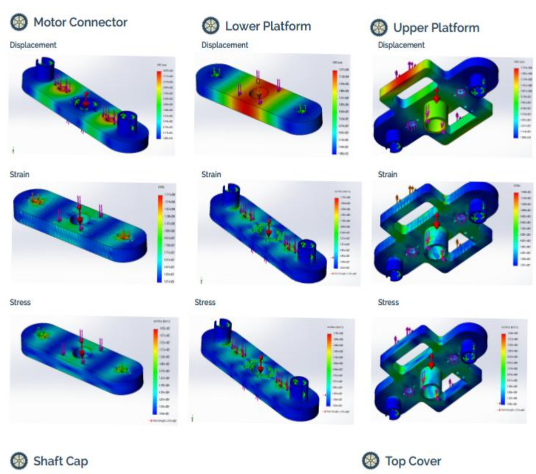


Figure 4-11. FEA Analysis

Chapter 5: Motor Control & Experimentation

5.1 Motor Control

5.1.1 Noise Smoothing Method

Removing objects that are noise is an important goal of data cleaning as noise hinders most types of data analysis. Most existing data cleaning methods focus on removing noise that is the product of low-level data errors that result from an imperfect data collection process, but data objects that are irrelevant or only weakly relevant can also significantly hinder data analysis. Our team carried out the tests for the LiDAR sensor readings, which showed that the readings of the sensor contained great amount of noise in the data set. The readings were fluctuating around certain fixed positions with a magnitude of 8mm (-3mm to +5mm). These noises would eventually result in a great fluctuation of the actuator’s displacement at the steady state which is not desirable. Hence, it is essential for us to find a solution to filter out the noises. We have tried out two methods to achieve this: one is the Moving Average method and the other is Exponentially Weighted Moving Average method.

Moving Average. The current reading is going to be predicted as the average of a subset of the previous data. The subset is “shifting forward” with the updating of the new readings. We have tested the performance of the Moving Average method by giving the size of subset as 5, 10, 15 and 20. As seen in *Figure 5-1* (Moving Average Filtering Size Selection), both the filtering sizes of 15 and 20 had shown a good performance in the damping effect at the static state. However, the filtering size 15 had more closer readings to the actual sensor reading when the actuator moved to approach the reference position. Hence, we have chosen filtering size 15 for the moving average noise smoothing method.

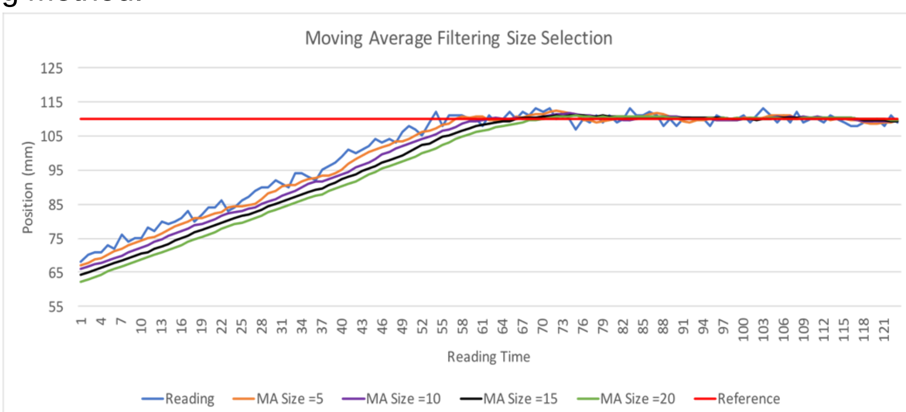


Figure 5-1. Moving Average Filtering Size Selection Graph

Exponentially Weighted Moving Average (EWMA). EWMA is a type of Infinite Impulse Response (IIR) filter that applies weighting factors which decrease exponentially but never reaches zero (Wiki). Unlike Moving Average that has the same weightage for all the data in the subset while ignoring the elder data points, EWMA provides exponentially decreasing weightage to all of history data. The EWMA value (S(t): for a series of observations (X(t)) can be calculated recursively as shown: (Wiki: https://en.wikipedia.org/wiki/Moving_average)

Initial: S(t) = X(t) when t=1

Recursive: S(t) = $\alpha X(t) + (1-\alpha)\, S(t-1)\ \ if t \neq 1$

Constant Smoothing Factor: $0 \leq \alpha \leq 1$

Weightage associating with datum point X(t-i) is$\alpha(1-\alpha)^{i-1}$

Figure 5-2 indicates different noise smoothing effects associated with α changing from 0.6, 0.7, 0.8, to 0.9. (EWMA Alpha Selection) We selected the curve that had the best damping effect coupled with the least error magnitude: when alpha equals to 0.7.

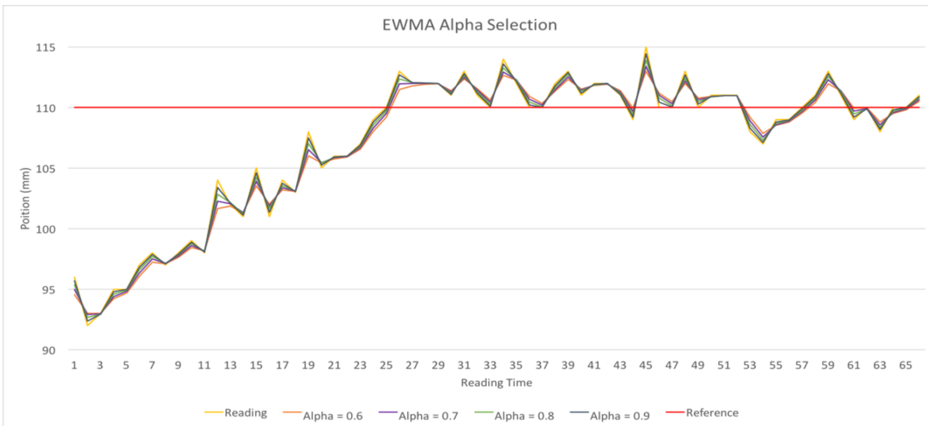


Figure 5-2 EWMA Alpha Selection Graph

Comparison of EWMA and Moving Average Noise Smoothing Methods.*Figure 5-3* has shown that the EWMA has a better damping and noise filtering performance as compared to Moving Average method. (Comparison Between EWMA and MA) In the next sections, we will be integrating the noise smoothing method into the PID parameter tuning.

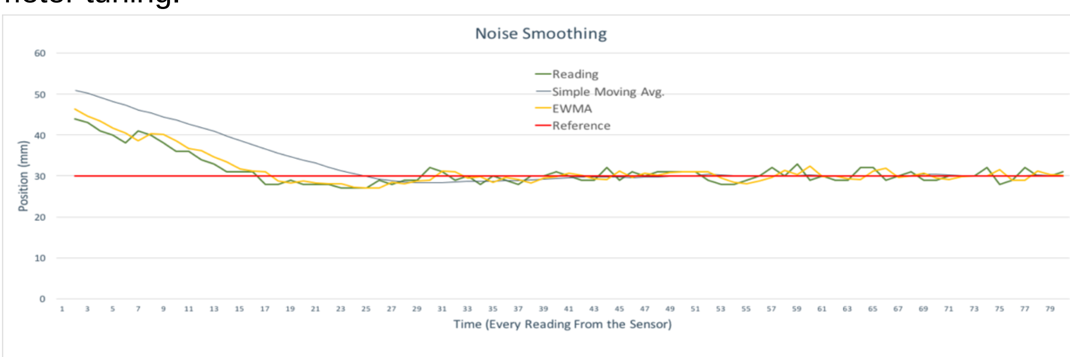


Figure 5-3. Comparison of EWMA and Moving Average Noise Smoothing Method Graphs

5.1.2 PID (Proportional-Integral-Derivative) Control

Our motor is required to output sufficient torque and speed to control the actuator to retract or extend to certain position within a certain time (E.g. Extend to 1 centimeter within 1 second). Proportional-Integral-Derivative Control is a feedback forward loop that control the motor continuously with time instant readings. As shown in *Figure 5-5*, the reference output will be given by the formula as shown in *Figure 5-4*. Where Kp, Ki, Kd are non-negative coefficients for proportional, integral and derivative terms respectively. r(t), e(t), and y(t) denote the reference value, error and output at time t.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

*Figure 5-4.*Feedback loop equation

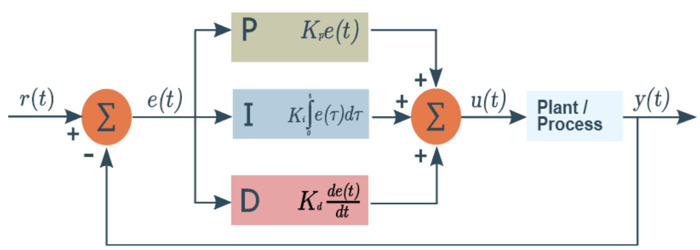


*Figure 5-5.*Feedback loop Diagram

5.1.2.1 DC Motor PID

In the case of DC motor control, we have added a position PID loop that provides angular velocity reference to the motor encoder. Firstly, we have tuned the Kp parameter by changing from 0.8, 1, 1.5 to 2. The Kp parameter decides how much the error term will contribute to the change of the output. Kp should be large enough to control the actuator to move to the reference position within a short enough time. As shown in the figure 5-6, when Kp equals to 1.5 or 2, it can overshoot the reference position while 0.8 and 1 cannot. Since we are going to choose a bit larger overshooting fluctuating curve that can be damped out by the later tuning, we have chosen Kp=2.

Figure 5-6. Kp Tuning Graph

Secondly, we have tuned Kd parameter by changing from 0.01, 0.03 to 0.05. The Kd parameter decides how much the derivative gain is going to damp the fluctuation by taking care of the rate of change (shown as the slope of the curve in the *Figure 5-7*). We have chosen Kd=0.03 that provides the best damping effect.

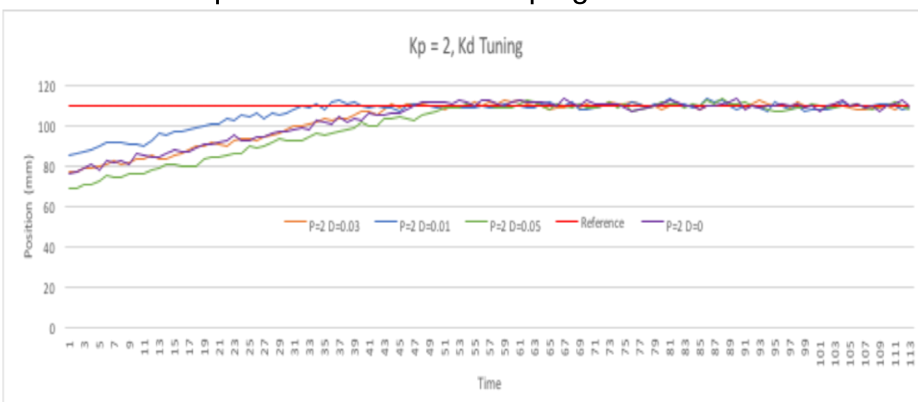


Figure 5-7. Kd Tuning Graph

Thirdly, we have tuned the Ki from 0.1, 0.5, 1, 1.5 to 2. The integral gain gives the accumulated offset that should have been corrected previously, which compromises for the statistical error over the time. However, during our testing, the contribution of the integral terms resulted in more fluctuation of the actuator that worsens the performance. Thus, we decided on the PD control instead of the PID control for our DC motor.

5.2.1.2 PMSM (Permanent Magnetic Synchronous Motor)

Field Orientated Control. The Field Orientated Control (FOC) involves controlling three-phase stator currents to control the torque of the motor. The three-phase system that is time and speed dependent is converted into a two-coordinate system (d and q co-ordinates) using ‘park transformation’. Field orientated controlled machines need two constants as input references: the torque component (aligned with the q co-ordinate) and the flux component (aligned with d co-ordinate).

Torque ∝Torque component * Rotor flux

By maintaining a constant rotor flux the Torque can be controlled by varying the torque component of the stator current vector.

Three Loop PID Control. (Figure 5-8)The brushless PMSM motor is controlled in a much more complex way than DC brush motor with the three-loop PID control mechanism. The most outside loop is the position PID control, which provides the velocity reference given the current position reading and target position. Followed by the second loop, it reads the instantaneous velocity by taking the first-order derivative of its position, and provides the acceleration reference for the most inner loop. Finally, the inner acceleration PID control reads the instant acceleration by taken the second-order-derivative of the current position and sends the acceleration control signal to the motor.

The PMSM has an encoder that works in a similar way as the two inner PID loops. It obtains the motor angular velocity readings directly from the hall sensor instead of taking the derivative over the displacement. Moreover, the acceleration control is further achieved by the Field-Oriented Control (FOC) by integrating both torque and flux PID control. However, the PMSM encoder does not have the position control. We have added our own external position PID control loop inside the controlling language, and we have tuned the Kp, Ki, Kd parameters in a similar way as DC motor. The parameters tuned for PMSM motor were given as: kp =700, Kd=100, Ki=100.

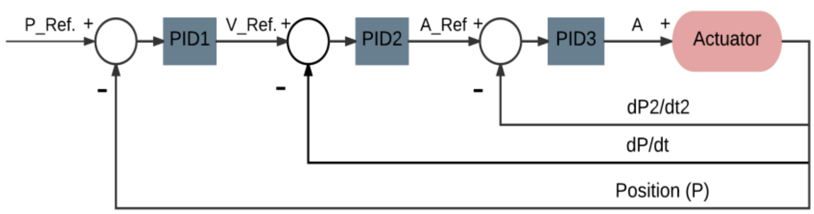


*Figure 5-8.*PID Feedback Loop for PMSM

5.2 Experiment Design

The experiment tests are designed to test on the functionality of the prototype in three aspects: accuracy, repeatability and fail-safe mechanism.

5.2.1 Accuracy Test

Unlike the stepper motor that can measure accurately measure the distance with the number of steps, both Brush DC Motor and the Permanent Magnet Synchronous Motor (PMSM) used for our final prototype are not able to measure the accuracy directly. Hence, we have designed the experiment to test on the accuracy level of the actuator, which is shown in *Figure 5-9*.

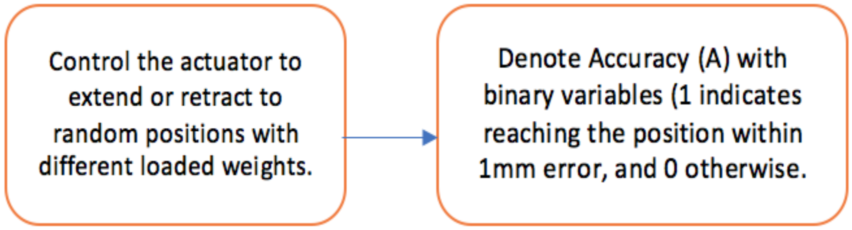


Figure 5-9 Accuracy Test Procedure Block Diagram

The positions are generated randomly from range of 0 to 100mm for every trial and the experiments have been conducted continuously for each of the loaded weights. Around 100 experimental datums were collected for each loaded weights. The independent Variables are: time instance (t) that denotes the trial time, binary variable (ER) that denote retraction or extension, loaded weight (W), displacement (D) that denotes distance traveled from t to t+1 and position (P).

