Engineering Portfolio

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Contents

Simulink Modelling

After finishing my last undergraduate semester, I was motivated by my enjoyment of the subject “Systems Modelling & Analysis”. This pushed me to make the decision to learn Simulink in the summer break, since it was briefly mentioned during subject content delivery. I used various sources, including ChatGPT, to design a 4-module Simulink training course, aligned with my personal interests. Knowing that ChatGPT understands its capabilities better than I do, I gave it an initial prompt to create its own prompt, tailored the contents while keeping the depth, and requested a full study plan, with the initial prompt provided below.

While mainly sticking to the structure, I recognised during module 4 that I would learn more from building the active aero system of a vehicle at varying speed rather than a a simple velocity profile from a wind tunnel.

Initial Prompt:
Create a detailed prompt which fulfils the following criteria: “Develop a self-guided Simulink course based on my understanding of systems modelling. Include relevant YouTube videos and challenges with a focus on real-world applications”

¼ Car Suspension Modelling

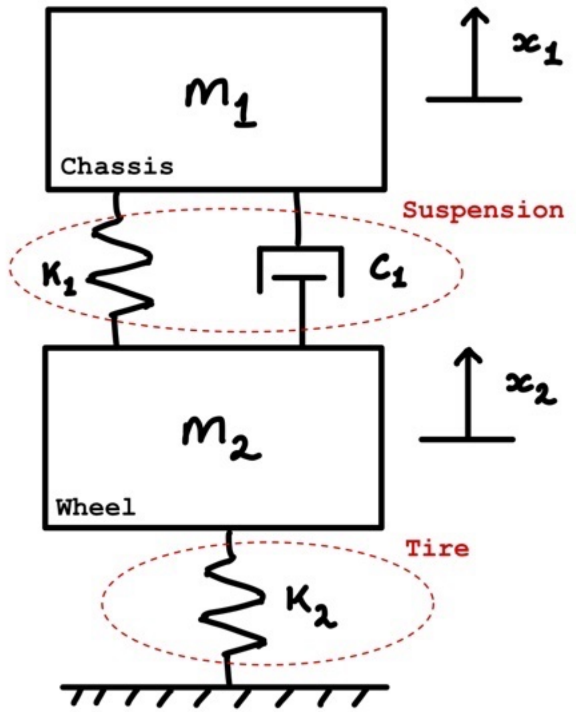
I modelled a 2 degree of freedom ¼ car suspension using Simulink. The model captures the dynamics of a sprung and unsprung mass, spring and damping elements, and a road bump input. I implemented a parameter sweep in MATLAB to identify suspension parameters which achieve a target overshoot and settling time.

Base equations:

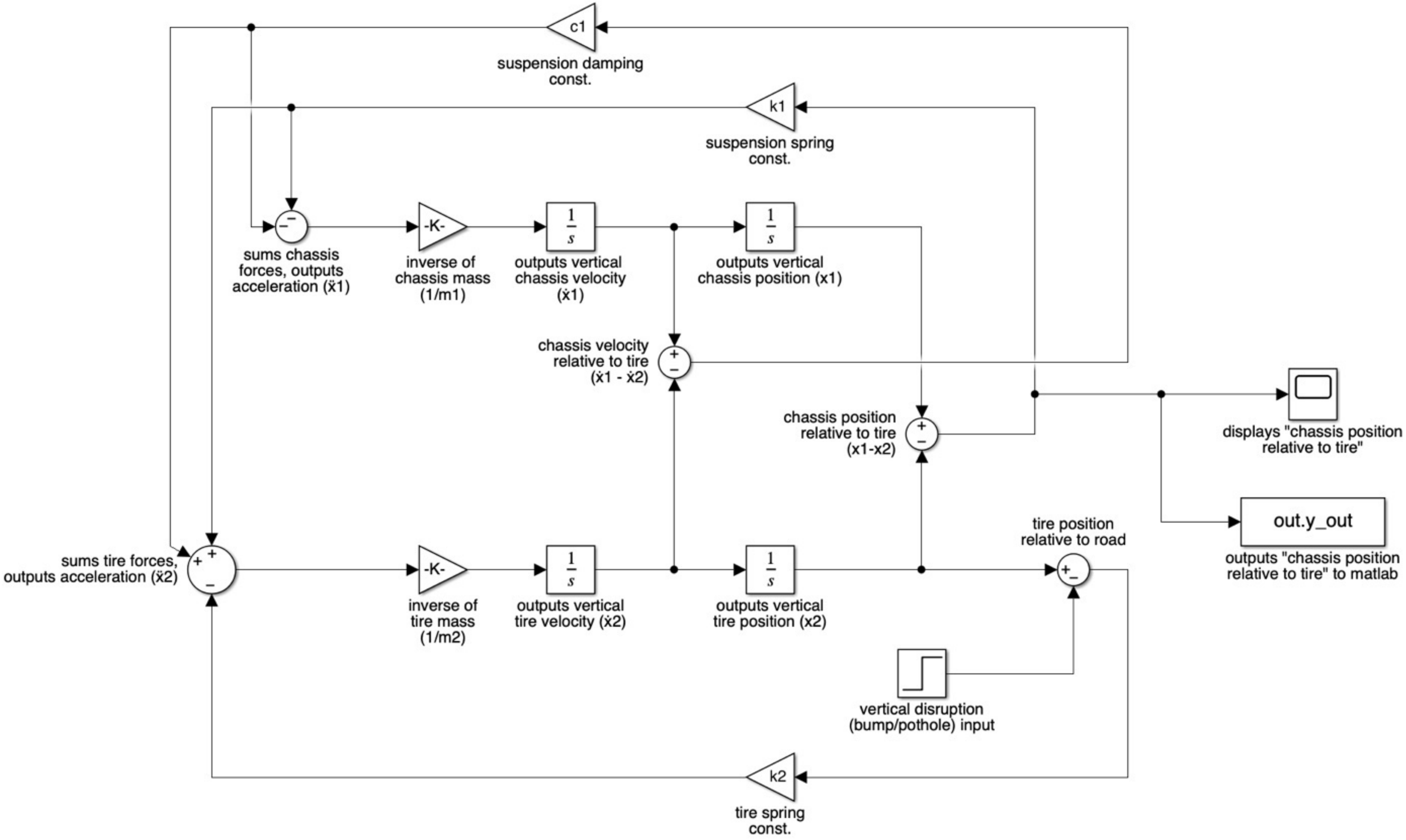
$$\ddot{x}_1 = \frac{1}{m_1}\left(-k_1(x_1 - x_2) - c_1(\dot{x}_1 - \dot{x}_2)\right)$$

$$\ddot{x}_2 = \frac{1}{m_2}\left(k_1(x_1 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) - k_2(x_2 - x_r)\right)$$

Physical interpretation:



Simulink Diagram



MATLAB Parameter Sweep

I wanted to set a target overshoot percentage (M_p) and settling time (T_s) for the suspension. Through a second order approximation of the system, I derived expressions for the damping ratio (zeta) and natural frequency (w_n) in terms of known values. However, I encountered challenges with achieving both goals at the same time due to the nature of the actual fourth order system. As such, I decided to focus on achieving a desired overshoot as I saw this to be the more important target.

Given the 10cm drop being modelled by the step input, I defined M_p to be 5%. After researching realistic ranges for the spring (k1) & damping (c1) constants in the suspension, I built a script which pushes each parameter pair (k1, c1) to the Simulink workspace, runs a simulation, extracts the output, and computes the peak response value. The value is stored in a matrix, then the matrix is converted to an overshoot percentage and compared to the target, extracting the spring & damping constants which gave the closest overshoot to the target.

