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Design of a Thrust Vector Controlled Model Rocket

Terms of reference
Mechatronic Project 478

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2021

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ECSA EXIT LEVEL OUTCOMES

ECSA Outcomes Assessed in this Module	
ECSA Outcome	**Addressed in Sections:**
ELO 1. Problem Solving: Demonstrate competence to identify, assess, formulate and solve convergent and divergent engineering problems creatively and innovatively.	4; 5; 6; 7; 8; 9; 10; 11 ;12; Appendix B
ELO 2. Application of scientific and engineering knowledge: Demonstrate competence to apply knowledge of mathematics, basic science and engineering sciences from first principles to solve engineering problems.	5; 7; 8; 9; 10; Appendix B
ELO 3. Engineering Design: Demonstrate competence to perform creative, procedural and nonprocedural design and synthesis of components, systems, engineering works, products or processes.	4; 5; 6; 7; 8; 9; 10; 11; 12; Appendix A-E
ELO 5. Engineering methods, skills and tools, including Information Technology: Demonstrate competence to use appropriate engineering methods, skills and tools, including those based on information technology.	4; 5; 6; 7; 8; 9; 10; 11; 12; Appendix A-E
ELO 6. Professional and technical communication: Demonstrate competence to communicate effectively, both orally and in writing, with engineering audiences and the community at large.	Final Project report, Oral presentation and poster
ELO 8. Individual, Team and Multidisciplinary Working: Demonstrate competence to work effectively as an individual, in teams and in multi-disciplinary environments.	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12; Appendix A-E
ELO 9. Independent Learning Ability: Demonstrate competence to engage in independent learning through well-developed learning skills.	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12; Appendix A-E

Executive Summary

Title of Project
Design of a Thrust vector-controlled model rocket.
Objectives
Design, develop and test an autonomous thrust vector-controlled model rocket that is capable of in-flight stabilization and safe recovery.
What is current practice and what are its limitations?
Model rockets are made from cardboard and have stationary engine mounts. Stabilisation relies solely on the aerodynamic forces acting on the fins of the rocket. This limits the rockets design, weight and velocity to an aerodynamically stable design.
What is new in this project?
In this project the fins are eliminated from the rocket, causing the rocket to be unstable. Sensors are added to the rocket and a TVC mount is fitted for motor control. A flight computer with control systems is designed and implemented for in-flight stabilization, utilizing the sensors and the TVC mount.
If the project is successful, how will it make a difference?
This project will determine if it is viable to develop a small scale TVC model rocket.
What are the risks to the project being a success? Why is it expected to be successful?
The gyroscope might produce inaccurate data, which will cause unstable flight. Factors that were not considered might cause the control systems to be insufficient. Further, the control systems will be experimentally tested, designed and improved to eliminate all insufficiencies.
What contributions have/will other students made/make?
Future students can build on this project by increasing the model size, experimenting with different engine fluids, adding roll control and attempting to land the model rocket vertically with TVC.
Which aspects of the project will carry on after completion and why?
N/A
What arrangements have been/will be made to expedite continuation?
The entire project will be documented in detail to ensure that it is repeatable and that future projects can expand on it.

Dedication

I dedicate this project to God Almighty my creator, my strong pillar, my source of inspiration, wisdom, knowledge and understanding. He has been the source of my strength throughout this program and on His wings only have I soared.

I also want to dedicate this project to every person, family member, teacher, mentor and friend who have been part of my university journey. Every one of you have made this possible and have played a crucial role in my life. No one will be forgotten.

Acknowledgements

Firstly, I would like to thank God for blessing me with the talents to pursue my dream and for giving me strength in hard times.

I would like to give a thanks to Dr. Lourens Visagie for his guidance throughout the project, for always listening and showing an interest in my work, encouraging me throughout the project and allowing me to choose my own course. I could not have asked for a better supervisor you are an inspiration Sir.

I would also like to express my gratitude to Mr. Wessel Croukamp for always having an open door, for putting his work on hold to help me on mine and for showing a sincere interest in my work.

To my Dad, Marius Nel, thank you for setting an example of hard work and determination. Thank you for always being there for me, for believing in me and pushing me to greater hights. I will carry your name with pride.

To my Mom, Mariette Nel, thank you for all your love and care. Thank you for always checking up on me and being there for me throughout my academic career.

To my Brothers, Rinus & Rohan Nel, thank you for being my best friends. Thank you for always believing in me, investing in me and always ready to listen. I appreciate your love and care. As a team we are going to go far in life!

To Marina van Tonder, thank you for all the proof reading, motivation and listening in times of despair or playing a game of darts to up my mood. Your interest in the project and your help on stressful launch days is much appreciated.

To all my friends and other students that was apart of this project I would like to give a big thanks.

I would lastly like to thank Stefan Stoltz from Rocketry SA for all the supplies he donated for this project and all the questions he answered. Without you this project would not have been possible.

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List of Abbreviations

TVC	Thrust Vector Control
LEO	Low Earth Orbit
DC	Direct Current
ESC	Electronic Speed Control
MECO	Main Engine Cut-off
RAM	Random-access Memory
SD	Secure Digital
App	Application
CAD	Computer Aided Design
RGB	Red Green Blue
LED	Light Emitting Diode
PCB	Printed Circuit board
CP	Centre of Pressure
CG	Centre of Gravity
ISS	International Space Station
CMR	Conventional Model Rockets
IMU	Inertial Measurement Unit
EEW	Electrical and Electronic workshop

List of Symbols

P / k_p / k_1	Proportional gain
I / k_i / k_2	Integral gain
D / k_d / k_3	Derivative gain
ρ	Air density
m	Total rocket mass
S	Parachute surface area
g	Gravitational acceleration
V	Velocity
C_d	Parachute drag coefficient
$\|q\|$	Quaternion norm
$\omega_{x,y,z}$	Angular velocity
$\emptyset$	Angular velocity vector length
dt, Δt	Elapsed time
$q[0,1,2,3,4]$	Quaternions
w,x,y,z	Quaternion base
$\dot{q}_{0,1,2,3}$	Rate of change of the quaternions
θ	Pitch
ϕ	Roll
ψ	Yaw
P	Current Pressure
R	Universal gas constant
M	Molar mass of Earth's air
P_b	Zero altitude pressure
T_b	Current Temperature
g_0	Gravitational acceleration
L_b	Standard temperature lapse rate
h_b	Zero altitude

1 Introduction

1.1 Background

Space explorations is the investigation by means of a crewed and uncrewed spacecraft beyond the Earth's atmosphere. These explorations are done to gain knowledge about the cosmos and to benefit humanity. The industry was only pursued by government organizations, because of the high costs associated with getting an object into space. Spacecrafts and rocket engines are majority single use, which leads to few missions being carried out as costs are too high. Cost had to be reduced if humanity wanted to know more about the universe beyond earth's atmosphere, and if humanity wanted to succeed at being a multiplanetary specie.

Lowering cost was accomplished by SpaceX when they successfully landed and reused the first vertical-take-off rocket in 2015. The rocket flew 100 kilometres up after which it deployed a satellite to orbit, it then returned to earth to ultimately land on a landing pad, built by SpaceX. In 2016 SpaceX achieved the first landing on a drone ship at sea and reused that same booster in a launch in 2017. This was made possible by utilizing thrust vector control (TVC), thrust control and control system algorithms to successfully land the rocket (Fernholz, 2017). TVC occur when the thrust is directed at a controlled angle, by gimbaling the thruster nozzle or rocket motor.

When a rocket has the ability to change the angle of its motor's thrust it is known as thrust vectoring or vectored thrust (Hall, 2015). This thrust vectoring is used to stabilize a rocket when it is launched in flight and to accomplish precise vertical landings. TVC is also used to fly the rocket into a specific orbit – as required by the satellite payloads that it deploys into orbit.

SpaceX set out to make rockets reusable and they achieved this goal when they recovered every booster that they attempted to land in 2017 and launched two reused rocket boosters.

Model rockets are very basic in comparison to actual rockets. They are made from cardboard and have a fixed motor mount. Flight stability relies on the rocket body's design being stable resulting in aerodynamic stability inflight. This project concentrates on adding active stabilization through TVC to a model rocket. The focus will be on the design, manufacturing and testing of a thrust vector-controlled model rocket without fins, thus resulting in an unstable rocket design, that can take off and perform inflight stabilization. The control systems will be designed, experimentally tested and improved to acquire satisfactory results.

1.2 Objectives

The project entails the design, manufacturing, and testing of an autonomous solid propellent model rocket with thrust vector control. The objectives are:

1. Design and manufacture a functional model rocket with a TVC mount for the rocket motor.

2. Add a gyroscope and accelerometer sensor to the rocket to determine the orientation and acceleration of the rocket.

3. Implement a data logger system to collect data in-flight that will be used for flight and control system optimization.

4. Design and program a flight computer with autonomous control systems that can stabilize the rocket in-flight and safely return the rocket back to ground with a recovery system.

5. Design and manufacture a Wi-Fi launch controller and an android app that will be used to launch the TVC model rocket.

6. Design and build a launchpad that will ensure a safe launch environment.

7. Assemble all the subsystems and test the TVC rocket with actual launches. The data gathered in the launches will be analysed and used to improve the rocket and determine if the project was successful.

1.3 Motivation

Model rockets are simplistic and don’t have any active control. This project focuses on bringing large scale industry rocket control to the model world. Control systems will be designed and optimized to ensure active in-flight stabilization of a model rocket with implementation of a TVC mount. The end goal of the project is to achieve an autonomous stable flight and the recovery of a designed and manufactured model rocket.

Firstly, the literature review in this report gives a brief history of rockets, it outlines model rockets in detail, thrust vector control is further explained and BPS Space TVC model rockets are described. BPS Space were used because it is the only accessible company that builds and records TVC model rockets. Thereafter, a safety and risk analysis were completed, followed by the design requirements. The next section is the conventional model rocket (CMR). In this section the CMR’s design and how it was built is explained and the procedure to obtain a rocket license in accordance with SAAMSA is outlined. This section also gives an insight to how CMR work and aids in understanding how TVC model rockets differ and the complications associated with them. In Section 6 the flight computer design is described. Further, the hardware design is explained in detail including the design of the rocket body, the TVC mount and the recovery system. The orientation which includes the quaternion and Euler angles, follows. Thereafter, in this report the control system design is explained. In this section the reader will be informed on the design of the stabilization, the servo motor constraints, the PID control in Arduino IDE and the experimental determining PID values. Next, the state machine's flow diagram and experiment are explained. The testing and evaluation of the final launch follows. Here the two launches, launch 1 and launch 2, that were conducted is given in detail. Lastly, a conclusion is drawn of the outcome of the research done on TVC model rockets.

2 Literature review

This section summarizes relevant literature and provides necessary background information to justify further design choices. Section 2.1 gives a brief history of rockets, Section 2.2 outline detailed model rockets, Section 2.3 explains thrust vector control and Section 2.4 describe BPS Space TVC model rockets.

2.1 Rocket History

Rocket principles dates back 2000 years, were space exploration application dating back only 70 years. Rockets that are currently in use, routinely take payloads to other planets in our solar system and closer to earth rockets carry supplies to the International Space Station (ISS) and return to earth where they ultimately land autonomously back on the launch pad (Howell, 2018).

Early rocketry started around 400 B.C., with Archytas, a Greek mathematician and philosopher. A wooden bird suspended on wires were pushed forward by escaping steam as displayed in Figure 1. The bird utilized the action-reaction principle, which was only documented as a scientific law in the late 17th century (Howell, 2018) (Benson, 2021).

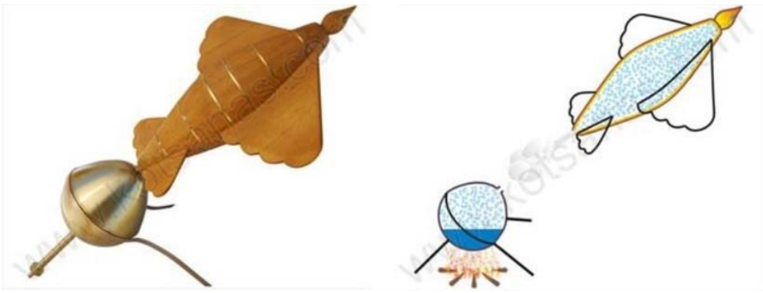

Figure 1: Flying pigeon of Archytas (Gellius & Nights, 2021).

The next advancement in rocketry was around 300 years after the pigeon experiment. Hero of Alexandria, a Greek, invented aeolipile, Hero's engine, a rocket like device that also uses steam as propulsion as displayed in Figure 2. The device consisted of a sphere that sat on top of a pool of boiling water. The gas entered the sphere and escaped through two L-shape tubes on opposite sides of the sphere. This thrust led to rotation of the sphere (Howell, 2018) (Benson, 2021).

Figure 2: Aeolipile or Hero's engine (Benson, 2021).

The time stamp when the first true rocket was built is unclear, but the Chinese experimented with gunpowder-filled tubes in the first century. They attached these tubes to arrows and launched them with bows to create explosions during festive seasons. They then discovered that the tubes could be launched by themselves through the power of the escaping gas as displayed in Figure 3. Later in 1232 the Chinese used these fire-arrows to repel Mongol invaders (Benson, 2021).

Figure 3: Chinese Fire-Arrows (Benson, 2021).

In the latter part of the 17th century Sir Isaac Newton laid the scientific foundation for modern rocketry. He categorized physical motion into three scientific laws that explain how rockets work and why they can work in a vacuum. Newtons laws of motion:

1. The first law of Newton states that an object, at rest or one which is moving in a straight line at a constant speed, will stay at rest or continue moving at a constant speed in a straight line until a force acted upon it. (Gregersen, 2021)

2. The second law of Newton is a measurable description of the variations that a force can generate on the movement of an object. This law states that the acceleration of change of the momentum of an object is equal to the force inflicted on the object both in direction and magnitude. (Gregersen, 2021)

3. The third law of Newton states that when two objects interact, they apply forces with equal magnitude to one another, nonetheless in the opposite direction. (Gregersen, 2021)

The first liquid rocket was designed in the early 20th century by Robert H. Goddard. The first rocket reached an apogee of 12.5 m and had a flight time two and a half seconds. This was the start of modern rocketry. He has been called the father of modern rocketry. He also developed a gyroscope system for flight control, a payload compartment and parachute recovery systems (Benson, 2021).

After World War II (1960s) the space race started. The first satellite that was sent to space was a Soviet satellite on Oct. 4, 1957, in the Sputnik mission. Afterward the United States launched its Explorer 1 satellite onboard a Jupiter-C rocket in February 1ste 1985. Shortly afterwards animals were launched into space and then humans in 1961 (Howell, 2018).

The United States made history when they flew astronauts to the moon and safely back to earth with the Apollo mission. They achieved this magnificent feat with the Saturn V rocket and the Apollo spacecraft (Sharp, 2018). On July the 20th 1969 Neil Armstrong climbed down a ladder onto the mood and gave his first step with words that have echoed through history: "That's one small step for man. One giant leap for mankind." (Baese-Berk, 2019).

Several companies have joined the space exploration race and now manufacture uncrewed rockets that routinely fly to the ISS and launch experiments into space. SpaceX and Blue Origin are among the leaders in rocket technology and autonomy and have developed reusable first stage rockets (Howell, 2018).

2.2 Model Rockets

Model rockets feature a simple design. They compromise of a body tube, a set of fins, a nose cone, a recovery system with a parachute, recovery wadding and a rocket motor to supply thrust. The recovery wadding is fire-retardant and is placed between the rocket motor and the parachute to protect the parachute from the ejection charge (Rockets, Unknown).

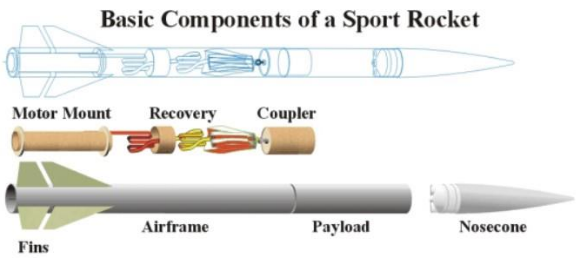

Figure 4: Basic components of a model rocket (Fly Rockets, Unknown).

2.2.1 Flight stages of a model rocket

The motor is ignited with a spark and starts burning. When the motor starts burning it propels the rocket upward at an increasing velocity. The velocity is too small for the fins to supply sufficient stability during launch and therefore a launch rod is used to guide the rocket until the velocity is sufficient. The Fins then provide aerodynamic stability to the rocket. After the propellent in the rocket burns out the rocket coasts upward and reaches its maximum altitude (apogee) where it then stops and starts freefalling back to earth. A small ejection charge in the tip of the motor explodes and creates enough pressure to push the parachute and nosecone out of the body tube. The rocket then floats safely back to earth

(Fly Rockets, Unknown). Figure 5 displays the flight stages of a model rocket as discussed above.

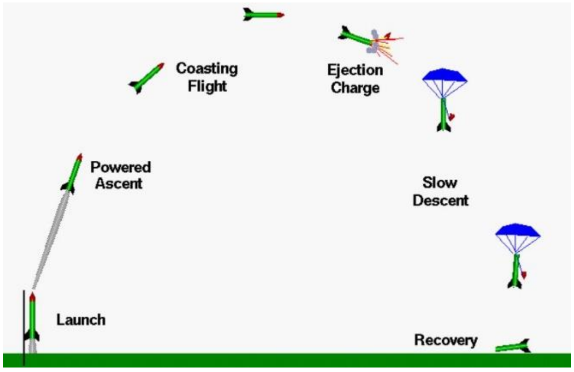

Figure 5: Flight stages of a model rocket (Benson, 2021).

2.2.2 Forces acting on a model rocket

While in-flight the rocket is subject to four forces: Gravity (Weight), thrust, lift and drag. The magnitude of the weight force depends on the mass of the rocket and acts downwards to the earth as it is a function of gravity. The force acts through the yellow point as illustrated in Figure 6, and is called the centre of gravity (CG) or sometimes also called the Centre of Mass. The thrust is supplied by the rocket motor and depends on the mass flow rate through the engine and the pressure and velocity values at the nozzles exit. All common model rockets have a stationary motor mount and therefore, the motor thrust acts along the longitudinal axis of the rocket and thus through the centre of gravity. A full-scale rocket can gimbal the motor, this is called Thrust-vector control. This results in a torque around the centre of gravity that can be used to steer the rocket (Benson, 2021)

The magnitude of the aerodynamic forces, lift and drag, are dependent on factors such as the size, shape and velocity of the rocket and atmospheric properties. These forces act through the yellow point with the black centre illustrated in Figure 6, and is known as the Centre of Pressure (CP). Model rockets rely on aerodynamic forces for a stable flight where for full-scale rockets these forces are not that important as they only spend a short amount of time in the atmosphere (Benson, 2021). These four forces constantly change direction and magnitude in-flight. Aerodynamic stability is ensured when the centre of mass is in front of the centre of pressure. The fins that are added to model rockets move the centre of pressure point towards the bottom of the rocket, thereby ensuring aerodynamic stability.

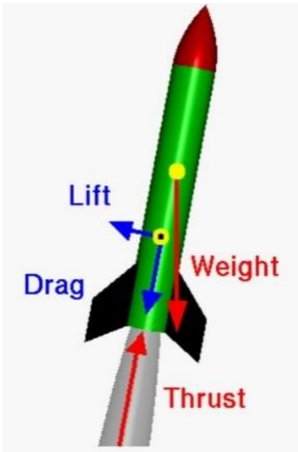

Figure 6: Forces acting on a rocket in-flight (Benson, 2021).

2.2.3 Model rocket motors

Model rocket motors come in various sizes. They are classified according to their 'total impulse' value and then assigned a letter as displayed in Table 1. With each increasing letter the total possible impulse doubles. For example, a "B" motor has twice the impulse of a "A" motor (Fly Rockets, Unknown).

Table 1: Table of Rocket Motor Impulse by Letter Designation (Apogee Rockets, 2004).

Rocket Motor Letter Code			
Class	Total Impulse (Newton-seconds)		
A	1.26	-	2.5
B	2.5	-	5
C	5	-	10
D	10	-	20
E	20	-	40
F	40	-	80
G	80	-	160
H	160	-	320
I	320	-	640
J	640	-	1280
K	1280	-	2560
L	2560	-	5120
M	5120	-	10240
N	10240	-	20480
O	20480	-	40960
P	40960	-	81920
Q	81920	-	163840

A model rocket motor's letter is followed by a number as can be observed in Figure 7 with the D12-5 motor. The first number indicates the average thrust of the motor in newtons. The last number is called the delay time of the motor. This indicates the time between motor burnout and the firing of the motor's recovery ejection charge. When burnout is reached the rocket is still traveling at a high velocity. The delay time allows the rocket to cruise to its apogee and slow down before the parachute is ejected. This ensures that the parachute isn't ejected at maximum velocity and then breaks when ejected (Fly Rockets, Unknown).

Figure 7: Single use model rocket motor: D12-5.

2.2.4 Model rocket stability

Rocket stability is essential to achieve a successful flight. Wind gusts and thrust inconsistency can make the rocket wobble in-flight. The rocket rotates around its centre of gravity (CG), displayed as the yellow dot in Figure 8. If the rocket rotates then a displacement angle (a) can be observed from the vertical axis. Due to this inclination a lift force will be generated by the fins of the rocket and the body. The drag force can be assumed to stay constant for small displacement angles. Aerodynamic forces, namely lift and drag, acts through the centre of pressure (CP) displayed as a yellow dot with a smaller black dot inside in Figure 8 (Benson, 2021).

The centre figure in Figure 8 displays the rocket in an undisturbed condition where the rocket's orientation is aligned with the flight direction and thus no lift is generated. The drag force is vertically down along the flight direction axis. The left figure displays a rocket that is under powered flight and has tilted to the right. The right figure displays a rocket that is coasting and that has tilted to the left. The off course or displacement angle is denoted as 'a'. Drag and lift generates a counter-clockwise torque on the left figure and a clockwise torque on the right figure. In both cases the torque moves the nosecone back to the flight direction and thus these forces are also referred to as restoring forces. This is only true when the CP is below the CG. If, however the CP is above the CG then these forces will keep their orientation and thus cause an inverse torque resulting in the nosecone being pushed away from the flight direction and thus these forces are classified as de-stabilizing forces (Benson, 2021).

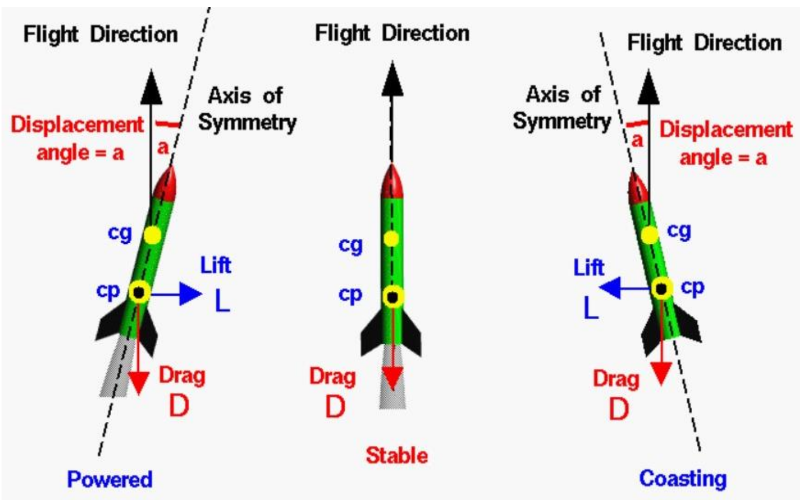

Figure 8: Model rocket stability (Benson, 2021).

A simple swing test can be performed to ensure a rocket is stable to fly. The test requires that a sting is tied around the rockets CG and that the rocket is in a ready to launch state. This entails that the recovery systems should be loaded and a rocket motor must be inserted. The rocket is then swung around a person and observed. For a rocket to be stable the nosecone must point forward in the direction of rotation, this means that the CP is below the CG. A rocket is unstable if the rocket wobbles or the nosecone points opposite the direction of rotation. To increase stability weight can be added to the nosecone to increase the height of the CG or by increasing the fin size and thus lowering the CP (Benson, 2021).

2.3 Thrust Vector Control

Two important concepts of rockets are stability and control. Toy or model rockets utilize aerodynamic forces to ensure the rocket is stable in-flight, but these rockets have no system to do in-flight control of the rocket. For practical real-world missions, a rocket requires stability and control. The rocket requires a guidance system with sensors and computers to determine the rocket's location, speed and orientation. Several systems exist to manoeuvre/control the rocket in-flight, only the most commonly used systems will be displayed below. The first system is controllable aerodynamic surfaces as with airplanes. This system is used mainly for rockets that do not leave the earth's atmosphere and is displayed in Figure 9 (Benson, 2021).

Figure 9: Movable aerodynamic fins (Kopp, 2009).

The second system is thrust vanes. These vanes are installed in or near the rockets motor thrust and vectors the thrust in the desired direction as displayed in Figure 10 (Benson, 2021). When the exhaust gasses exit the nozzle, they are deflected by the vanes thus changing the thrust angle.

Figure 10: Thrust vane control (Kopp, 2009).