For example, the actuator starts at 0mm position and the randomly generated positions are 32mm, 65mm and 45mm for first three time instances. The independent variables will then be recorded as following: (*Table 5-1*)

T (Trial Time)	P (Position)	D (Displacement)	ER (Retraction/Extension
1	32	32	1
2	65	65-32=33	1
3	45	I45-65I=20	0

Table 5-1. Accuracy Test table for first 3 instances

While the dependent variable is the binary variable (A) that denote Accuracy as described in the diagram, variable t is designed to capture the deficiency in the performance when the motor keeps running for a long time.

5.2.2 Repeatability Test

The Repeatability experiment is designed to test whether the actuator is able to reach the same position within 0.1 mm error (1% accuracy level). This test is also designed similar to that of the accuracy test as seen in figure 5-10.

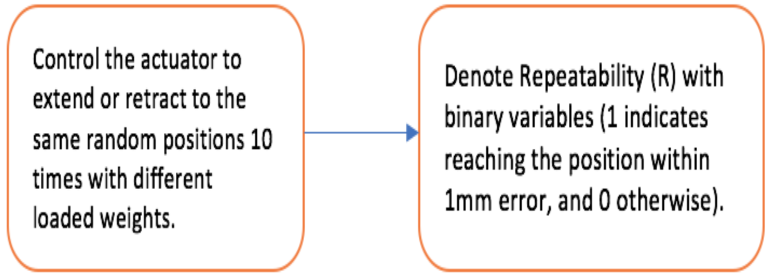


Figure 5-10. Repeatability Test Procedure Block Diagram

Some changes were made to the independent variables from the Accuracy test: Repeat Time (RT) that captures the potential deficiencies in the number of repeat times instead of Trial Time (T), and the displacement (D) is removed as repeating displacement will be the same as the position (P). While the dependent variable is Repeatability (R) instead of Accuracy (A), the first time of reaching a certain position will not have the Repeatability value.

5.2.3 Logistic Regression Model

For our project, we have used the Logit (Logistic) Regression model to predict the probability of an event happening (Prob(Y)=1), where Y represents either Accuracy or Repeatability. The logit regression model will predict Accuracy and Repeatability as shown in the equation in *Figure 5-11*.

$$Log\left(\frac{prob(A=1)}{prob(A=0)}\right) = \beta_0 + \beta_1 t + \beta_2 ER + \beta_3 W + \beta_4 P + \beta_5 D$$

$$Log\left(\frac{prob(R=1)}{prob(R=0)}\right) = \beta_0 + \beta_1 t + \beta_2 ER + \beta_3 W + \beta_4 P + \beta_5 RT$$

Figure 5-11. Logit Regression Equation

The recorded data set will be divided into test and train data sets to test on the model performance. In our expectation, we didn't expect any significant variables except for the intercept because both property factors, accuracy and repeatability, should not be affected by any factors such as the motor's operation time or the loaded weights. However, if significant variables do exist, we would make potential improvements to our prototype. For instance, if variable 't' is significant with negative coefficient meaning the longer the operation time, the less probability of accuracy. We could consider adding the cooling system to our prototype to assure the feasibility of longer operation.

5.2.4 Fail-Safe Mechanism Test

The Fail- Safe mechanism test is shown in the following chart: (*Figure 5-12*)

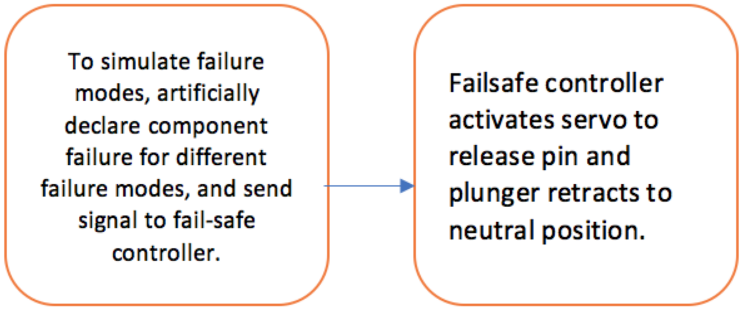


Figure 5-12. Fail-safe Mechanism Test Procedure

5.3 Experiment Results & Analysis

The experiments designed for both accuracy and repeatability were intended to take the output force into consideration. It was planned to have around 100 tests for each weight loaded. However, in practice, our sensor for the prototype was not able to withstand the rigour of the high number of tests. Thus, we have collected 120 data points each for both accuracy and repeatability tests unloaded. (Attach the Excel Data sheet) The logit regression models were build using the R software with all the data as the train set, and the models were tested on the same training data (with all data) for the prediction.

5.3.1 Accuracy Logistic Regression Model

Model 1 (With all Independent Variables). *Table 5-2* shows the summary of the logit regression model for the accuracy test. The estimators were independent variables, coefficients referred to beta parameters, and Pr(>|z|) column provided the significant level of the estimators (the less the better). All independent variables were not significant while the intercept predictor was significant at 0.01 level (Pr(>|z| <0.01). The Akaike Information Criterion (AIC) value for this model was 111.82, which is a criterion to measure the model performance and the less the AIC the better the performance. The results met with our requirement that the accuracy won’t be affected by any other factors.

Estimate	Coefficients	Std. Error	z value	Pr(>|z|)
(Intercept)	2.3389683	0.852331	2.744	0.00607
Test Time	0.0048207	0.0073405	0.657	0.51136
Position	0.0009545	0.0125352	0.076	0.9393
ER	-0.7686799	0.8262362	-0.93	0.3522
Displacement	-0.0129206	0.0096878	-1.334	0.1823

Table 5-2 Accuracy Logit Regression Model Summary

Model 2 (With Intercept Only). The intercept predictor is significant at 0.001 level and the AIC value has decreased to 107.54, indicating a better model with intercept predictor only.

Prediction Results. The logit regression model provided us with the probability of whether the trial is accurate or not. In order to predict accuracy, we are required to set a threshold of some probability, 'p'. When predicting probability larger or equal to 'p', it predicts 1, and 0 otherwise as shown in the equation of Figure 5-11. The accuracy of both model's prediction reached about 85%.

Pred. \ True	0	1
0	2	1
1	17	102

Accuracy Model 1
Threshold: 0.7
Accuracy Level: 85.2%

Pred. \ True	0	1
0	-	-
1	19	103

Accuracy Model 2
Threshold: 0.7
Accuracy Level: 84.4%

Figure 5-13 Accuracy Prediction Results

5.3.2 Repeatability Logit Regression Model

Model 1(With all Independent Variables). All the variables are insignificant and AIC value is 117.1. The repeatability test results met with our requirement that the repeatability should always be maintained regardless of other factors.

Estimate	Coefficients	Std. Error	z value	Pr(>|z|)
(Intercept)	1.11287	0.79428	1.401	0.161
Position	0.01135	0.01516	0.748	0.454
ER	-0.94796	1.07991	-0.878	0.38
RT	-0.04309	0.08217	-0.524	0.6

Table 5-3. Repeatability Logit Regression model summary

Model 2 (With Intercept Only). The intercept predictor is significant at 0.001 level and the AIC value has decreased to 112.22, indicating a better model with intercept predictor only.

Prediction Results.Both models for repeatability had the prediction results as shown in *Figure 5-13*. The accuracy of both prediction were larger than 75%.

Pred. \ True	0	1
0	1	2
1	23	74

Repeatability Model 1
Threshold: 0.65
Accuracy Level: 75%

Pred. \ True	0	1
0	-	-
1	24	76

Repeatability Model 2
Threshold: 0.6
Accuracy Level: 76%

Figure 5-13. Repeatability Prediction Results

Chapter 6: Project Management

6.1 Work Breakdown Structure

The Work breakdown structure (WBS) provides the overview of the tasks that needs to be completed. The tasks are grouped into different phases of the project. Research and Planning phases are in term seven while execution, improvement and close-out phases are in term eight. Each end node in the WBS has a bunch of corresponding work tasks package. Each work task package contains the details of each task – task scope, estimated duration, budget allocated, resources and the person-in-charge. The task scope breaks into specific actions that should be taken to accomplish the task. The duration of the activity was estimated using three-point estimation approach which will be discussed later. Budget allocated to each task is estimated from the budget plan which will also be covered in “Budgeting” section.

Having a complete list of resources allows the team to prepare ahead to avoid circumstances such as delivery lead time, unavailability of fabrication lab facilities or unavailability software. Detailed WBS can be found in Annex H.

6.2 Responsibility Matrix

The WBS identifies elementary work tasks which are distributed among our team members. The responsibility matrix shows the people who will be leading a task, while the rest of the team take up supporting roles. Every team member will have a role to play in each task, ensuring that everyone is involved and informed of the tasks. As shown in the matrix, “R” represents the person who is responsible for ensuring the corresponding task is completed, and “S” represents the supporting people. Additionally, the matrix extends into the external support from professors, company mentors, writing center, IDC mentor and Fab lab mentor. “C” represents the person who has relevant expertise in the selected task and will be approached for consultation as required. An example of Responsibility Matrix of Execution Phase is shown in *Figure 6-1*.

RAC Matrix

	Project Team Members					External Resources							
Project Deliverable (or Activity) / Role	Andrew	Alvee	Hezu	Kajol	Yiran	Prof. Naga	Prof. Ugar	Writing Center	RR Mentor Tomasz	RR Mentor Felix	IDC Mentor	NAMIC	Fab Lab Mentor
Execute Phase Activities													
Advanced Mechanical Evaluation + Sketches	S	S	R	S	S				C	C	C		
Material Analysis	S	S	S	R	S				C	C	C		
Numerical Calculation	S	S	S	S	R				C	C	C		
Fail-Safe Mechanism Design Finalization	R	S	S	S	S	C	C		C	C		C	C
Fail-Safe Mechanism 3D Sketches	S	S	R	S	S				C	C			
Prototype Build Up	S	R	S	S	S	C	C		C	C		C	
Experimental Design	S	S	S	S	R	C	C						
CAD Simulation	S	S	R	S	S				C				C
Prepare 3rd Review	R	S	S	S	S			C					

*Figure 6-1.*Responsibility Matrix

6.3 Dependency Matrix

When planning, and executing a list of tasks, ensuring proper handling of the order of each event will enable the smooth running of the project. Some tasks are dependent on other tasks to be completed before it can be started. This will prevent unnecessary waiting time. Some tasks are independent which can be carrying out concurrently to avoid the idling of resources. The purpose of the dependency matrix is to prevent the wastage of time and resources of the team. The dependency matrix reflects the row of the activities that should be executed prior to a certain column activity denoted with marker “x” in the chart. For example: task A3, “identify required technology” should be processed after task A2, “survey on the precedents”.

6.4 Three Point Duration Estimate

To estimate the task duration, each activity was given optimistic duration, pessimistic duration and most likely duration which were represented by a, b and m respectively. The duration of the activity is calculated using the formula: .

For example, task B7, “build up preliminary prototype” can be completed in nine days if everything goes well i.e. purchasing the materials during the weekends and fabricating in a week. It can be done in at least six days if the team is not busy with other tasks. However, if things go wrong, such as unavailability of 3D printer or insufficient materials purchased, the tasks will be delayed to a maximum of 14 days. Thus, the task may take most likely nine days with six, nine, fourteen as a, m, b respectively. The full table can be found in Annex I.

6.5 Activity on Nodes (AON) & Activity on Arc (AOA)

Each node in the AON chart stands for an activity and it provides a better visualization of the dependencies between each activity. By looking at AON charts for both term seven & eight, it is easy to identify the starting activity and the ending activity of the whole planning process. Tasks from different phase are marked with different color.

Each arc in the AOA chart represents a task and its corresponding duration calculated using the three-points duration estimate approach. *Figure 6-2* illustrated the AOA charts for term 8 execute, improvement and close-out phases. Like the AON chart, AOA is another way to visualize the dependency relationship between tasks. However, the AOA provides a unique representation of concurrent activities with a dummy activity φ. This dummy activity has 0 duration and represents that all activities before the dummy arc should be done before proceeding to next. For example, in planning phase, node four, five and six should all be accomplished before moving on to node 7. Additionally, the critical paths and tasks are marked red in all AOA charts of different phases. The critical path is the longest duration path from start node to the end node, indicating the shortest possible phase completion time. The length of critical paths for research, planning, execution, and improvement & close-out phases are 34 days, 35 days, 43 days and 43 days respectively.

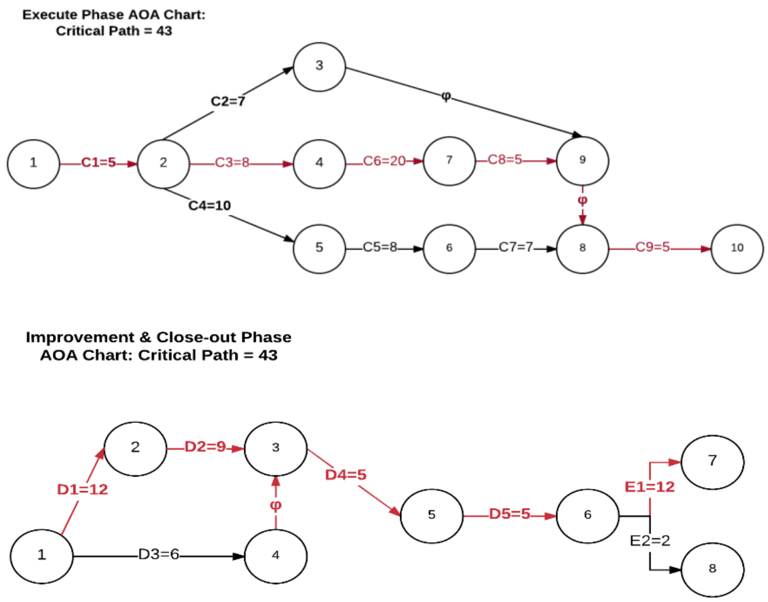


Figure 6-2. Execute, Improvement and Close-Out phases AOA Chart

6.6 Gantt Chart

The Gantt Chart provides task durations and timeline schedules in a graphical way for both term seven and term eight. It also includes the milestones that are defined corresponding to standard reviews and meeting agendas with Rolls Royce in term seven. The task duration includes both weekends and weekdays to allow for more flexibility for everyone. Based on the critical path duration calculated from the AOA chart, it was necessary for us to start the planning phase on 7th March during the recess week to make sure all tasks were done before the milestone. Additionally, based on the risk analysis in Section 5.5, it is required for high risk tasks such as task C4, “advanced prototyping” to be provided with some buffer time. Thus, we will be utilising the vacation time to start research and mechanical evaluation to provide some buffer time for the high-risk tasks.

Another advantage of having a Gantt chart would be that the chart shows the slack of some tasks. Activities like “cost estimation (B2)” as a slack period of a weeks. This allows the person in charge to quickly identify by how much the end date can be postponed without delaying the whole project, meanwhile he/she can support the tasks on the critical path. Detailed Gantt Chart can be found in Annex J.

6.7 Risk Management

The Risk Breakdown Structure (RBS) is a hierarchical representation of risks, starting from higher level risks moving down to finer level risks. For this project, as shown in annex E, the top level of the hierarchy is split into 3 parts – technical risk, external risk and project management risks. Each branch is then broken down into finer levels such as technology risks and estimation risk, and each end nodes further breaks down to different risk events. The detailed RBS can be found in Annex K.

6.7.1 Probability and Impact Matrix

The probability and impact matrix identifies which risk events should be given additional attention considering both the likelihood and impact of that risk, ranked from 1 to 5. This will help the team decide which to prioritize and be ready for. The impact number is decided on the following criteria (*Table 6-1*). The Risk Value is calculated by the formula: Risk Value = Impact* Likelihood.