Key concept for simulation loop:

```
for ik = 1:Nk
    for jc = 1:Nc
        assignin('base', 'k1', k1_list(ik));
        assignin('base', 'c1', c1_list(jc));

        simOut = sim(model, 'StopTime', '10');
        y = simOut.get('y_out');
        y_max_mat(ik,jc) = max(abs(y(:,1)));
    end
end
```

Key concept for parameter selection:

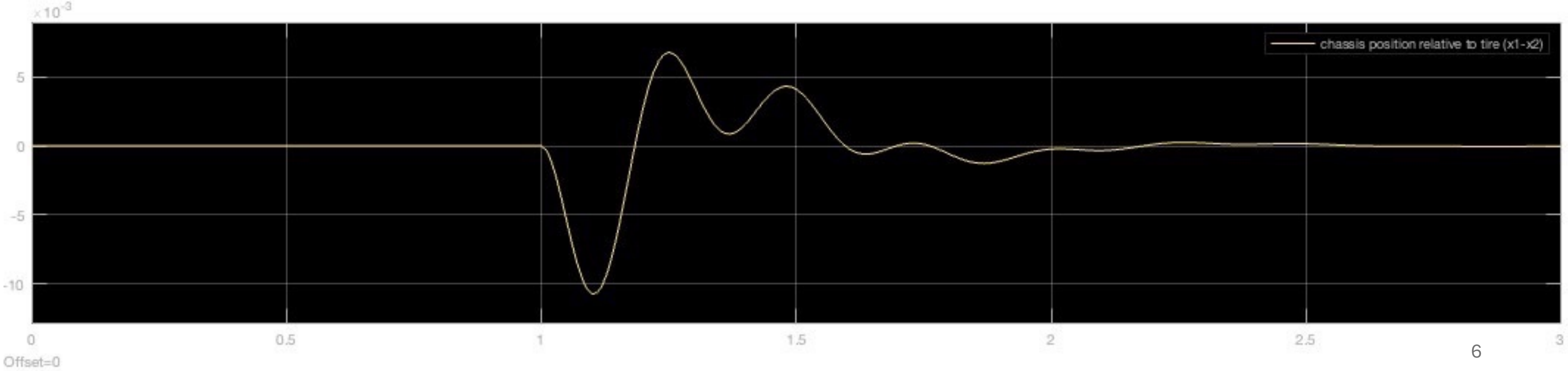
```
Mp_matrix = y_max_mat ./ bump_amp;
diff_matrix = abs(Mp_matrix - (1 + desired_Mp));
[min_diff, idx] = min(diff_matrix(:));
[row_idx, col_idx] = ind2sub(size(diff_matrix), idx);
best_k1 = k1_list(row_idx);
best_c1 = c1_list(col_idx);
```

Results

Parameters:
m1 = 300kg; m2 = 40kg; k2 = 190kN
Step amplitude: -0.01m @ 1s
Target overshoot: 5%

```
Best match to 5% overshoot:
  k1 = 15000 N/m
  c1 = 2000 N*s/m
  Achieved overshoot = 7.50%
```

peak vals	c1_1000	c1_2000	c1_3000	c1_4000	c1_5000
k1_10000	0.0137	0.0111	0.0093	0.0077	0.0070
k1_15000	0.0131	0.0108	0.0090	0.0074	0.0067
k1_20000	0.0126	0.0099	0.0086	0.0072	0.0064
k1_25000	0.0121	0.0100	0.0083	0.0070	0.0065
k1_30000	0.0117	0.0097	0.0081	0.0068	0.0063



Observations

Through exploring the ¼ car suspension model, I encountered significant variances with a single degree of freedom mass-spring model. With both chassis and wheel masses, the model now has 2 modes instead of 1, with the chassis responding slowly through the suspension system while the stiffness of the tire encourages quick responses. The step input excites both modes at the same time, however the chassis responds with a low frequency while the wheel responds with a higher frequency.

As such, the general 2nd order rules determining overshoot and settling time no longer hold. While for a one-mass system changing k and c predictably shifts overshoot and settling time, the two-mass suspension also change the strength of interaction between modes. Increasing stiffness or damping in this case affects not only body motion, but the way energy is transferred through the wheel mode. Thus, overshoot can increase or decrease based on the alignment of modes, even if the suspension damping ratio stays the same.

The ¼ car behaves exactly as a real suspension would, where you cannot independently tune overshoot and settling time using only the suspension. Improving one usually worsens the other because the two modes pull the system in different directions. This complexity represents one of the fundamental compromises in suspension design.

Wind Tunnel Fan & Actuator Modelling

I constructed a DC motor model and PID controller from first principles. I explored how these systems behave under both position and angular velocity control. The models took an input signal dictating wind speed, and controlled the voltage to the motor to achieve the desired output. Controller constants were experimentally adjusted to minimise overshoot and rise time.

Base equations:

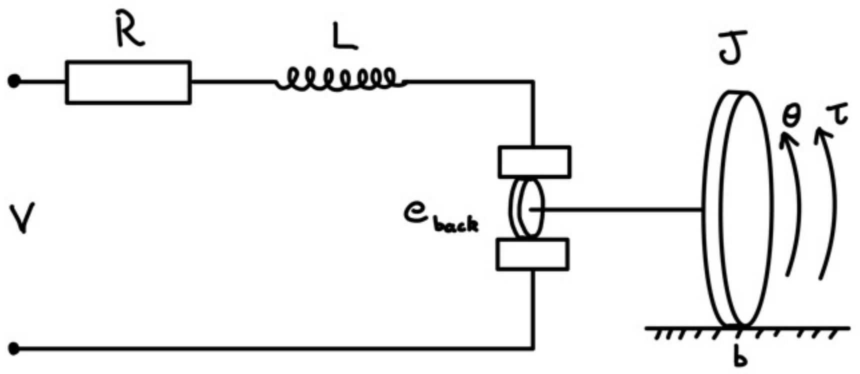
DC Motor

$$J\ddot{\theta} + b\dot{\theta} = K_t i(t) - \tau_{load}$$
$$L\frac{di}{dt} + Ri(t) = V(t) - e_{back}$$
$$e_{back} = K_e\dot{\theta}, \qquad K_e = K_t = K$$

Controller

$$u(t) = K_P \cdot e(t) + K_I \int e(t)dt + K_D \frac{de}{dt}$$
$$e(t) = u_{ref}(t) - u(t)$$

Physical interpretation:

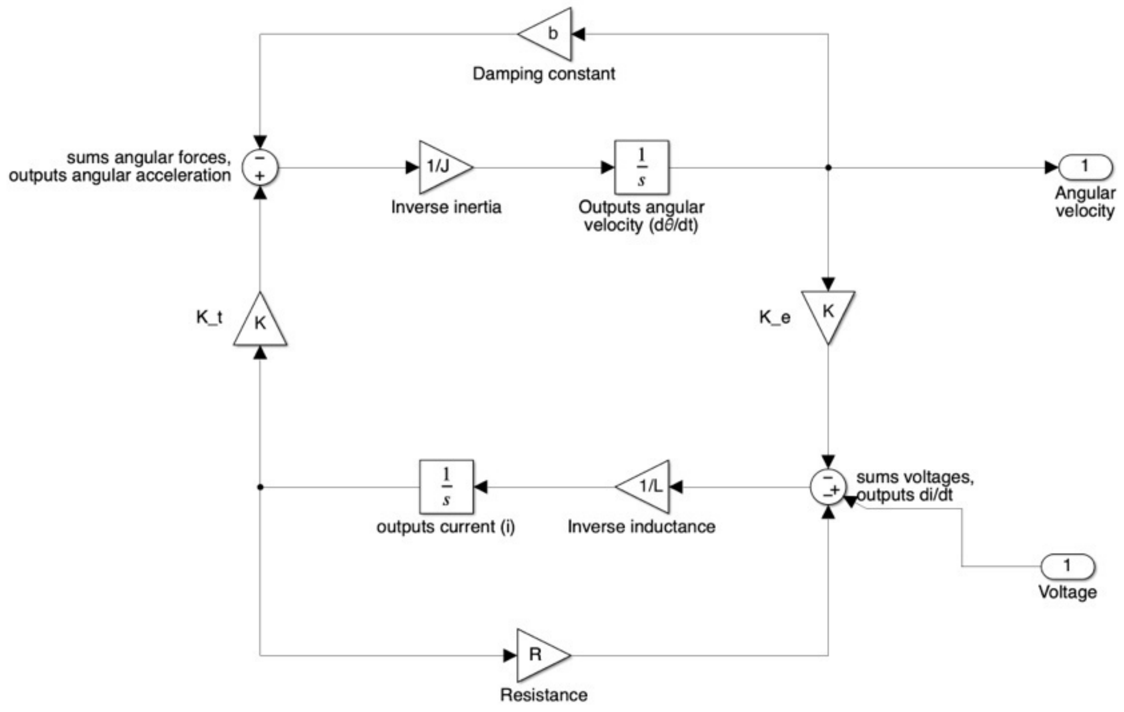


Simulink Diagram – Wind Tunnel Fan

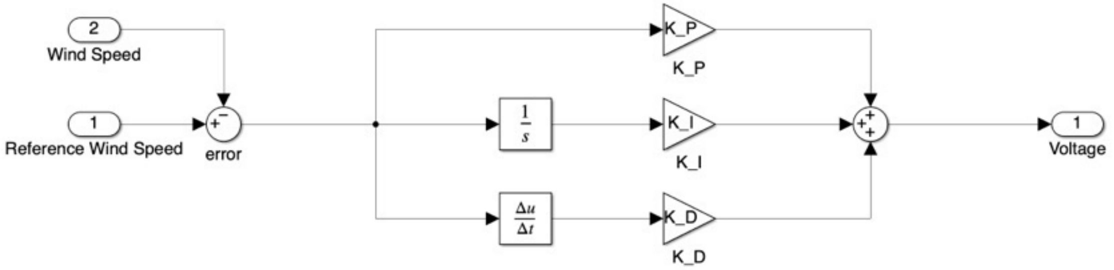
```
J = 0.02;
b = 0.02;
K = 0.15;
R = 1.2;
L = 5e-3;
```