The final system is used in modern rockets and is called gimbaled thrust. This is where the exhaust nozzle is gimballed to vector the thrust as displayed in Figure 11. The middle figure displays the normal flight condition where the nozzle is not gimbaled and thus the thrust is in line with the CG and thus no torque is created. The figure on the right has the nozzle gimballed to the left at a gimbal angle denoted as 'a'. This introduces a counter-clockwise torque around the CG that causes the nosecone to rotate to the left. The rocket on the right preforms the inverse of the rocket on the left with the nozzle now gimbaled to the right. This causes a clockwise torque and in turn rotates the nosecone to the right (Benson, 2021).

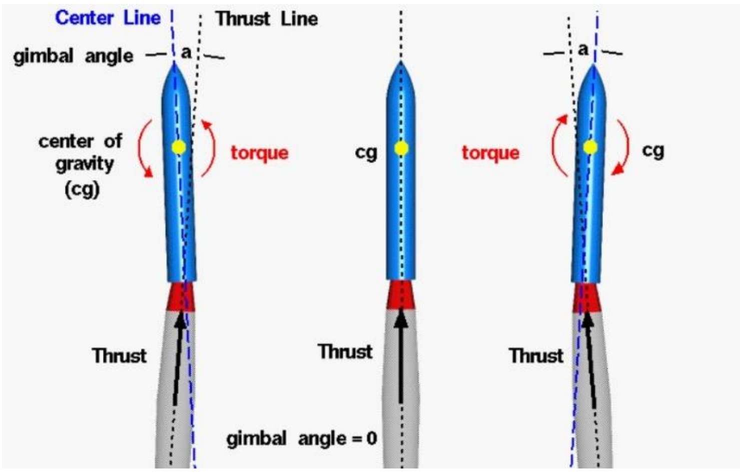

Figure 11: Gimbaled thrust (Benson, 2021).

2.4 BPS Space TVC model rockets

BPS Space is a model rocket aerospace company situated in the USA. BPS Space is one of the only companies that develops active stabilization-controlled model rockets to closely match the space industry. The company uses gimbal TVC to stabilize their rockets and has had more than 40 successful flights. The gimbal consists of an outer ring that houses the yaw servo motor and an inner ring that houses the pitch servo motor as displayed in Figure 12. The mount also has a inner tube where the motor is inserted. The mount is 3D printed using PLA and screws and wires are used for assembly. The mount can withstand 40 N of thrust and has a maximum gimbal angle of about 5° (Barnard, 2021).

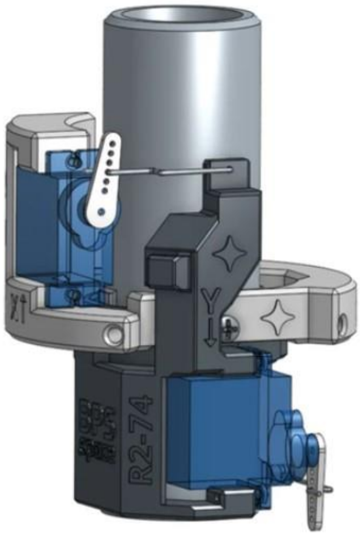

Figure 12: BPS Space TVC mount (Barnard, 2021).

BPS Space developed their own flight computer called 'Signal' and is illustrated in Figure 13. The flight computer controls the thrust vectoring, data logging, parachute ejection and in-flight emergency aborts. It also has an embedded antenna for in-flight data streaming, Bluetooth connectivity and a status LED and buzzer. The software tracks the rocket's flight dynamics while in-flight via the barometer and IMU. The flight computer utilises a state machine with different state switching conditions. The states are pad-idle, lift-off, burnout, apogee, ballistic descent, parachute descent and landing. Once the computer is switched on it switches into pad-idle mode where it can sense lift-off in under 10 ms. Once detected the TVC is activated, in-flight abort is armed and high-frequency data logging begins.

The flight data logging takes place at a speed of 40Hz. All available data is recorded to a high-speed flash chip during the flight. When the flight computer switches to the landing state then the computer creates a new CSV file on the onboard micro-SD card and saves the data from the flash to the CSV file on the SD card. Certain flight settings can also be programmed via a settings file on the Micro SD card.

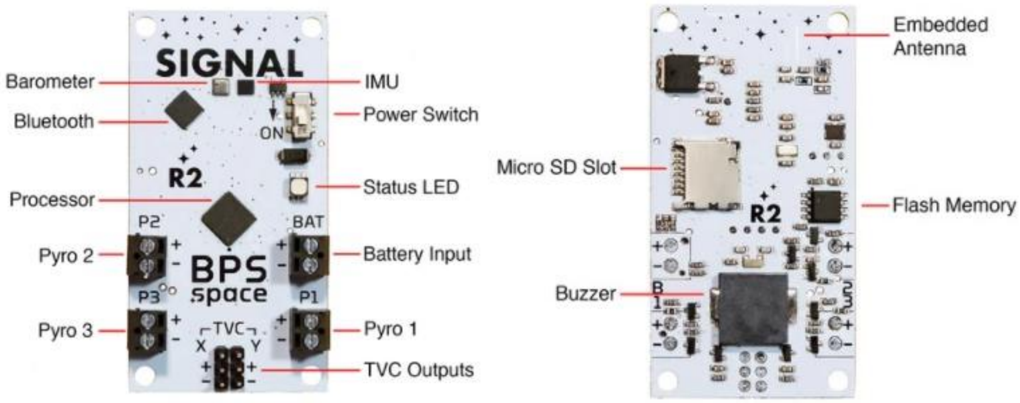

Figure 13: BPS Space flight computer named 'Signal' (Barnard, 2021).

BPS Space's first launchpad consisted of a wooden frame and a circular holder for the rocket with an exhaust gas deflection tube at the bottom as displayed in Figure 14. The launchpad utilized an Atmel ATmega328P for the launchpad code to communicate with the rocket and ignite the motor.

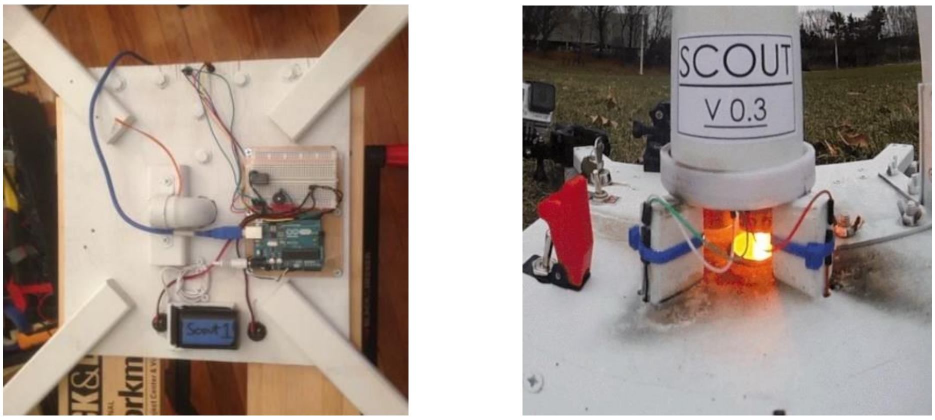

Figure 14: BPS Space launchpad version 1 (Barnard, 2021).

3 Safety and Risk Analysis

In this section the risks associated with the project with regards to safety and the successful completion of the project will be discussed. Appendix E.1 displays a risk and safety report.

The biggest risk category of this project is safety. The rocket uses black powder/composite rocket engines that poses a fire and safety hazard. These risks will be mitigated by compiling a launch safety checklist. This list will include steps that need to be followed before each launch is performed. Safety measures must also be in order. One of the most important steps is to ensure that the safety perimeter at the launch site is equal to the highest altitude the rocket could reach. A fire extinguisher must always be accessible when working with the rocket engine.

There is a risk that the project may exceed the estimated cost. This risk will be mitigated by performing inhouse manufacturing, incorporating cost limitations in the design and choosing the components and materials by keeping the cost factor in mind.

The second major risk is exceeding the projected time duration and falling behind schedule. This risk will be mitigated by strictly adhering to the Gannt Chart in Appendix D.2 and working overtime if it is necessary. The project's Gannt Chart also has some slack to allow delays and other unforeseen circumstances to not influence the overall project deadline.

4 Design Requirements

Design requirements were created from the objectives in Section 1.2. The requirements were created as Technical Performance Measures (TPM). The TPMs are listed below in

Table 2: TPMs for the design of a TVC model rocket.

System	TPM ID	Value
Recovery system	TPM1	The rocket shall deploy a parachute to ensure safe landing. The parachute shall ensure a descent rate of less than 5 m/s to ensure reusability.
	TPM2	The parachute should inflate fully in an altitude decrease of 5 m after deployment.
Data logger	TPM3	In-flight data shall be stored to the onboard RAM for post flight analysis. The data shall be logged at a rate of 100 Hz or 10 ms.
	TPM4	The flight computer should save log data to an SD card when the rocket has landed. The data should be saved in a text file.
Gyroscope	TPM5	A MEMS gyroscope shall be used to measure the rocket angular rates.
Accelerometer	TPM6	The accelerometer shall be used as a failsafe for lift-off detection. It shall detect lift-off in less than 500 ms.
Control system	TPM7	The control system shall dynamically calculate servo values for flight correction and shall have a control loop period of 10 ms or less.
	TPM8	The control system shall ensure flight stability with Pitch and Yaw angles smaller than 15°.
TVC mount	TPM9	The TVC mount shall manipulate the rocket motor in the pitch and yaw direction. The minimum pitch and yaw angles range shall be 5°.
Launchpad	TPM10	The launchpad shall hold the rocket upright and ensure that the exhaust fumes are deflected away from the rocket and the ground.

Launch controller	TPM11	This component shall enable a launch signal communication from the launch controller to the rocket. The GPIO connection between the launch controller and the rocket shall have a common ground.
	TPM12	Wi-Fi connectivity shall be required to control the launch. A Wi-Fi hotspot shall be created for a cell phone to connect to the launch controller with a connectivity range of 50 m or greater.
	TPM13	The launch controller shall have a minimum battery life of 30min.
	TPM14	It shall have the ability to switch a relay, with a 12V connection to the igniter, to ignite the motor.
Mission control app	TPM15	An arm and disarm button shall be implemented in the App as a safety feature. When armed the rocket shall be launched with a T-minus ten second count down.
	TPM16	The Mission control app shall require Wi-Fi connectivity to be able to connect to the launch controller Wi-Fi hotspot.
	TPM17	The App shall have a launch button. When the button is pressed the app shall send a signal to the launch controller to launch the rocket.
Flight computer	TPM18	A custom double sided PCB board should be used to house all the sensors and other components.
	TPM19	The flight computer shall fit inside the rocket body and be as light as possible. Therefore, the size of the flight computer shall be limited to a width less than 75 mm and shall not exceed a length of 120 mm.

5 Conventional Model Rocket

A conventional model rocket (CMR) was built and tested to obtain a rocket license in accordance with SAAMSA. The rocket was also used to measure the TVC rocket against and gain insight into the dynamics of a rocket.

5.1 The Design of the CMR

OpenRocket software was used to design and simulate the conventional model rocket. In Figure 15 the design of this rocket can be seen and Figure 19 shows the simulation. The rocket has four fins with a total length of 56.7cm, a diameter of 5.5cm and a total weight of 203g.

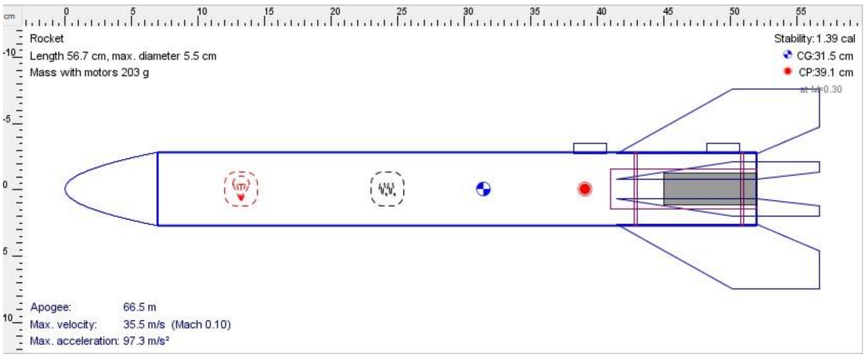

Figure 15: OpenRocket Model Rocket design.

A steel launchpad, with a launch guide rod as displayed in Figure 16 was built to ensure the rocket has sufficient velocity before the rocket leaves the rod.

Figure 16: Rocket launchpad with guiding rod.

5.2 The Stability of the CMR

Model rockets can be classified a stable or unstable by calculating their stability factor. The stability factor is an indication of the rocket's inflight aerodynamic stability. If the stability factor is greater than 1 then the rocket is stable and if it is smaller than 1 then the rocket is unstable. The greater the stability factor the more stable the rocket is inflight. The stability factor is calculated using the CP, CG and the rockets body diameter as displayed in equation 1 below. From this equation it is noted that the CP must always be at least half a rocket body diameter below the CG to achieve any sort of stability.

5.2.1 OpenRocket Software

After completing the final design of the CMR, using OpenRocket software, the results showed that the rocket had a stability of 1.39, a CP located at 39.1 cm and a CG located at 31.5 cm from the top of the rocket. The rocket is therefore stable because the stability factor is greater than 1 according to OpenRocket.

5.2.2 Analytical analysis

The stability equation below was used to determine the rocket's stability analytically (Sawicki, 1966):

$$CG - CP > 0.5 \times Body\ diameter \tag{1}$$

The CG of the rocket was determined by establishing the balance point of the rocket and measuring the distance from the bottom of the rocket to the CG. This was determined and found to equal to 23 cm.

To determine the CP 'The Shadow cut-out method' were used and is illustrated in Figure 17.

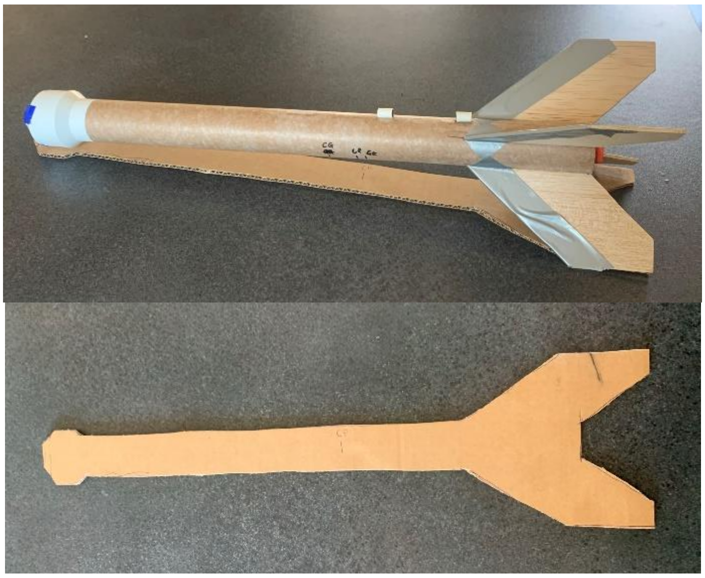

Figure 17: Shadow cut-out method.

For this method the rocket was placed on a cardboard sheet and the rocket's shadow was cut-out of the cardboard. The balancing point of the cut-out was a conservative estimate of the rockets CP. The CP was determined to be located at 19.5 cm.

Thus, using the stability equation above, the stability factor was determined to be equal to 1.27 as shown below.

$$23 - 19.5 > 0.5 \times 5.5$$
$$3.5 > 2.75$$
$$Stability\ factor = \frac{3.5}{2.75} = 1.27$$

This ensured that the rocket was stable and correlated with the OpenRocket stability factor of 1.39. Due to human error and material mass distribution inconsistency the two factors varied by 9% which is acceptable as both indicated that stability was achieved.

Lastly, a 'Swing test' was preformed to validate the stability of the rocket experimentally. The swing test was conducted by tying a 2 m string around the CP of the rocket. The rocket was then swung around a person's head and the flight was observed. If the rocket flew in a straight line with its nosecone pointing in the forward flight direction, then the rocket was considered stable and ready to launch. However, if the nosecone pointed backward or flew sideways then the rocket was unstable. Initially the CMR flew backwards and was therefore unstable. The stability of the CMR was increased by moving the CG forward. This was achieved by adding weight to the nosecone and to repeat the swing test again until a satisfactory result was obtained as shown in Figure 18.

Figure 18: Stability Swing Test.

5.2.3 Simulation and Flight

The rockets flight was simulated in OpenRocket with a C11-5 motor as displayed in Figure 19. From the simulation the following data was observed:

- The Apogee was equal to 66 m

- The Maximum velocity was equal to 35.5 m/s
- The Maximum acceleration was equal to 97.3 m/s^2

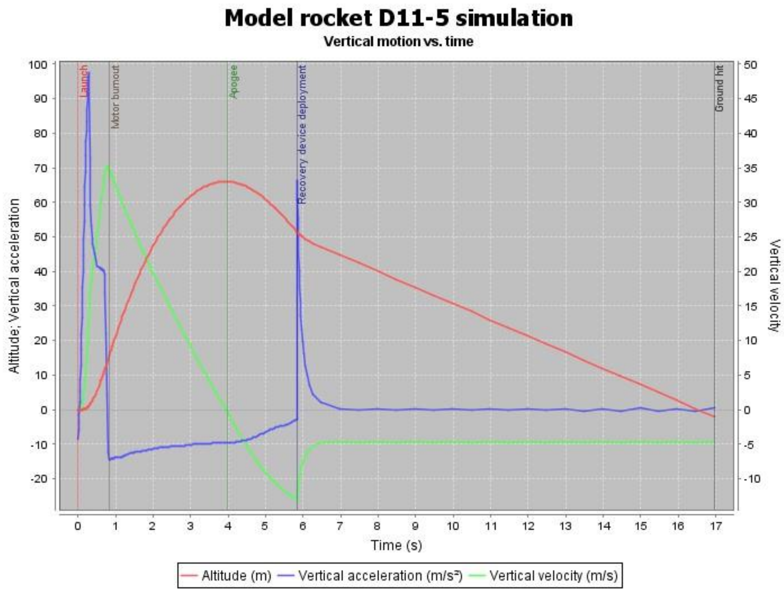

Figure 19: OpenRocket Model Rocket flight simulation.

The launch of the model rocket was performed on Stellenbosch University's rugby field and in Figure 20 the rocket, leaving the launch rod, is illustrated. The launches were all successful with an estimate apogee reached of 70 m and successful recoveries.

Figure 20: Model rocket leaving the launch rod.

6 Flight Computer Design

A flight computer was designed for the rocket. It houses all the sensors, microcontrollers and power managing systems. The flight computer was designed with the following features:

- Voltage regulation
- Program for Autonomous control systems
- Data collection and storage
- Altitude calculation
- Orientation and acceleration
- Program state indication system

Specific sensors and components were selected to achieve the above-mentioned features.

The Teensy 4.1 microcontroller was selected to control the rocket. It also has extra RAM and an on-board SD card slot for data collection and storage. The teensy requires 5V power and therefore a LM7805 voltage regulator circuit was designed. A DPS310, barometric pressure and temperature sensor, was selected for altitude calculations. It has an accuracy of +-0.02 m and about 0.5°C. For orientation and acceleration, the 9-DOF BNO055 absolute orientation sensor was selected. It has a 3-axis gyroscope, accelerometer and magnetometer. A RGB LED and Buzzer was selected to indicate the state. Different lights and sounds were used to indicate a range of system states.

In Figure 21 the high-level connection diagram of the flight computer is illustrated. A 11.1V 350mAh Lipo battery was used for the power source and the battery was connected via a power terminal to an On/Off switch. The voltage was stepped down by the voltage regulator circuit to 5V. The 5V was supplied to the Teensy, BNO055, DPS310 and all three servos and the DPS310 and BNO055 were connected to the Teensy via I^2C. The RGB LED was controlled by three PWM signals to create a range of different colours once it varied. Lastly, the buzzer was controlled by a square wave.

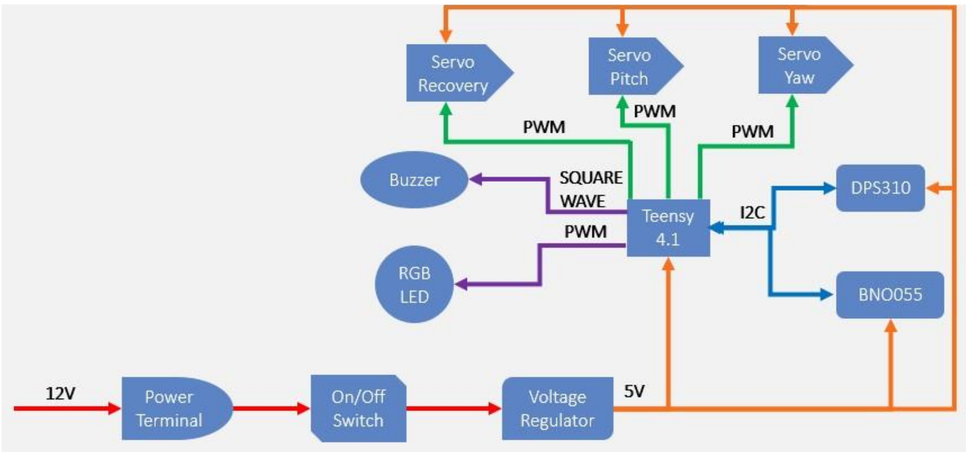

Figure 21: Flight computer high level connection diagram.

After the sensors were selected and the high-level connections were sorted out, the complete schematic was designed in EAGLE as can be seen in Appendix A.1. The circuit was built and tested in a breadbord before desining the PCB. After confirming that all the connections were correct the PCB bord layout was designed as seen in Figure 22. The board's size was first determined to fit inside the rocket body. It was determined that the boards maximum width could be 71 mm and the height should be as short as possible to reduce weight. The components were placed and then the routes were drawn. A track with of 2 mm was used to ensure the tracks were strong and to reduce resistance. The bottom of the board was routed starting with the signal tracks and then the power and ground tracks. After the bottom of the PCB was full vias were created and the remaining connections could be routed on the top of the PCB. Orientation arrows and voltage polarity connections were added to the board.

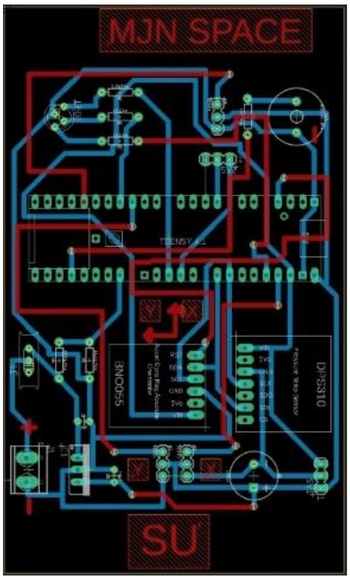

Figure 22: Flight computer board layout.

The final assembled PCB is displayed in Figure 23 below. The black and red wires at the bottom left is the power input and the two sets of black, red and yellow wires in the bottom middle, is the TVC servo wires.

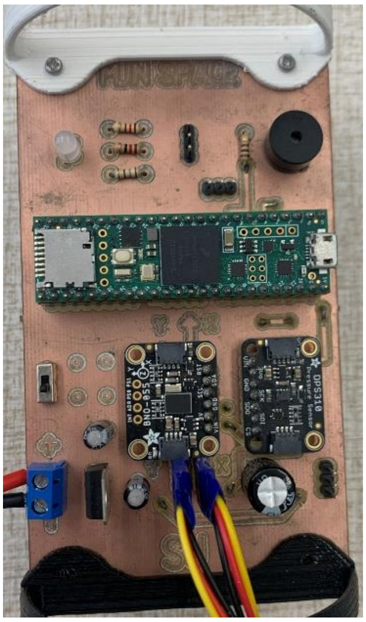

Figure 23: Final flight computer assembled.

7 Hardware design

7.1 Rocket Body

Figure 24 illustrates the full 3D design of the TVC model rocket in CAD. Additional engineering drawings is displayed in Appendix C. The rocket is 730 mm tall, with a diameter of 80 mm and a total weight of 700 gram including the parachute. The rocket body has cutouts to decrease the overall weight of the rocket, to allow the TVC servos full range of motion and to allow access to the flight computer. M2 screws were used to fasten the nosecone, the rocket body, the flight computer mounts and the TVC mount. The rocket body consits of four main parts namely the nosecone, top body part that houses the flight computer, middle body part and the bottom body part that houses the TVC mount and the guide fins for the launchpad. The middle body part is used to increase the height of the centre of gravity and therefore the moment arm that the torque applied from the TVC force. The rocket's centre of gravity is located at a height of 420 mm from the bottom of the rocket.