Main Impact	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
Time	Insignificant Time Increase	<5% Time Increase	5%-10% Time Increase	10-20% Time Increase	>20% Time Increase
Project Scope	Scope decrease barely noticeable	Minor areas of scope affected	Major areas of scope affected	Scope reduction unacceptable to sponsor	Project end item is effectively useless

Table 6-1. Risk Evaluation Number Criterion

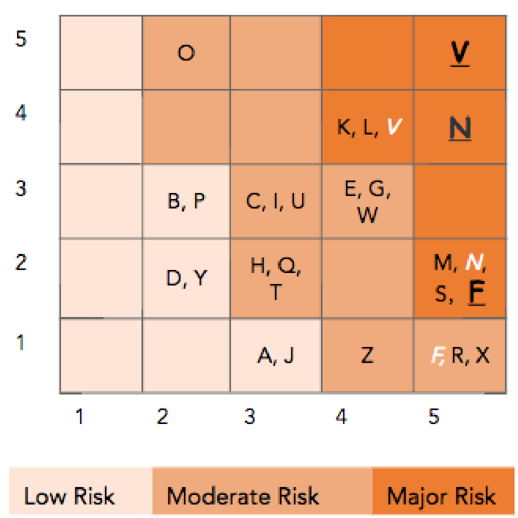


Figure 6-3. Risk Impact Matrix

From the (2D) Impact matrix shown in *Figure 6-3*, there are six major risks that are categorized into the red area. The risk response plan provides the risk mitigation actions for all risk events and the plan for major risks can be found in Annex L.

6.8 Budgeting

Our project budget for individual tasks has been planned so that we will not exceed the budget we have been given. The estimation is based on general component costs and will be updated as soon as our prototype components list has been finalized. Budget has also been put aside for further improvement of the prototypes if we encounter any issues. We are still within the allocated transportation budget and foresee that we will not exceed it.

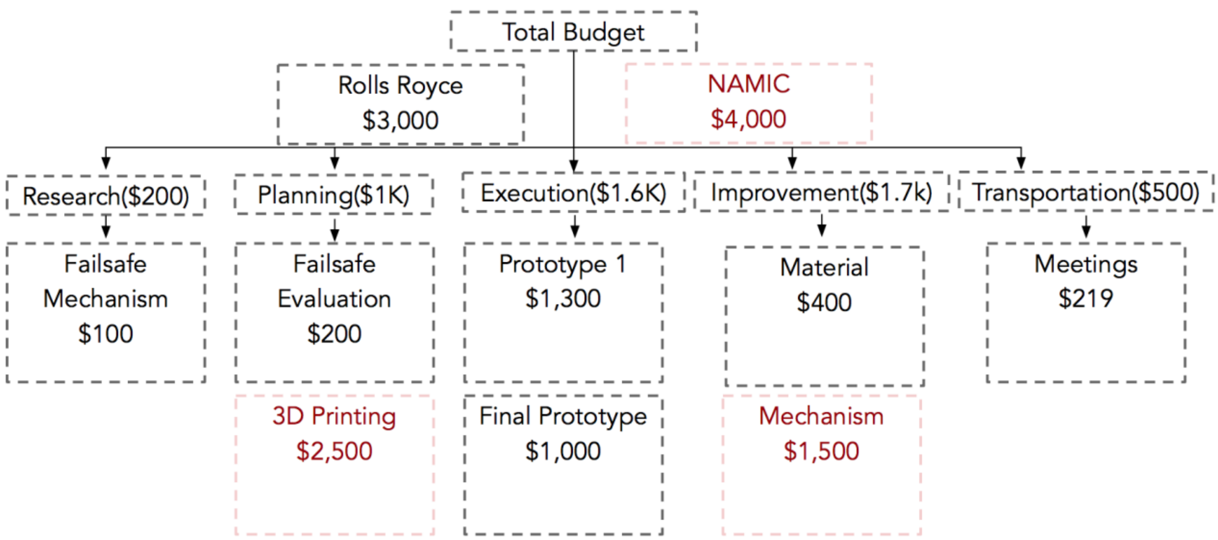


Figure 6-4. Budget Tree

6.9 Concepts and Theory Involved

To improve how we analyze the performance of the prototype, the following *Table 6-1*shows which tools and courses that we tap on to achieve the project requirements.

No.	Module(s)	Applications(s)	Simulation/Verification Tools
1	Machine Element Design, Material Science, Structures and Materials	Stress, Component Integrity and Fatigue Analysis	SolidWorks 3D, Autodesk Fusion360
2	Project Management, Cost Estimation, Microeconomics	Project Framing	Responsibility Matrix,
		Project Scheduling	Work Package,
		WBS	Risk Breakdown Structure
		Estimation of Duration	Gantt Chart
		Risk Management	
3	Circuits and Electronics,	Electrical Circuitry	NI Elvis, Circuits.io
4	Systems and Control	Control	

Table 6-1. Courses and Theory Utilized

Chapter 7: Health, Societal & Environmental Concerns

Climate change is a prevalent issue and aircraft industry alone has a share of 12% in the emission of Greenhouse gases (GHG) in the world. Hence, more and more research is done in the airline industry for being sustainable by converting their aircraft parts from Hydraulic/Fueldraulic to Electrical. Our project aims in the cutting of the environmental which later leads to health problems by converting the actuation system of the aircraft which is currently running on fuel to be more electrical.

Environmental. Our electromechanical actuator will aim to improve the efficiency of the engine by removing the need for the fuel pump to distribute the pressure to the actuator. The improvement of engine efficiency will lead to less burning of fuel and hence, beneficial to our environment

Health. Our design will consider the inclusion of attachments to facilitate the maintenance of the actuator. Heavier components will then be easier to replace and shift around, preventing injury on the maintenance technicians

Chapter 8: Conclusion

Our project has undergone a series of processes and iterations that has resulted in the final prototype being a success. We have met the scaled-down requirements of our client and have validated it with a series of test and data analysis. The various results have proven that the scaled down prototype can function and perform, and when scaled up, could possibly match the requirements of the full system.

The key lessons learned embarking on this project include our team learning to appreciate the technical aspect of actuation systems in the Aerospace industry. The precedent research and evaluation allowed us to appreciate the different systems and its pros and cons. Additionally, our team has taken away vital technical skills in the process of fabrication and testing, ensuring the various prototypes have been designed to be functional and effective in achieving its goals. Analytical skills have also been gained while performing the numerous tests to ensure the reliability and accuracy of our prototype. Our team has also been fortunate to be imparted with valuable industry knowledge from our mentors from Rolls-Royce, further allowing us to enhance and improve our project and our knowledge. Soft skills such as project management, team collaboration and communication skills have also been nurtured throughout which has vital to the flow of the overall project.

Our project has been a great learning experience and our team are pleased with the results and process undergone to make this a success. We hope that our project will be able to influence and be a game changer to the current VSV actuation technologies, to help create a better world by design.

References

http://www.te.com/usa-en/industries/sensor-solutions/insights/lvdt-tutorial.html http://dl.acm.org/citation.cfm?id=1112781

http://embeddedsystemengineering.blogspot.sg/2016/03/arm-cortex-m3-stm32f103-tutorial-i2c.html?m=1

http://www.st.com/content/ccc/resource/technical/document/datasheet/c4/11/28/86/e6/26/44/b3/DM00112632.pdf/files/DM00112632.pdf/jcr:content/translations/en.DM00112632.pdf

http://www.ti.com/lit/an/slva704/slva704.pdf

http://www.ti.com/lit/an/bpra073/bpra073.pdf

Appendices

Annex A - Client's Needs and Requirements

Needs	Requirements
Safe	● Actuation System fail-safe Mechanism ● Non-flammable ● Ambient Conditions should not affect design and hence, the safety
Functional	● Must have a linear output with a stroke length of **100mm** ● Power consumption does not exceed **270V** DC source ● Actuator Speed = **100mm/s** ● Output force = **20KN** (Extend)/= **10KN** (Retract)
Durable and Reliable	● Working Temperatures: **-40°C** to **150°C** ● Consistent Repeatability of **+/- 0.5mm** ● Withstand shocks and vibration
Highly Integratable	● Actuator must be attached using similar mounting methods ● IR = 1250, OR=1000mm, width=350mm
Lightweight	● Material chosen must withstand actuation forces and stress ● Lightweight yet durable

Maintenance	• Should be low maintenance design
Overall Cost Efficiency	• Efficiency should be better than current actuator

Annex B - Interview with IDC Mentor

Location:	International Design Centre, SUTD
Date:	31/03/2017
Time:	3:30pm
Attendees:	Kajol Sethia, Alvee Ahmed, James Tan

Agenda items

1. Present our ideas to him and get his opinions of each type of the actuators we decided to work on.

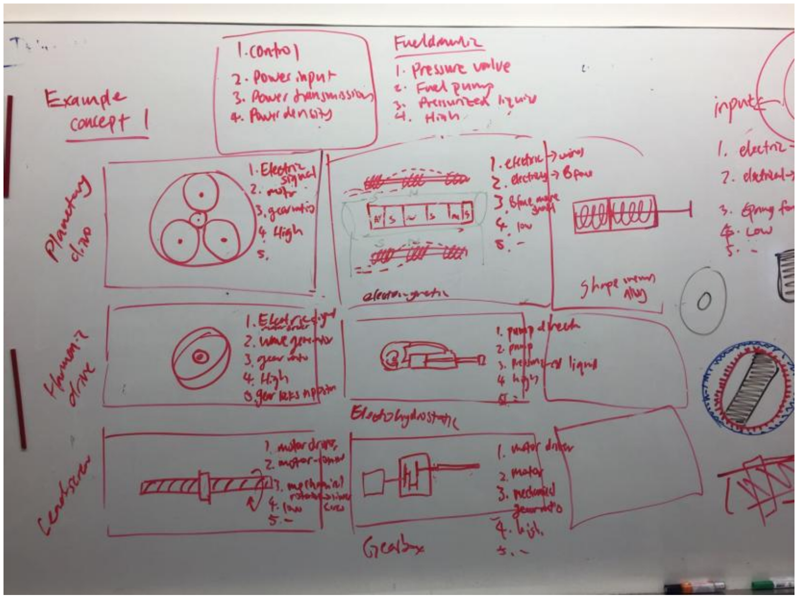
2. Discuss on different types of actuators in the market and list down few of the type which is feasible for our project.

3. Learn more on electrostatic and electromagnetic actuator from Mr. James Tan.

4. Discuss on the heat properties of the compressor vanes.

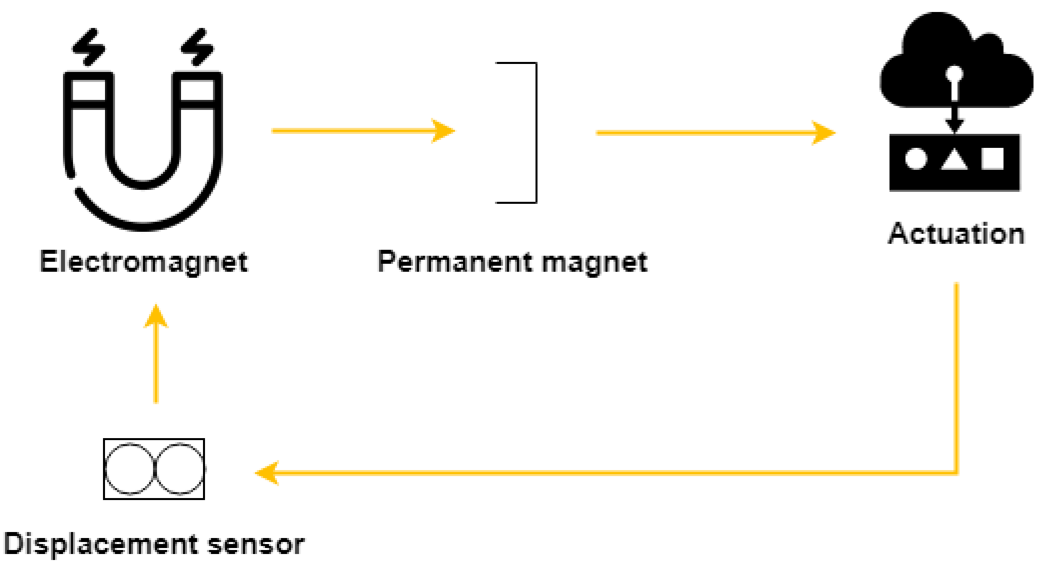
Action items	Owner(s)	Deadline	Status
Blade Element Theory	Alvee	15/04/2017	Completed
Working mechanism of Jet Engine	Kajol	15/04/2017	Completed