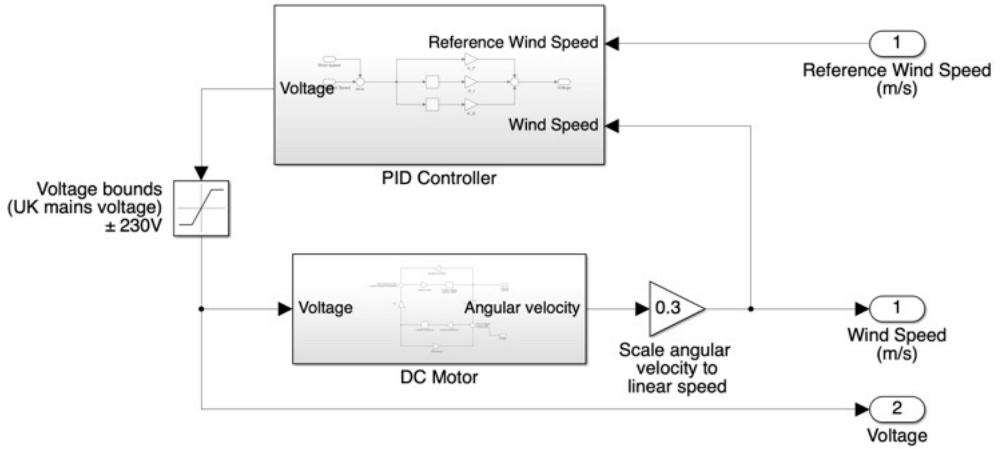
```
K_P = 500;
K_I = 0;
K_D = 60;
```

DC Motor:



PID Controller:





Results

Fan (ref. sig. 30 m/s at t = 1s)

Observations

Building the DC motor allowed me to observe the interaction between coupled electrical and mechanical systems, and allowed as a familiar foundation to begin exploring system controllers. I chose to start by building my own PID controller (with proportional constant K_P, integral constant K_I and derivative constant K_D), to gain a better understanding of its behaviour in different cases through experimental testing. In each case, I aimed to keep overshoot within 5% and have a settling time within 1s.

For the wind tunnel fan, I started by exploring how the controller behaved in the absence of saturation, noting that K_P dictated rise time and general behaviour, K_I adjusted the steady-state value and K_D reduced overshoot. However, lack of saturation is unrealistic, and so voltage was bound between ±230V. This significantly altered the behaviour of the system, where the controller could only act as an integrator for the first part of the system and fan speed rose linearly. Once the back emf of the system reduced the required voltage to below saturation values, the dynamics became smooth and well-damped as all three controller gains were available. I had to include a gain block on the output of the DC motor, since the motor system outputs the fan angular velocity while I wanted the wind linear velocity, deeming a scalar multiple to be adequate in the case of this system.

In general, it can be said that the proportional term determines how quickly the controller pushes the motor when voltage is available, the integral term modifies the long-term behaviour, and the derivative term impacts the system behaviour when rapid changes occur. In practice, these rules can be affected by applying saturation and bounding the voltage, constraining the system to behave differently.

Cruise Control Modelling

I designed the cruise control system for a nonlinear vehicle model. In designing and tuning the PI controller, I explored the importance of saturating outputs and implementing anti-windup. The model has a variable initial velocity, a cruising speed of 100km/h for the controller reference, and additional resistance introduced after system stabilisation to observe adjustments.

Base equations:

Vehicle

$$m\dot{v} = F_{drive} - F_{drag} - F_{hill}$$

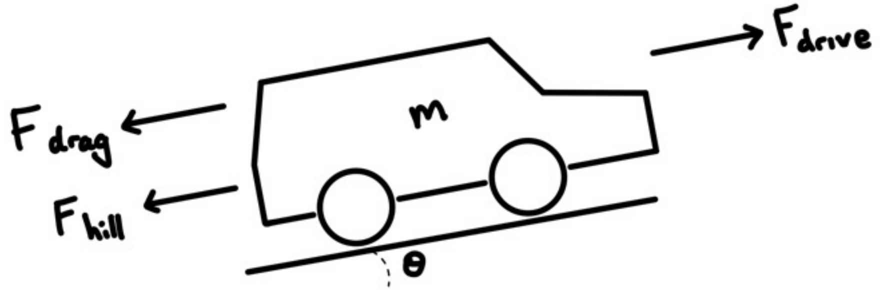
$$F_{drag} = \frac{C_d \rho A}{2} v^2 \qquad F_{hill} = mg\sin(\theta_{hill})$$

Controller

$$u(t) = K_P \cdot e(t) + I(t)$$

$$\dot{I}(t) = K_I e(t) + K_{aw}(u_{sat} - u_{req})$$

Physical interpretation:

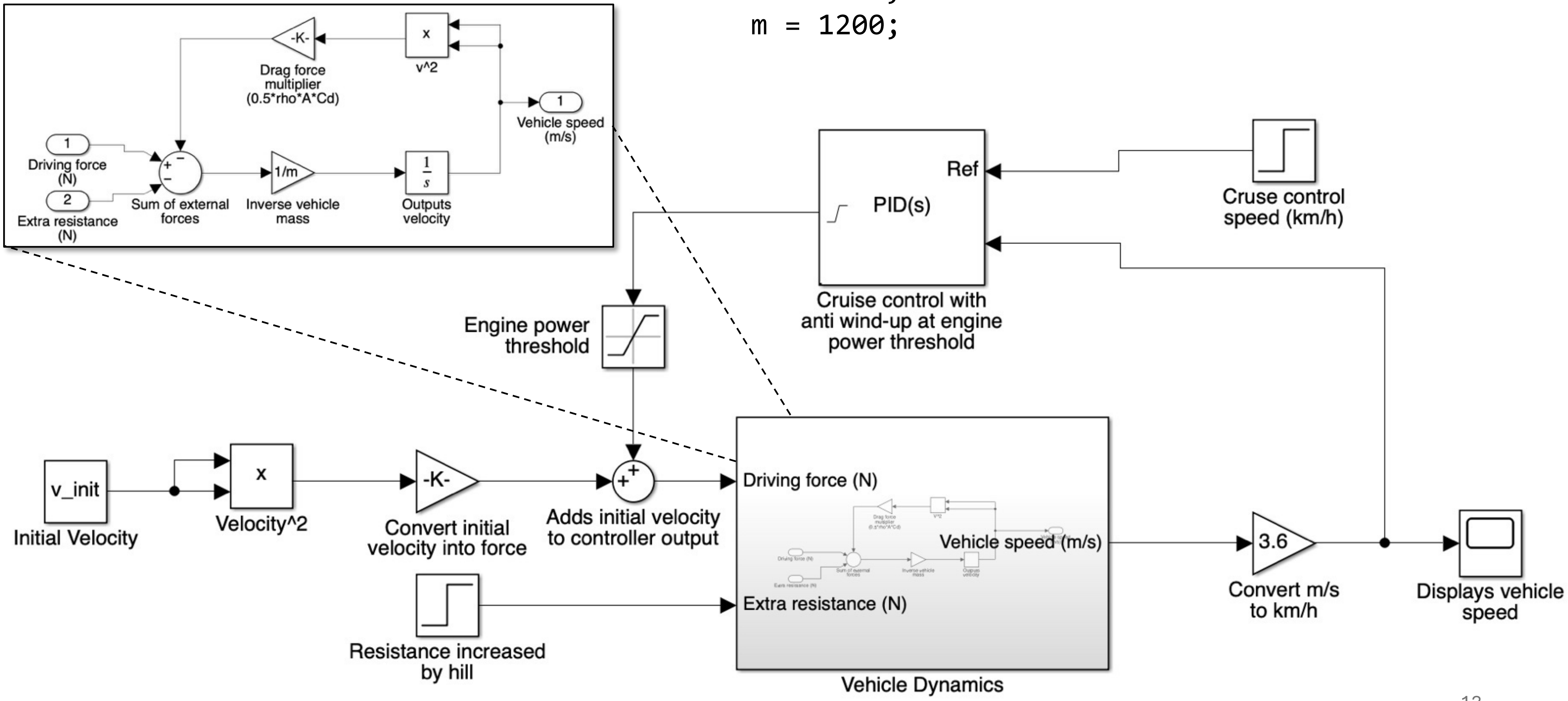


Simulink Diagram

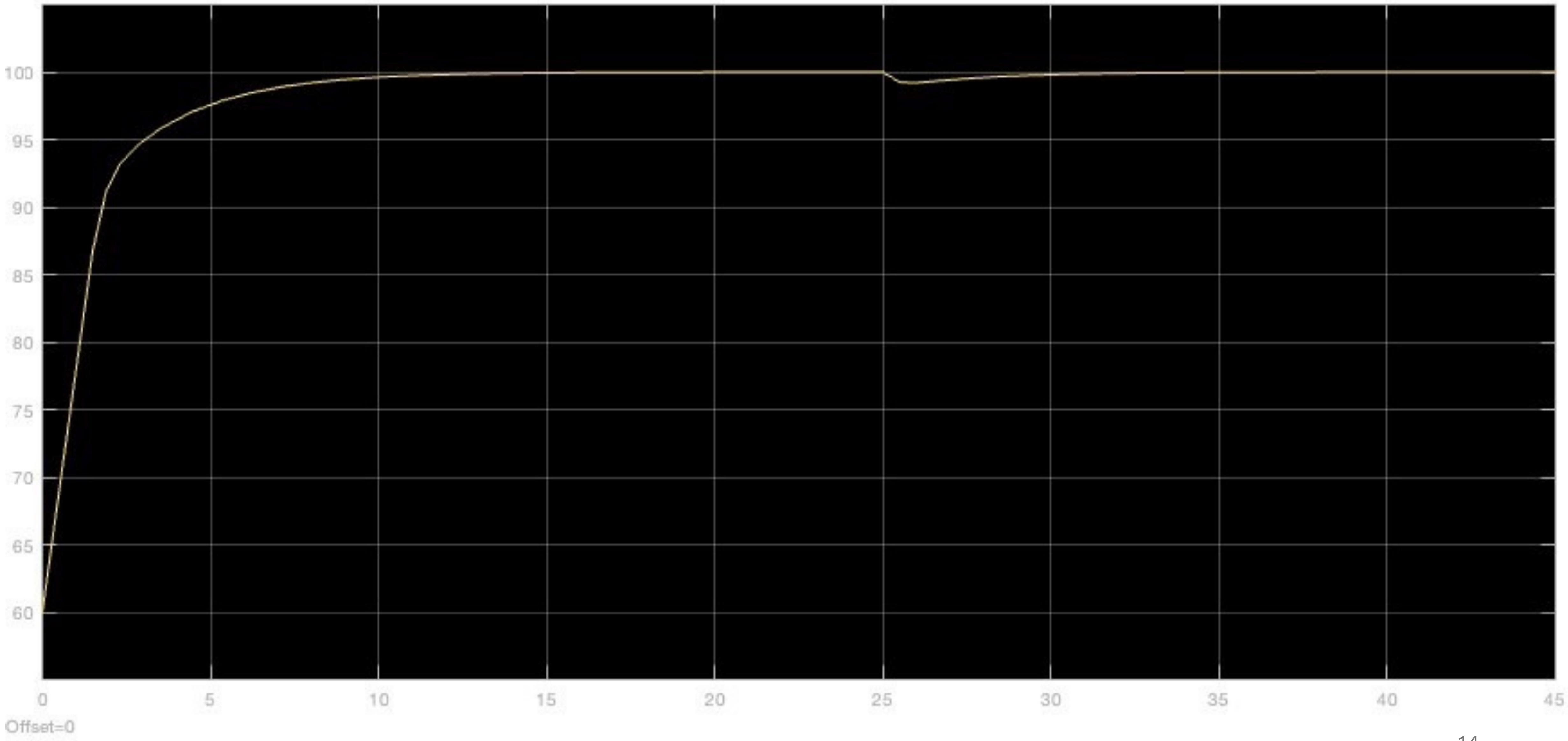
```
rho = 1.2;
g = 9.8;
A = 2;
Cd = 0.3;
m = 1200;
```

```
v_init = 60;
eng_power = 6000;
grade = 10;
```

```
K_P = 1200;
K_I = 400;
K_D = 0;
```



Results – extra resistance from 10% hill at 25s



Observations

While setting parameters for the PI controller, I experienced significant difficulties in achieving no overshoot and a reasonable settling time. This turned out to be a result of enforcing an engine force limit through the saturation block, resulting in a large error. While the controller output was bound by saturation, the integrator kept storing this large speed error which resulted in huge overshoot and slow recovery after the controller exited saturation. This led me to explore the importance of anti-windup for saturated controller systems.

As shown in the base equations, anti-windup is an additional term in the integrator. When the required input u_{req} is less than the saturation limit, $u_{sat} = u_{req}$ and the anti-windup factor is zeroed out. However, when $u_{req} > u_{sat}$ the difference is multiplied by a factor K_{aw} and removed from the total error. With the implementation of anti-windup, the model could accelerate to the cruise speed without overshoot, and recover quickly and realistically from any changes in resistance while respecting the engine limitations. While I experimented with increasing and decreasing K_{aw}, keeping it at 1 gave a result consistent with the desired behaviour.

Modelling this system opened my eyes to the importance of anti-windup in a PI controller to reduce the error being integrated. It highlighted the importance of saturation boundaries along with K_P and K_I constants, and how misleading the output of a controller can be when dominated by saturation. It also reinforced the idea that a PI controller is only reliable when its internal states are consistent with what the system can physically achieve, directly aligning with the role of anti-windup.

Active Aero Modelling

I developed an active aero controller that adjusts wing downforce based on vehicle acceleration. A differentiated and smoothed braking signal maps braking magnitude to a desired downforce level, which is converted into a reference force. The actuator is modelled as a first-order lag, and a feed-forward term provides the ideal wing angle based on current velocity and target downforce. This structure allows the system to track braking-dependent downforce commands smoothly and predictably.

Base equations:

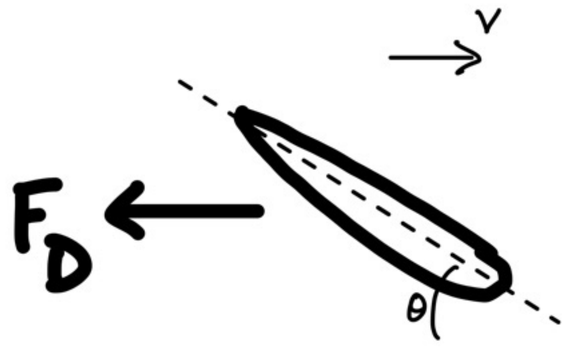
Wing

$$\mathrm{F_D} = \frac{1}{2}\rho A(C_{L0} + C_{L1}\theta)v^2$$

Controller

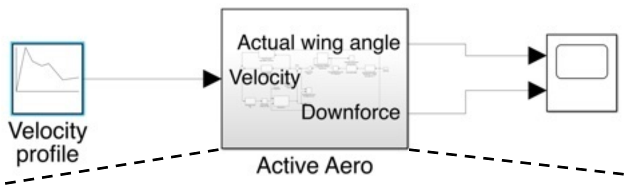
$$u(t) = K_P \cdot e(t) + I(t) + K_D \cdot e(t)$$
$$\dot{I}(t) = K_I e(t) + K_{aw}(u_{sat} - u_{req})$$

Physical interpretation:

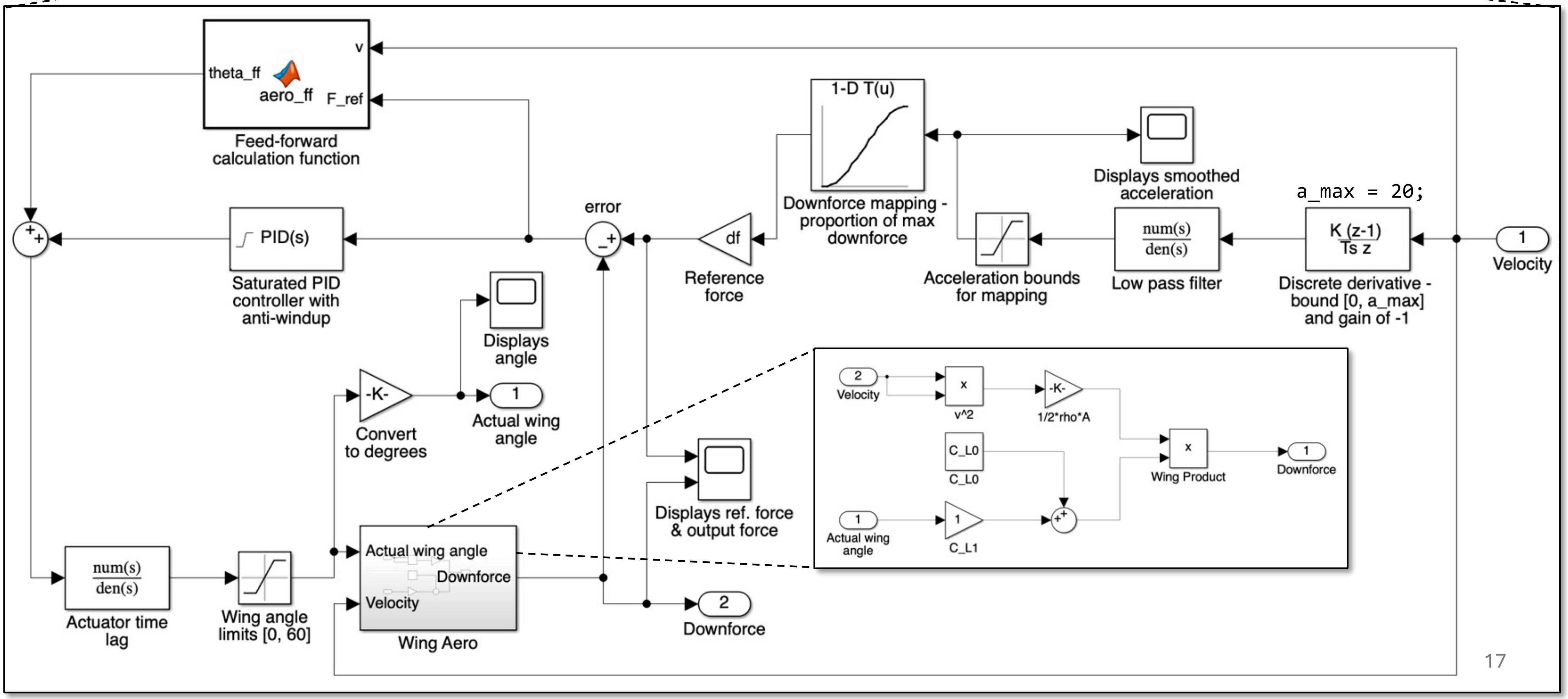


NASA models drag as approximately linear between low and high angles, with a small constant due to skin friction. Thus, I have chosen to model drag with a constant factor added to a factor varying with angle, $C_{L0}+C_{L1}\theta$

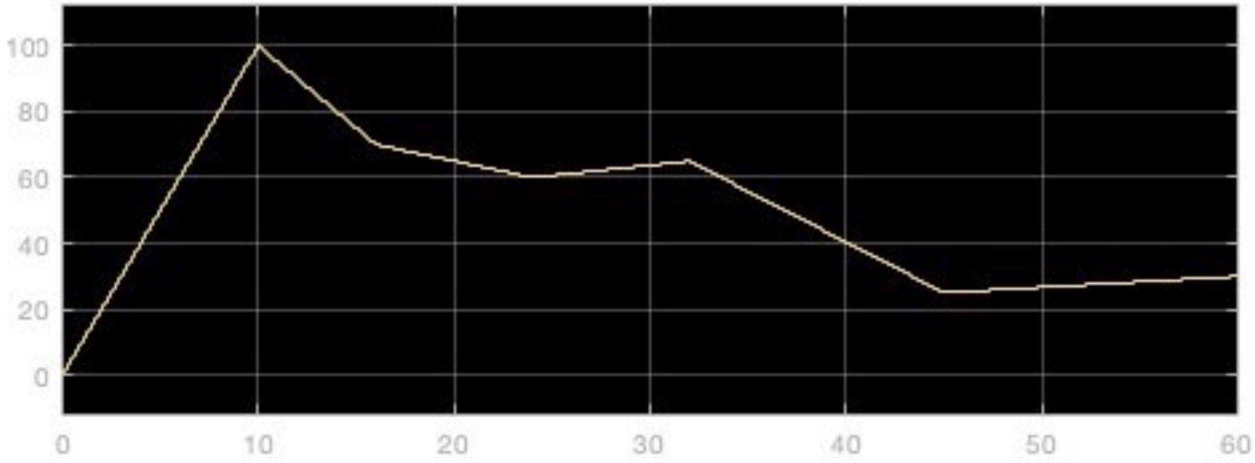
Simulink Diagram

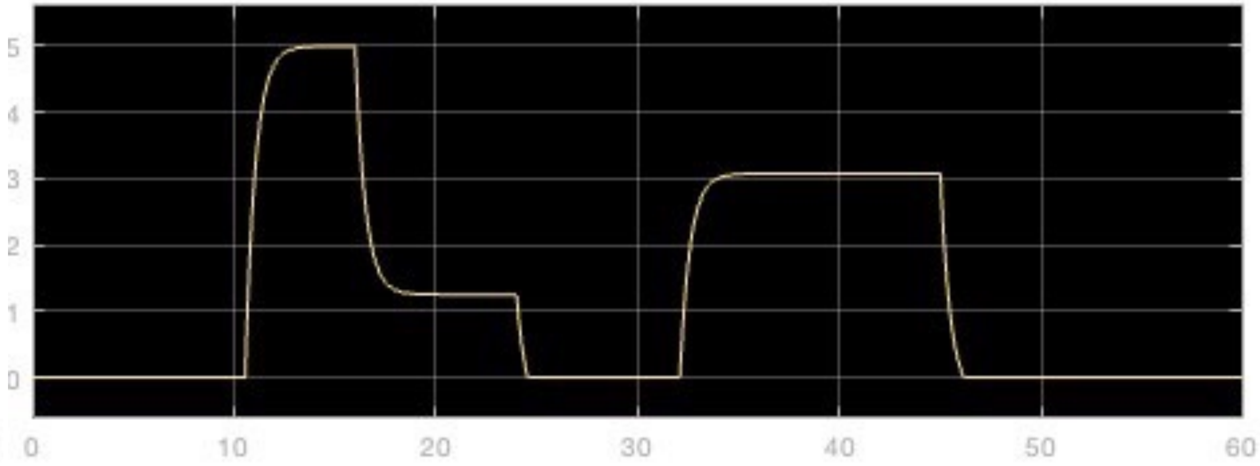



```
K_P = 500e-6;    A = 1.5;
K_I = 5000e-6;   m_car = 1200;
K_D = 100e-6;    C_L0 = 0.01;
                 C_L1 = 0.2;
                 df = m_car*g*df_fact
```



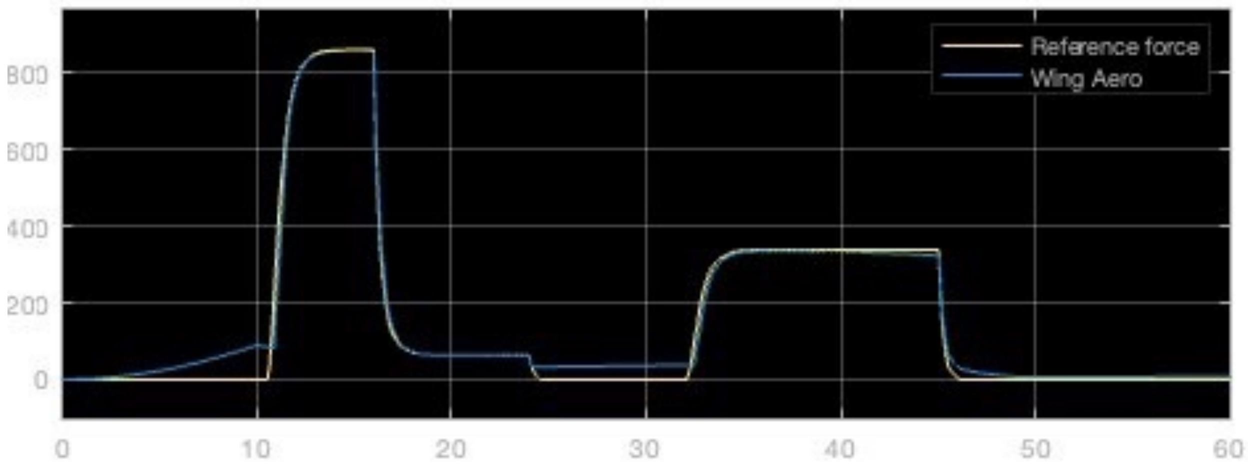
Results

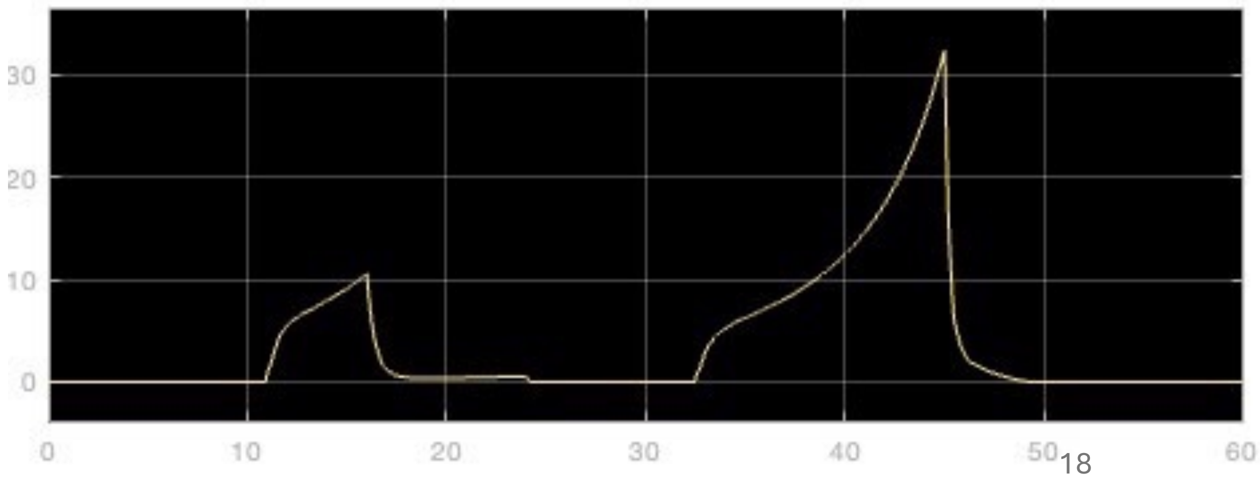




Above – Velocity input (m/s); Below – Actual & ref. downforce (N);