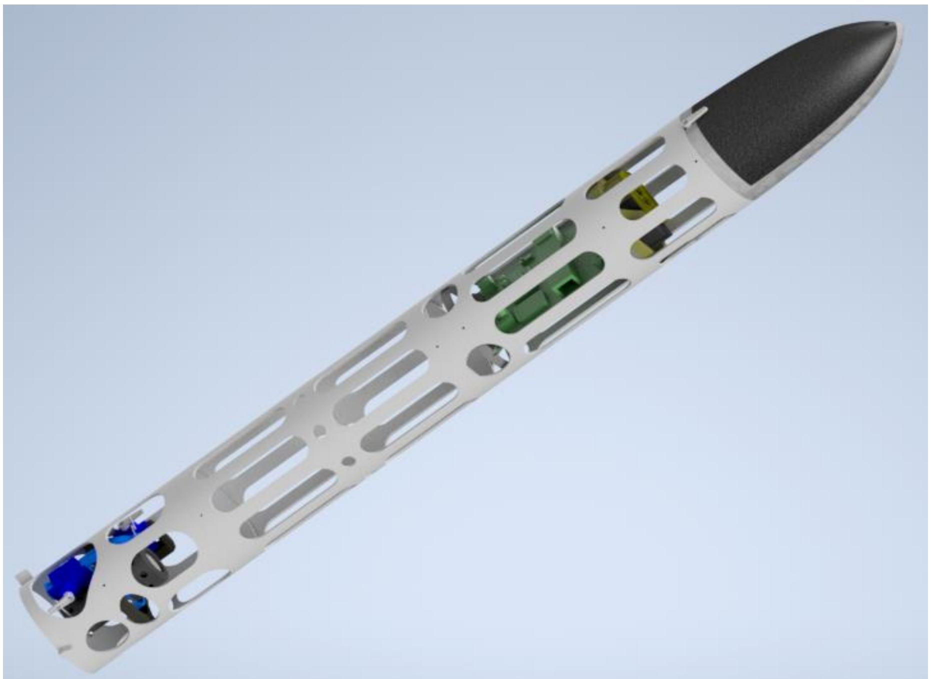

Figure 24: Full 3D design of the TVC model rocket.

7.2 TVC Mount

Displayed in Figure 25 is the TVC mount that was developed using AutoDesk Inventor . The mount utilizes three 3D printed parts, two metal servos and two connection rods. The TVC mount is a two axis gimbal with the motor mount in the middel, to hold the rocket motor.

The outer (black) mount houses one servo and is fixed to the rocket body. The outer servo controls the yaw angle of the motor mount and in turn corrects the yaw of the rocket. The inner mount (blue) houses the second servo that controls the pitch angle of the motor mount and in turn corrects the pitch of the rocket. The mount is designed to allow about 10° rotation from the centre in the yaw and pitch axis. The rods are designed to ensure the motor mount is in its centre position when both servos are at 90°.

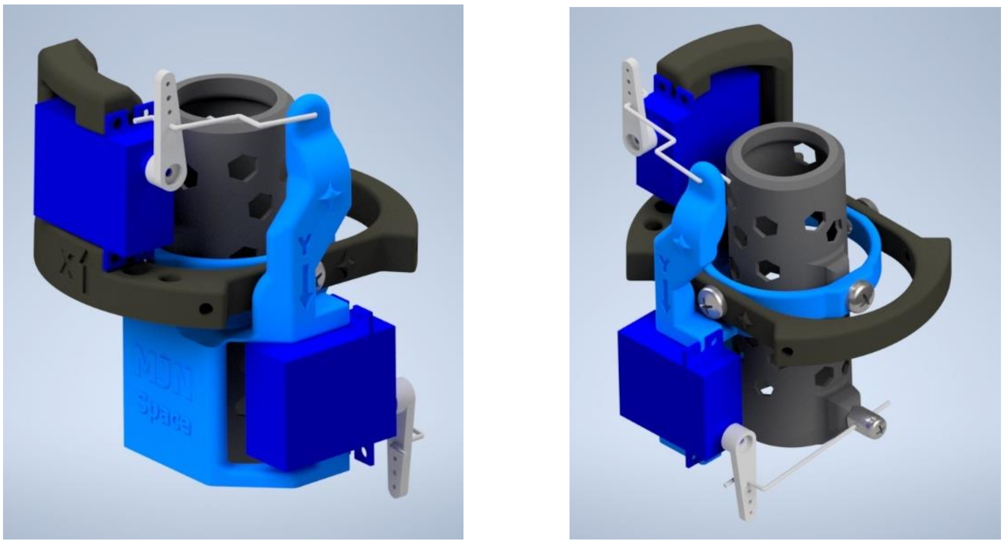

Figure 25: TVC mount CAD.

7.3 Recovery System

7.3.1 Nose cone and parachute design

Figure 26 shows the nosecone and recovery system that was used to ensure the rocket lands safely. The nosecone was designed in Inventor as a five-piece 3D printed part. It consists of the main body, the door which is cut in two parts, the connection ring between the nosecone and the rocket body which also houses the servo and the ejection platform. To ensure that the parachute is ejected quickly, a blue platform was attached to a spring and to the circle housing in the back of the nosecone. The parachute was used to push the platform back and compress the spring. The nosecone door was used to push the parachute in and close the nosecone. To ensure that the parachute did not get caught in the door and that the door breaks away from the parachute, the nosecone door was cut in half.

Six screws were drilled into the nosecone. Three in the front and three in the back. These screws were used to attach an elastic cord, starting at the back top screw where the string was attached and then string around the nosecone to hold the door tight and stop the spring from pushing the parachute out. The other end of the string was attached to the servo in the nosecone. The servo kept the string from releasing and the parachute from opening. When the servo turned the string unwinds, the spring pushed the parachute out and the door separated.

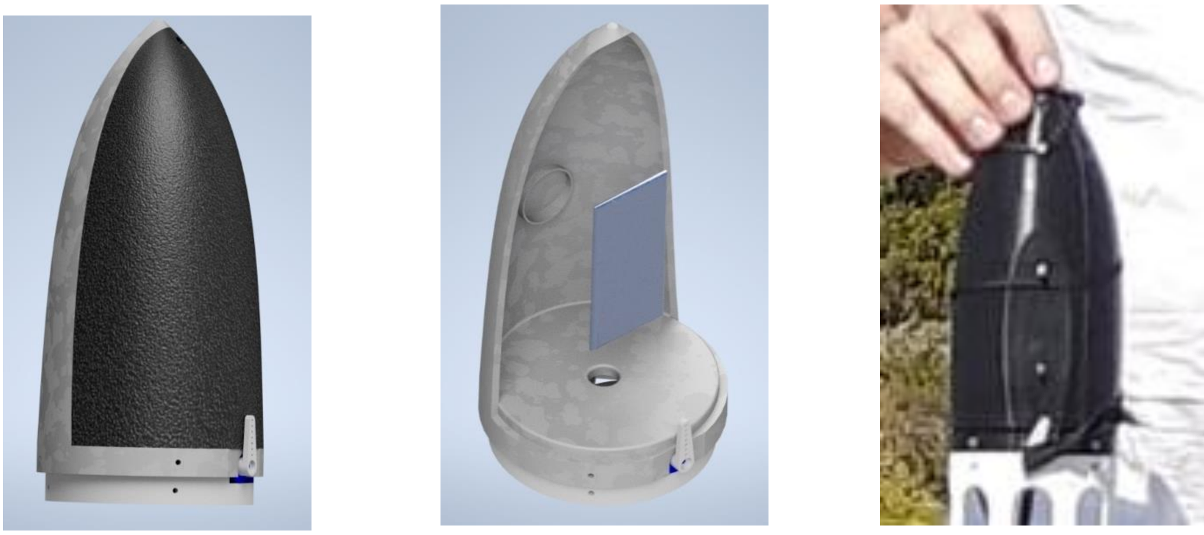

Figure 26: Nose cone/Recovery system.

The parachute was designed to have a decent rate (V) of less than 5 m/s^2 to ensure reusability. Equation **2** below was used to determine the descent rate for various parachute diameters. An octagon parachute was used with a surface area (S) formula of $S = 0.828 \times Diameter^2$. A parachute drag coefficient of 0.75 was assumed. Other constants that were used were the gravitational acceleration (g = 9.81 m/s^2) and the air density in Stellenbosch (ρ = 1.18 kg/m^2). The rocket has a mass (m) of 700g.

$$V = \sqrt{\frac{2 \times g \times m}{\rho \times S \times C_d}} \qquad 2$$

(Van Milligan, 2017)

Calculating the descent rate for a parachute with a diameter of 1m gives a descent rate of:

$$V = 4.33\frac{m}{s^2}$$

therefore, a parachute with a diameter of 1m was selected.

7.3.2 Recovery system testing

A 1 m diameter parachute was built using an old umbrella and shockcord. A swivel was added between the cords form the parachute and the rocket connection cord. The swivel prevents the chute lines from twisting and therefore, shortening the lines which in turn decreases the parachute area and the drag. When the drag decreases then the descent velocity increases. The recovery system was tested by throwing the rocket from a 14 m ledge with and without the parachute and determining the descent speed in both cases as shown in Table 3.

Table 3: Recovery system testing.

Scenario	Fall time [s]	Descent speed [m/s]	Error (Analytical)
Without parachute	1	14	-
With parachute	3	4.4	1.6%

From the experiment it was determined that the parachute had a 66% reduction in descent speed and was satisfactory to the 5 m/s descent speed that was aimed for. The experiment also revealed that the parachute requires 5 m to eject and fully deploy.

The experiment data was also used to confirm the accuracy of the parachute drag coefficient (C_d) that was assumed to be 0,75 in section 7.3.1. Solving equation 3 for C_d yields the equation below.

$$C_d = \frac{2 \times g \times m}{\rho \times S \times V^2} \quad (3)$$

Using this together with parachute descent speed in Table 3, the drag coefficient was calculated as:

$$C_d = 0.73$$

and thus, the assumption made in section 7.3.1 is considered acceptable.

8 Launch system design

In this chapter the systems outside the rocket will be described.

8.1 Launch controller

A wireless launch controller was designed for remote launches to ensure safety. The launch controller electronic design is displayed in Appendix A.2. Figure 27 displays the launch controller.

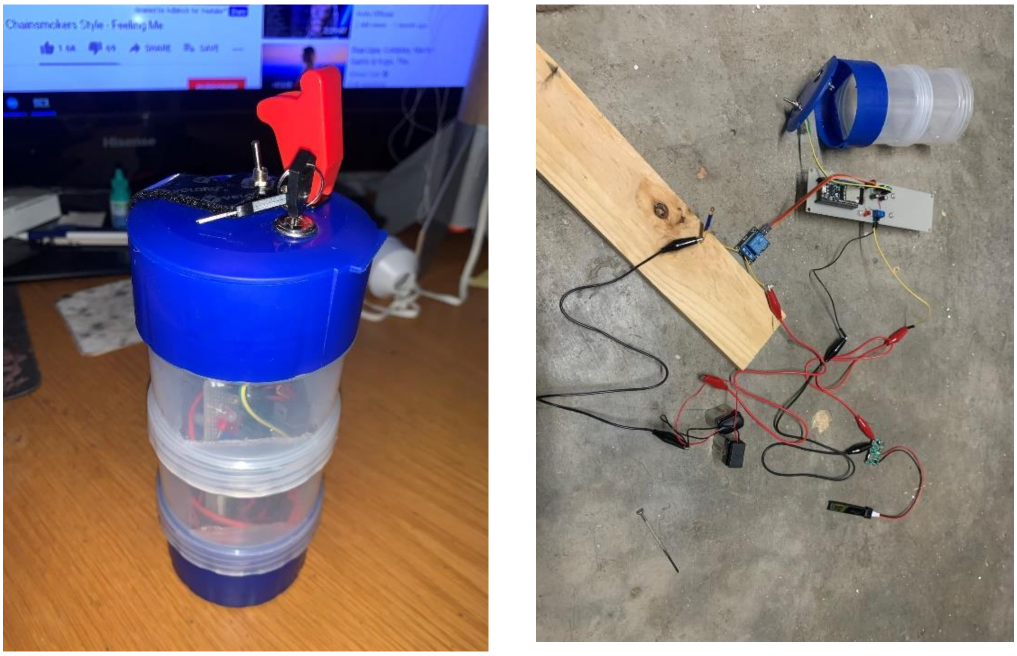

Figure 27: Launch Controller.

The launch controller consists of a ESP32-S for Wi-Fi connectivity, a LM7805 for voltage regulation and a relay to ignite the rocket motor. The launch controller also has a missile cover toggle switch and key switch for safety. To indicate that the ESP32-S is powered an indication LED was added with the necessary resistors. The ESP32-S is powered by two 3.8V lipo batteries in parallel that is stepped up to 12V and then stepped down to 5V by the LM7805 and necessary capacitors. The capacitors sizes were used from the LM7805 datasheet. A 12V lead acid battery is used to ignite the starter when the relay circuit is closed and in turn light the rocket motor. Lastly, the ESP32-S was programmed to create a hotspot for a cell phone to connect to.

8.2 Launchpad

The launchpad was designed in CAD and built out of wood, metal, a 3D printed rocket stand and wood as shown in Figure 28. The launchpad has an exhaust gas deflection tube to ensure the motors exhaust gases does not damage the launch controller or the environment. It also has a holder for the launch controller and four pin mounts to level the launchpad with.

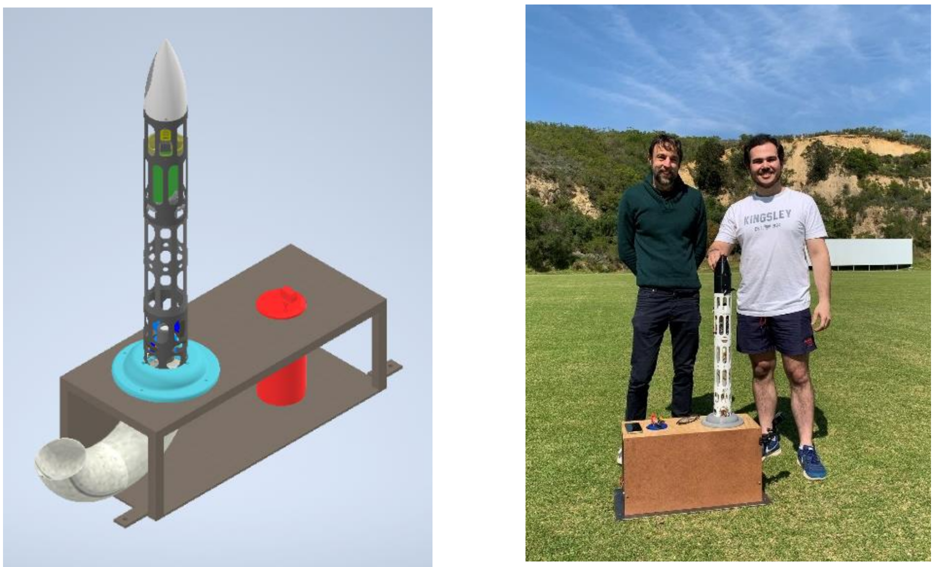

Figure 28: Launchpad.

The launch communication line between the flight computer and the launchpad is connected using pogo pins as displayed in Figure 29. Two pins are used, one to create a common ground as the two microcontrollers are powered by different batteries and the other line is the launch signal from the launch controller. In Figure 29 the 3D printed rocket guide/stand is also illustrated. The 3D printed part has a circular cut-out for the rocket to stand in and three thin slots where the three small guide fins of the rocket fits in. This keeps the rocket upright on the launchpad and assists in guiding the rocket at lift-off.

Figure 29: Communication line connection between the flight computer and the launch controller.

8.3 Mission Control Application and ESP32-S code

To connect to the ESP32-S hotspot an android phone was used. Thus, an android application (.apk) was designed and programmed to enable remote launch capabilities. The App is shown in Figure 30.

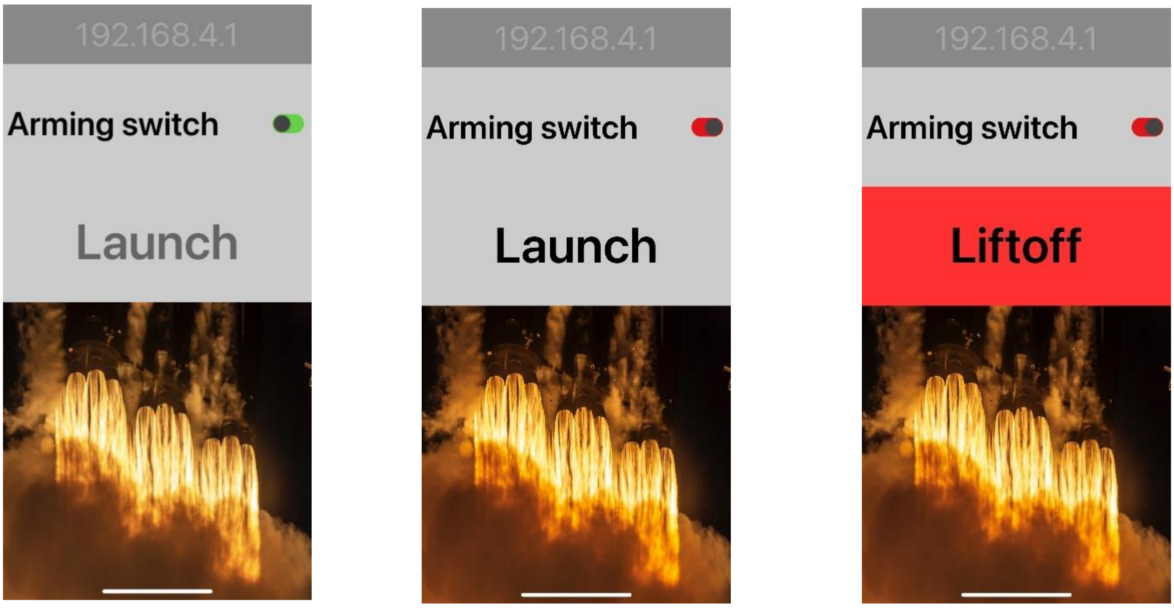

Figure 30: Mission control android application.

The App was designed and programmed with MIT App Inventor. The App also utilizes two safety features namely an arming switch and a T-minus ten second count down. The arming switch must be armed for the launch button to become active as this ensures that the rocket can't be launched by accident. The rocket can also be disarmed while the ten second count down commences if the user identifies a safety hazard.

Figure 31 displays the high-level flowchart of the mission control app. When the app is opened it connects to the Wi-Fi hotspot of the ESP32s. The app then moves into an idle state where it waits for the arming button to be switched to true. When the arm switch is switched on, the app enables the launch button and starts an audio 10 second count down to launch. The launch can be aborted by pressing the arm switch again and therefore, disarming the rocket. The app will then move back to idle mode and disable the launch button. If the rocket was not disarmed and the launch button was pressed, then the app will set the following address 'http://IP_Adress/26/on' which will set the GPIO pin high that in turn switches the relay on and ignites the rocket motor.

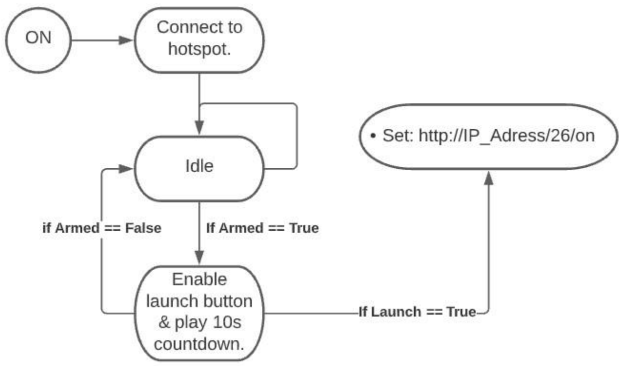

Figure 31: Flowchart for the mission control app.

9 Orientation

This section displays how the rocket's attitude was calculated by utilizing the gyroscope on a BNO055 sensor. The Orientation was determined at a rate of 100 Hz to enable in-flight stabilization by utilizing the TVC mount.

9.1 Quaternions

The raw gyroscope rates, in the x, y and z axis, were used to calculate the quaternions. The right-hand rule is used for the positive axis notation and is displayed in Figure 32. Therefore, the following convention is applied:

- Rotate counter-clockwise around the x-axis is positive roll.
- Rotate counter-clockwise around the y-axis is positive pitch.
- Rotate counter-clockwise around the z-axis is positive yaw.

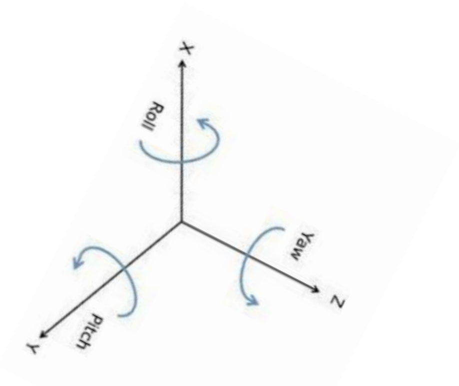

Figure 32: Positive axis notation.

The equations below (Madgwick, 2010 & Narayan, 2017) were used to calculate the quaternions rate of change which in turn was used to calculate the Euler angles in Section 9.2.

Firstly, the quaternion norm ($\|q\|$) is calculated using the three-axis angular velocity's (ω) in equation 4 below.

$$\|q\| = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2} \qquad 4$$

The norm is then multiplied with the elapsed time (dt) to obtain the length of the angular velocity vector ($\emptyset$) in equation 5 below.

$$\emptyset = \|q\| \times dt \qquad 5$$

The scalar value (q[0]) and the three vector values (q[1,2,3]) of the four quaternions was then calculated using equation 6 and 7 below.

$$q[0] = \cos\left(\frac{\emptyset}{2}\right) \tag{6}$$

$$q[1] = -\left(\frac{x}{\|q\|}\right) \times \sin\left(\frac{\emptyset}{2}\right) \tag{7}$$

$$q[2] = -\left(\frac{y}{\|q\|}\right) \times \sin\left(\frac{\emptyset}{2}\right)$$

$$q[3] = -\left(\frac{z}{\|q\|}\right) \times \sin\left(\frac{\emptyset}{2}\right)$$

The rate of change quaternion base (w,x,y and z) is then set for the next orientation calculation.

$$w = \dot{q}_0$$

$$x = \dot{q}_1$$

$$y = \dot{q}_2$$

$$z = \dot{q}_3$$

Lastly, the rate of change of the quaternions ($\dot{q}_{0,1,2,3}$) is calculated with the formulas below.

$$\dot{q}_0 = (q_0 \times w) - (q_1 \times x) - (q_2 \times y) - (q_3 \times z)$$

$$\dot{q}_1 = (q_0 \times x) + (q_1 \times w) + (q_2 \times z) - (q_3 \times y)$$

$$\dot{q}_2 = (q_0 \times y) - (q_1 \times z) + (q_2 \times w) + (q_3 \times x)$$

$$\dot{q}_3 = (q_0 \times z) + (q_1 \times y) - (q_2 \times x) + (q_3 \times w)$$

9.2 Euler Angles

Rate of change quaternions were used to obtain the orientation of the model rocket in Euler angles (Roll, Pitch and Yaw) with equation 8,9 and 10 below. The sequence that was used is x-y-z or Roll-Pitch-Yaw (Madgwick, 2010).

$$\phi\ (Roll) = \tan^{-1}\left[\frac{2(\dot{q}_0\dot{q}_1 + \dot{q}_2\dot{q}_3)}{1 - 2(\dot{q}_1^2 + \dot{q}_2^2)}\right] \tag{8}$$

$$\theta\ (Pitch) = \sin^{-1}[2(\dot{q}_0\dot{q}_2 - \dot{q}_3\dot{q}_1] \quad 9$$

$$\psi\ (Yaw) = \tan^{-1}\left[\frac{2(\dot{q}_0\dot{q}_3 + \dot{q}_1\dot{q}_2)}{1 - 2(\dot{q}_2^2 + \dot{q}_3^2)}\right] \quad 10$$

The positive angles are displayed in Figure 33. These angles calculated above are used as the actual orientation angles in the PID controller to calculate the error and therefore, to generate a control signal as discussed in section 10.

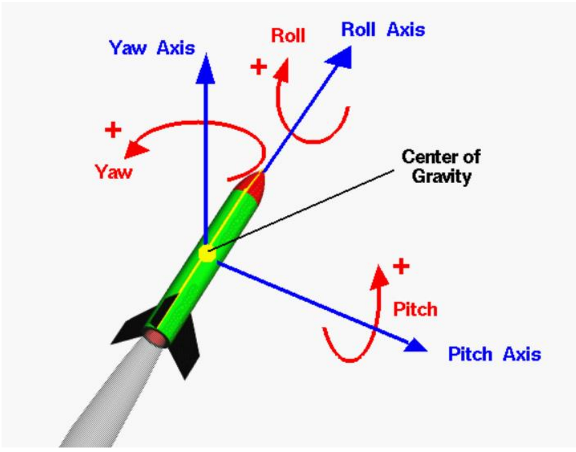

Figure 33: Euler angles axis (Benson,2021).

10 Control System Design

This section displays the control systems design for active thrust vector controlling with the use of Euler angles and a PID controller with a limited integral.

10.1 Stabilization

The rocket's setpoint is vertically up from the launchpad – this implies a reference pitch and yaw angle of zero. The current attitude is calculated by the BNO055_data() function, which samples the gyroscope and performs the Euler angle calculation from equation 8 to 10. The error signal is calculated as the difference between the setpoint and the current orientation.

The error signal is then fed to the PID controller displayed in Figure 34 and a control value is obtained.