Annex C - Ideation Methodology

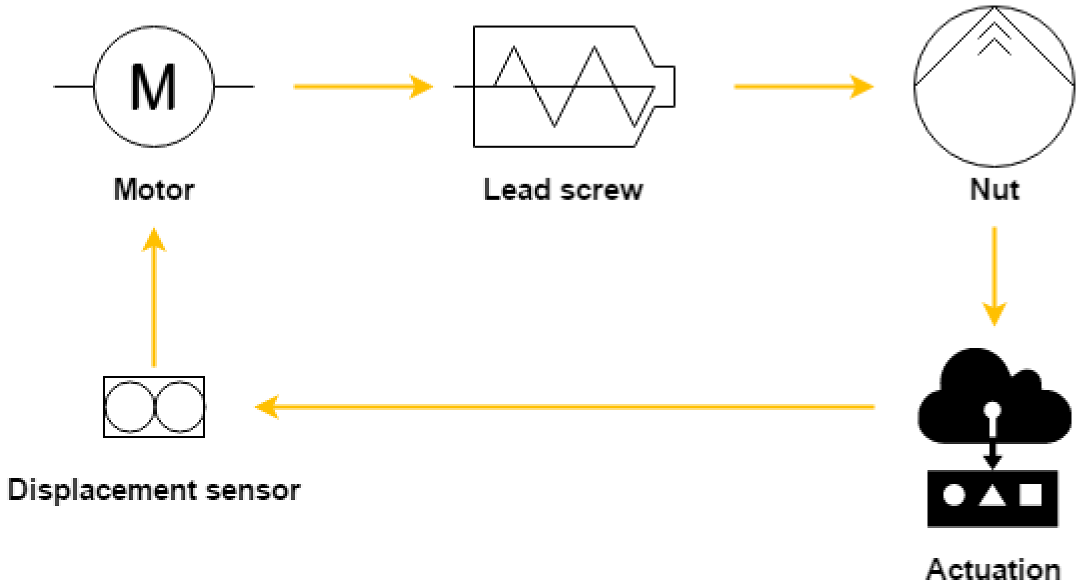


REMM

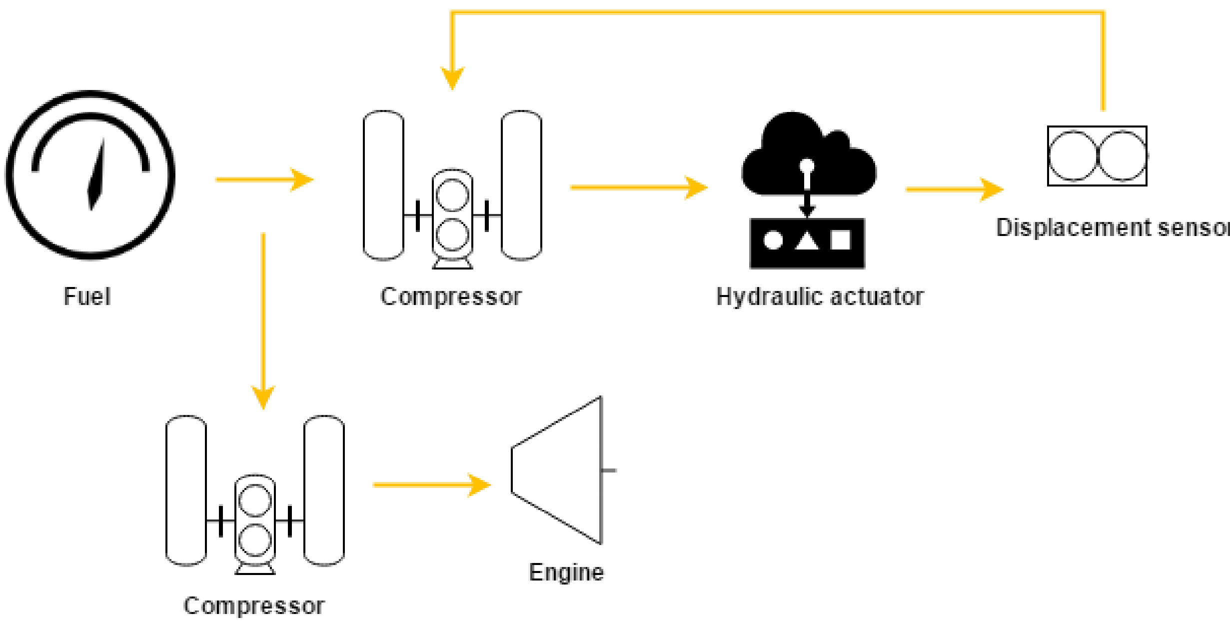
Electromagnetic



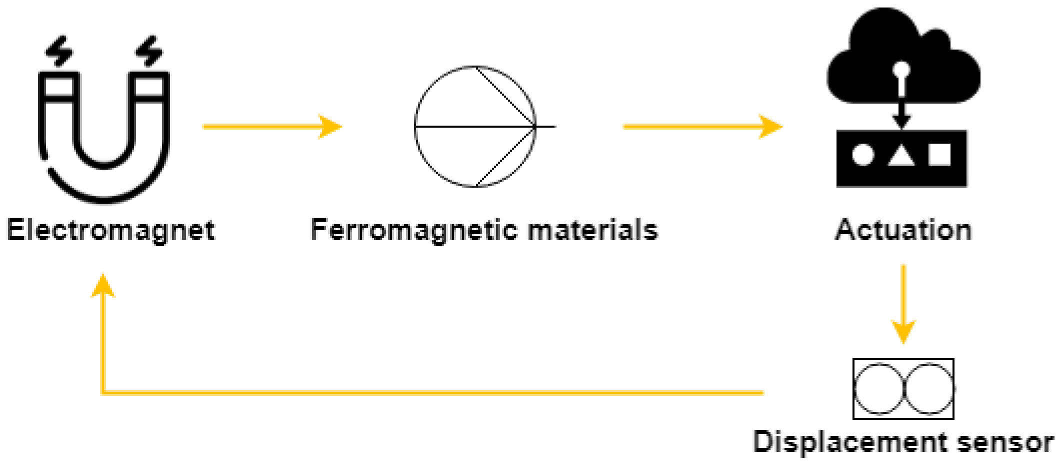
Lead-Screw



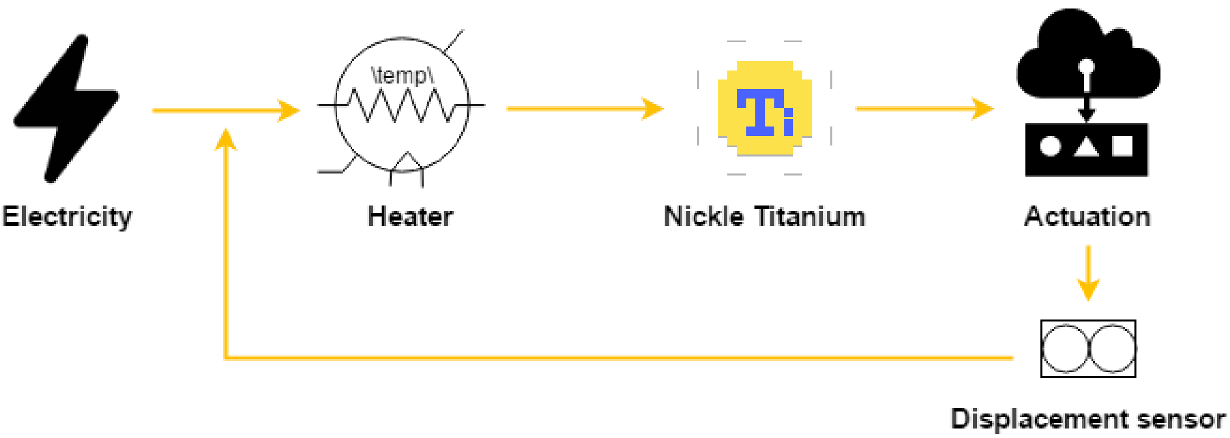
Electohydraulic



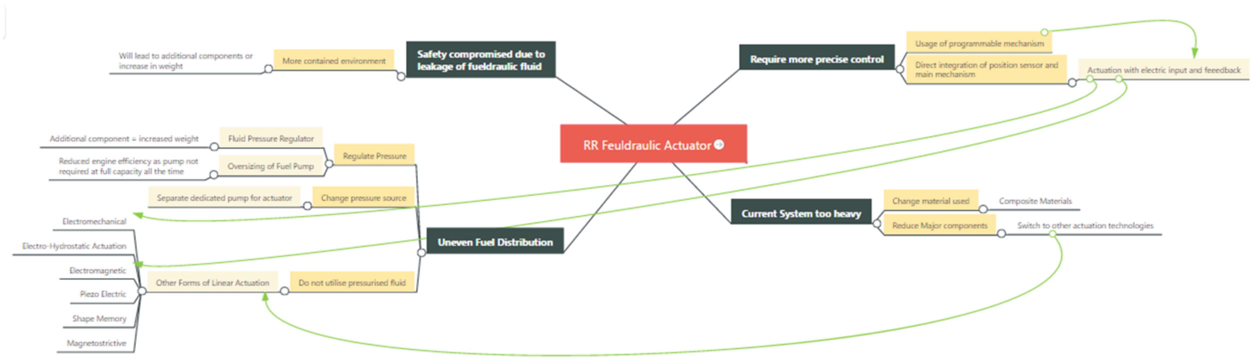
Magnetostrictive



NiTi Wire



Mind-Mapping



Cross-Evaluation Chart

	Hydraulic	Pneumatic	Electrical
Safety	1	2	3
	Liquid Leakage and Fire Hazard	Inertia gas unlikely catch fire	No leakage nor fire hazard
Limitation on Working Environment	2	1	3
	Not able compatible with extreme temperature, -20°C to 150°C	Not ideal to work under environments for high pressure as gas is highly compressible	Engage insulator that can withstand extreme temperature
Manufacture component (Linear Motion)	2	2	1
	Simple mechanism structure but require many companion parts for linear motion	Accommodate for linear motion, but require additional air pump	Every electronic components require customization
Output Force (compared with its size)	3	1	2
	High horsepower--to--weight ratio by 1 to 2 hp/lb	Pressure loss in the actuator cylinder	Less force density compared to Hydraulic; Electric motor
Weight	1	2	3
	Massive Linear Motion Components + Liquid +Pump	Additional Pump	No pump is required
Flexibility	1	1	3
	Not Programmable: manual adjustment on change in force, velocity, etc. Require additional sensors for data collection	Not Programmable: manual adjustment on change in force, velocity, etc. Require additional sensors for data collection	Precise control over dynamic
			performance as it can be
			reprogrammed quickly and provide adequate feedback
Maintenance	2	1	3
	Changing Oil filters periodically	Easy contamination of air by oil	Easy detect the errors
Initial Cost	2	2	1
Total	15	12	19

Annex D - Ideation Pugh Chart Criterion

Pugh 1 Criteria

Criteria	Definition
Safety	Flammability, Reliability, Does ambient environment affect the mechanism's safety?
Durability	How durable will it be to withstand high-temperatures and shocks?
Reliability	Does this mechanism fail easily under numerous cycles?
Weight	What is the weight compared against the current system?
Repeatability	Ability to provide the same result, under the same circumstances, over and over again
Accuracy	Difference between measured and “true” values
Maintenance	Does this mechanism require regular maintenance and is it hard to maintain the mechanism?

Criteria	Definition
Safety	Flammability, Reliability, Does ambient environment affect the mechanism's safety?
Durability	How durable will it be to withstand high-temperatures and shocks?

Reliability	Does this sensor fail easily under numerous cycles?
Resolution	Smallest reliable measurement that a sensor can make
Repeatability	Ability to provide the same result, under the same circumstances, over and over again
Accuracy	Difference between measured and “true” values

Annex E - Calculations

Platform Bending Stress Calculations

1. A beam is in equilibrium when it is stationary relative to an inertial reference frame. The following conditions are satisfied when a beam, acted upon by a system of forces and moments, is in equilibrium:

$\Sigma Fx = 0$:   HB = 0

$\Sigma MA = 0$:   The sum of the moments about a point A is zero:

- P1*0.06 + RB*0.12 = 0

$\Sigma MB = 0$:   The sum of the moments about a point B is zero:

- RA*0.12 + P1*0.06 = 0

2. Solve this system of equations:

HB = 0 (N)

Calculate reaction of pin support about point B:

RB = (P1*0.06) / 0.12 = (200*0.06) / 0.12 = 100.00 (N)

Calculate reaction of roller support about point A:

RA = (P1*0.06) / 0.12 = (200*0.06) / 0.12 = 100.00 (N)

3. The sum of the forces is zero: $\Sigma Fy = 0$:   RA - P1 + RB = 100.00 - 200 + 100.00 = 0

Platform bending

$$\sigma_{bending} = \frac{M_x y}{I_x}$$
$$I_x = \frac{bh^3}{12} = 5.09x10^{-9}$$
$$y = 0.005m$$
$$M_x = 6Nm$$

$$\sigma_{bending}\, x\ safety\ factor = 5.89MPa\ x\ 2 = 11.78MPa$$
$$Yield\ stregth\ of\ 3D\ printing\ material, \sigma_{y(PLA)} = 70MPa$$
$$therefore, platform\ will\ not\ break\ as\ \ \sigma_{bending} < \sigma_{y(ABS)}$$

R- Code

```
d <- 10/100 # total extension distance m

v = 1/100 #0.01m/s linear speed

l <- seq(0.5, 20,0.5) # mm

l <- l/1000 # pitch m

F = 200 #output force N

e = 0.5 # efficiency

t = F*l/(2*pi*e) #torque Nm

w <- v/l #angular speed rps

sf <- matrix(seq(1.5,2,0.1),nrow=1) #safety factor

A <- matrix(t*w,nrow=1)
```

```
P <- 2*pi*(t(A) %*% sf)  # Power Matrix

df <- data.frame(l,t, w)
```

Spring Calculations

$Freelength = 8\ mm$
$Extension\ length, x\ = 13.54mm$
$Load\ on\ Spring, F\ = 0.023kg\ x\ 9.81\ x\ 7 = 1.5794N$
$F\ = kx$
$k\ = 292.483N/m$

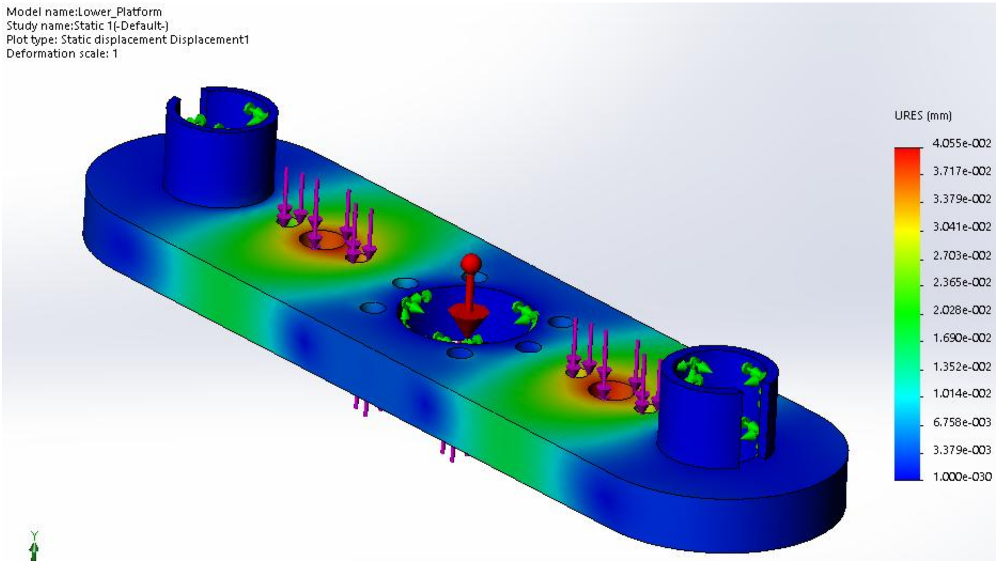
Annex F - Failsafe Pugh Chart Criterion

Requirements	
Functionality	Can the failsafe perform its function of retracting the actuator to its neutral position
Reactivity	How reactive is the failsafe to a failure signal
Maintenance	Does the failsafe mechanism require constant maintenance
Weight	Will the failsafe add significantly to the weight of the system?
Size Requirement	Does the failsafe fit the dimension restrictions?0