Above – Smoothed braking forces (m/s^2); Below – Wing angle (deg)





Observations

Modelling an active-aero system drove me to consider how aerodynamic forces, mechanical dynamics and control structures interact. Translating braking behaviour into meaningful downforce demand meant converting a velocity profile into acceleration before I could think about how to map it to a reference downforce. Early variations highlighted errors in modelling, where unrealistic constants and sign errors resulted in inconsistent scope readings. With these issues resolved, the behaviour of the controller could be explored. Modelling an instantaneous actuator response would result in drastic angle changes, and so a lag term of $G = \frac{1}{\tau s+1}$ was introduced to capture the finite speed of a physical system, where τ represents the time taken for the actuator to reach 63% of it's final value.

Introducing a ”feed-forward” term challenged my interpretation of how a PID controller works. Initially, I thought this term was overloading the controller with downforce it had to counteract. Once I understood its role of calculating the ideal output from the reference downforce, it re-framed the PID as a tool for “fine-tuning” rather than dictating. With accurate coefficients, the feed-forward term aligned with the reference signal almost immediately and allowed the controller to correct small tracking errors, producing a response that reliably followed braking events. The variances between the “reference downforce” and “wing aero” are a result of the C_{L0} coefficient creating downforce due to velocity.

Building this system highlighted how much structure lays underneath a deceptively simple control task. Learning about feed-forward was crucial in my understanding of control, providing the system with an informed estimate of the required output to reduce PID workload. By trimming small variances rather than fighting large errors, the controller response is stabilised and allows the system to behave predictably under rapid change. Pairing this with physical properties like actuator lag and the drag model clarified the importance of using prediction alongside correction in a controller to built stable systems.

F1 in Schools (now STEM Racing)

F1 in Schools is the premier STEM competition in the world for students aged 9-19. Teams of 3-6 members design and manufacture a miniature Formula 1 car using CAD/CAM design tools. These cars race along a straight 20m track, powered by CO_2 and tethered by a nylon wire. Teams also collaborate with industry partners to secure funding and mentorship across state, national, and world finals where they are judged across racing, exhibition displays, verbal presentations, and engineering, enterprise & project management portfolios.

The project management portfolio documents the team's journey towards the competition. Assessment covered the project's initiation processes, planning, executing, and monitoring & controlling. The subsequent pages include that portfolio, which I was responsible for producing to compete in the 2023 F1 in Schools World Finals in Singapore. This work received top marks and was the team's highest scoring project element, contributing to our placing 17th out of the 68 teams who qualified to compete Additionally, I played a significant role in our car's design. My contributions to the team's engineering is shown on the pages following the project management portfolio.

Through my role as the team's project manager, I was able to introduce a new paradigm to my engineering toolkit. The experience forced me to consider the structure of complex engineering tasks, how dependencies & risks are identified, and how resources, timelines & roles interact within a larger project. I learned how to anticipate bottlenecks, build processes which keep technical work aligned with project objectives, and translate high-level goals into actionable, measurable tasks.


constellation
PROJECT MANAGEMENT
PORTFOLIO
Constellation - 2023 Aramco F1 in Schools World Finals

Initiation

constellation WORLD FINALS 2023

WELCOME

Table of Contents

SCORECARD CRITERIA: INITIATING

INITIATING

Kick Off Meeting

A kick off meeting's purpose is to start a team in the right direction, and build the foundations for a strong and cohesive team.

Constellation's kick off meeting occurred on the 10th of June 2022, where we had three goals. This became the underlying model of all future team meetings during our campaign, as, due to their frequency, a more detailed and structured event would have compromised the meeting quality. Therefore, all future team meetings would be modelled around a few key points to address, reducing intensity and avoiding burnout.

Kick-off meeting agenda
Source: Constellation

Firstly, we brought our newest member, Matthew Westerman, up to speed on our journey to date. This allowed him to understand team objectives, principles and enabled effective collaboration with the team and productivity. Afterwards, the remaining meeting goals were addressed: defining the project by answering the underlying questions for to project comprehension, identifying stakeholders and drafting a project charter to authorize the project.

We settled on the following answers to the six key questions as follows:

- **Who is this work being done for?**

  We are undertaking this project for ourselves (the team), our futures, our external stakeholders and our school.

- **What are we going to deliver?**

  Our deliverables consist of three portfolios, cars, a scrutineering booklet, verbal presentation, pit display, sponsorship prospectus, branding guidelines, uniforms, and all media.

- **When will we produce these deliverables?**

  Our prospectus and interim uniform should be completed at the very latest by the commencement of the New Year. Assuming submission in mid-August, our car should be finished by mid-June. All other project elements should be completed by early August, so deadlines are not an issue.

- **Where will the deliverables be used?**

  The prospectus will be sent to prospective stakeholders. Our interim uniform will be worn for public events and media events. All other elements will be submitted with our final project.

- **How are we going to achieve the project's goal and objectives? How will success be measured?**

  We will achieve our goals by working as a team to collaborate and integrate our individual skillsets into one collective project. Following project management routines will ensure we stay on-task, and ensure completion of the highest standard. Success will be measured primarily by the team's satisfaction with the quality of work, and our final results at the competition.

- **Why is the project being initiated? What is the reason for the project?**

  This project is being launched to delve into the highest tier of the Formula 1 in Schools competition and achieve the title of 2023 Formula 1 in Schools World Champions.

Identifying Stakeholders

A stakeholder can be identified as being any individual or group impacted by the success of our team. As a result, we created a stakeholder register in order to more easily communicate with our stakeholders.

The team assessed our National Finals stakeholder register and used it as a base for creating our World Finals stakeholder register. We cleared out any entries who were no longer stakeholders, and created categories for any existing and forthcoming stakeholders. These were: team members, supervising adults, sponsors, mentors, judges, and supporters. After constructing these groups, we began to allocate new stakeholders to their respective categories, accompanied by their name, email, and organisation. The register was updated throughout the competition.

[redacted]	Sponsor
	Sponsor
	Mentor
	Sponsor
	Sponsor

Project Charter

A project charter is A document with the aim of obtaining authorisation for a project to move forward. Its main job is to outline the project description, project manager, team members and other stakeholders, purpose, deliverables, constraints, milestones and risks of a project, as well as clarify any assumptions and identify resources required, seeking approval to commence the project.

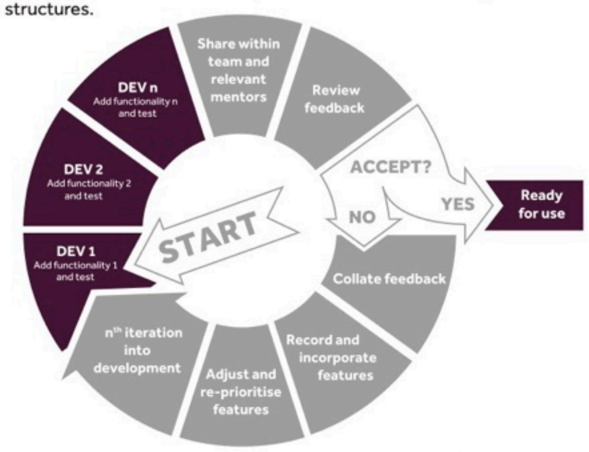
During our kick-off meeting, we created a list of categories based on our National Finals project charter and examples our Project Manager found through research. Then, we sat and drafted bullet points for each category, allowing our Project Manager to walk away from the meeting with enough information to write an initial draft.

Project Charter excerpt
Source: Constellation

After working through this draft with our teacher, further alterations were made. Finally, we sat down as a team once more to review the updated document, before our Project Manager and teacher signed off on it, authorising our project. The final iteration of our project charter can be seen in the column prior.