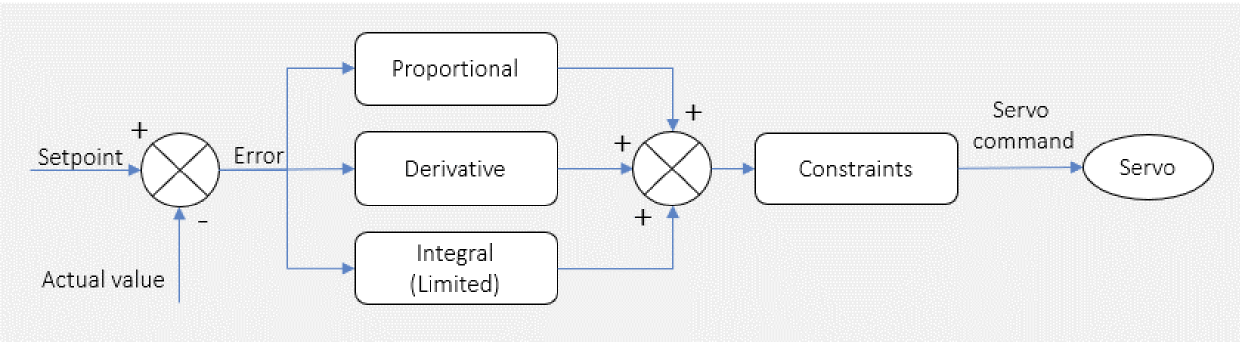

Figure 34: PID controller for TVC.

The control value is then constrained to the TVC servo range to allow 10° rotation from their centres. A check is added to see whether the control value is greater or smaller than the servo centre PWM value, plus or minus the servo range PWM value. The value is constrained to the PWM limits when it is either greater or smaller than the PWM limits.

When the rocket yaw to the left then the servo should move the bottom of the TVC mount to the opposite side to bring the rocket back to a vertical position. A yaw to the left is positive and thus results in a negative error signal. This ultimately decreases the servo value. The Servo was orientated in the motor mount in a way that a decrease in the servo value results in a motor mount yaw in the same direction and thus moves the bottom of the motor mount to the opposite direction as the rockets yaw. This is true for a yaw to the negative or right side as well and for pitch in both forward and backward direction.

The high velocity and turbulent environment that the rocket is exposed to inflight demands a high response rate from the PID controller. A PD with limiting I term controller is used. The proportional gain increases the response rate of the system, whereas the derivative term decreases overshoot, increases the system stability and speeds up the transient response. Due to the aerodynamic effect, wind and other external factors that would stop the rocket from achieving a perfect zero steady state error, the integral term was limited to prevent integrator wind-up.

10.2 Servo Motor Constraints

The TVC mount utilizes two 5V servos. One servo actuates the mount in the pitch axis while the other servo actuates the mount in the yaw axis. The servos are powered by a 11.1V LiPo battery that is stepped down through a linear voltage regulator (LM7805) to 5V on the flight computer. The servos receive PWM control signals from the Teensy to perform specific actuations.

The servo horns are separately connected to the inner and outer gimbal of the TVC mount by means of a thin metal wire. The mount rotation is not equal to the rotation of the servo horn; therefore, the servo values where experimentally determined for a desired mount angle and are displayed in Table 4, below. The metal wire connection was adjusted to ensure that both servos had the same PWM values. The values in Table 4 was determined by incrementing the PWM value and measuring the TVC mount angle. A linear relationship was assumed between the servo horn rotation and the TVC mount rotation. Table 4 below displays the servo PWM constraints. The PWM range can be determined from its centre position (90) as about 60.

Table 4: The TVC mount angle vs Servo PWM signal.

Servo/TVC Mount Position	TVC mount Angle [°]	Servo PWM signal value
Centre	0	90
Minimum	-10	30
Maximum	+10	150

10.3 PID control in Arduino IDE

The PID algorithm utilizes a continuous time domain whereas the Teensy functions on a discrete time domain. Thus, the integral and derivative functions had to be discretised to the discrete time domain to enable compatibility. The derivative control estimation is displayed in equation 11. The integral control estimation is displayed in equation 12.

$$ErrorSlope = \frac{ErrorSignal - ErrorSignalPrev}{\Delta t} \tag{11}$$

$$ErrorSum = \sum_{i=1}^{n} ErrorSignal \times \Delta t \tag{12}$$

With the derivative and integral control now in the discrete time domain the complete PID algorithm is displayed below in equation 13.

$$PID_{value} = k_p \times ErrorSignal + k_i \times ErrorSum + k_d \times ErrorSlope \qquad 13$$

10.4 Experimentally determining PID values

Due to a complex rocket shape and weight distribution the PID values were experimentally determined using the PID test gimbal displayed in Figure 35. The rig is made from 3D printed parts and four pillow bearings.

Figure 35: PID two axis gimbal testing rig.

The motor thrust was simulated with a brushless DC motor, ESC for speed control and a three-blade drone propeller that was mounted to the bottom of the TVC mount. The PID test gimbal allows about 40° free rotation from a vertical position in both the pitch and yaw axis. The rocket was mounted at its centre of mass or rotation point. The DC motor was then switched on to supply thrust and the flight computer was switched on to activate the TVC. Data was logged and analysed after each test.

Testing started with only proportional control. When the system responded too slow, k_p was increased to increase the response speed and in turn if the system had to great of an overshoot, k_p was decreased. The proportional gain was tuned until minimal overshoot was observed.

Next a derivative gain was added at half the size of the proportional gain. The k_d value was increased to decrease the overshoot of the system and to increase the transient response speed. This increased the stability of the system. When the system had to slow of, a response k_d was decreased. The derivative and proportional gain was tuned until minimal overshoot, a fast response time and stability was observed

Lastly, an integral gain was added. The k_i value was chosen as half the derivative gain to ensure it has a small effect on the control. The value was also limited to a finite number to prohibit it from growing over time. The k_i value and the limitation number was tuned until a satisfactory zero steady state error was reached

11 State Machine

11.1 State machine flow diagram

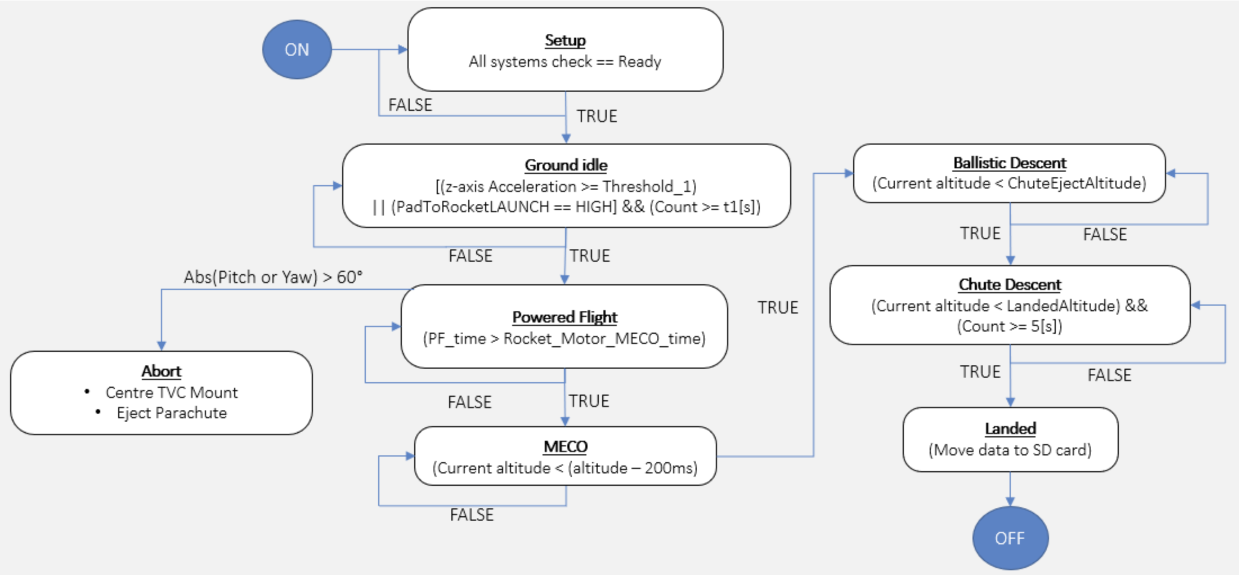

Figure 36: State machine flow diagram.

In Figure 36 the flow diagram of the state machine is illustrated. Each state is explained below:

- <u>Setup (0)</u>

  The flight computer is switched on and the system moves into state one which is setup. In setup a system's check is done to determine if the SD card is present and if the BNO055 and DPS310 is outputting data to the Teensy. If these checks are successful, the system moves to Ground Idle, otherwise it stays in setup.

- <u>Ground Idle (1)</u>

  The TVC mount is locked in a centre position and the moving average bias is calculated for the gyroscope and the accelerometer. The barometer is used to set a ground pressure level to determine altitude inflight. The system then waits for the launchpad to set the 'Pad_to_Rocket_LAUNCH' variable to 'HIGH' to indicate motor ignition and lift-off or until a vertical acceleration of 2 m/s is sensed by the accelerometer. The system then moves to powered flight.

- <u>Powered Flight (2)</u>

  The TVC is activated and the flight data is stored in an array on the onboard RAM of the Teensy. If the absolute angle of yaw or pitch is greater than 60° then the system moves to abort flight. Upon entry to the powered flight state a time is started. When this timer is greater than the motors MECO time, which is hard coded into the program for each motor used, then the system moves to MECO.

- MECO (3)

  The TVC is centred and deactivated. Data recording continuous. The system checks for apogee every 200 ms. This is done by comparing the current altitude to the altitude reading 200 ms ago, if the current altitude is smaller than the previous altitude, then the previous altitude is saved as apogee and the system moves to ballistic descent. The 'ChuteEjectAltitude' variable is set as 95% of the apogee.

- Ballistic Descent (4)

  Data recording continuous while the system checks every 100 ms if the current altitude is smaller than the 'ChuteEjectAltitude'. When the current altitude is smaller than the 'ChuteEjectAltitude' the system moves to chute descent.

- Chute Descent (5)

  The parachute is deployed and data recording continues. The system checks every 100 ms if the current altitude is smaller than the 'Landed' altitude variable for 5 s. When this is true the rocket has landed and the system moves to landed.

- Landed (6)

  Data recording stops and the flight data is saved from the RAM to the onboard SD card in a new flight log. The flight is completed.

- Abort (7)

  If the absolute value of either the yaw or pitch angle was greater than 60° while in the powered flight state, the system would have moved to this state. The TVC is deactivated and centred, the parachute is ejected and the data is saved from the RAM to the SD card to avoid losing data in the crash landing.

11.2 State machine experiment

An experiment was designed to test the state machine in a controlled environment before flight to ensure reliability. A pully system was installed at a height of 14 m in an enclosed environment. The one side of the rope was tied to the rocket and the other side was used to pull the rocket up to the maximum height and then let it down to simulate a dummy flight.

Parameters that were tested and their desired values in the experiment:

1. Launch detection through launch pad communication.

2. Launch detection through acceleration as a failsafe in less than 500 ms.

3. Apogee detection with an accuracy of 5%.

4. Parachute deployment at parachute ejection altitude with an accuracy of 5%.
5. Sensed that the rocket has landed and saves the data to the SD card.
6. Abort state is triggered when the absolute angle of either pitch or yaw is greater than 60°.
7. Data that is recorded is reasonable. Compare data apogee data with estimated apogee.

Figure 37 displays one of the dummy flights plotted. The plot has time on the x-axis, state on the primary y-axis and altitude on the secondary y-axis. The orange line is altitude where the blue line is the current state of the flight computer. The red cross is the apogee determined by the flight computer and the green cross is the parachute ejection altitude.

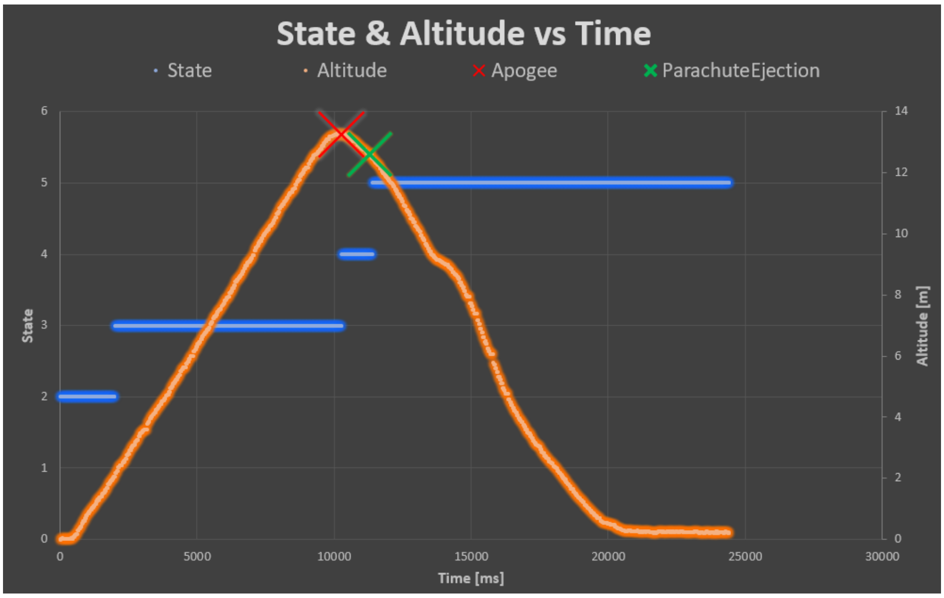

Figure 37: Dummy flight state machine test.

Launch detection was successful by means of the launch pad and the backup acceleration detection with an average launch detection delay of 240 ms.

Table 5 display that the apogee detection and parachute ejection code is functional and reliable. The actual heigh of the pully was 14 m and the rockets heigh is 70 cm thus the expected apogee is 13.7 m which correlates with the measured apogee of 13.28 m and thus the data is reliable. The graph in Figure 37 verifies that data was moved to the SD card and landing has been detected successfully. A test was done where the rocket was pitched and yawed over 60° separately and in both instances the abort state was triggered. The results confirms that the state machine is reliable and successful.

Table 5: Dummy flight experiment parameters.

Variable	Actual [m]	Measured [m]	Error [%]
Apogee	13.28	13.26	0.15 %
Chute ejection altitude	12.6	12.49	0.87 %

12 Testing and Evaluation

Before the whole system was launched the individual subsystems was tested to ensure each systems functional performance was acceptable and if not, the subsystems could easily be adjusted and rapidly prototyped. The subsystems were then combined and ready for flight.

12.1 The Final launch

After all the systems were individually tested and verified, the entire rocket was built and ready to launch. The Stellenbosch University Cricket fields were chosen as the launch site as it has a large open space and therefore could be safely evacuated and observed. In Figure 38 the launch site used and the rocket at lift-off is illustrated.

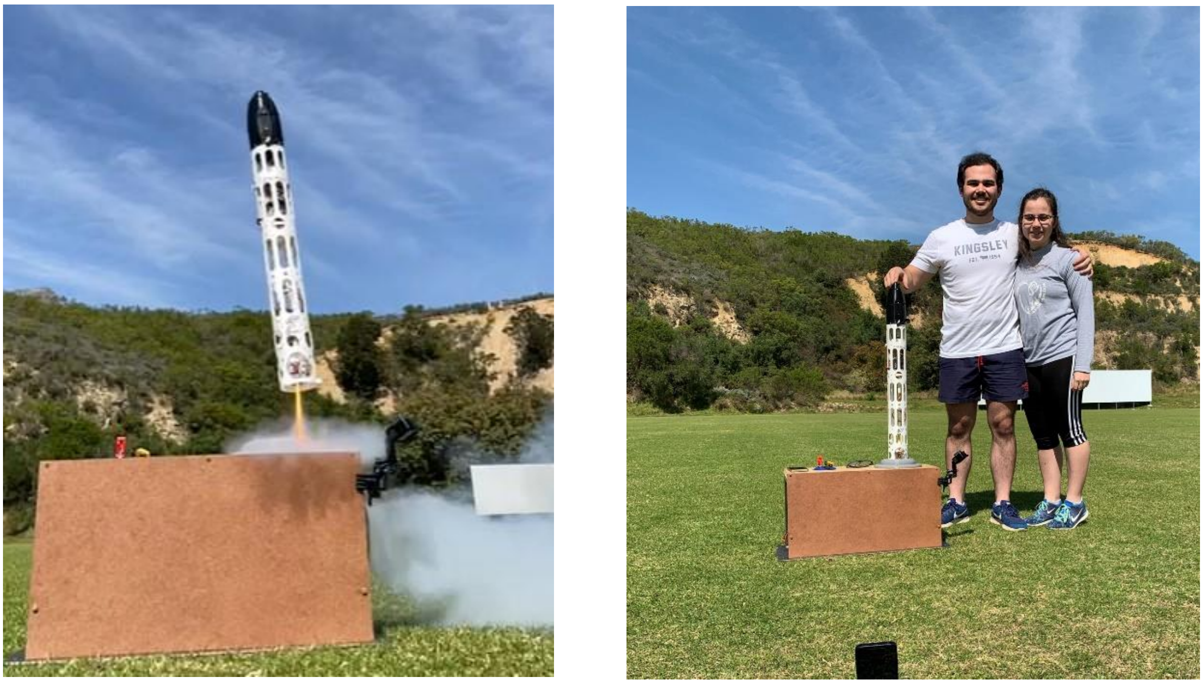

Figure 38: Launch site and lift-off.

The conditions on the day of launch were as follow:

- Wind speed of 15 km/h
- And the temperature was 22 °C.

12.1.1 Launch 1

A D12-0 Estes rocket motor was used. It supplies an average thrust of 10 N, peak thrust of 30 N and has a burnout time of 1.65 s. Figure 39 displays the motors thrust curve.

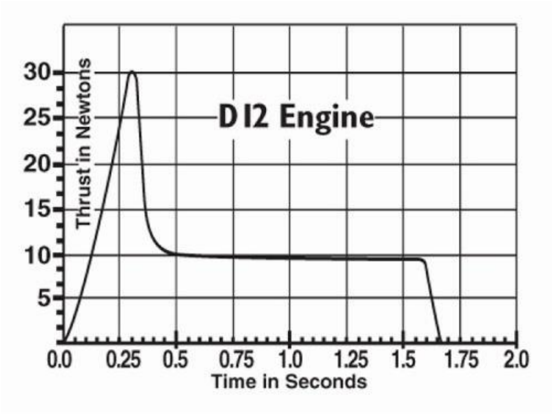

Figure 39: D12-0 Thrust curve (Coker, 1998).

Figure 40 illustrates the maiden flight data. The plot shows the time in ms on the x-axis, state on the primary y-axis and altitude in m on the secondary y-axis. The orange line is altitude where the blue line is the current state of the flight computer. The red cross is the apogee determined by the flight computer and the green cross is the parachute ejection altitude.

Figure 40 shows that the altitude reached 4.68 m and that the apogee determined by the flight computer was also 4.68 m thus, a 0 % error with altitude detection in the first launch. The states switched perfectly, and the parachute was ejected. Due to the motor not having enough thrust and therefore achieving the low altitude the parachute did not have enough time to open the rocket freefall to the ground. Fortunately, only a few 3D parts were broken and was fixed onsite for flight two.

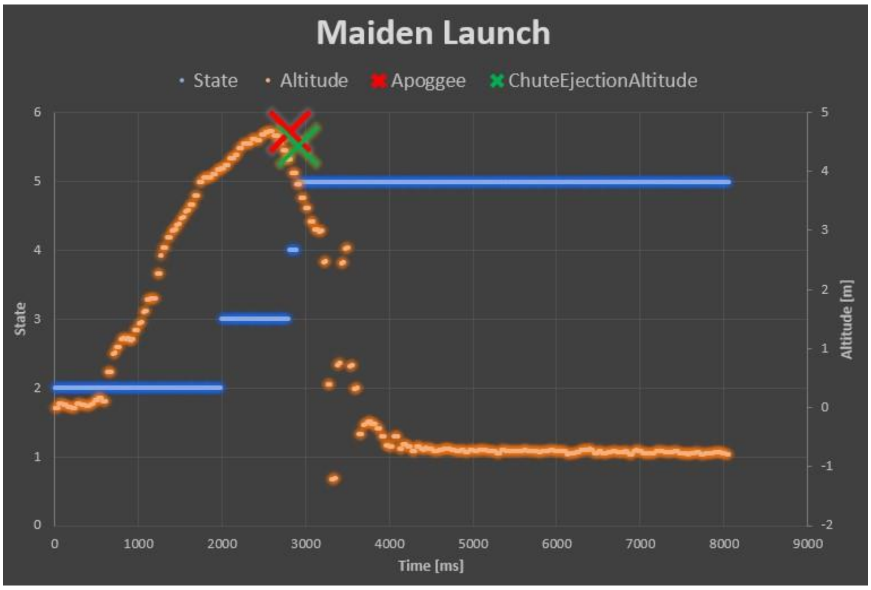

Figure 40: Maiden Launch Graph.

Figure 41, Figure 42 and Figure 43 displays the pitch, yaw and roll data respectively for flight one for the first two seconds or the powered flight state.

In flight 1 the rocket had increasing oscillations (Blue line) in the pitch axis around the 0° or vertical angle as displayed above in Figure 41. The servo value starts out at its centre position for the first 500 ms and then starts correcting for a yaw offset likely induced by the wind. The servo overcompensates and turns the other way and maxes out the servo angle with a PWM value of 150. The rocket angle is corrected in the opposite direction but overshoots again and this time with a greater amplitude. This was the case for the entire flight. The first conclusion drawn is that the PID controller is too sensitive and its k_p value is too great. The second conclusion was that the D12-0 motor does not have enough thrust and therefore cannot do sufficient orientation correction.

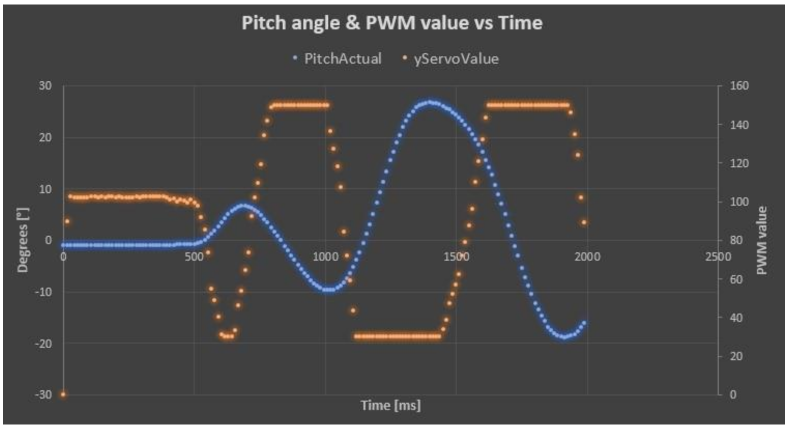

Figure 41: Launch 1 Pitch data.

In flight 1 the rocket had increasing oscillations (Blue line) in the yaw axis as displayed above in Figure 42. The yaw angle starts out with a 2.24° error. This is acceptable due to the low-cost sensor that is used. The centre or zero position value of the yaw angle also drifts with time as seen with the negative oscillation centre point drift. The same conclusions can be drawn as with the pitch angle.

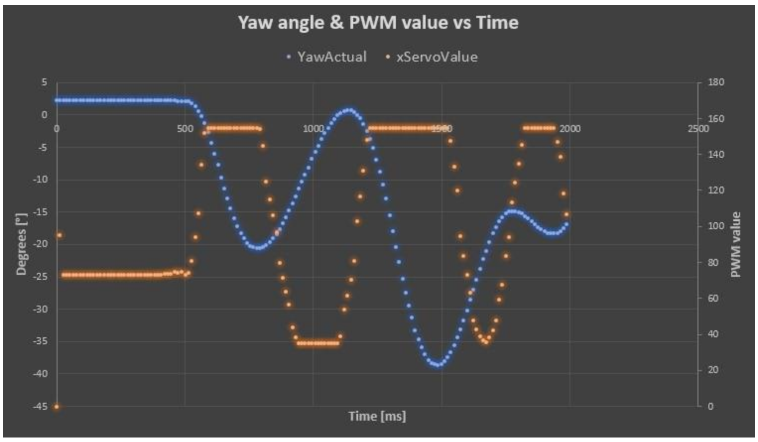

Figure 42: Launch 1 Yaw data.

Figure 43 displays the roll angle for flight 1. The roll angle has about 10° oscillations for the first 1600 ms and then the roll angle grows. The motor reaches burnout after 1600 ms and the TVC mount therefore has no control after that. This is acceptable as the TVC mount cannot compensate for roll and thus no roll control is implemented.