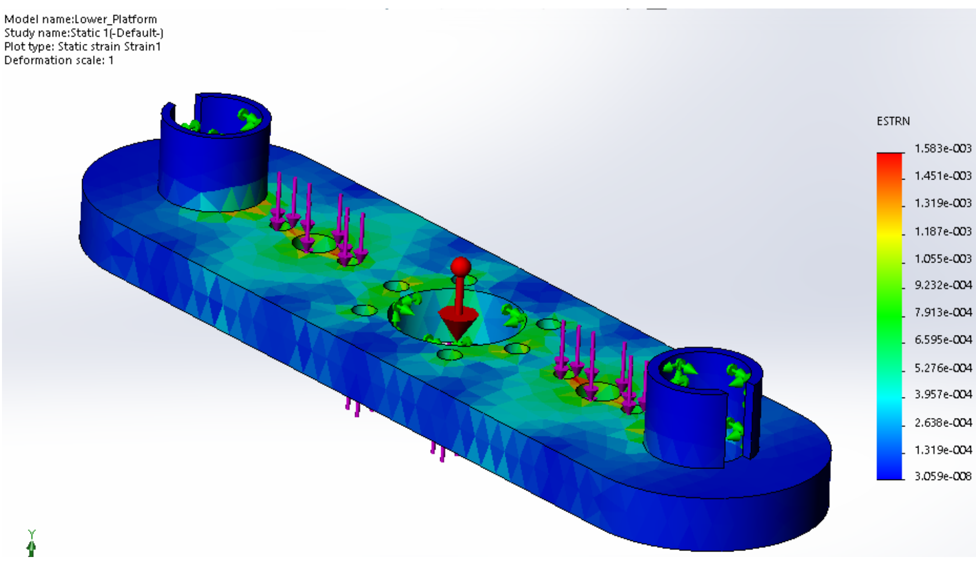
Annex G - FMEA Model

Lower Platform

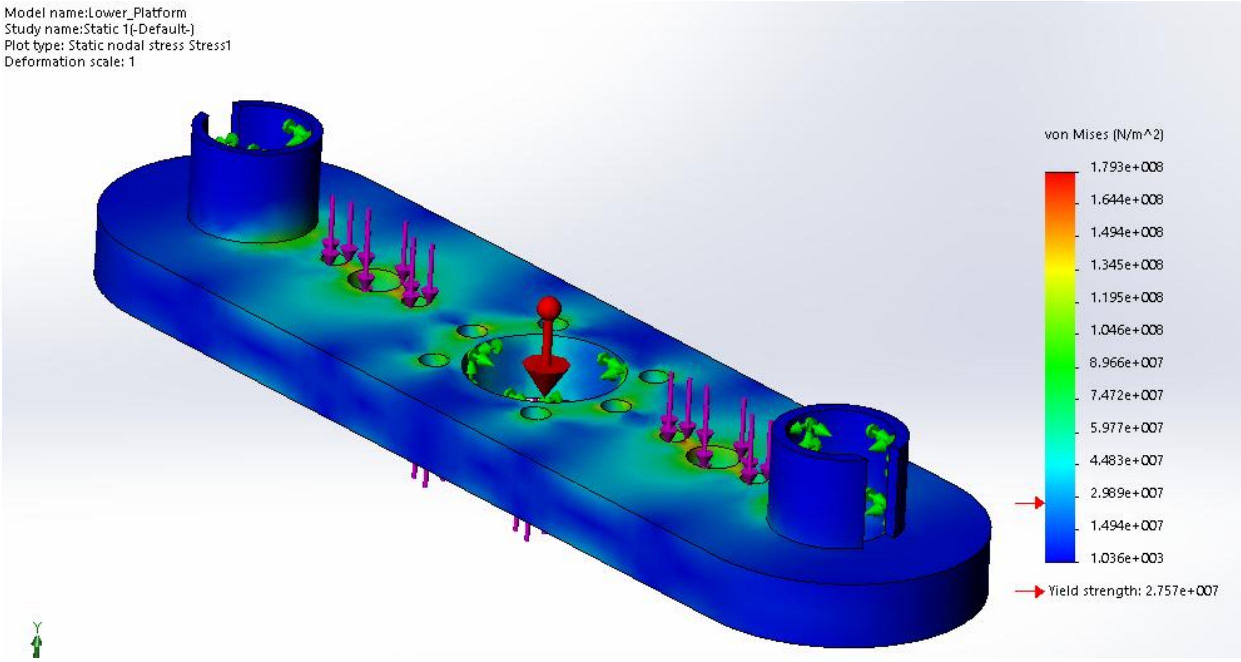
Displacement Diagram



Strain Diagram

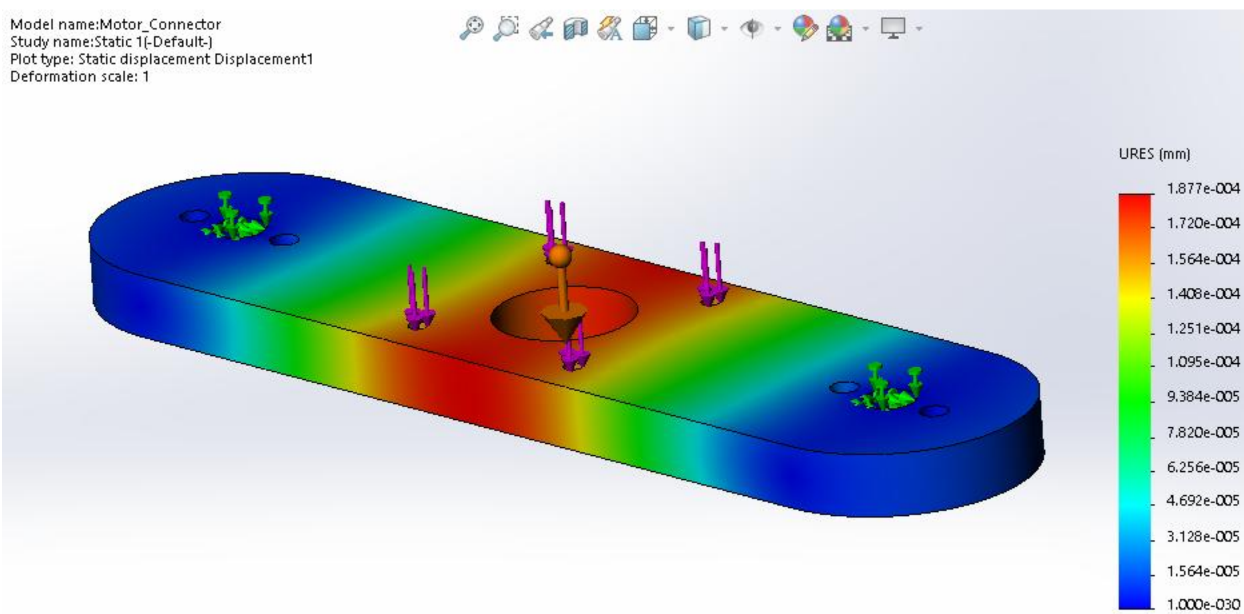


Stress Diagram

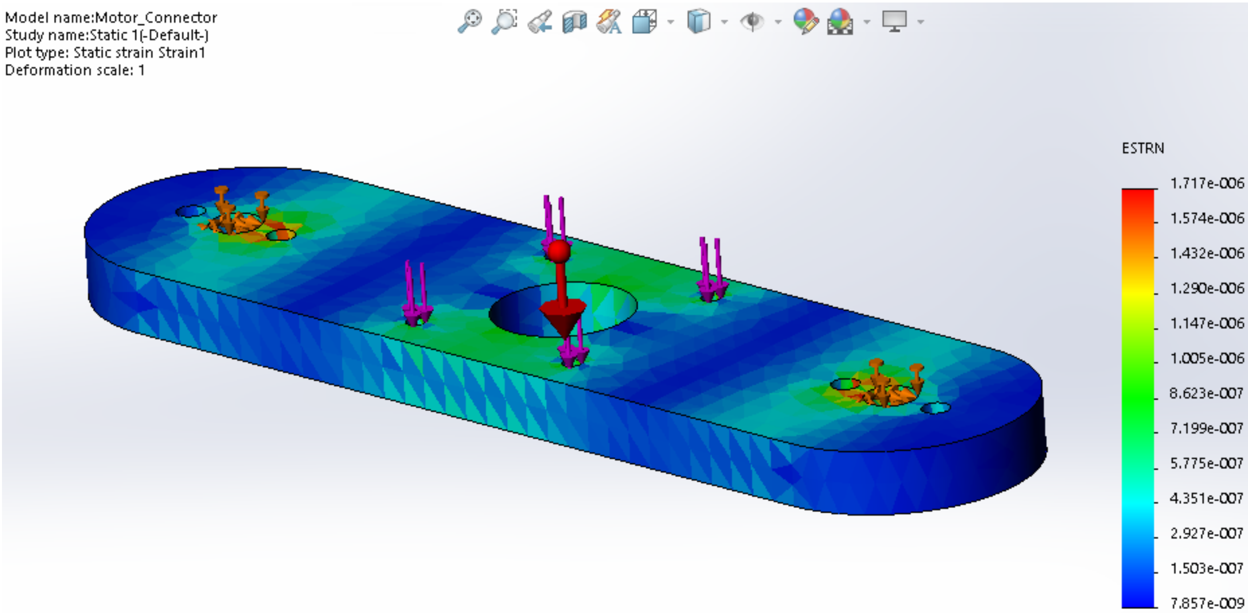


Motor Connector

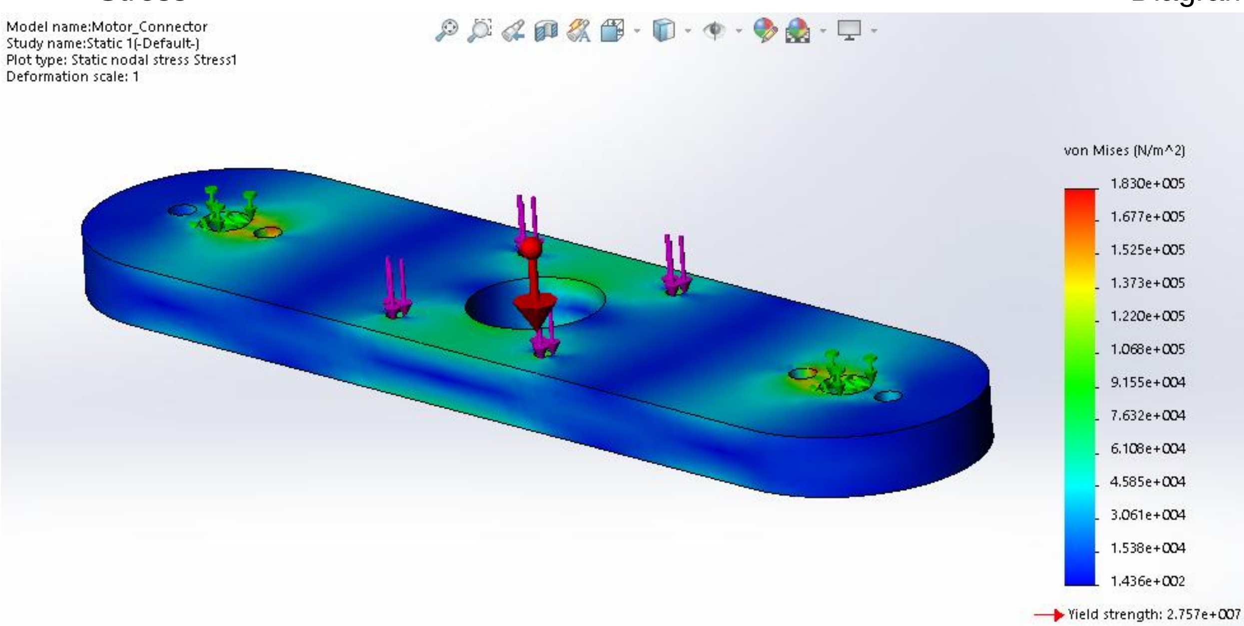
Displacement Diagram



Strain Diagram

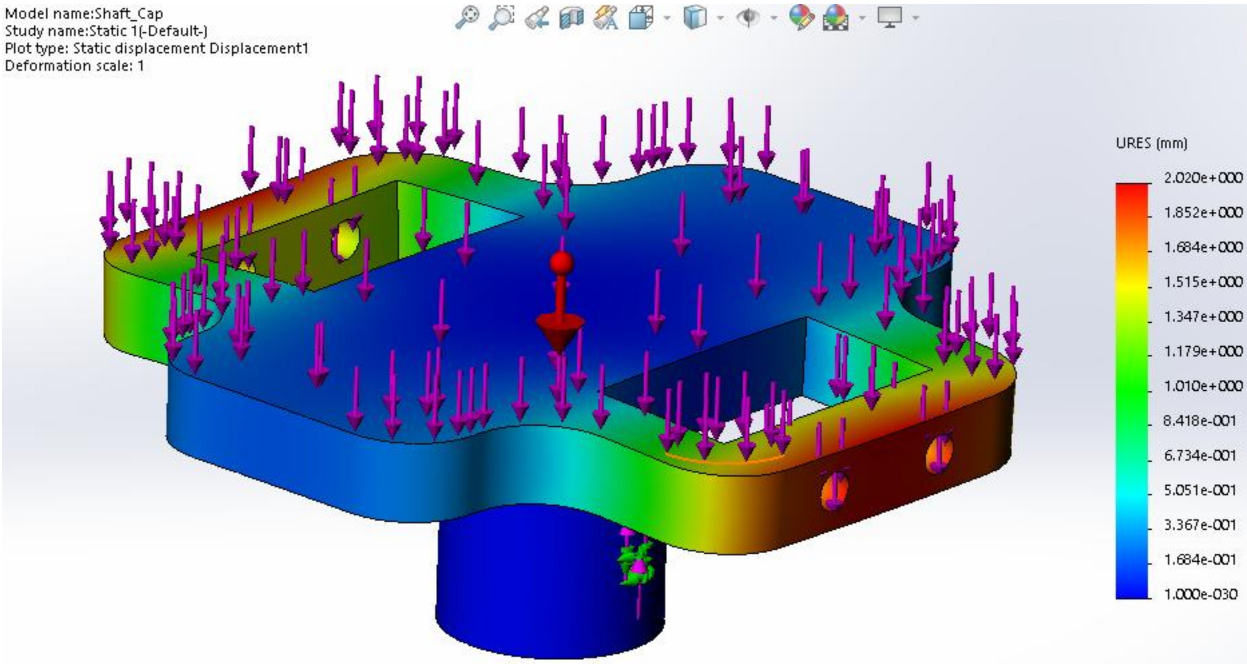


Stress Diagram

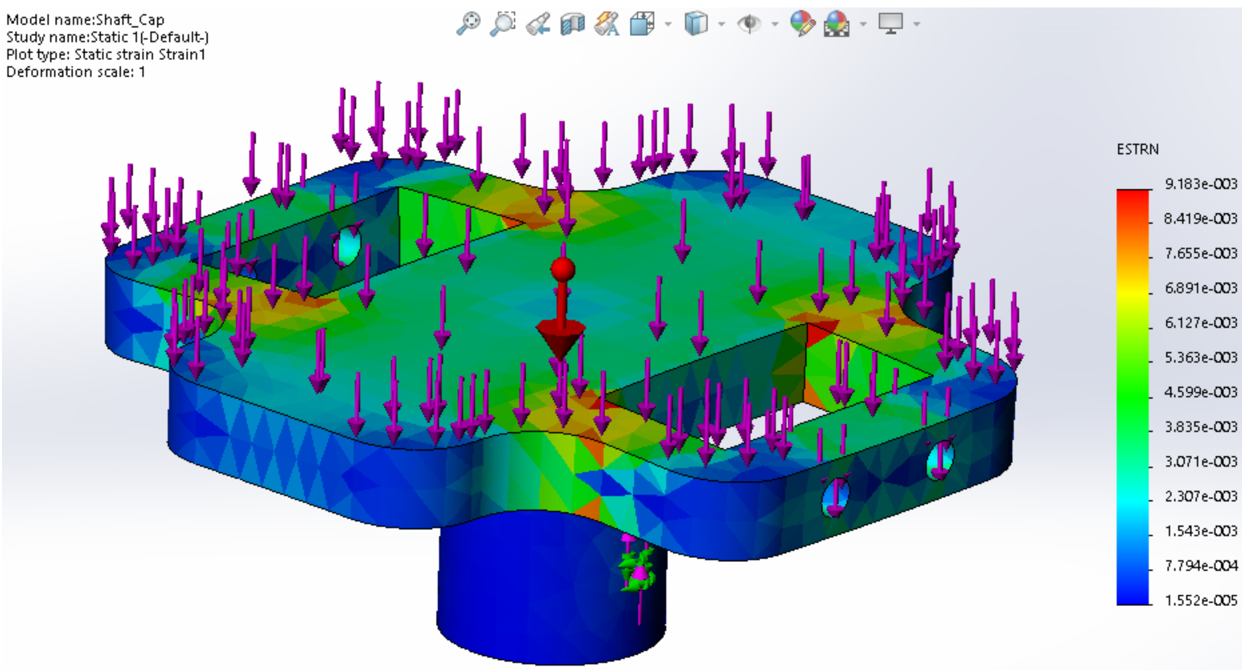


Shaft Cap

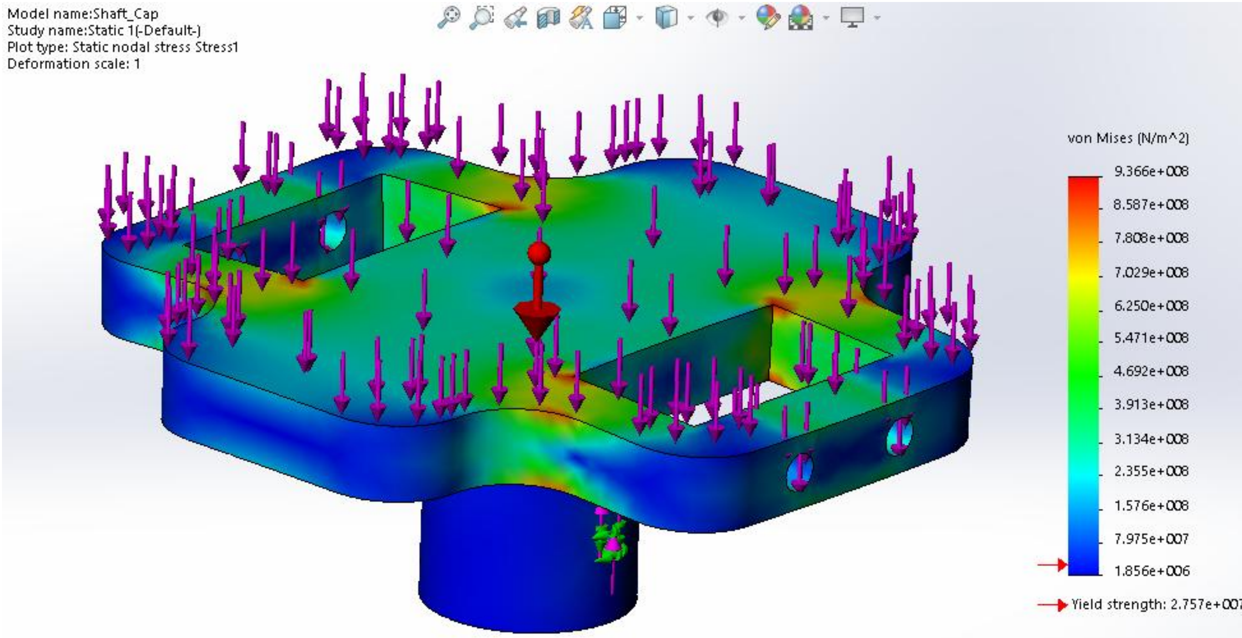
Displacement Diagram



Strain Diagram

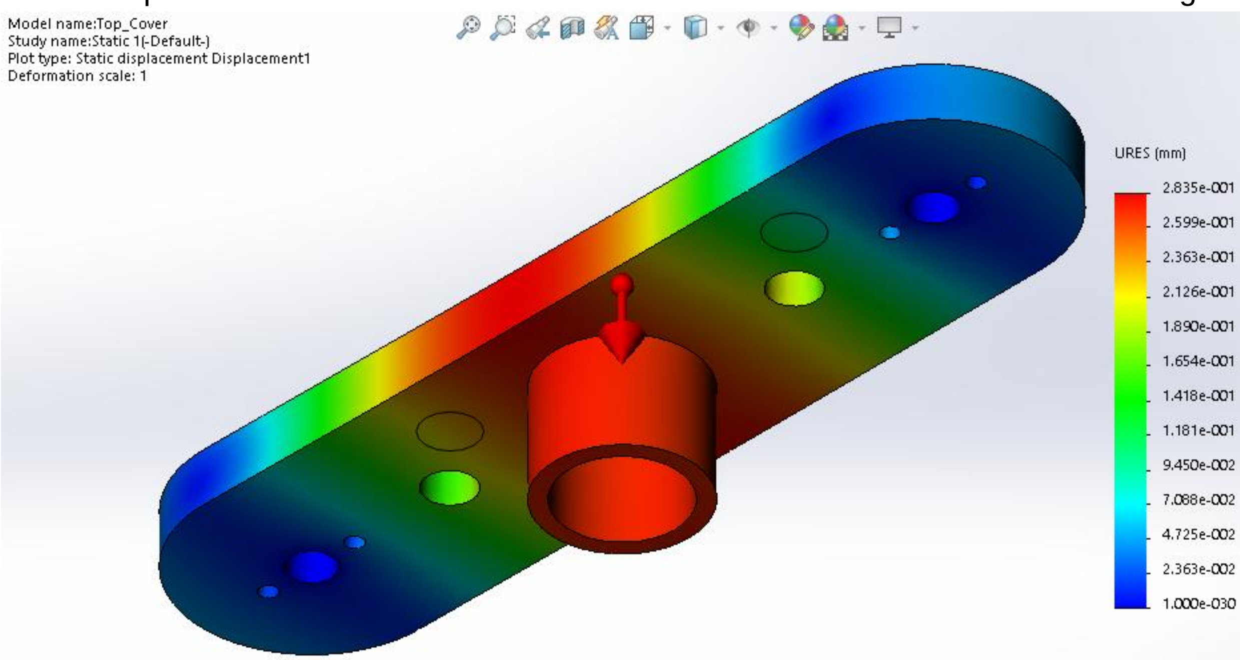


Stress Diagram

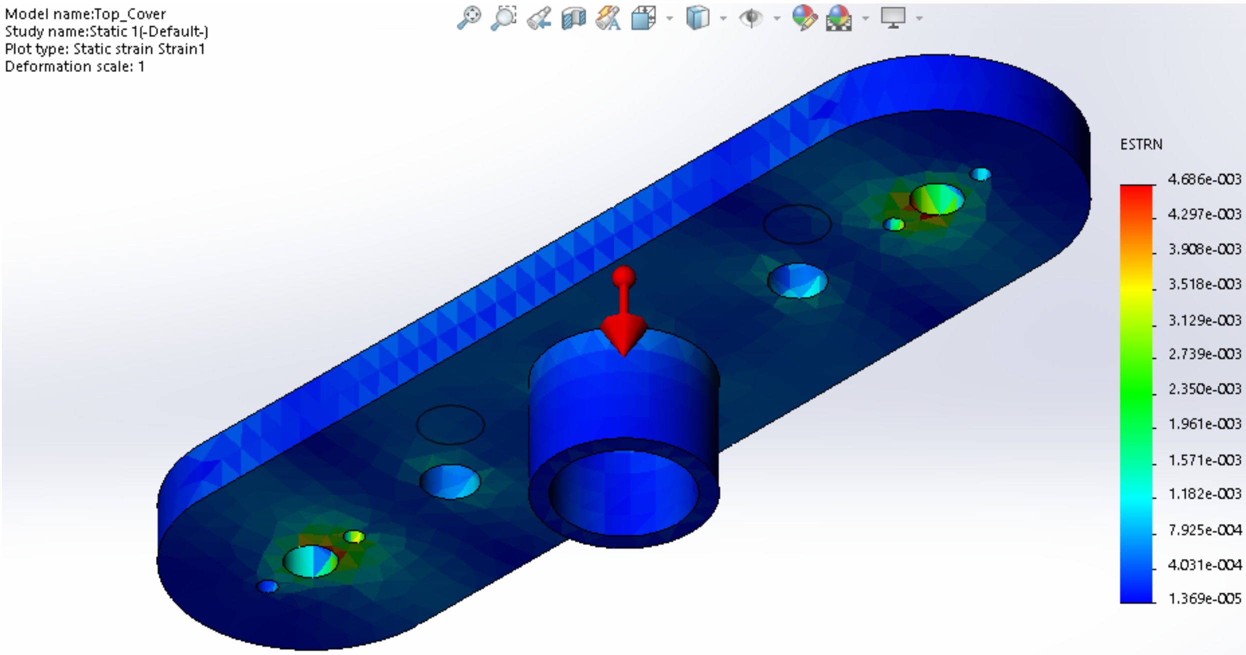


Top Cover

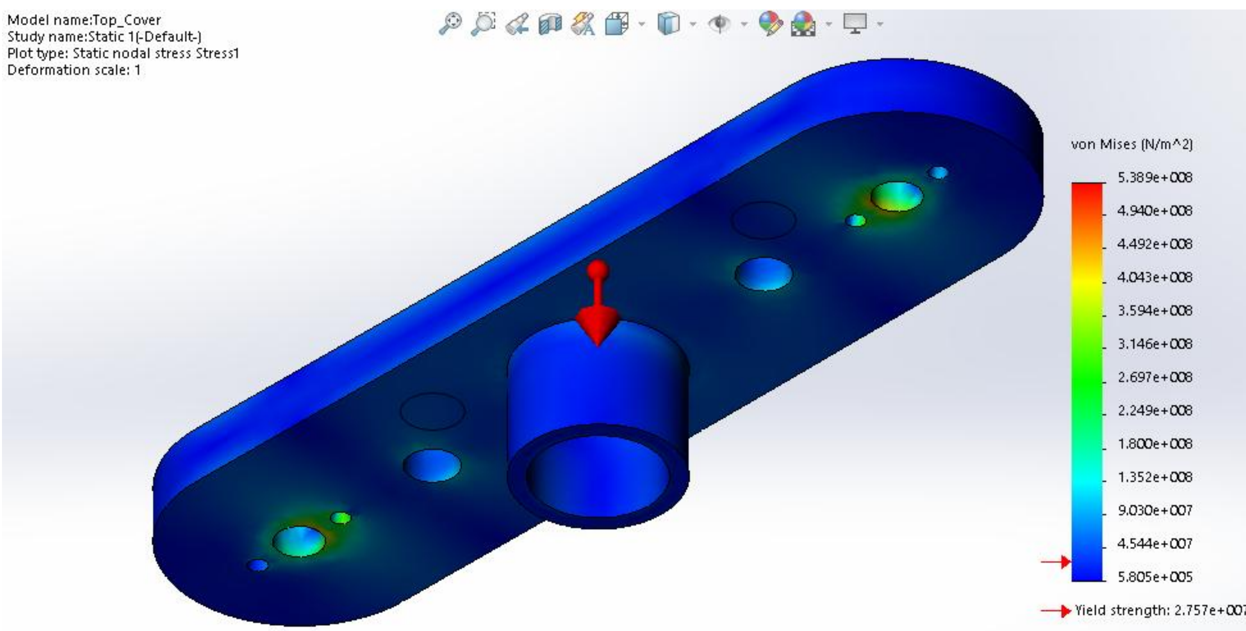
Displacement Diagram



Strain Diagram

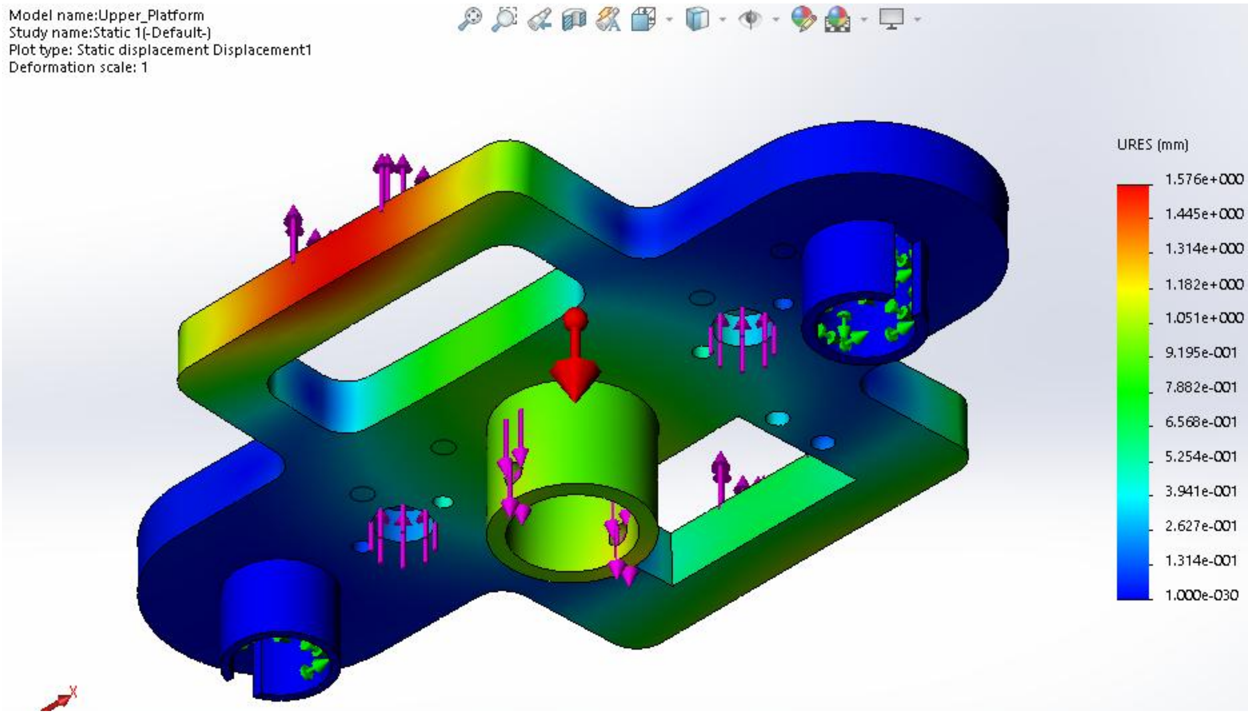


Stress Diagram

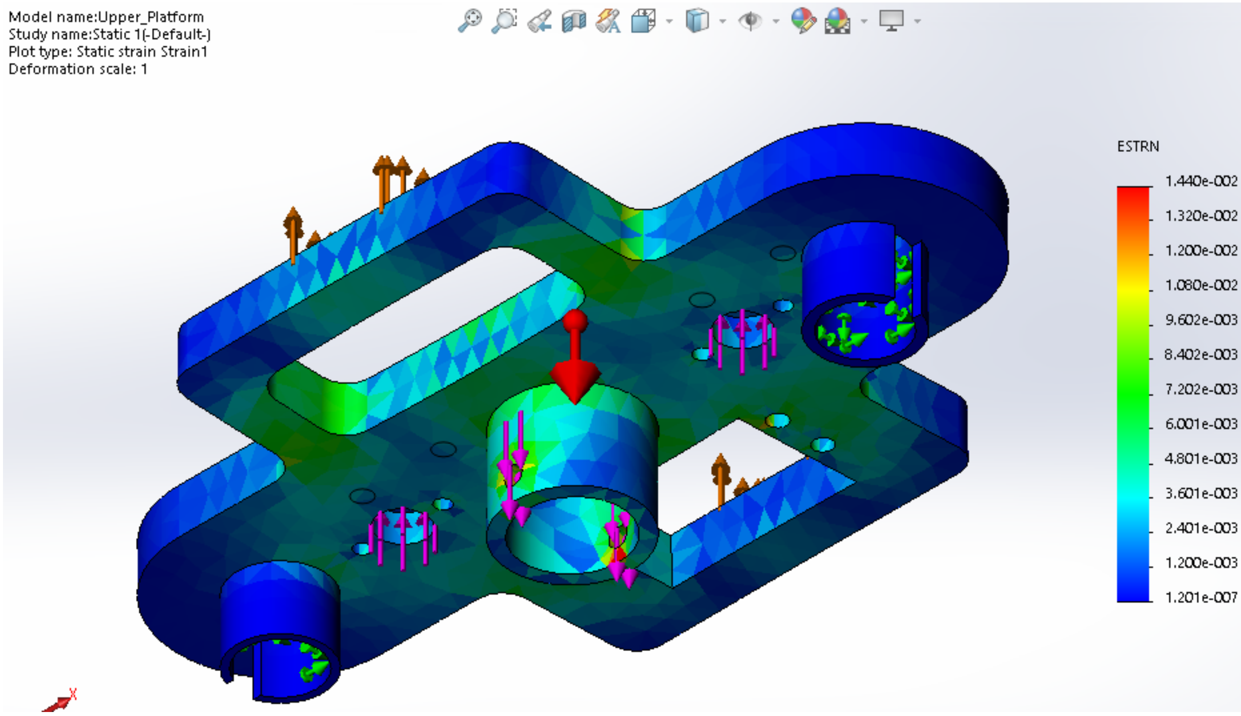


Upper Platform

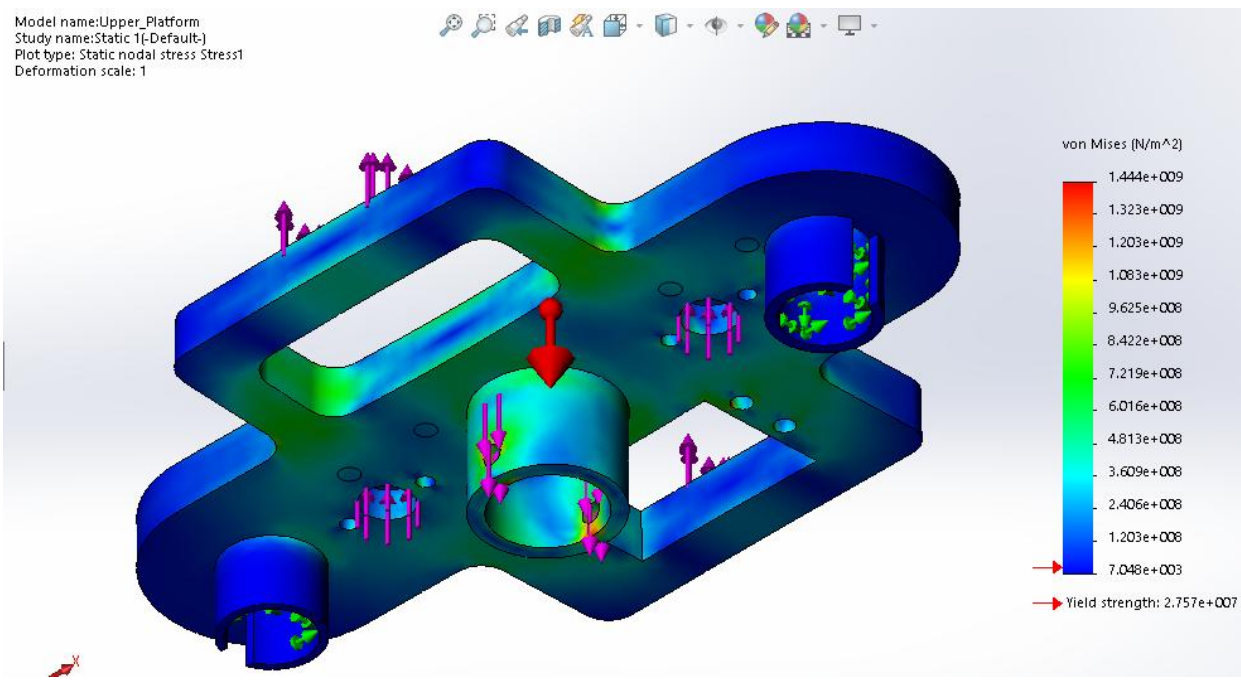
Displacement Diagram



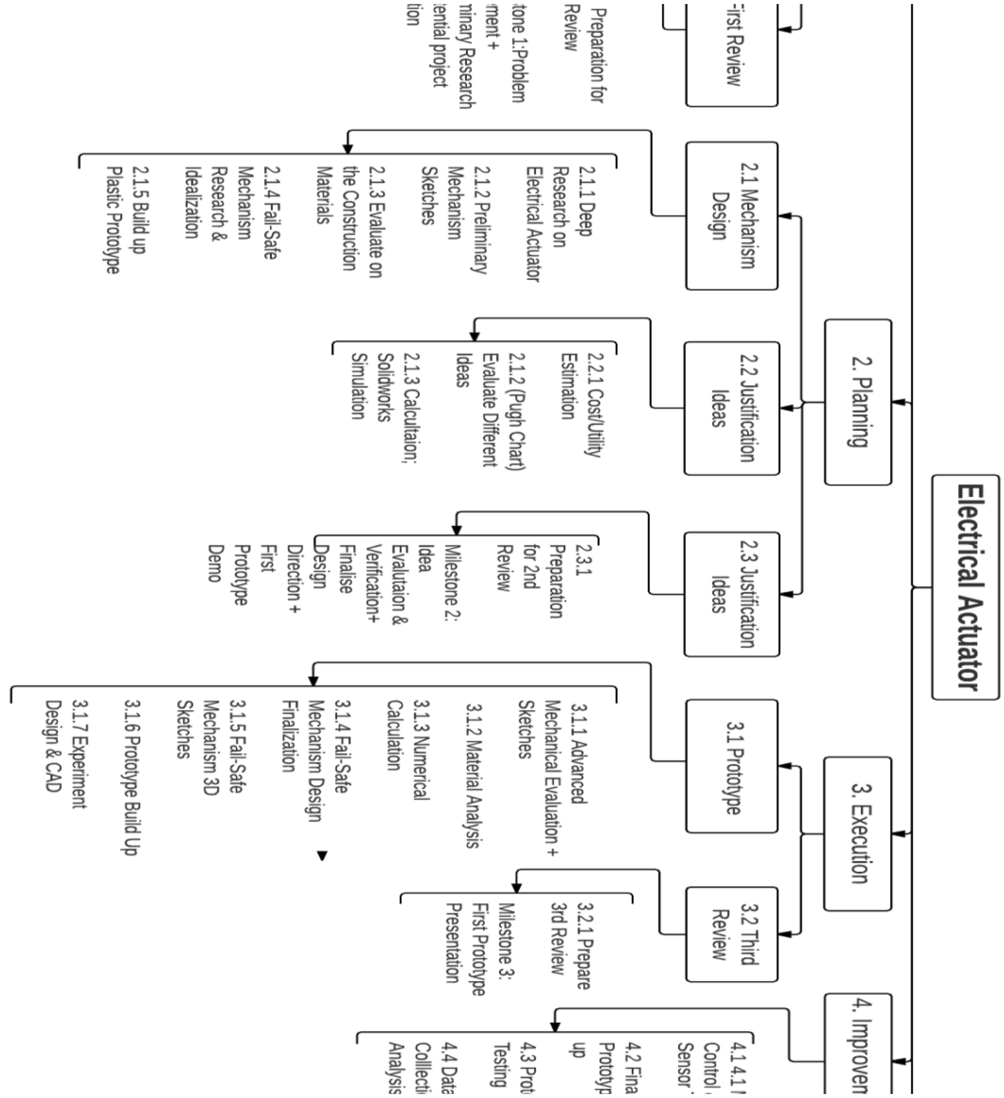
Strain Diagram



Stress Diagram



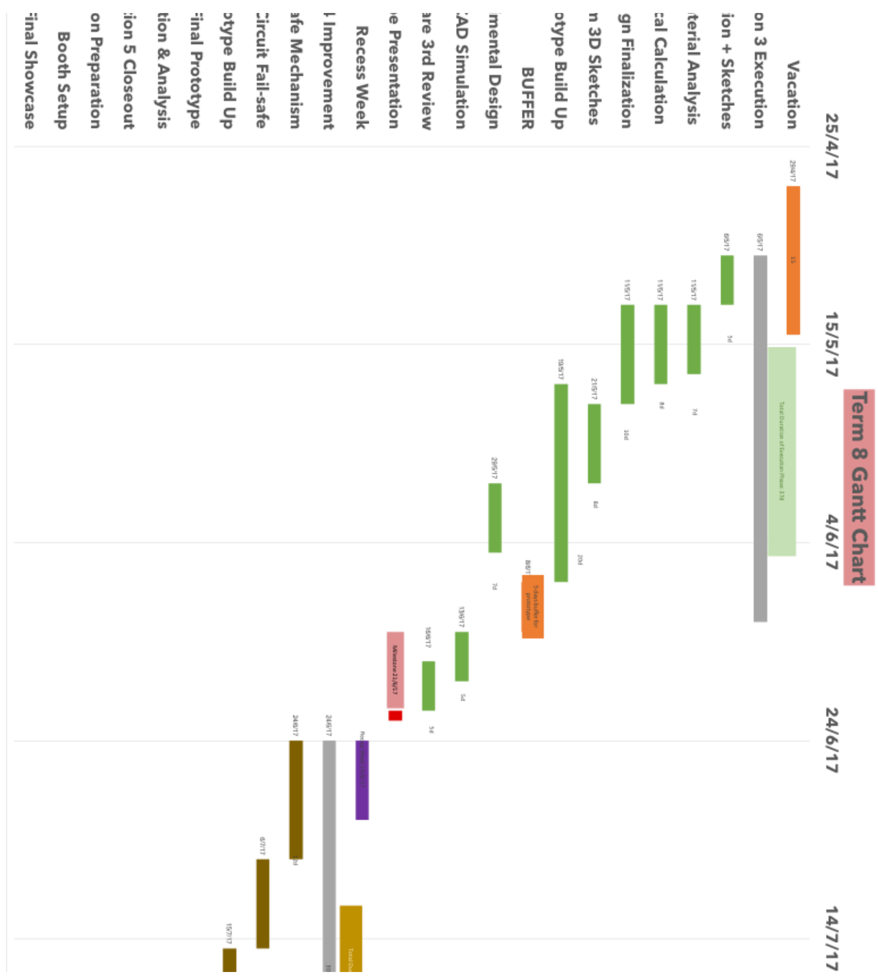
Annex H - Work Breakdown Structure



Annex I - Three Point Duration Estimation

Tasks	a	m	b	te
Project Framing & Scoping	4	3	10	4
Survey on Precedents	3	5	12	6
Identify Required Technologies	5	7	14	8
Cost Estimation	4	5	7	5
Verify & Validate User Requirement	3	4	7	4
Brainstorming on Ideas	4	5	7	5
First Review Preparation	4	5	7	5
Deep Research on Electrical Actuator	3	6	8	6
Cost/Utility Estimation	5	7	12	8
Create Preliminary Mechanism sketches	7	14	22	14
Evaluate on the Construction Materials	2	4	5	4
Fail-Safe Mechanism Research & Idealization	4	5	15	7
(Pugh Chart) Evaluate Different Ideas	5	7	10	7