The team's project management approach was also outlined in the scope statement, determining application of certain project management methodologies; including tools and processes to be used to plan, execute, monitor and control the project.

We used Agile methodology to complement our project management due to our extended timeline and limited information about deadlines during initiation. Agile is a flexible and adaptive approach focusing on incremental and iterative development. We took advantage of frequent feedback and communication between team members allowing us to identify and address issues early on. Additionally, Agile enabled us to be more responsive to changes in the project's scope and requirements, which improved our ability manage resources effectively, and deliver a successful project on time and within budget, in turn minimising scope creep. Further, we established communication procedures and other management structures.



Agile circular flow diagram | Source: Constellation

Team Identification

SCORECARD CRITERIA: PLANNING

Management Process

Sufficient planning, documentation and assessment was necessary for the success of the team. Aligned with Constellation's ideology of iterative progress, the team put in place a structured process to guide the management of out project.

1 Initial Planning - Defining tasks, acceptance criteria and team roles.
2 Budgeting - Estimating when, where and how resources are acquired and used, setting a schedule for tasks, planning for risk and communication.
3 Monitoring - Recording use and acquisition of resources and cash. Weekly check-ins and status reports to constantly monitor progress of tasks allowing for adjustments to be made if necessary.
4 Evaluation - Variance reports constructed to outline deficiencies enabling timely mitigation and forward planning.

INITIAL PLANNING

Team Members

For a project to be successful, team roles must be allocated to optimise each individual member's skillsets, and complement each other in working towards an overall goal. We knew that to win, relevant knowledge and experience was crucial. Below is a register of each team member.

Jenson Galvin
Team Principal
Director of Marketing

Matthew Westerman
Team Project Manager
Director of Development

James Mitchell
Team Engineer
Director of Partnerships

James Tan
Team Quality Control
Director of Innovation

Job Functions

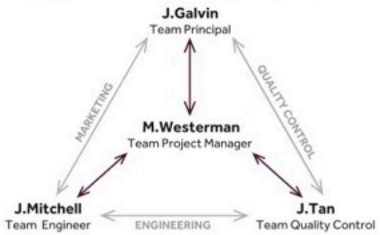
With these roles in mind, each team member was allocated two roles. The primary roles, or 'team' roles, reflected the priority responsibilities, while the 'director' roles align with supplementary responsibilities. These roles are explored below.

- **Team Principal:** Responsible for the day-to-day operation of the team, and administrative tasks. Point of contact between team and In Country Co-ordinator.
- **Team Project Manager:** Responsible for the long-term operation of the team. Keeps sub-projects on track, and keeps track of progress.
- **Team Engineer:** Responsible for design of car, booth, and all other CAD-based requirements.
- **Team Quality Control:** Responsible for proofing all document and CAD progression.
- **Director of Marketing:** Manages the creation and distribution of marketing and digital media material, and oversees team public image.
- **Director of Partnerships:** Manages outreach and communication between stakeholders and the team.
- **Director of Development:** Oversees physical and virtual testing, and collaborates with the Team Engineer to optimise design choices.
- **Director of Innovation:** Manages the application of team innovations, and works with Engineering to ensure all decisions are calculated.

Team Structure

A well-defined team structure is one of the fundamental concepts of a successful team.

Our team aimed to employ a composite organisational structure, reflecting common practice in industry, tapping into the advantages of projectised and matrix organisational structures. However, we found early on that due to our small team size and the overlap in team roles between Enterprise and Engineering, a network-based organisational structure developed. This allowed for constant, fluid communication between members across the duration of the project, where collaboration was encouraged, and support structures were put in place.



Team Structure Diagram | Source: Constellation

RACI Matrix

To distribute responsibilities effectively, RACI matrices are used due to their simple and accessible design. By assigning each team member-task pair as Responsible, Accountable, Consulted, or Informed, the project was suitably broken down.

We developed a master matrix during project initiation, where our inputs were our Work Breakdown Structure, job functions, and the scorecards for the 2022 World Finals. This allowed for easy visualisation of individual task accountability during the front half of the project timeline.

When the 2023 Competition Regulations were released, an updated RACI matrix was created to reflect the scorecard criteria, and can be seen below.

Project Management	Jenson G	James M	James T	Matt W
Initiation Process	C	I	I	R
Project Schedule	A	I	I	R
Budget & Resource Management	R	C	R	A
Roles & Responsibilities	R	C	C	R
Team & Stakeholder Communications	A	I	I	R
Risk Management	C	C	I	R
Monitoring & Controlling	A	I	C	R

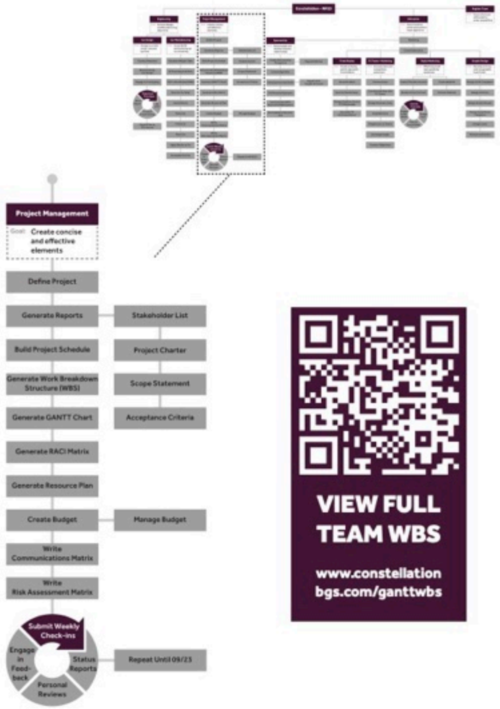
RACI Project Management Excerpt Source: Constellation

Work Breakdown Structure (WBS)

A Work Breakdown Structure (WBS) is a hierarchical decomposition of a project into smaller, more manageable components used to visualize and organize the tasks required to complete a project.

Our WBS built off our scope statement, as well as previous initiation steps and was a development of our National Finals WBS. We broke down our project into smaller work packages, which our project manager could assign to team members, then track and monitor their progress. This started with the project as the top-level component, and then branched out into the major deliverables. We broke each major deliverable down further into smaller components using the 100% rule, where the sum of the smaller components should equal 100% of its parent deliverable.

Creating a WBS early in the project provided a clear, concise idea of the project's scope and helped to identify potential risks, dependencies, and milestones, crucial for developing our budgets, timeline, RACI matrix, and risk management sheet.



VIEW FULL TEAM WBS
www.constellationbgs.com/ganttwbs

Work Breakdown Structure, Project Management zoomed in | Source: Constellation

Constellation™ Formula 1® in Schools Team

Budgeting and Planning

constellation WORLD FINALS 2023

SCORECARD CRITERIA: PLANNING

BUDGETING

Timeline

Following the kick-off meeting, we reviewed various resources available to us and drew up a preliminary timeline, seen below.

Constellation preliminary timeline | Source: Constellation

We were able to use this as a rough template for deadlines, and tweaked it as more information became available, ending with the timeline seen below.

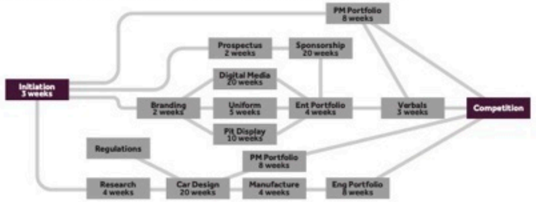
Constellation final timeline | Source: Constellation

Determining a Sequence

With tasks defined and acceptance criteria set, it was then necessary to plan when tasks were completed. Certain tasks had to be finished or reach a specific stage before others could begin. The team used a combination of Critical Chain and Critical Path ideologies while considering these dependencies and acceptance criteria to identify tasks that could not be delayed, as well as resources that had to be acquired for those tasks to be completed on time. This provided a clear roadmap for the team, highlighting when, where and how resources were to be acquired and used for completion of project elements.

The team allocated 20% of the time as a buffer by cutting down the task durations. This addressed the issue of overestimating time and procrastination, encouraging prompt task starts and enabling early progression to the next task if completed ahead of schedule.

Tasks were also subdivided to allow for partial dependencies to start earlier once a certain part of a task was completed early. For example, we completed our wheel research and development early in our car development process due to the estimated long lead time of wheel manufactures to meet the deadline for manufacturing.



Constellation dependency chart | Source: Constellation

MONITORING

Resources and Project Deliverables

Planning for the resources required for success was crucial for setting up a structure for the team's campaign. Understanding when, where and how resources are to be used enables planning for cash and scheduling.