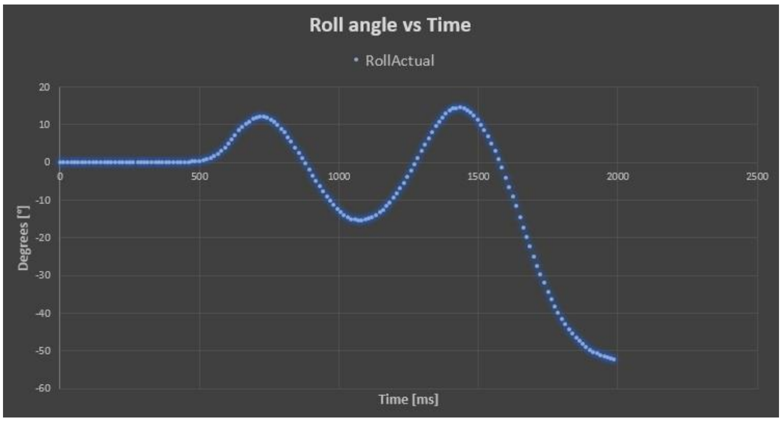

Figure 43: Launch 1 Roll data.

Figure 44 displays the vertical (x-axis) acceleration and the altitude of the rocket vs time. The data displays a maximum acceleration reached of 22.97 m/s^2. The acceleration goes to zero at 1.3 s into the flight as gravitational acceleration equals the rockets acceleration. At apogee the acceleration switched direction and is equal to the earth gravitational acceleration. The downward acceleration is found to be -9.85 m/s^2. When the rocket impacts the ground at 3.3 s the rocket bounces and causes the scattered acceleration data. After the rocket comes to a standstill the acceleration data is at a constant of -9.85 m/s^2.

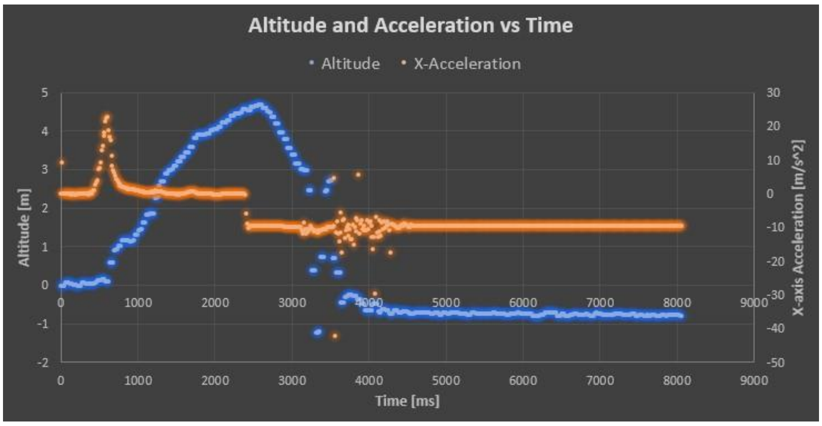

Figure 44: Launch 1 Acceleration and Altitude vs Time plot.

Figure 45 displays the vertical (x-axis) velocity and the altitude of the rocket vs time. The data displays a maximum velocity reached at 4.04 m/s. The maximum downward velocity is found to be -8.41 m/s, as the parachute did not have enough altitude to open.

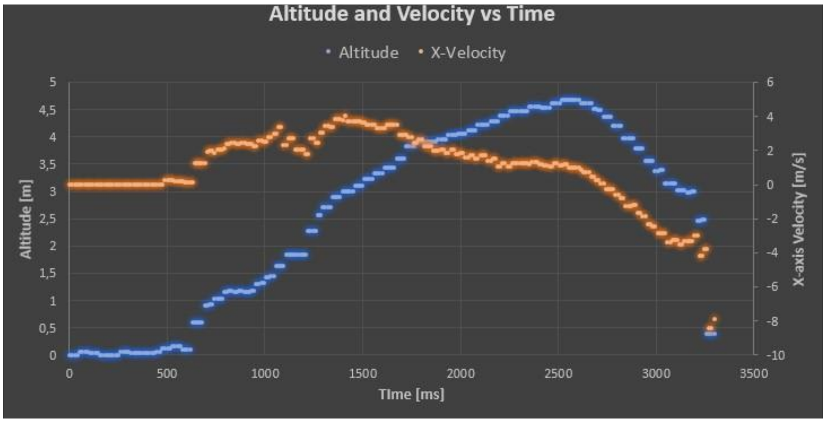

Figure 45: Launch 1 Velocity and Altitude vs Time plot.

12.1.2 Launch 2

After analysing the data and fixing the rocket a second flight was attempted on the same day with a larger thrust motor. The code was not altered. This time a E15-PW Aerotech rocket motor was used. It supplies an average thrust of 21.8 N, peak thrust of 34.9 N and has a burnout time of 1.6 s. The average thrust is doubled from the previous flight. Figure 46 displays the motors thrust curve.

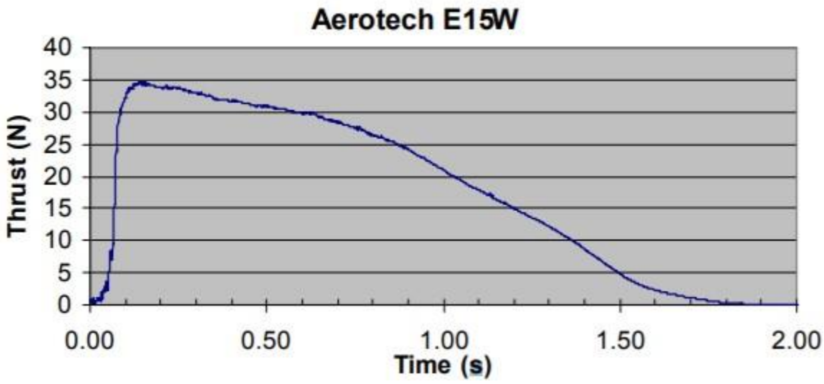

Figure 46: E15-PW Thrust curve (Coker et al., 2009).

After analysing the flight data, it was concluded that there was sensor or data transfer malfunctions in the flight. The following arguments supports the claim:

- The data displays a maximum altitude reached of 0.07 m while from observing the flight an estimated maximum altitude of 10 m was reached.
- The data displays a maximum Pitch angle of about 5° where observing the flight indicates a maximum angle of at least 30° at some instances in the flight.
- The data displays a maximum Yaw angle of 2° where observing the flight indicates a maximum angle of at least 30° at some instances in the flight. The Yaw angle also

experiences no drift in the second flight which does not correlate with the phenomenon in flight one.

Launch two was an improvement to launch one in terms of altitude reached, but the performance of launch one was better. This is due to the flight computer compensating for pitch and yaw angles that did not reflect the rockets actual orientation.

13 Conclusions

Space flight is becoming more common and attractive. It opens a universe of opportunities for businesses, researchers, universities, and students. This project aimed to add the functionality of full-scale rockets to a model rocket with active stabilization through TVC. The report serves as a documentation and instructions on how this was accomplished.

A literature review was conducted in section 2. The history and dynamics of rockets were investigated along with different TVC techniques that are used in the aerospace industry. BPS space's TVC model rockets were also discussed. In section 4, the design requirements were developed to successfully complete the project. During section 5, conventional model rockets were described regarding their design and stability. This set the base for developing the TVC model rocket. The flight computer's design is displayed in section 6. The flight computer is the brain of the rocket and controls all the processes of the rocket in-flight. Furthermore, the hardware design was documented in section 7. Here the rocket's body, TVC mount and recovery system is displayed. The recovery system's drag tests were also tabulated and displayed that the parachute decreased the descent velocity from 14 m/s to 4.4 m/s which is acceptable for recovery and reuse. Section 8, explains the launch system that was developed for wireless launches. The section displays the Wi-Fi enabled launch controller that was developed for remote launching and the mission control app that was programmed in MIT's app inventor. The launchpad's design and features were also displayed. The orientation calculations and axis are displayed in section 9. Further in section 10, features the control system's design, that is responsible for active TVC stabilization. The control systems were used in a PD controller with a limited I term. The gain terms were experimentally determined in a two-axis testing gimbal. In section 11, the state machine and the dummy flight test, that was performed with a pully system to test the state machine is explained. This proved valuable in identifying errors in the state machine. Lastly, the testing and evaluation was documented in section 12. The maiden flight's data is displayed and discussed with different graphs. The flight was underpowered due to the motor being undersized. The TVC was active and stabilizing the rocket, but the thrust was too small for a smooth flight. Flight two had no data sensor or data transfer malfunction and no data was therefore recorded.

All the objectives were satisfied except the rocket which had an angle error greater that the 15° as specified as the maximum angle error for a well stabilized flight. The rocket displayed the ability to autonomously ignite, take-off, stabilise and recover itself.

The next step would be to improve the control system's design through simulation modelling and an improved control systems design. A torque based compensated control systems can be recommended as the rockets thrust changes in-flight and therefore the controller gains should also change in-flight for better control. Adding roll control will also stabilise the rocket and ensure a smoother flight.

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Appendix A Electrical connections

A.1 Flight computer schematic

The flight computer was designed in EAGLE. The schematic is displayed in Figure A.1.1 below.

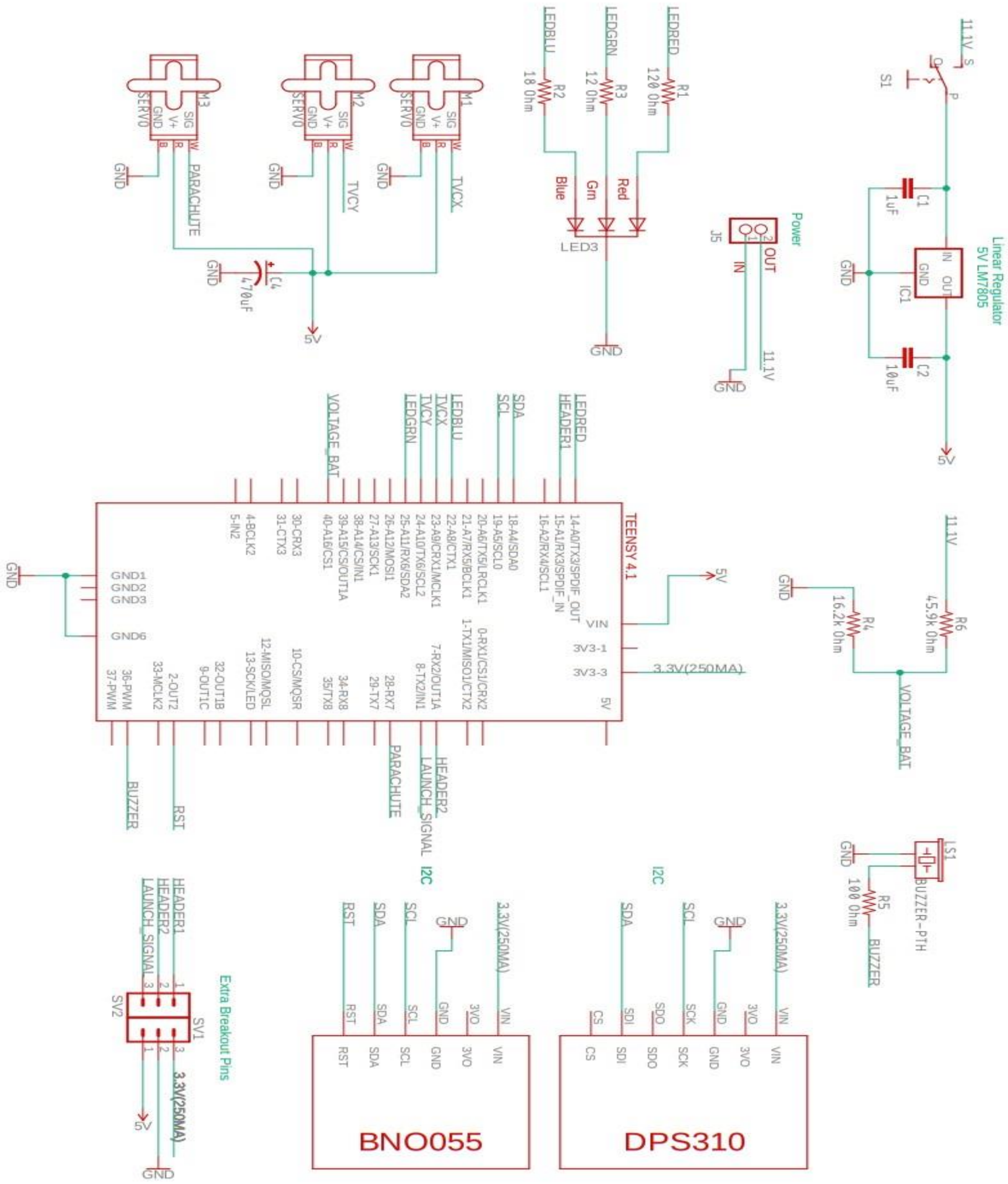


Figure A.1.1: Flight computer electronic schematic.

A.2 Launch controller schematic

The launch controller's electronic layout and connections were designed in EasyEDA and is displayed below in Figure A.1.2. The launch controller was built on a protoboard.

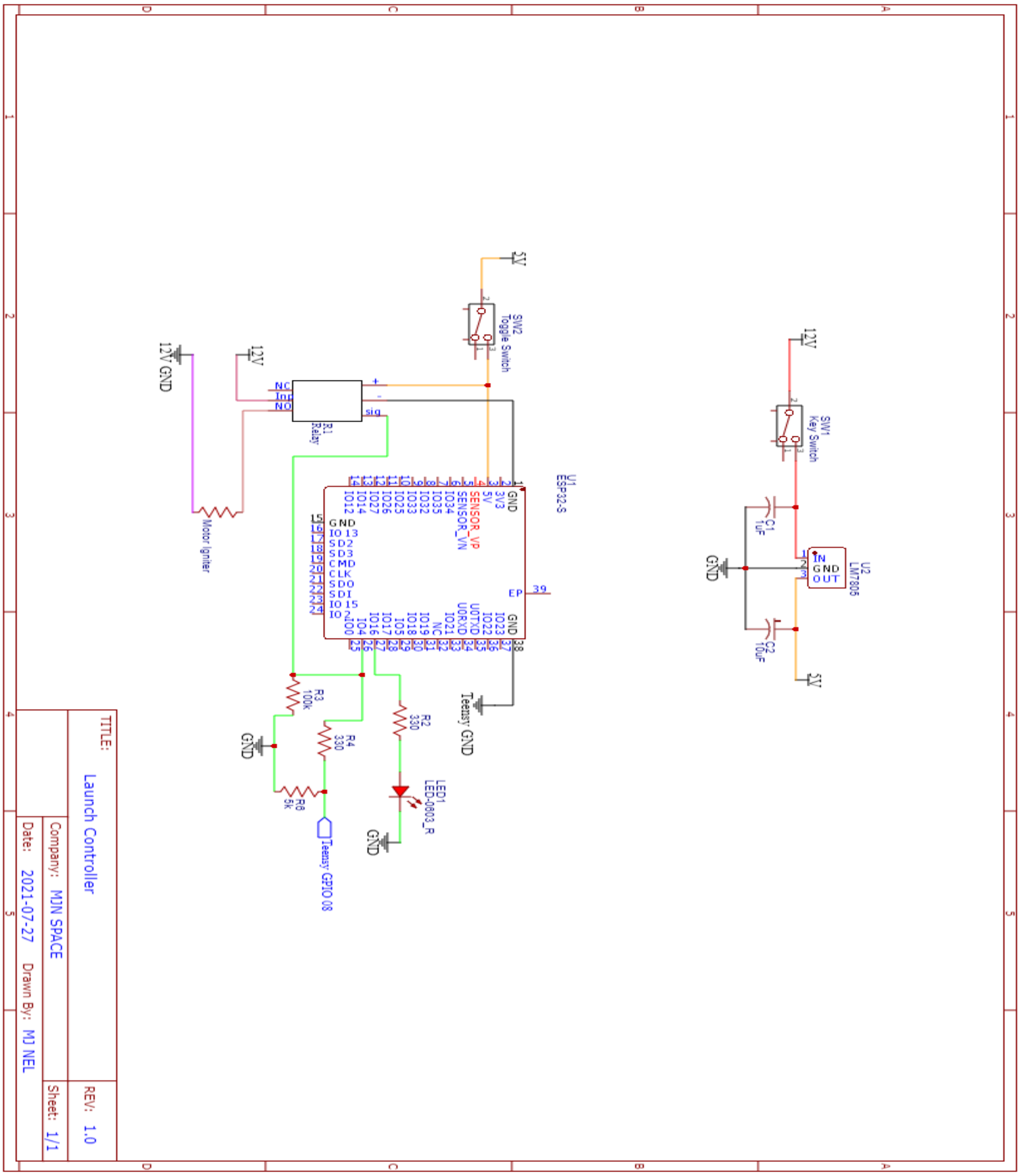


Figure A.1.2: Launch controller electronic schematic.

Appendix B   Software

Figure B.1 displays the software for automatically numbering the text files that store the flight data. The function does a comparison test to see if the file name exists and if the file does exist it increases the log number at the end of the file and checks again until the file does not exist then the program moves on with the last file name created.

```
/*
  ==========================================================
  ===            Dynamic log number increase           ===
  ==========================================================
*/
char fileName[13] = "Flight00.txt";  // Filename
File dataFile;                        // File Object
uint8_t i = 0;                        // Increases flight log number

// -- Increases flight log -- //
// Checks if the filename already exists on the SD card if it does
// then increase number.
while (SD.exists(fileName)) {
  i++;
  fileName[6] = i / 10 + '0';
  fileName[7] = i % 10 + '0';
}
```

Figure B.1: Dynamic log file numbering function.

Figure B.2 displays the SD card function. This function is used to transfer the data array in the RAM to the SD card when the flight is over.

```
/*
  ==========================================================
  ===                  SD Card Function                ===
  ==========================================================
*/
void SDcardWrite() {

  dataFile = SD.open(fileName, FILE_WRITE);

  // if the file is available, write to it:
  if (dataFile) {
    dataFile.println(Array_DMA);
    dataFile.close();
    // print to the serial port too:
    Serial.print("Done writing to ");
    Serial.println(fileName);
  }
  // if the file isn't open, pop up an error:
  else {
    Serial.print("error opening ");
    Serial.println(fileName);
  }
}
```

Figure B.2: SD card data transfer function.

Figure B.3 is a flow diagram of the altitude calculation function. When the sate is ground idle then the function assigns the current pressure to the zero pressure variable that is used in the altitude formula below. The temperature unit is kelvin and the pressure is in hPa. The other constants used were the universal gas constant ($R = 8.31432 \left[\frac{N*m}{mol*K}\right]$), the standard temperature lapse rate ($L_b = -0.0065 \left[\frac{K}{m}\right]$), the gravitional acceleration ($g_0 = 9.796 \left[\frac{m}{s^2}\right]$) and the molar mass of Earth's air ($M = 0.0289644 \left[\frac{kg}{mol}\right]$). The variable h_b is set as 0m as the difference in altitude is measured from the surface and not sea level.

$$P = h_b + \frac{T_b}{L_b} \times \left\{ \left(\frac{P}{P_b}\right)^{\left[\frac{-R \times L_b}{g_0 \times M}\right]} - 1 \right\}$$

$$Altitude = \frac{Current\ Temperature}{-0.0065} * \left\{ \left(\frac{Current\ Pressure}{Zero\ Pressure}\right)^{\left[\frac{-8.31432*(-0.0065)}{9.796*0.0289644}\right]} - 1 \right\}$$

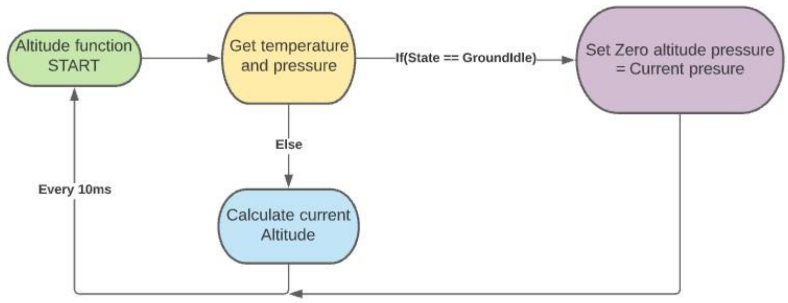


Figure B.3: Flow diagram for the altitude function.

Figure B.4 displays the flow diagram for the TVC function.

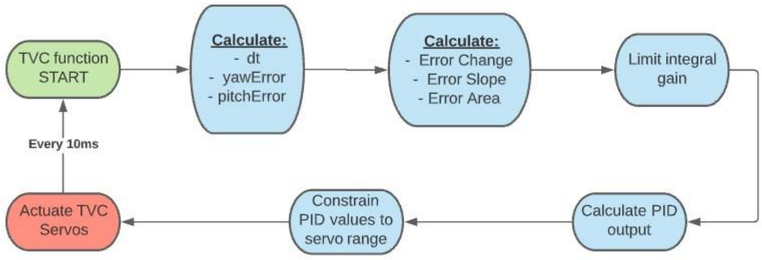


Figure B.4: Flow diagram for the altitude function.

Figure B.5 displays the block program for the mission control app that was built in MIT's App Inventor. The app is packaged in a .apk and an android is used to utilize the app.

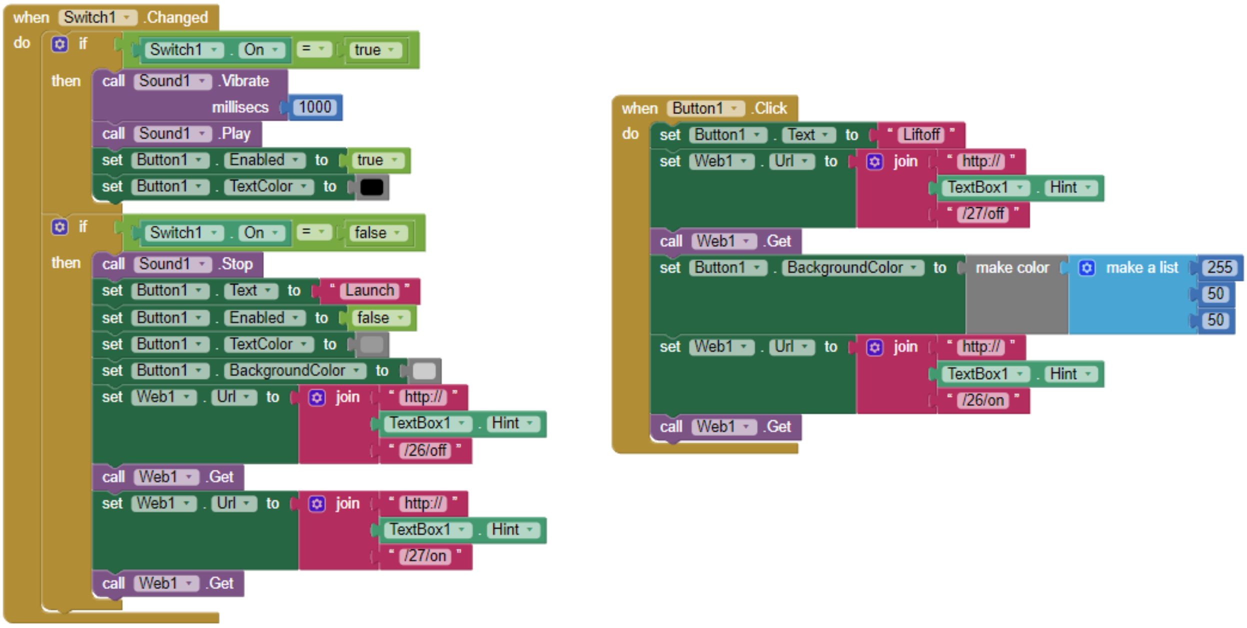
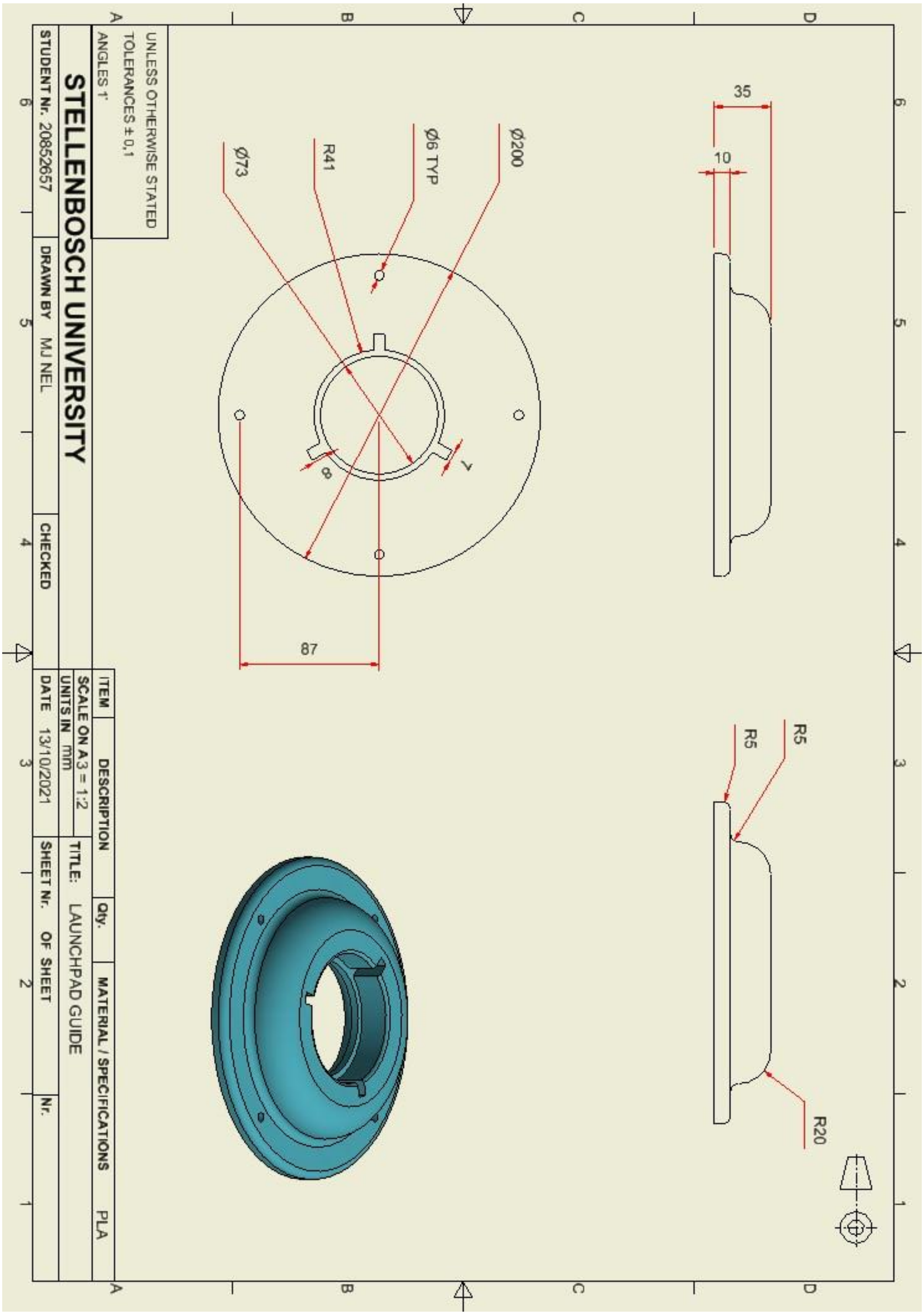


Figure B.5: Mission control (App) software programmed in MIT App Inventor.