Build up Preliminary Prototype	6	9	14	9
Calcultaion; Solidworks Simulation	5	7	14	8
Prepare for 2nd Review	5	10	15	10
Advanced Mechanical Evaluation + Sketches	4	5	8	5
Material Analysis	5	7	9	7
Numerical Calculation	5	7	14	8
Fail-Safe Mechanism Design Finalization	7	10	15	10
Fail-Safe Mechanism 3D Sketches	5	7	15	8
Prototype Build Up	18	18	28	20
Experimental Design	3	7	10	7
CAD Simulation	3	5	7	5
Prepare 3rd Review	4	5	6	5
Prototype Finalisation CAD with Sensor & Fail-Safe Mechanism	8	12	16	12
PMSM motor Control + Electric Circuit Fail-safe	5	9	7	8
Final Prototype Build Up	4	5	13	6
Testing of Final Prototype	2	5	6	5
Data Collection & Analysis	2	5	6	5
Report+Poster+Presentaion Preparation	7	12	15	12
Booth Setup	2	2	2	2

Annex J - Gantt Chart



Annex K – I2C Protocol Code (STM32)

```
void i2c_start()
{
    // Wait until I2Cx is not busy anymore
    while (I2C_GetFlagStatus(I2C2, I2C_FLAG_BUSY));

    // Generate start condition
    I2C_GenerateSTART(I2C2, ENABLE);

    // Wait for I2C EV5.
    // It means that the start condition has been correctly released
    // on the I2C bus (the bus is free, no other devices is communicating))
    while (!I2C_CheckEvent(I2C2, I2C_EVENT_MASTER_MODE_SELECT));
}

void i2c_stop()
{
    // Generate I2C stop condition
    I2C_GenerateSTOP(I2C2, ENABLE);
    // Wait until I2C stop condition is finished
    while (I2C_GetFlagStatus(I2C2, I2C_FLAG_STOPF));
}
```

```
void i2c_address_direction(uint8_t address, uint8_t direction)
{
    // Send slave address
    I2C_Send7bitAddress(I2C2, address, direction);

    // Wait for I2C EV6
    // It means that a slave acknowledges his address
    if (direction == I2C_Direction_Transmitter)
    {
        while (!I2C_CheckEvent(I2C2,
            I2C_EVENT_MASTER_TRANSMITTER_MODE_SELECTED));
    }
    else if (direction == I2C_Direction_Receiver)
    {
        while (!I2C_CheckEvent(I2C2,
            I2C_EVENT_MASTER_RECEIVER_MODE_SELECTED));
    }
}
```

```
void i2c_transmit(uint8_t byte)
{
    // Send data byte
    I2C_SendData(I2C2, byte);
    // Wait for I2C EV8_2.
    // It means that the data has been physically shifted out and
    // output on the bus)
    while (!I2C_CheckEvent(I2C2, I2C_EVENT_MASTER_BYTE_TRANSMITTED));
}

uint8_t i2c_receive_ack()
{
    // Enable ACK of received data
    I2C_AcknowledgeConfig(I2C2, ENABLE);
    // Wait for I2C EV7
    // It means that the data has been received in I2C data register
    while (!I2C_CheckEvent(I2C2, I2C_EVENT_MASTER_BYTE_RECEIVED));

    // Read and return data byte from I2C data register
    return I2C_ReceiveData(I2C2);
}

uint8_t i2c_receive_nack()
{
    // Disable ACK of received data
    I2C_AcknowledgeConfig(I2C2, DISABLE);
    // Wait for I2C EV7
    // It means that the data has been received in I2C data register
    while (!I2C_CheckEvent(I2C2, I2C_EVENT_MASTER_BYTE_RECEIVED));

    // Read and return data byte from I2C data register
    return I2C_ReceiveData(I2C2);
}
```

```
void i2c_write(uint8_t address, uint8_t data)
{
    i2c_start();
    i2c_address_direction(address << 1, I2C_Direction_Transmitter);
    i2c_transmit(data);
    i2c_stop();


}

void i2c_read(uint8_t address, uint8_t* data)
{
    i2c_start();
    i2c_address_direction(address << 1, I2C_Direction_Receiver);
    *data = i2c_receive_nack();
    i2c_stop();
}
```