Appendix C Hardware design

Appendix C contains the engineering drawings of all the TVC rocket parts.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Ø73
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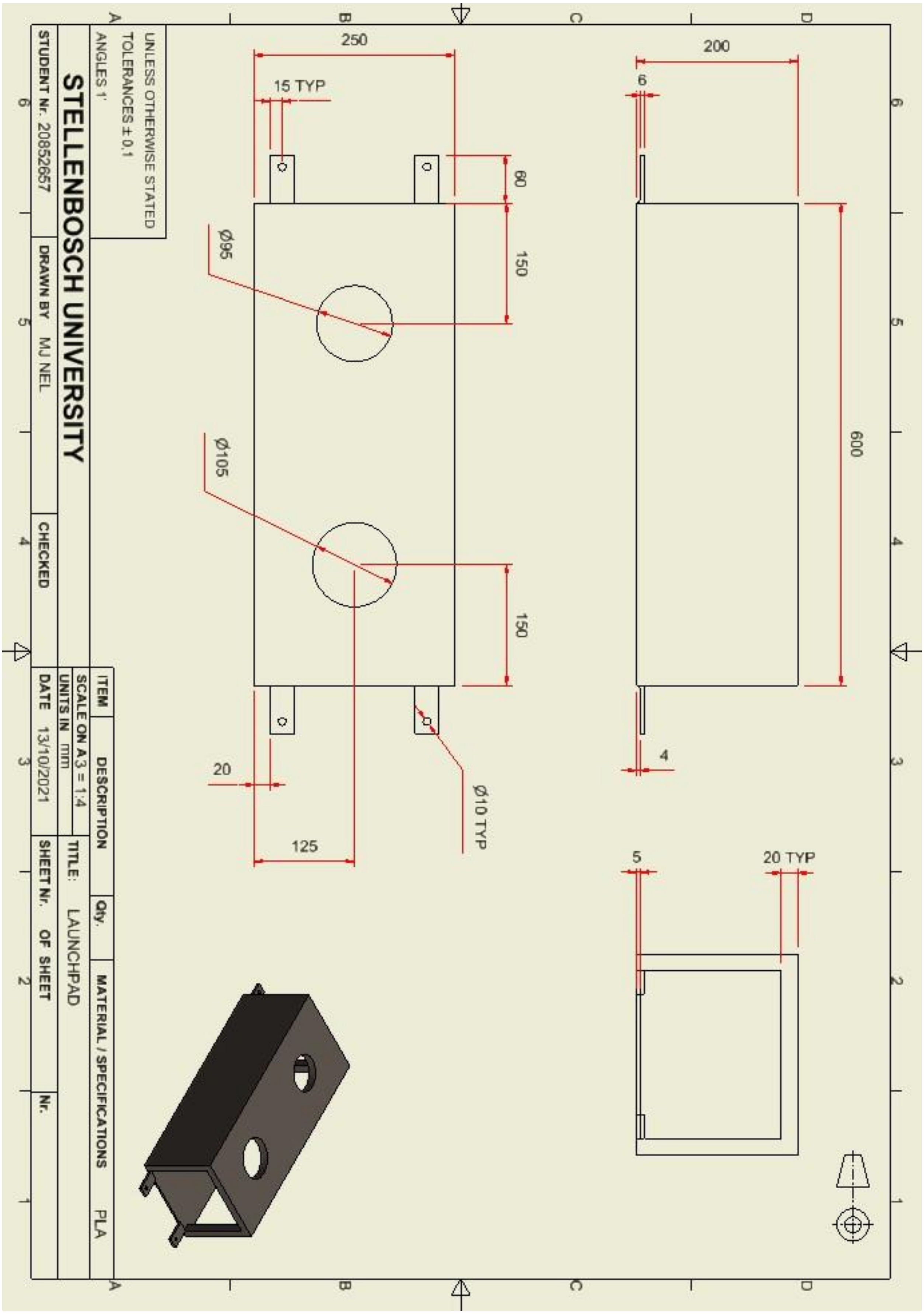
7
R5
R5
R20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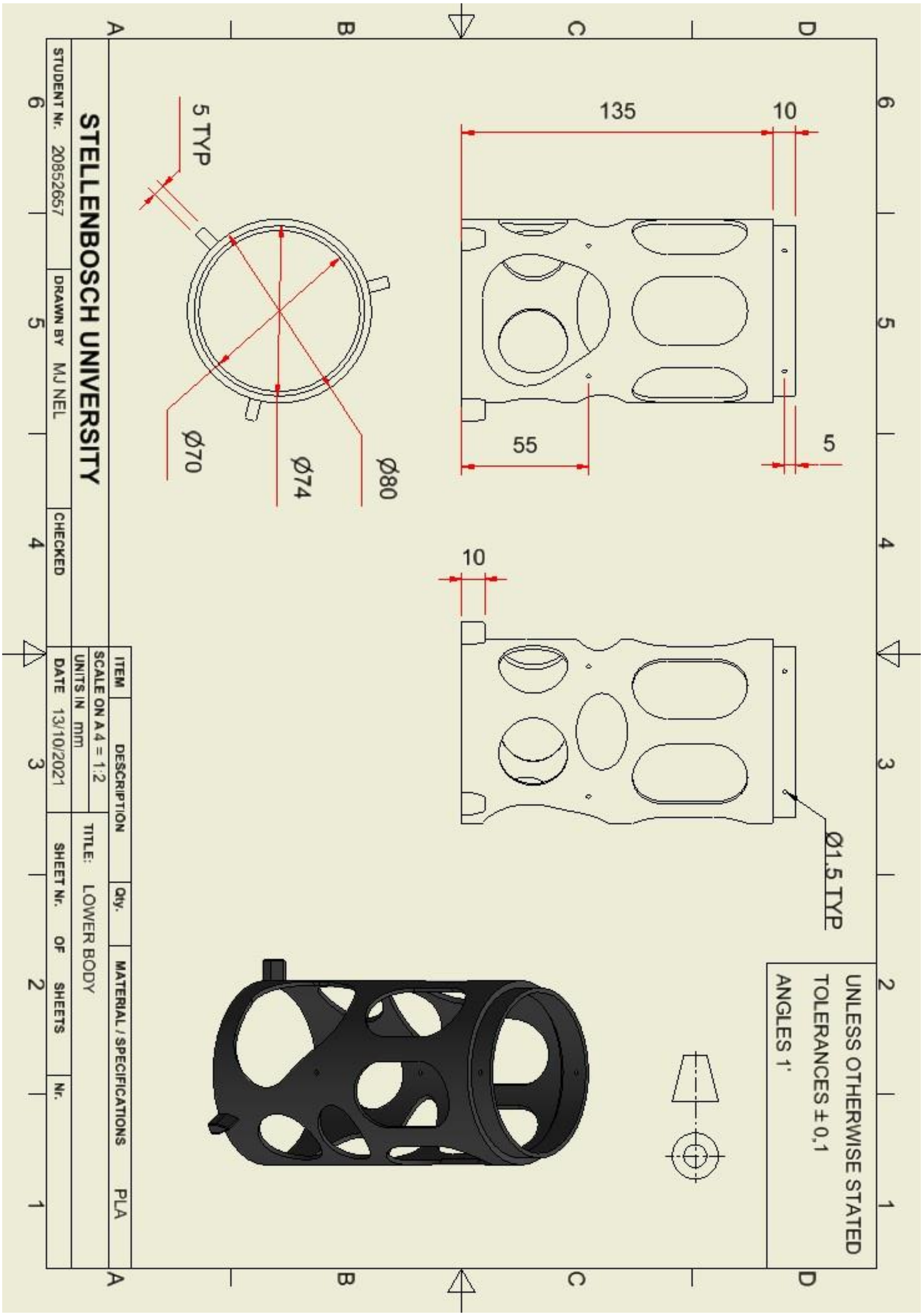
4
5
20 TYP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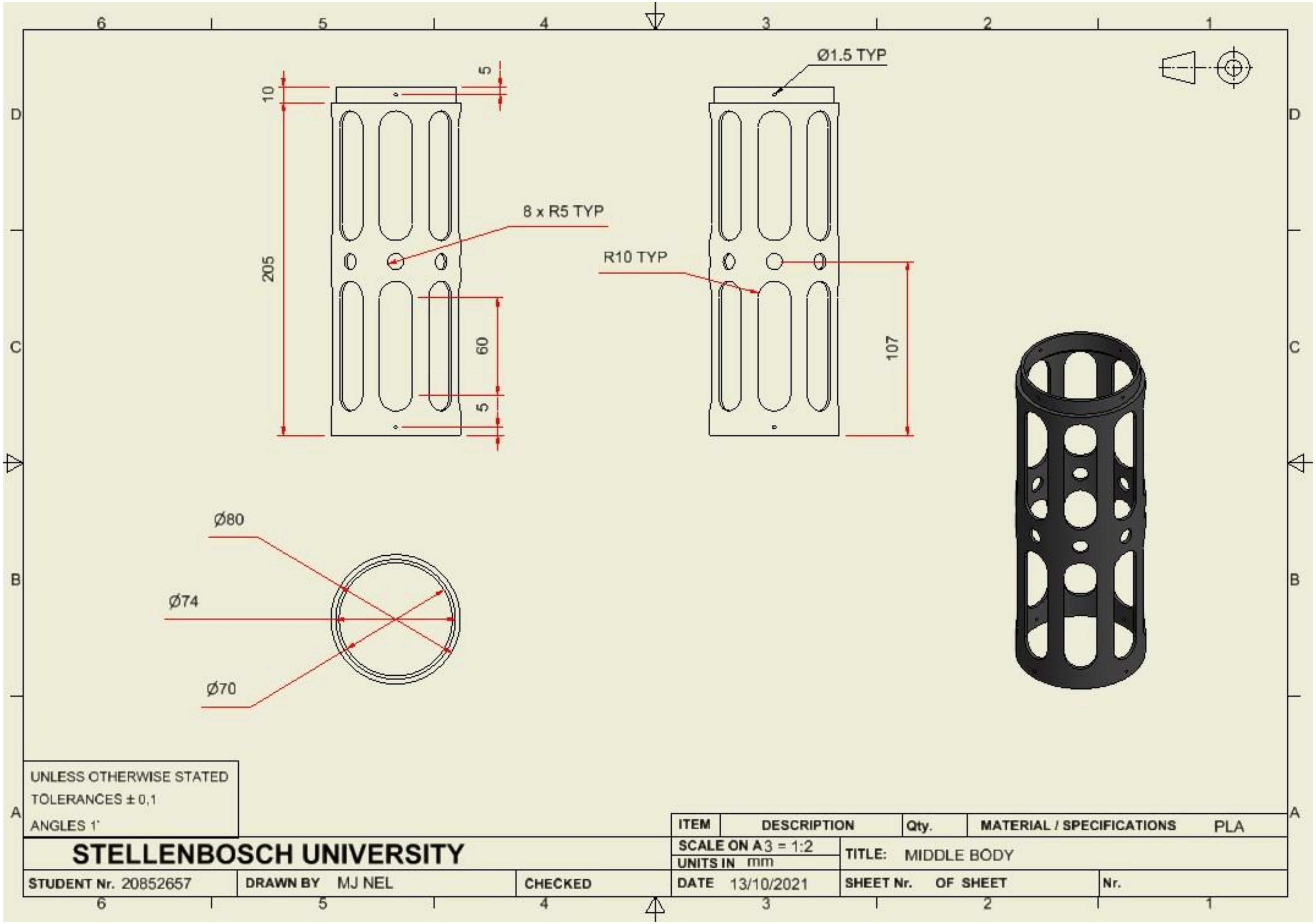
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8 x R5 TYP
R10 TYP
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5
107
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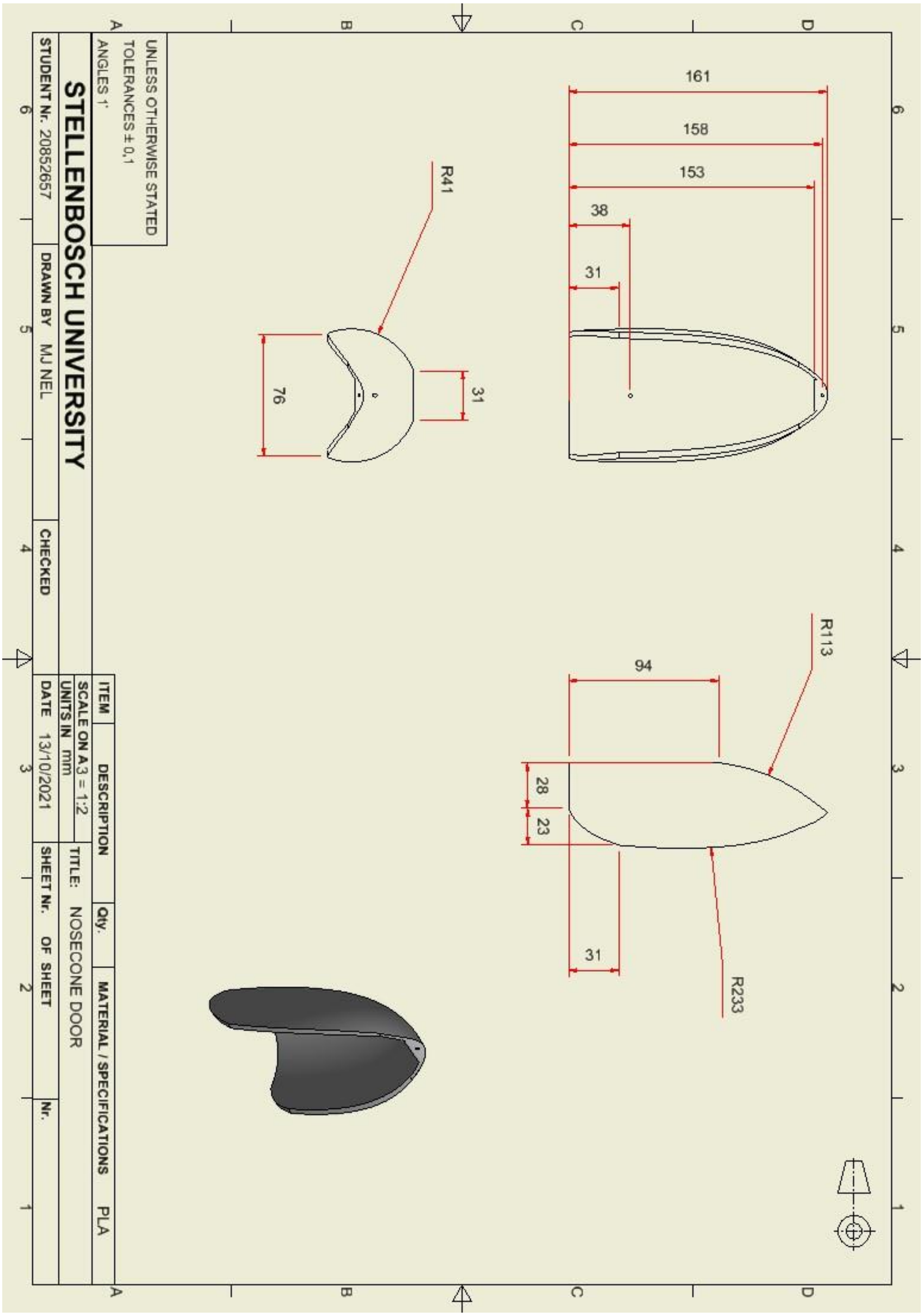
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23
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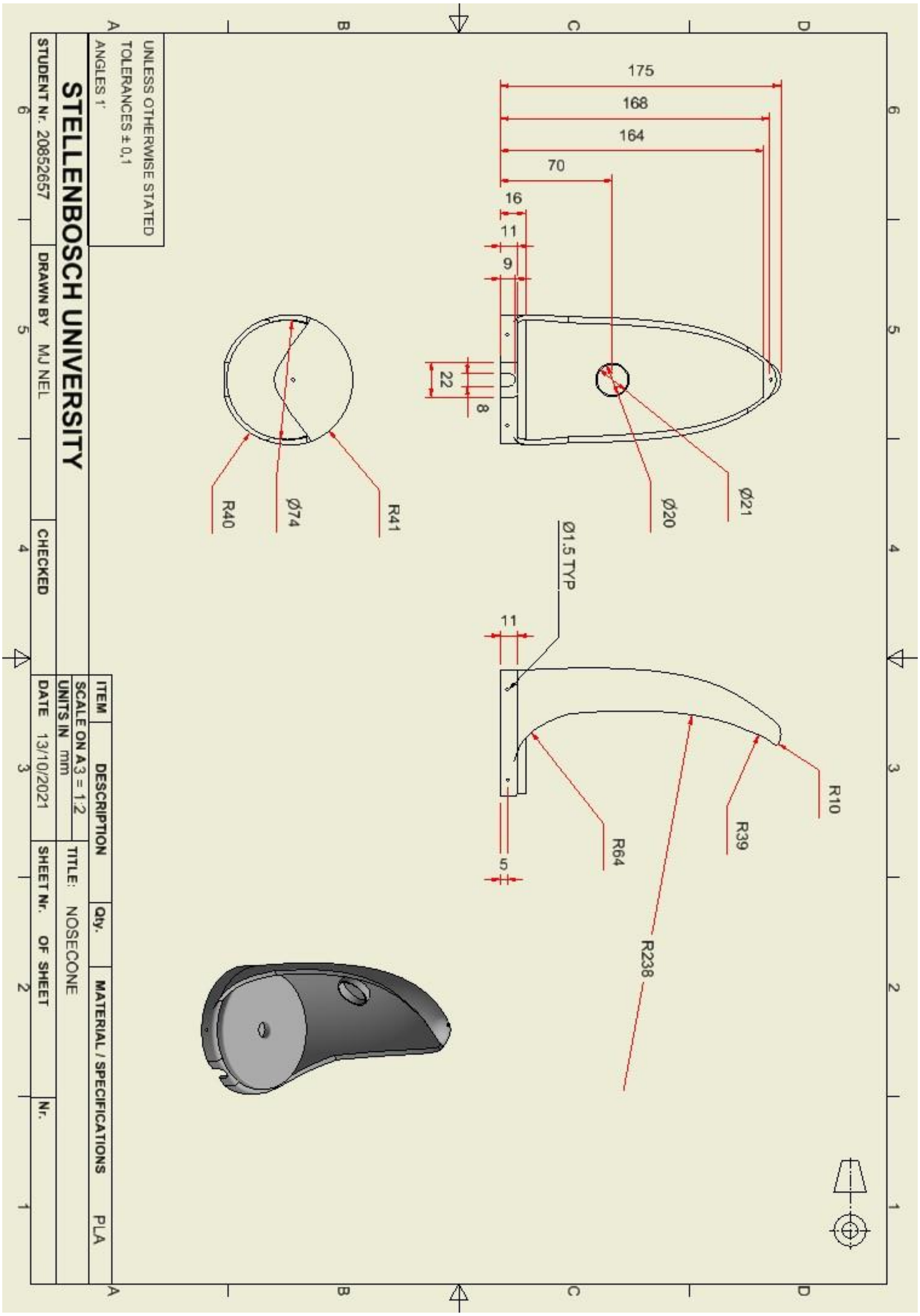
R233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164
70
16
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Ø20
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R40
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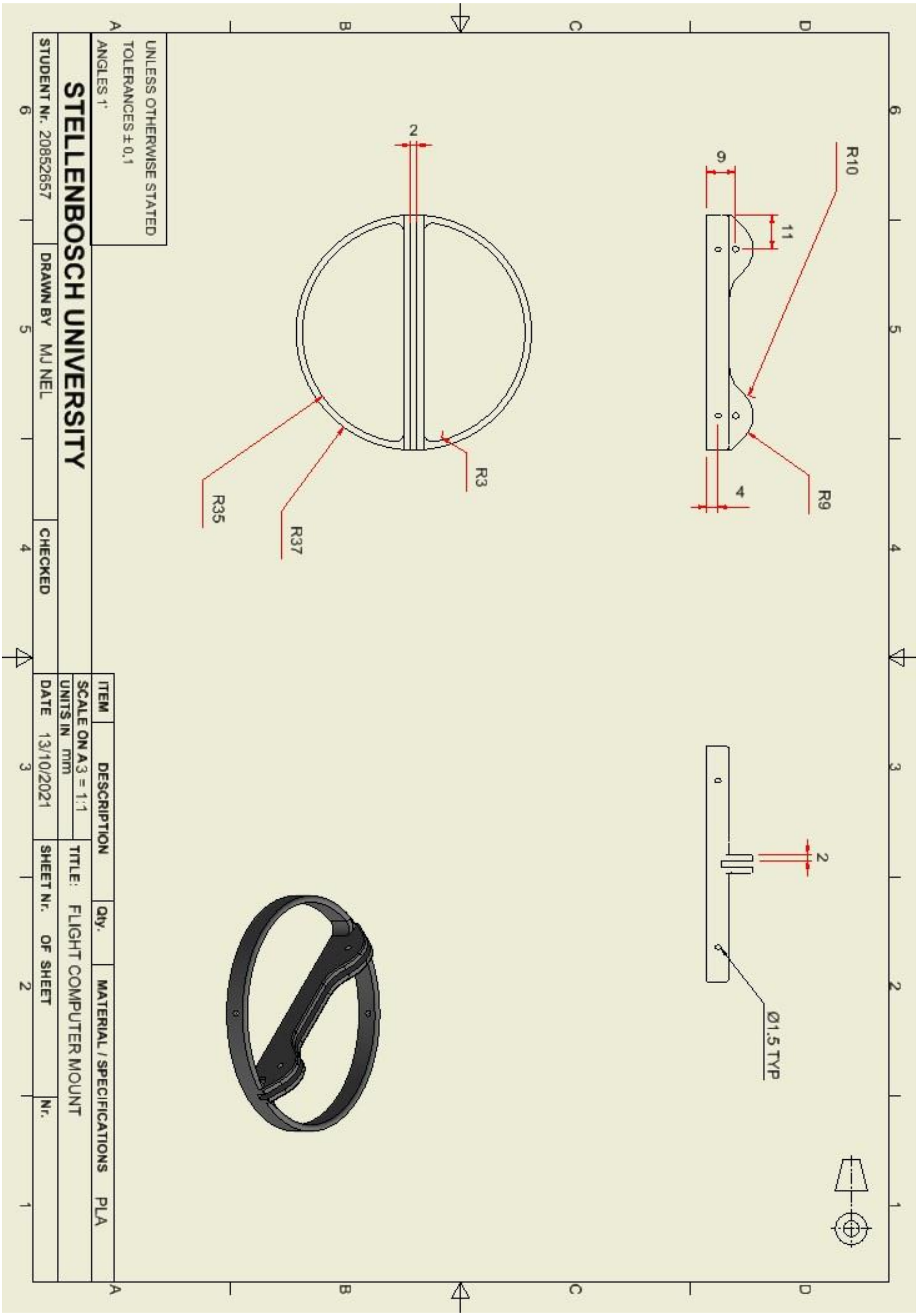
R39
R64
R238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R35
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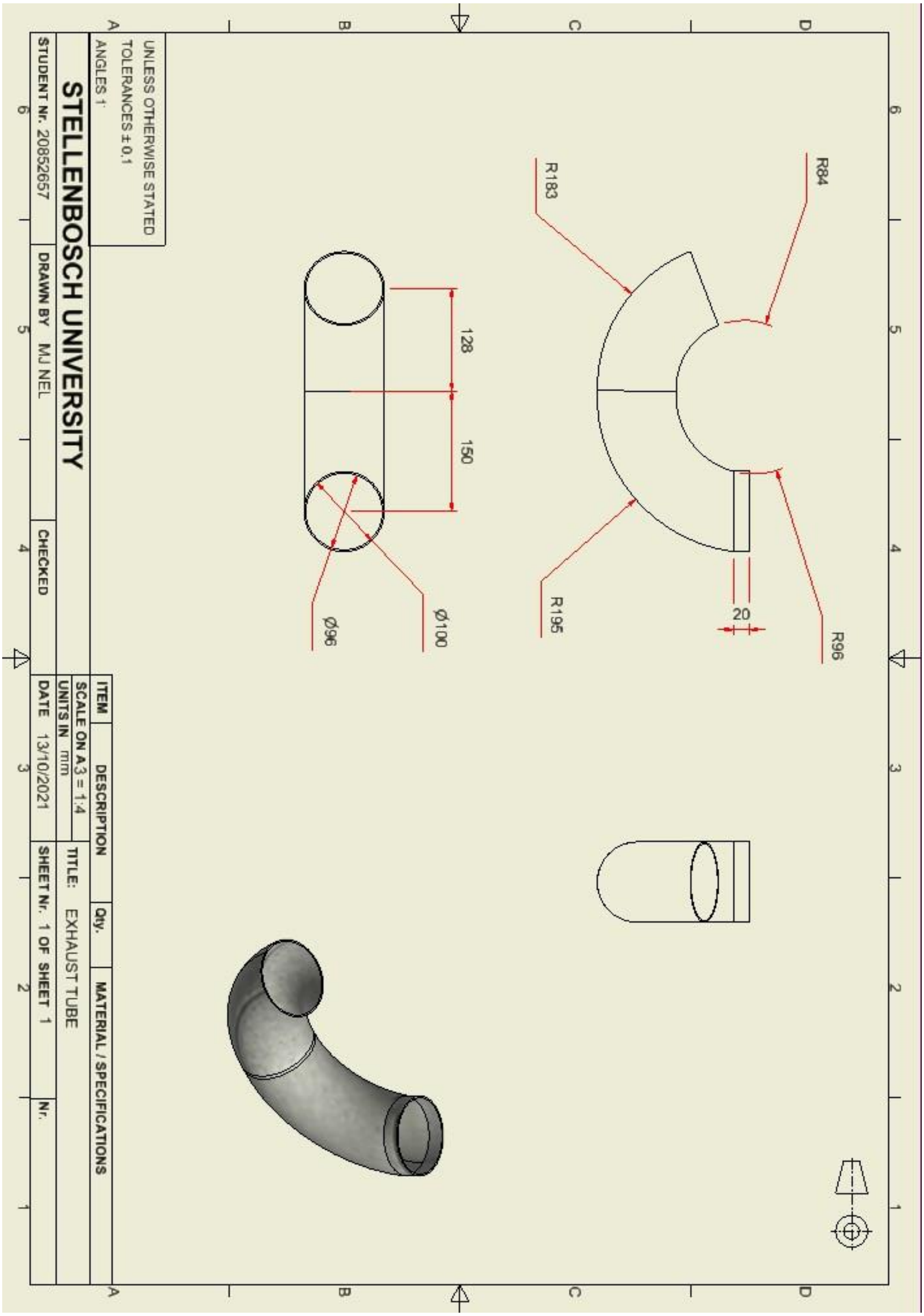
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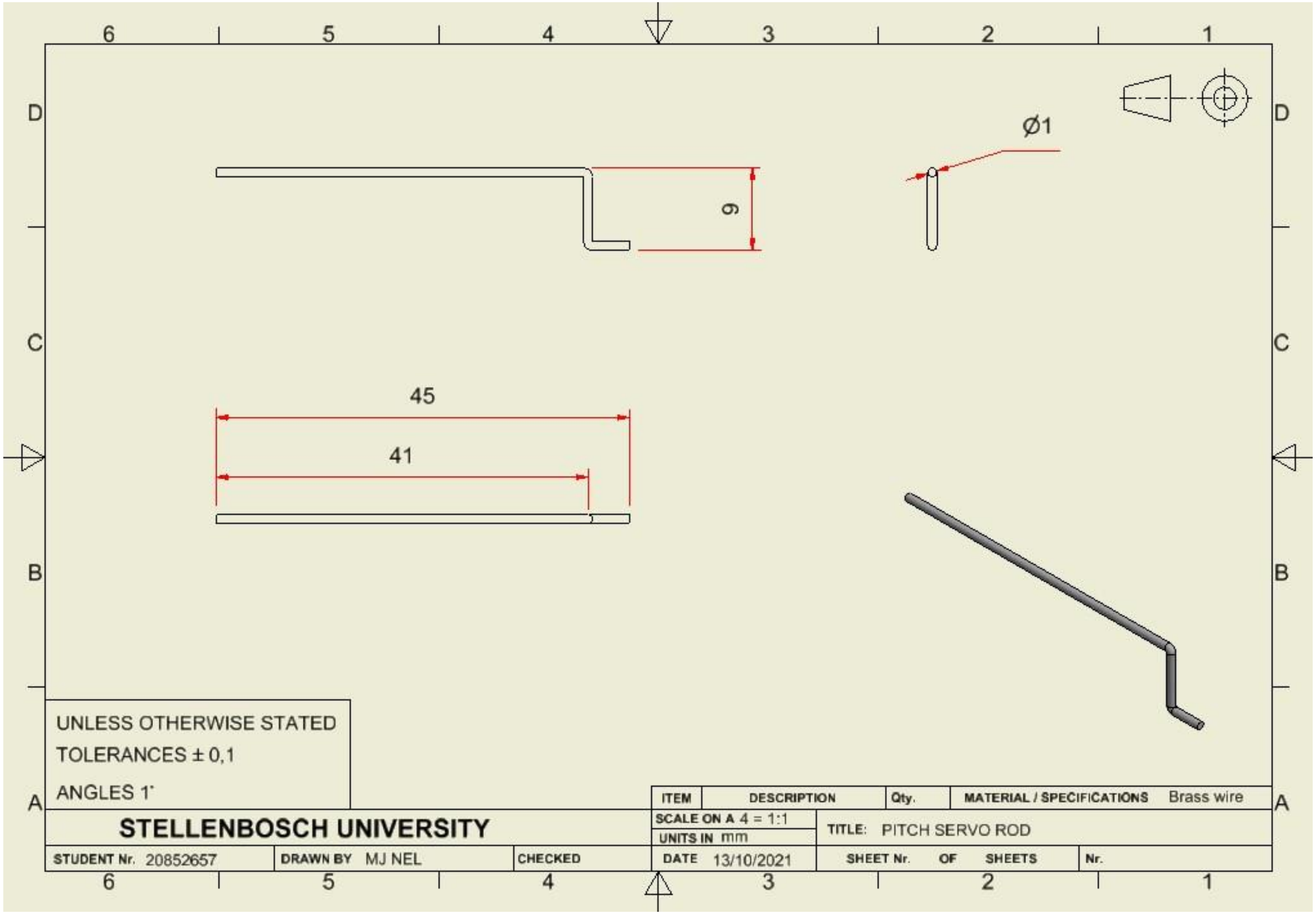