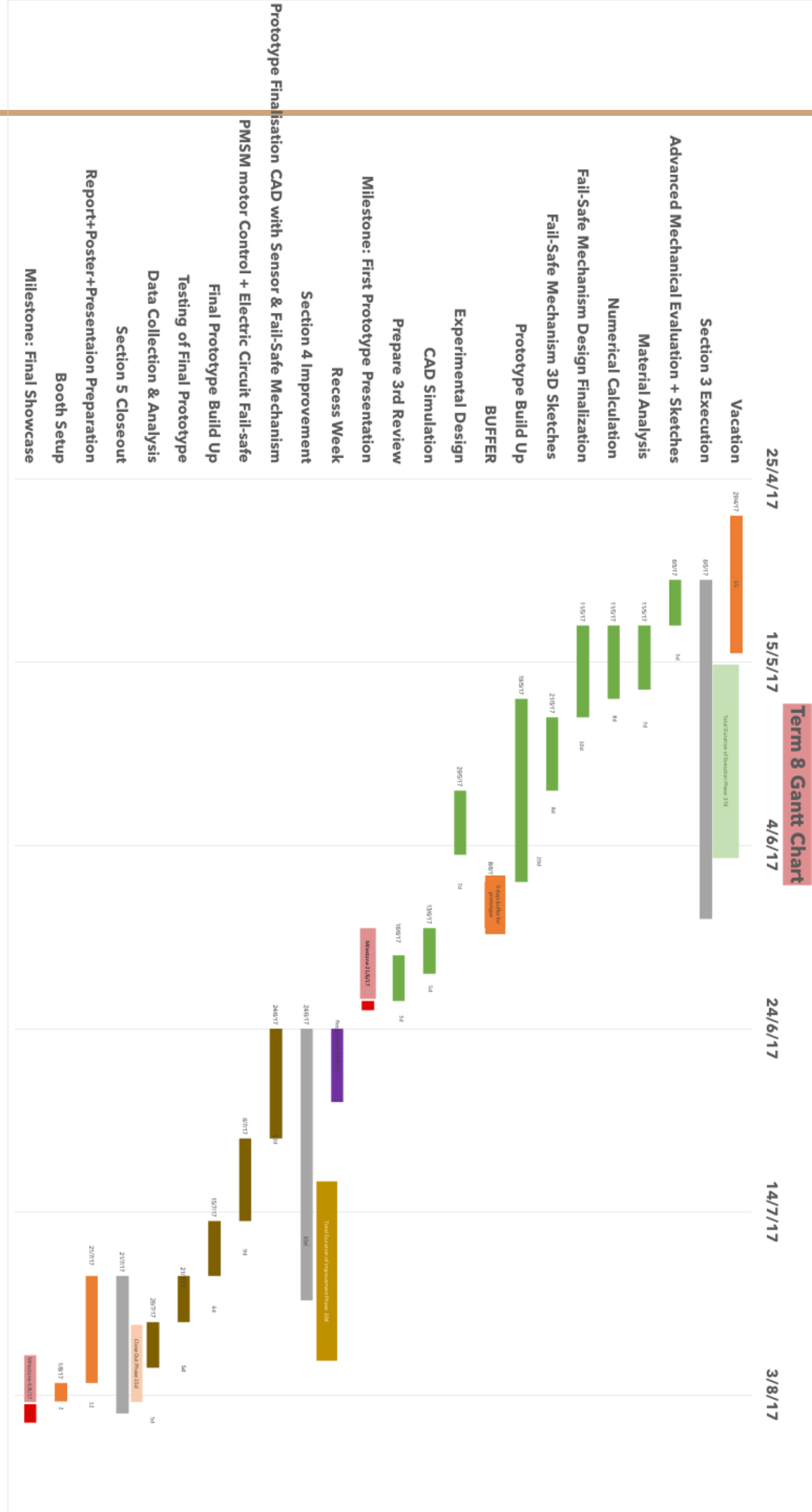
```
 // I²C address of VL6180X shifted by 1 bit
 //(0x29 << 1) so the R/W command can be added
///////////////////////////////////////////////////////////////////
// Split 16-bit register address into two bytes and write
// the address + data via I²C
///////////////////////////////////////////////////////////////////
void WriteByte(u16 reg,char data) {
 char data_write[3];
 data_write[0] = (reg >> 8) & 0xFF;; // MSB of register address
 data_write[1] = reg & 0xFF; // LSB of register address
 data_write[2] = data & 0xFF;
    i2c_start();
    i2c_address_direction( SLAVE_ADDRESS << 1 , I2C_Direction_Transmitter);
    i2c_transmit(data_write[0]);
    i2c_transmit(data_write[1]);
    i2c_transmit(data_write[2]);
    i2c_stop();
}
///////////////////////////////////////////////////////////////////
// Split 16-bit register address into two bytes and write
// required register address to VL6180X and read the data back
///////////////////////////////////////////////////////////////////
char ReadByte(u16 reg) {
 char data_write[2];
 char data_read[1];
 data_write[0] = (reg >> 8) & 0xFF; // MSB of register address
 data_write[1] = reg & 0xFF; // LSB of register address

    i2c_start();
    i2c_address_direction( SLAVE_ADDRESS << 1 , I2C_Direction_Transmitter);
    i2c_transmit(data_write[0]);
    i2c_transmit(data_write[1]);
    i2c_stop();
    i2c_start();
    i2c_address_direction(SLAVE_ADDRESS << 1, I2C_Direction_Receiver);
    data_read[0]= i2c_receive_nack();
    i2c_stop();


 return data_read[0];
}
```

```
///////////////////////////////////////////////////////////////////
// load settings
///////////////////////////////////////////////////////////////////
int VL6180X_Init() {
  //addalvee
  char reset;
  reset = ReadByte(0x016);
  if (reset==1){
         // Mandatory : private registers
           WriteByte(0x0207, 0x01);
           WriteByte(0x0208, 0x01);
           WriteByte(0x0096, 0x00);
           WriteByte(0x0097, 0xfd);
           WriteByte(0x00e3, 0x00);
           WriteByte(0x00e4, 0x04);
           WriteByte(0x00e5, 0x02);
           WriteByte(0x00e6, 0x01);
           WriteByte(0x00e7, 0x03);
           WriteByte(0x00f5, 0x02);
           WriteByte(0x00d9, 0x05);
           WriteByte(0x00db, 0xce);
           WriteByte(0x00dc, 0x03);
           WriteByte(0x00dd, 0xf8);
           WriteByte(0x009f, 0x00);
           WriteByte(0x00a3, 0x3c);
           WriteByte(0x00b7, 0x00);
           WriteByte(0x00bb, 0x3c);
           WriteByte(0x00b2, 0x09);
           WriteByte(0x00ca, 0x09);
           WriteByte(0x0198, 0x01);
           WriteByte(0x01b0, 0x17);
           WriteByte(0x01ad, 0x00);
           WriteByte(0x00ff, 0x05);
```

```
            WriteByte(0x0100, 0x05);
            WriteByte(0x0199, 0x05);
            WriteByte(0x01a6, 0x1b);
            WriteByte(0x01ac, 0x3e);
            WriteByte(0x01a7, 0x1f);
            WriteByte(0x0030, 0x00);
            // Recommended : Public registers - See data sheet for more detail
            WriteByte(0x0011, 0x10); // Enables polling for 'New Sample ready'
             // when measurement completes
            WriteByte(0x010a, 0x30); // Set the averaging sample period
             // (compromise between lower noise and
             // increased execution time)
            WriteByte(0x003f, 0x46); // Sets the light and dark gain (upper
             // nibble). Dark gain should not be
             // changed.
            WriteByte(0x0031, 0xFF); // sets the # of range measurements after
             // which auto calibration of system is
             // performed
            WriteByte(0x0040, 0x63); // Set ALS integration time to 100ms
            WriteByte(0x002e, 0x01); // perform a single temperature calibration
             // of the ranging sensor
            WriteByte(0x001b, 0x09); // Set default ranging inter-measurement
             // period to 100ms
            WriteByte(0x003e, 0x31); // Set default ALS inter-measurement period
             // to 500ms
            WriteByte(0x0014, 0x24); // Configures interrupt on 'New Sample
             // Ready threshold event'

      // check to see has it be Initialised already
////////////////////////////////////////////////////////////////////
// Added latest settings here - see Section 8
////////////////////////////////////////////////////////////////////
 WriteByte(0x016, 0x00); //change fresh out of set status to 0
 }
 return 0;}
```

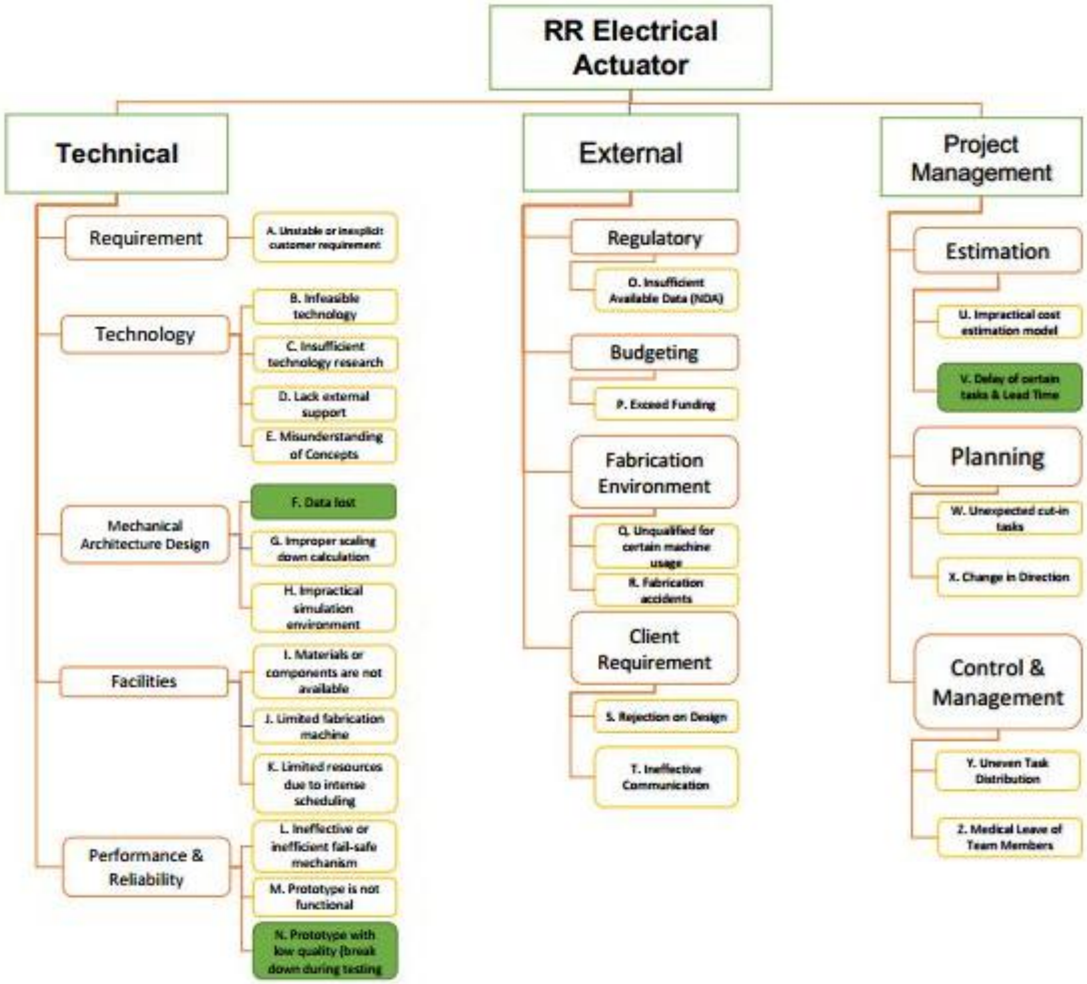
```
// Start a range measurement in single shot mode
////////////////////////////////////////////////////////////////////
int VL6180X_Start_Range() {
  WriteByte(0x018,0x01);
  return 0;
}
////////////////////////////////////////////////////////////////////
// poll for new sample ready ready
////////////////////////////////////////////////////////////////////
int VL6180X_Poll_Range() {
  char status;
  char range_status;

  // check the status
  status = ReadByte(0x04f);
  range_status = status & 0x07;

  // wait for new measurement ready status
  while (range_status != 0x04) {
  status = ReadByte(0x04f);
  range_status = status & 0x07;
  TB_Set_DisplayDelay_500us(2); // (can be removed)
  }
  return 0;
}
////////////////////////////////////////////////////////////////////
// Read range result (mm)
////////////////////////////////////////////////////////////////////
int VL6180X_Read_Range() {
  int range;
  range=ReadByte(0x062);
  return range;
}
```

```
// clear interrupts
////////////////////////////////////////////////////////////////////
int VL6180X_Clear_Interrupts() {
 WriteByte(0x015,0x07);
 return 0;
}
////////////////////////////////////////////////////////////////////
// Main Program loop
////////////////////////////////////////////////////////////////////
int readrange()
{
 int range;


 // load settings onto VL6180X
 VL6180X_Init();
 while (1){
 // start single range measurement
 VL6180X_Start_Range();

 // poll the VL6180X till new sample ready
 VL6180X_Poll_Range();

 // read range result
 range = VL6180X_Read_Range();

 // clear the interrupt on VL6180X
 VL6180X_Clear_Interrupts();

 // send range to pc by serial
 //wait(0.1);
 }
}
```



as

Annex K - Risk Breakdown Structure


RR Electrical Actuator
Technical
External
Project Management
Requirement
A. Unstable or inexplicit customer requirement
Technology
B. Infeasible technology
C. Insufficient technology research
D. Lack external support
E. Misunderstanding of Concepts
Mechanical Architecture Design
F. Data lost
G. Improper scaling down calculation
H. Impractical simulation environment
Facilities
I. Materials or components are not available
J. Limited fabrication machine
K. Limited resources due to intense scheduling
Performance & Reliability
L. Ineffective or inefficient fail-safe mechanism
M. Prototype is not functional
N. Prototype with low quality (break down during testing
Regulatory
O. Insufficient Available Data (NDA)
Budgeting
P. Exceed Funding
Fabrication Environment
Q. Unqualified for certain machine usage
R. Fabrication accidents
Client Requirement
S. Rejection on Design
T. Ineffective Communication
Estimation
U. Impractical cost estimation model
V. Delay of certain tasks & Lead Time
Planning
W. Unexpected cut-in tasks
X. Change in Direction
Control & Management
Y. Uneven Task Distribution
Z. Medical Leave of Team Members

Annex L

Main Impact	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
Time	Insignificant Time Increase	<5% Time Increase	5%-10% Time Increase	10-20% Time Increase	>20% Time Increase
Project Scope	Scope decrease barely noticeable	Minor areas of scope affected	Major areas of scope affected	Scope reduction unacceptable to sponsor	Project end item is effectively useless

Table K-1 Impact Number Ranking Criteria

Category	o.	Risk Event	Risk Mitigation Action
Facilities		Limited resources due to intense scheduling	Book the machine two weeks beforehand according to the Gantt Chart.
Performance & Reliability		Ineffective or inefficient fail-safe mechanism	Fail Mode Effective Analysis on every single components. Integrate the fail-safe mechanism into the mechanical architecture design.
Performance & Reliability		Prototype is not functional	Conduct 3D simulation with multi affecting factors beforehand.
Performance & Reliability		Prototype with low quality (break down	Integrate the components during fabrication and choose stubborn materials. Always have a plan B.

		during testing	
Client Requirement		Rejection on Design	Frequent meeting with company mentors and frequent update them on our design. Make sure both side are in agreement.
Estimation		(Time) Task Delay	Use three-point estimation on task duration and estimate the total project duration. Make some buffers on tasks with high impact and high possibility of postponing.

Table K-2 Risk Mitigation Actions on Major Risk Events