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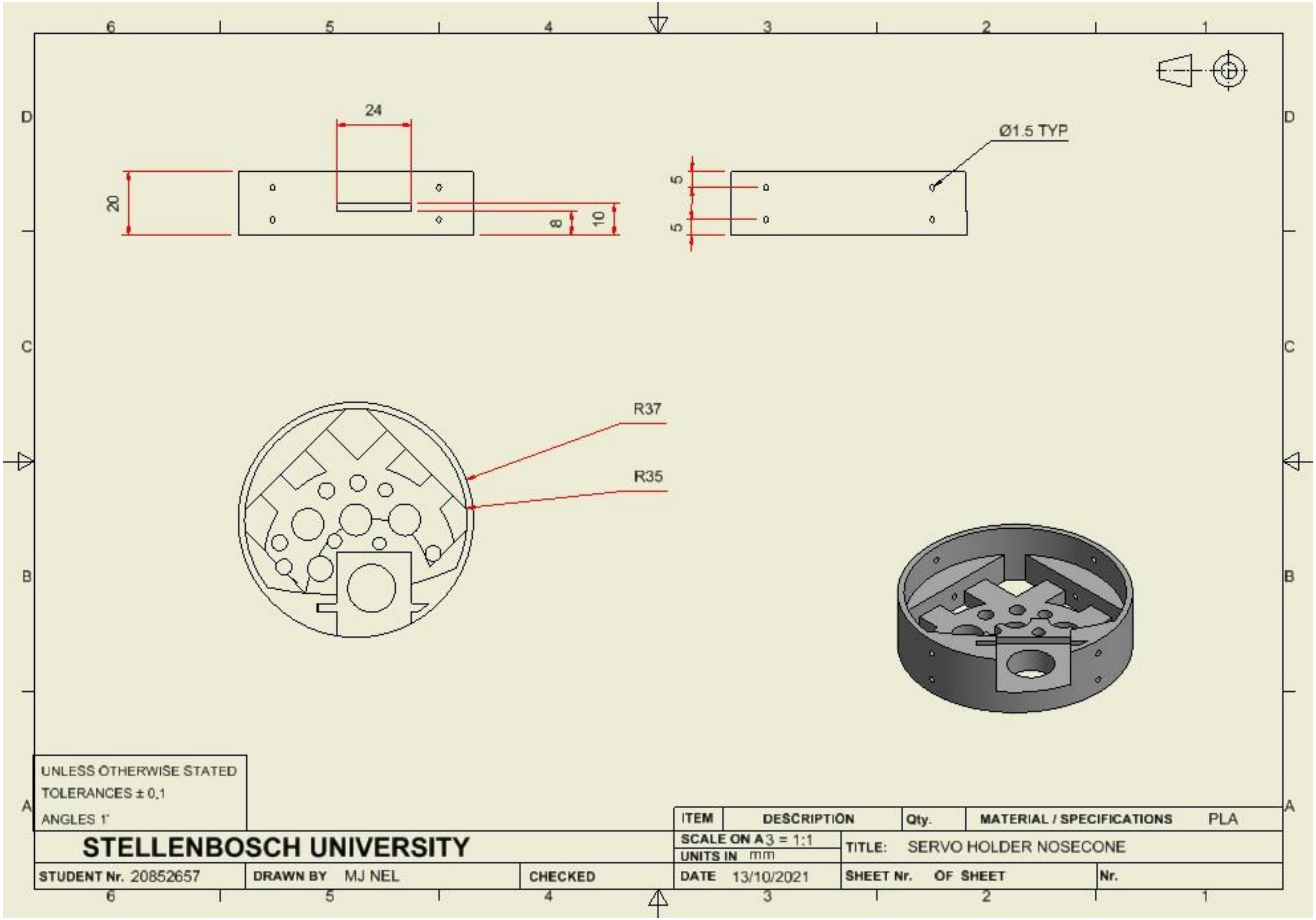
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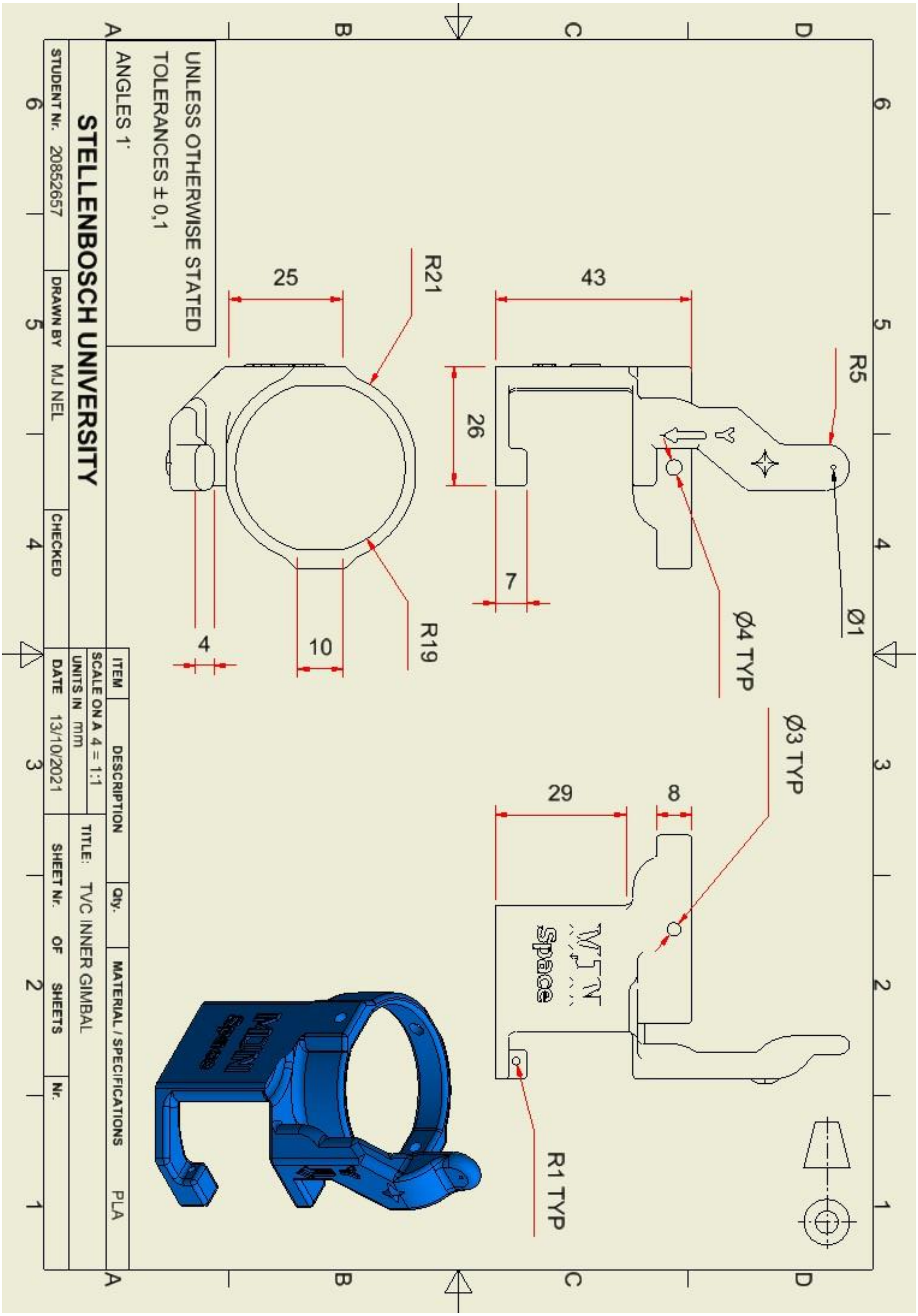
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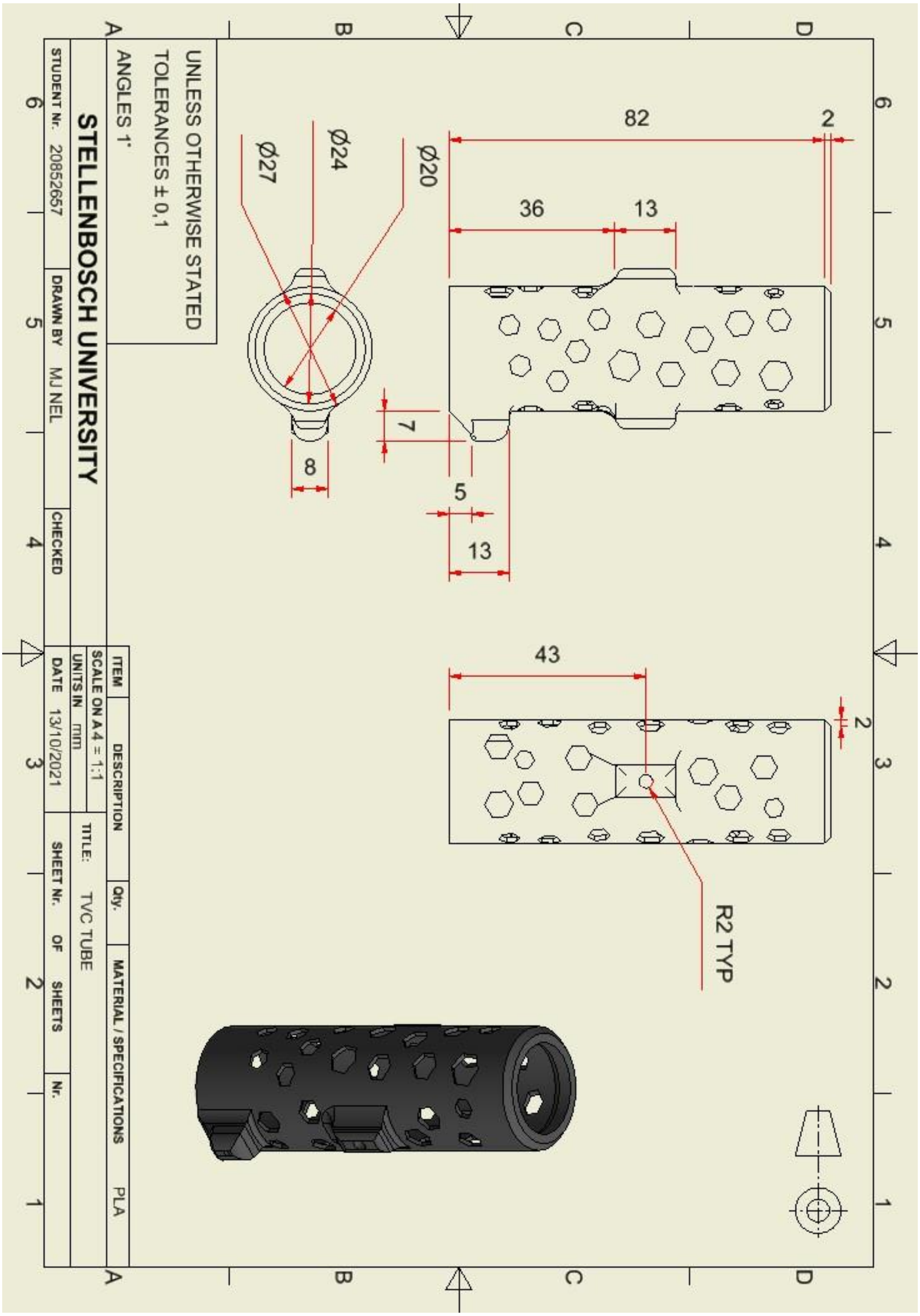
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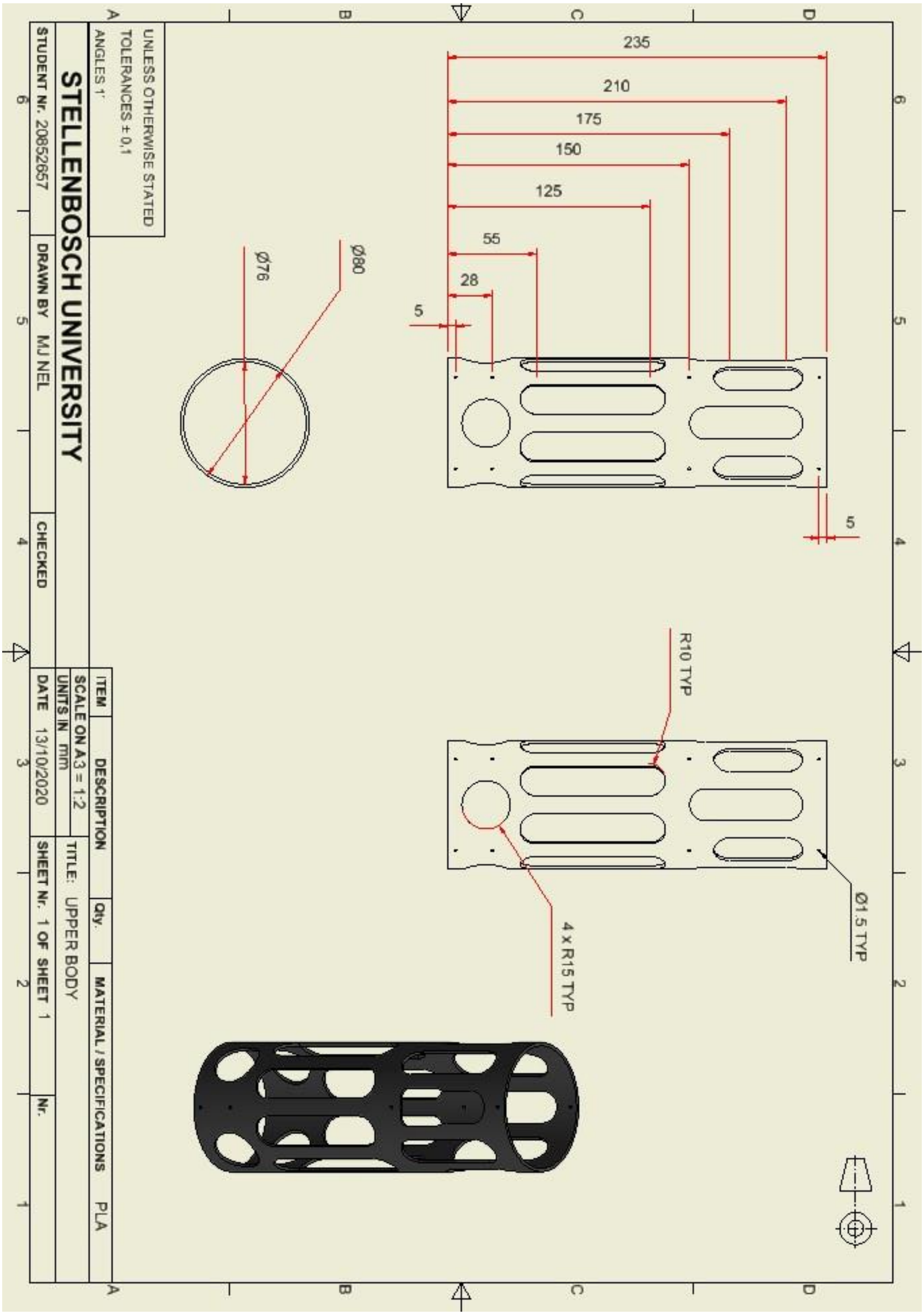
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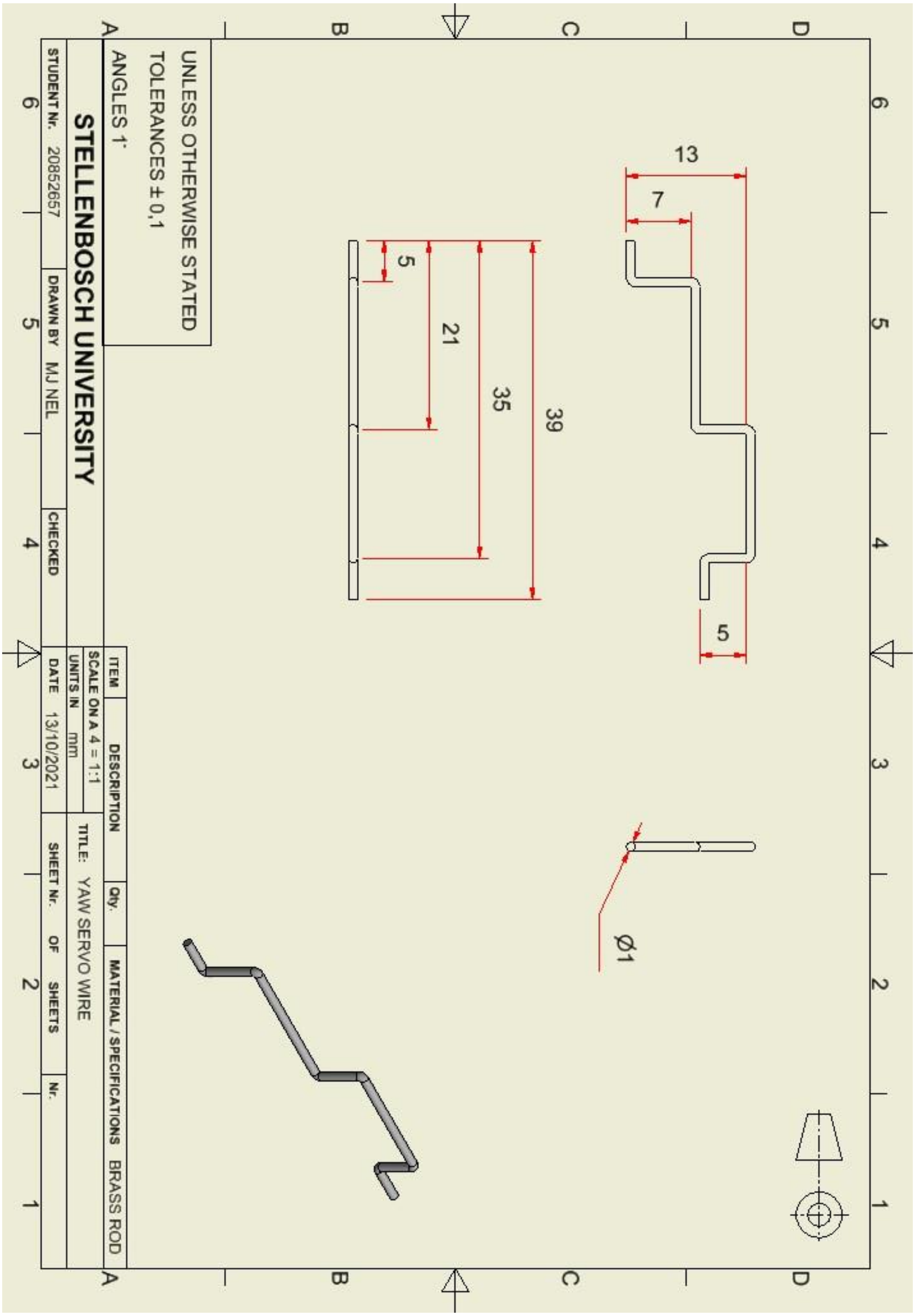
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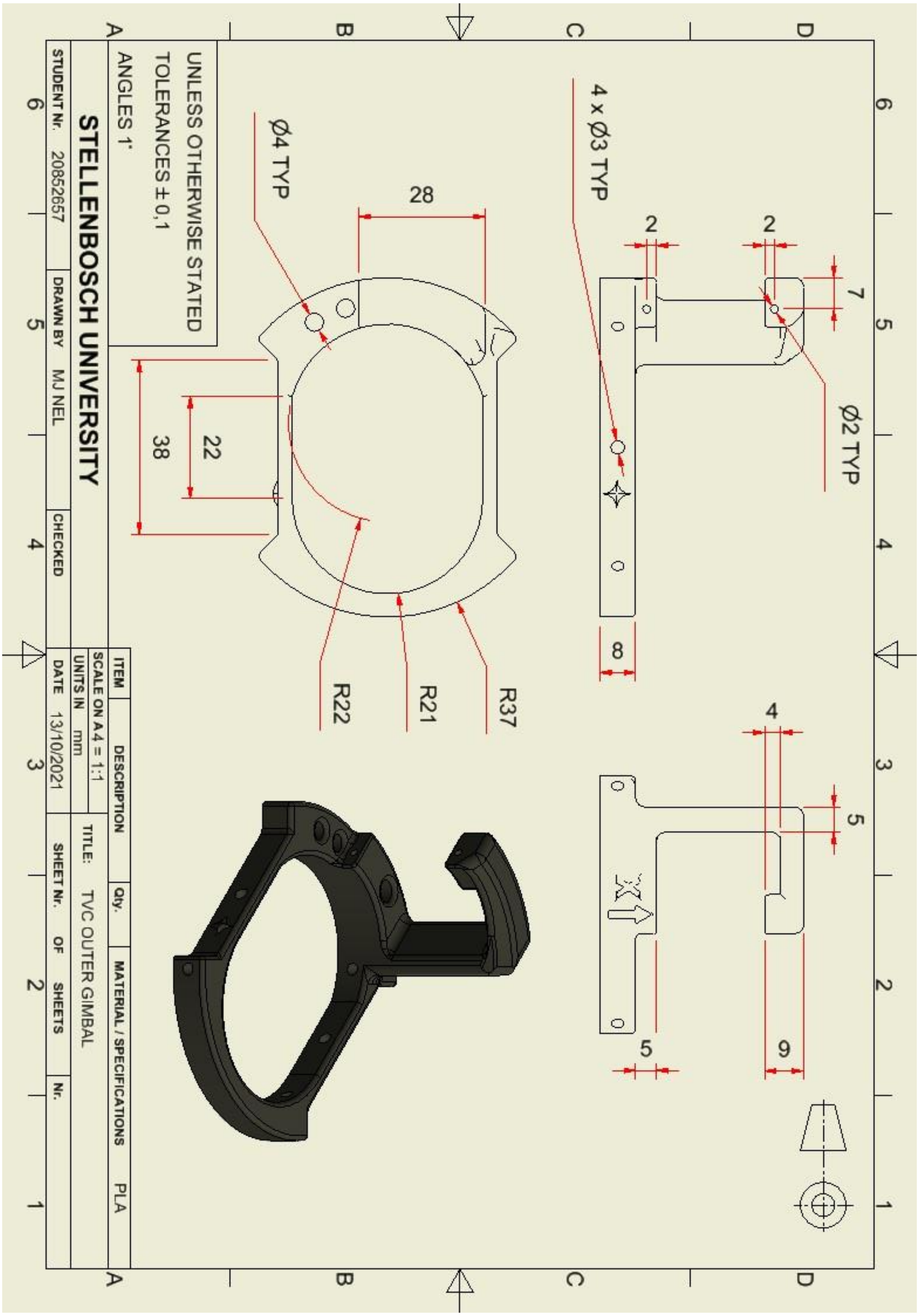
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Ø2 TYP
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38
22
R22
R21
R37
2
2
7
8
4
5
5
9

Appendix D Techno-Economic Analysis

A techno-economic analysis was preformed to evaluate the economic and technical impact of the project.

D.1 Project Expenditure

Table D.1.1 below displays the planned cost calculated in the project proposal. The project is divided into different activities and then for each activity the engineering time/cost, the running cost, the facility use cost, the capital cost, the Electrical and Electronic workshop (EEW) labour cost and the material used are calculated. The engineer's cost is set at R450.00 per hour where the EEW is calculated at R300.00 per hour.

Table D.1.1: Planned project expenses.

ID	Activity	Engineering Time		Running Cost	Facility Use	Capital Cost	EEW - Labour		EEW - Material	Total
		hr	R	R	R	R	hr	R	R	R
1	Literature Review	30	12000					0		12000
2	Safety and Risk Analysis	20	8000					0		8000
3	Generate Design Requirements	10	4000					0		4000
4	Design the Flight Computer	25	10000		250			0		10250
5	Design the Rocket Body and Recovery System	20	8000		200			0		8200
6	Design the Thrust Vector Control Mount	20	8000		200			0		8200
7	Design the Launch pad and Launch controller	20	8000		200			0		8200
8	Rocket Motor Selection	10	4000					0		4000
9	Design the Control Systems	30	12000		300			0		12300
10	Design Review	10	4000		500			0		4500
11	Manufacture the Model Rocket	40	16000	2500	2000		11	3300	1500	25300
12	Program the Flight Computer	85	34000		1000			0		35000
13	Test the TVC Model Rocket	100	40000	5000	1500			0		46500
14	Finalise Report	100	40000		500			0		40500
	Total	520	208000	7500	6650	0	11	3300	1500	226950

After completion of the project the costs of each individual activity was analysed and summed in a new table displayed below in Table D.1.2. Upon completion of the project the total actual expenditure was R276 350.00 where the panned total expenditure was R226 950.00. This is an overbudget percentage of 21.77%. This is mostly due to the engineer spending 621 hours to complete the project instead of the planned 520 hours which is an overrun 101 hours (19.4%) or R40 400.00. The other expenditure that increased the cost was the running cost which was 87% more than what was planned for. This was due to more expensive rocket motors that were needed for flight. This was offset by less EEW hours needed to complete the project and less expensive material cost by the EEW.

Table D.1.2: Actual project expenses.

ID	Activity	Engineering Time		Running Cost	Facility Use	Capital Cost	EEW - Labour		EEW - Material	Total
		hr	R	R	R	R	hr	R	R	R
1	Literature Review	23	9200					0		9200
2	Safety and Risk Analysis	10	4000					0		4000
3	Generate Design Requirements	8	3200					0		3200
4	Design the Flight Computer	35	14000		250			0		14250
5	Design the Rocket Body and Recovery System	25	10000		200			0		10200
6	Design the Thrust Vector Control Mount	25	10000		200			0		10200
7	Design the Launch pad and Launch controller	20	8000		200			0		8200
8	Rocket Motor Selection	3	1200					0		1200
9	Design the Control Systems	60	24000		300			0		24300
10	Design Review	12	4800		500			0		5300
11	Manufacture the Model Rocket	105	42000	5000	2000		20	6000	1300	56300
12	Program the Flight Computer	95	38000		1000			0		39000
13	Test the TVC Model Rocket	100	40000	9000	1500			0		50500
14	Finalise Report	100	40000		500			0		40500
	Total	621	248400	14000	6650	0	20	6000	1300	276350

Figure D.1. 1 displays the actual cost vs the planned cost in a comparison graph. Here the graph displays that the two activities that had the greatest cost overrun in cost was activity 9 and 11. Activity 9, Design the control systems, had a cost overrun of 100% due to the complexity of the control systems design process that was not fully comprehended when the project was planned. Activity 11, Manufacture the model rocket, 162.5% cost overrun. This was due to more design iterations required that was planned for and a more complex design.

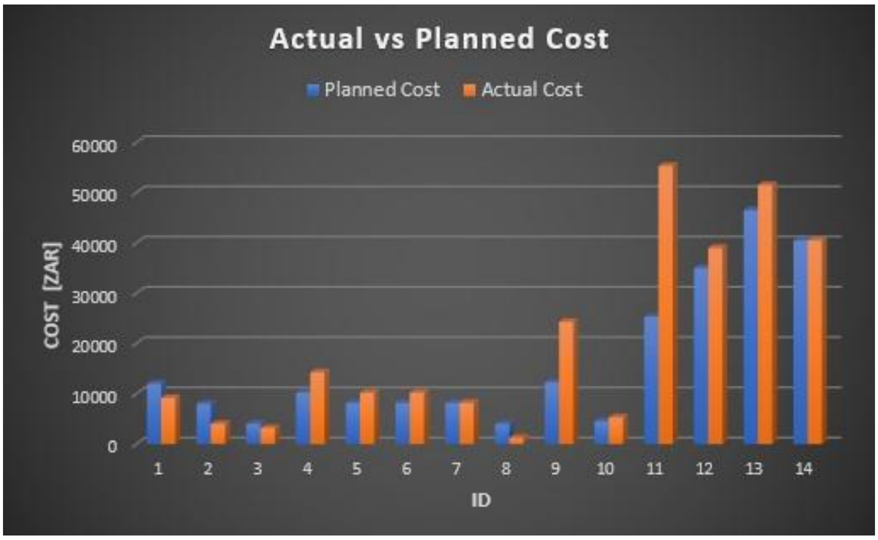

Figure D.1. 1: Actual vs Planned cost of the project by category ID.

The project's total cost overrun was 21.77% which was classified as acceptable. Table D.1. 3 below displays the individual component cost for manufacturing the model rocket not including the R9 000.00 spent on the rocket motors for testing the rocket.

Table D.1. 3: Component Cost.

Component	Quantity	Price
E&E Lab components	35	R 600,00
ESC and BLDC motor	1	R 1 000,00
LiPo Battery (1S)	2	R 300,00
LiPo Battery (3S)	3	R 1 000,00
ESP32S	1	R 200,00
Teensy 4,1	1	R 950,00
BNO055	1	R 450,00
DPS310	1	R 350,00
Servo	3	R 150,00
Total	48	R 5 000,00

D.2 Gannt Chart

Figure D.2.1 displays the projects Gantt chart. The project became behind schedule when the ‘Design the Control Systems’ activity overrun its allocated time. This was compensated for by programming the flight computer and manufacturing the rocket while the control systems was still being designed. Less time was left for testing the TVC rocket in actual flight which was not ideal. More launches would improve the rockets data and thus in turn the control systems can be improved.

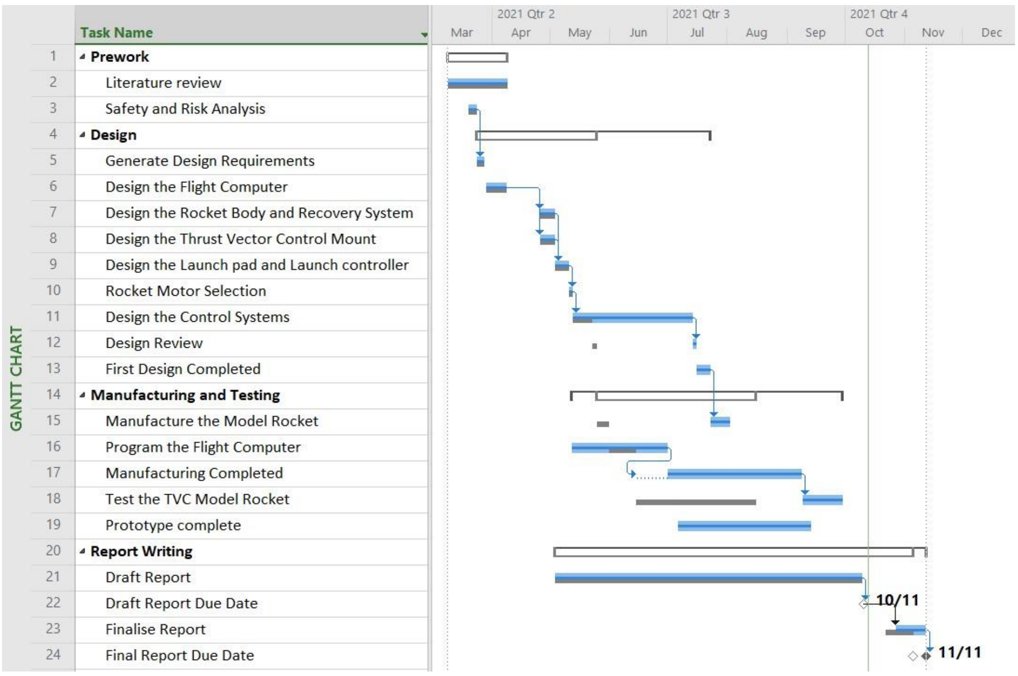

Figure D.2.1: Project Gantt Chart.

Appendix E Risk Analysis and Safety report

Appendix E contains the projects risk analysis documents and the safety aspects.

E.1 Risk assessment sheet

Design, build and test a model rocket with Thrust Vector Control.

Student: MJ Nel (20852657)
Supervisor: Dr L Visagie

Introduction:

There is a growing interest in model rocketry worldwide after the first human space flight was successfully conducted in a privately owned spacecraft, constructed by a company known as SpaceX. SpaceX and Blue Origin has been in the forefront of innovation in the space industry. With both successfully completing a first of its kind vertical landing manoeuvre with the help of thrust vector control. This paved the road for reusability and to lower space flight costs. SpaceX started out with model rockets to test electronics and control systems that they have designed. This is an inexpensive and low risk solution. In this project I will design, build and test a functional model rocket system with thrust vector control as its guidance system. This document will explain the objectives, planning and risks associated with this project.

Objective:

As mentioned above, this project is aimed at designing, building and testing a functional model rocket that uses thrust vector control (TVS) as its guidance system. The objectives of this project are therefore:

- Design and build the hardware for a model rocket.
- Design and assemble the electronics required for the control of the rocket as well as the recovery system.
- Design and program the control systems for the different states of the rockets flight.
- Do thorough ground testing on all the systems before assembling for maiden flight.
- Complete the maiden flight and improve on this flight and every flight that follows.

Planned Activities:

Research will be done on rocket dynamics and design. A 3D model of the rocket will then be designed and partially manufactured (e.g. Nose cone, Electronics mount, etc.). The rest of the parts will be bought commercially (Parachute, Rocket main body). The electronic system design will commence with the focus on Thrust vector control, a recovery system and flight data logging. A motor selection process will commence to ensure the correct motor is used for this model rocket. An autonomous launch pad will also be designed and a mission controller unit that will be used pre-flight as well as in-flight. The design and programming of the flight computer, launch pad and mission control will be the main part of this project.

Risks:

The risks are outlined in the following pages.

South African Laws:

SA law only states that certified motors should be used in rocket. Thus, I will only use certified, commercially made model rocket motors, and will not tamper with these motors or use them for any purposes except those recommended by the manufacturer. SA laws states that no flight plan is needed for a model rocket reaching hights of lower than 2km. SA laws also state that model rockets may not be launched within a 20km range of an international airport and 5km from a domestic airport.

UNIVERSITEIT STELLENBOSCH UNIVERSITY

Department of Electrical & Electronic Engineering

Health and Safety Representative
Mr P Petzer 021-8084316

RISK ASSESSMENT / RISIKO ANALISE

REV. NR. 1

Building / Area / Project: Design, build and test a model rocket with thrust vector control.		**US Number:**	20852657
		Assessment Undertaken: (Date)	17/03/2021
		People Involved: (Print Names)	MJ Nel
Job or Task:		**Safety Supervisor Authorisation (Print Name)**	
		Assessment Review Date:	

1 HAZARD AND HAZARD EFFECT List Here:	2 WHO / WHAT MIGHT BE HARMED? List groups of people who are especially at risk from the significant hazards which you have identified	3 IS THE RISK ADEQUATELY CONTROLLED? List existing controls here or note where the information may be found:	4 WHAT FURTHER ACTION IS NECESSARY TO CONTROL THE RISK? List the risks that are not adequately controlled and the action you will take where it is reasonably practicable to do more. You are entitled to take cost into account, unless the risk is high:	5 WHO IS RESPONSIBLE FOR THE ACTIONS? Person responsible and by when:		
				Person	Date for Completion	Date completed
Burn or collision injuries while launching.	Operators	A safe area will be chosen where the maximum altitude of the rocket will dictate the safety perimeter size of the launch site. The launch pad will also be autonomous, thus there will be no need to stand close to the rocket at the time of launch. A flight abort button will also be implemented.		MJ Nel	Before each launch	

1 HAZARD AND HAZARD EFFECT List Here:	2 WHO / WHAT MIGHT BE HARMED? List groups of people who are especially at risk from the significant hazards which you have identified	3 IS THE RISK ADEQUATELY CONTROLLED? List existing controls here or note where the information may be found:	4 WHAT FURTHER ACTION IS NECESSARY TO CONTROL THE RISK? List the risks that are not adequately controlled and the action you will take where it is reasonably practicable to do more. You are entitled to take cost into account, unless the risk is high:	5 WHO IS RESPONSIBLE FOR THE ACTIONS? Person responsible and by when:		
				Person	Date for Completion	Date completed
Static fire testing hazards include: Burning and unplanned flying rocket motor.	Operators	A safe area will be selected. The tests will take place outside. The rocket will be bolted down to a steel type frame throughout the tests. A safety net or fail-safe structure will be installed above the static testing pad in case of unplanned take-off.		MJ Nel	Before static fire testing	

1 HAZARD AND HAZARD EFFECT List Here:	2 WHO / WHAT MIGHT BE HARMED? List groups of people who are especially at risk from the significant hazards which you have identified	3 IS THE RISK ADEQUATELY CONTROLLED? List existing controls here or note where the information may be found:	4 WHAT FURTHER ACTION IS NECESSARY TO CONTROL THE RISK? List the risks that are not adequately controlled and the action you will take where it is reasonably practicable to do more. You are entitled to take cost into account, unless the risk is high:	5 WHO IS RESPONSIBLE FOR THE ACTIONS? Person responsible and by when:		
				Person	Date for Completion	Date completed
Uncontrolled flight does to errors in TVC programming or the hardware.	Operator.	The TVC hardware and control systems will first be tested without a motor. Tests will then commence starting with the least powerful motor in a static test. When the correct flight motor passes its static test only then will the project be moved to its maiden flight. The maiden flight will also start out with a smaller motor. This will increase the safety of the flight. Ones the maiden flight is successful only then can the correct motor be launched.		MJ Nel	Throughout the project.	

STEP 1 **HAZARD AND HAZARD EFFECT**	**STEP 2** **WHO / WHAT MIGHT BE HARMED?**	**STEP 3** **IS THE RISK ADEQUATELY CONTROLLED?**	**STEP 4** **WHAT FURTHER ACTION IS NECESSARY TO CONTROL THE RISK?**	**STEP 5** **WHO IS RESPONSIBLE FOR THE ACTIONS?**
Look only for hazards, which you could reasonably expect to result in significant harm under the conditions in your workplace. Use the following examples as a guide: • Slipping / tripping hazards (e.g. poorly maintained floors or stairs) • Fire (e.g. from flammable materials) / welding / burning. • Electricity (e.g. poor wiring). • Chemicals (e.g. battery acid). • Gas, fumes and dust. • Moving parts of machinery (e.g. blades). • Fume (e.g. welding). • Work at height (e.g. from mezzanine floors). • Manual handling. • Ejection of material (e.g. from plastic moulding). • Noise. • Pressure systems (e.g. steam/ hydraulics / compressed air). • Poor lighting • Vehicles (e.g. fork-lift trucks). • High / Low Temperatures. • Hazards to the environment. • Confined spaces. • Suspended loads. • Lone working. • Spills • Explosion. • Installation / Commissioning Hazards. • Any other hazards. You can only get a clear picture by looking at the work area.	There is no need to list individuals by name – just think about groups of people doing similar work or who may be affected, for example: • Office staff. • Maintenance personnel. • Contractors. • People sharing your workplace. • Operators. • Cleaners. • Members of the public. **Pay particular attention to:** • Staff with disabilities. • Inexperienced staff. • Visitors. • Lone workers. • Pregnant women. • Young workers (work experience). They may be more vulnerable. How will it harm the environment?	Have you already taken precautions against the risks from the hazards you listed? For example, have you provided: • Adequate control measures. • Adequate information. • Included information in operating and maintenance instructions? • Adequate systems or procedures? • Adequate protective equipment. **Do the precautions:** • Meet the standards set by a legal requirement? • Represent good practice? • Comply with a recognised industry standard? • Reduce risk as far as reasonably practicable? If so, the risks are adequately controlled, but you need to indicate the precautions you have in place. You may refer to procedures, manuals, company rules etc. giving this information. List other risk assessments, if applicable, for example SafeNet (Africa), noise, manual handling, provision and use of work equipment, display screen equipment, confined spaces risk assessment etc.	What more could you reasonably do fro those risks which you found were not adequately controlled? You will need to give priority to those risks, which affect large numbers of people and/or could result in serious harm. Apply the principles below when taking further action, if possible, in the following order: • Remove the risk completely. • Try a less risky option. • Prevent access to the hazard (e.g. by guarding). • Organise work to reduce exposure to the hazard. • Issue personal protective equipment. • Provide welfare facilities. • Include immediate short-term actions (e.g. erect warning notice and/or barriers).	• List the person who will do the work for immediate actions (e.g. erect barriers or notices). • List the person responsible for long-term actions (e.g. arrange engineering work to remove hazard). • Record the target date for completing the job. Ensure that the team is briefed on the precautions. Ensure actions are closed out before undertaking the work.

RISK RATING SHEET

LIKELIHOOD (THE PROBABILITY OF AN INCIDENT WHEN THE EVENT DOES OCCUR)	
	VALUE
MIGHT AS WELL BE EXPECTED (HAPPENS OFTEN)	10
QUITE POSSIBLE	6
UNUSUAL, BUT QUITE POSSIBLE	3
ONLY REMOTELY POSSIBLE (HAS HAPPEND SOMEWHERE)	1
CONCEIVABLE, BUT VERY UNLIKELY (HASN'T HAPPENED YET)	0.5
PRACTICALLY IMPOSSIBLE (ONE IN A MILLION)	0.2
VIRTUALLY IMPOSSIBLE (APPROACHES THE IMPOSSIBLE)	0.1
EXPOSURE (THE FREQUENCY OF OCCURRENCE OF THE EVENT)	
CONTINUOUS	10
FREQUENT (DAILY)	6
OCCASIONAL (WEEKLY)	3
UNUSUAL (MONTHLY)	2
RARE (A FEW PER YEAR)	1
VERY RARE (YEARLY)	0.5
NO EXPOSURE	0.1
CONSEQUENCE	
CATASTROPHIC (MANY FATALITIES, OR DAMAGE OVER - R 10 000 000,00)	100
DISASTER (A FEW FATALITIES, OR DAMAGE OVER - R1 000 000,00)	40
VERY SERIOUS (ONE FATALITY, OR DAMAGE OVER – R 100 000,00)	15
SERIOUS (SERIOUS INJURY, PERMANENT DISABILITY, OR DAMAGE OVER- R 10 000,00)	7
IMPORTANT (TEMPORARY DISABILITY, OR DAMAGE OVER- R 1 000,00)	3
NOTICEABLE (MINOR FIRST AID, OR DAMAGE OVER - R 100,00)	1
NEGLIGIBLE	0.4
FIRE RISK (BASED ON THE FIRE CHARACTERISTICS OF THE MATERIAL INVOLVED)	0-4 1

RISK SCORE	RISK CLASSIFICATION
OVER 400	VERY HIGH RISK: CONSIDER DISCONTINUING OPERATION
200- 400	HIGH RISK: IMMIDIATE CORRECTION REQUIRED
70-200	SUBSTANTIAL RISK: CORRECTION NEEDED
20-70	POSSIBLE RISK: ATTENTION INDICATED
UNDER 20	ACCEPTABLE RISK

RISK SCORE = ("FIRE RISK" X 10) + (LIKELIHOOD X EXPOSURE X CONSEQUENCE)

= 10 + 1 x 0.5 x 7

= 13.5