Since resources needed to be acquired before use, the team estimated the timeframe of the use of certain resources to plan for when resources needed to be acquired. Cost of acquisition, preferred and alternative suppliers as well as backup resources were also considered to plan for potential issues. This was estimated from past data, team's expectations of project deliverables, research, Work Breakdown Structure and Critical Path, producing a preliminary budget.

We created a centralised spreadsheet to monitor resource acquisition, usage, and movements. Each entry includes a brief description, quantity, cost, and storage details, enabling easy tracking and identification of issues. This ensured all team members understood resource movements so no time was wasted searching for resources.

Date	Category	Item	Description	Amount	Cost	Location
26/07/2023	Marketing	Rode Wireless Microphone	Purchased from JB-HIFI	1	-$211.09	F1 Room
28/07/2023	Car	Wheel Bearings	Arrived from supplier	100	-$3,162.34	JM Home
1/08/2023	Trade Display	Monitors	Purchased from scorptec	6	-$2,658.85	Thivi's Office
1/08/2023	Trade Display	Highgrade Fix LCD TV Wall M	Purchased from scorptec	3	-$51.00	F1 Room
2/08/2023	Car	Prototype Parts	Various SLS parts arrived for testing	2 Cars Worth	-$169.83	JM Home
3/08/2023	Uniform	Team Trousers	Bought Parts for competition	4	-$276.00	Team's Homes
4/08/2023	Car	Prototype Parts	Various SLS parts brought to school for testing	2 Cars Worth		F1 Room
4/08/2023	Car	Wheel Bearings	brought to school for testing	100		F1 Room
8/08/2023	Uniform	Team Jackets	Team Jackets Arrive	7	-$597.85	F1 Room
8/08/2023	Trade Display	NFC Tags	Purchased NFC Tags	N/A	-$25.93	F1 Room

Live resource spreadsheet excerpt | Source: Constellation

All files during the project were stored in the team OneDrive allowing for easy collaboration on project elements. The following naming system was created for ease of identification and tracking of files.

[Department]_[File Name]_[Creation Date]_[Additional Info].ext

PM_ProjectCharter_8.6.22_v3.docx

PM_PortfolioWorkingDraft_1.9.34_v10.indd

File naming system example | Source: Constellation

Cash

Before preparing cash budgets, the team needed to estimate the total cost of the project. Having estimated resources required and again using past data from the National Final campaign, other World Finals teams including Infinitude and Nebula, and available information at the time, the team was able to approximate the expected expenditure for individual items totalling to $41,550AUD.

The preliminary budget also needed to account for risk and any cash variances that may occur throughout the duration of the competition as funding for unexpected expenses cannot be acquired instantly. We created a contingency reserve of $5000AUD (~12%) due to the long timeframe and uncertainty.

We then allocated categories to each expected expense to simplify records and allow for easier comparison, then created a preliminary budget of cash inflows and cash outflows with an estimated timeframe of the expenditure. This allowed the team to plan the amount of cash needed to be raised through sponsors or otherwise and set deadlines to when cash needed to be raised, ensuring cash balance remained positive so the team could cover outflows, in particular meet the purchase of estimated resources and fund project elements.

Budgeted outflows (top) and inflows (bottom)| Source: Constellation

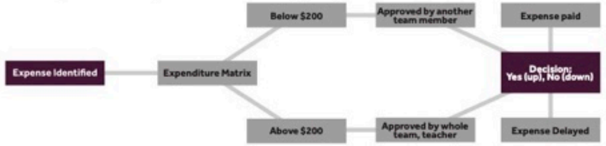
To track cash flows, the team used a spreadsheet detailing cash inflows and outflows including any necessary information such as the date, a description and category allowing for any user of the spreadsheet to easily understand entries. An expected cash flows spreadsheet was also created when accurate information about a future cash flow, which was almost certain to occur, was acquired. This document, separate to the budget, shows events that are highly likely to occur, giving the team more up-to-date information about the cash position than the monthly budgets, allowing for corrective action if necessary.

Category	Date	Description	Name	Amount
Travel	10/03/2023	Flights Payment	Emirates	-$ 4,110.40
Cash Sponsorship	16/03/2023	Capital Sponsorship	Bosch	$ 1,500.00
Misc - Outflow	29/03/2023	Trophy Engraving	Trophy Engraving	-$ 255.75
Cash Sponsorship	3/04/2023	Capital Sponsorship	ROKT Corporation	$ 6,000.00
Cash Sponsorship	3/04/2023	Capital Sponsorship	Ford/Macquarie Uni	$ 3,000.00
Marketing	3/04/2023	Website hosting fees	Squarespace	-$ 24.20
Car	6/04/2023	Prototype parts	Objective 3D	-$ 301.14

Live Cash Flow Spreadsheet | Source: Constellation

Acquisition Plan and Expense Control

While preparing budgets, we identified the cost and timeframe of acquisition of resources as well as suppliers and alternative resources. An expense approval process was implemented to reduce unnecessary spending. An expenditure matrix was used to determine if spending was necessary and cash utilized effectively. We also checked cash balance and budgeted upcoming payments to assess if unnecessary payments should be delayed in anticipation of other large expenses.



Expense approval procedure diagram | Source: Constellation

Constellation™ Formula 1® in Schools Team

Budgeting and Planning

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BUDGETING

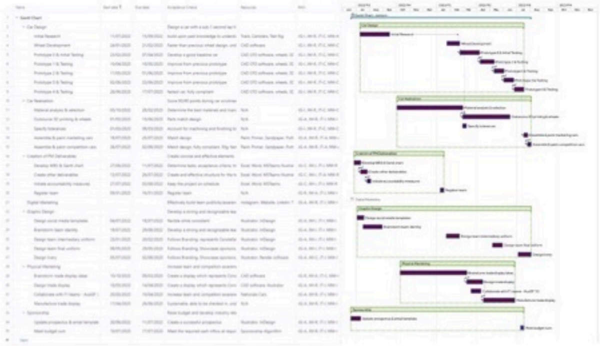
Gantt Chart

A Gantt chart was used to structure the flow of a project across its duration. We chose to use this tool due to its clear and organised structure, which allowed for each team member to be accountable for their deliverables.

When designing our Gantt chart, we chose to break it down into categories. These categories were discussed within the team during the realisation process, and allocated to each team member based on their roles as follows:

- **Car Design** — James M., Matthew W. & James T.
- **Car Realisation** — Matthew W., James M. & James T.
- **Creation of PM Deliverables** — Matthew W., Jenson G. & James T.
- **Digital Marketing** — Jenson G.
- **Physical Marketing** — Jenson G. & James M.
- **Graphic Design** — Jenson G.
- **Sponsorship** — James M. & Jenson G.

Since our project was initiated before any information about the competition was released, we expected to update and adjust our schedule throughout the competition and adjust it after assessment throughout the project following Agile methodologies. Having determined a sequence, we broke down the categories into smaller tasks using our WBS to further structure progress, allocated priorities to certain tasks at certain times and included resources required to complete each task.



VIEW FULL GANTT CHART
www.constellationbgs.com/ganttwbs

Constellation Gantt Chart Source: Constellation

We tracked task completion in a live document along with status reports (see page 7) and weekly check-ins to compare our progress against the project schedule. This allowed the team to quickly identify scope creep or the lack of resources for an upcoming task.

PLANNING

Risk Identification

Before we could start with risk management, we had to identify the risks which could occur during the project. These were defined to be events which impacted the progression of the project.

Initially, we stripped down our risk assessment from the National Finals to create a baseline register. To expand upon this, we employed the Nominal Group Technique. Our group comprised of our Team Principal, Team Project Manager, Team Quality Control, Primary Supervising Teacher, and our school's Project Manager.

Risks were also categorised by area of impact. In this case, these were decided using the NGT. After risks were identified, their impact was broken down into 3 categories: Resources, Schedule, and Quality.

Starting with our baseline register, each group member was given 10 minutes to create a list of potential risks, before the group reconvened to discuss and create a complete register. This register was reviewed and revised monthly. Find below an extract from our final risk register.

ENT - Risks to Enterprise	
ENT.1.1	Lack of financial backing
ENT.1.2	Adobe Creative Cloud subscription expires
ENT.1.3	Adobe discontinues product necessary for F1 in Schools
ENT.1.4	Application / Device crashes
ENT.1.5	Enterprise software is removed from laptop
ENT.1.6	Team is unable to meet with partners
ENT.1.7	Loss of partner contact
ENT.1.8	Loss of file/branding asset
ENT.1.9	Enterprise process causes mental health complications
ENT.1.10	Loss of connection to Squarespace/social media service

Risk register - enterprise section excerpt | Source: Constellation

Impact Assessment

The impact of a risk is important so mitigation can be prioritised across the project scope. In the case of our team, we employed a method of risk scoring to rank the likelihood and impact of each risk from very low (1) to very high (5). Using this, an average risk score could be taken and compared, where the higher the score, the more mitigation needed.

A table representing our risk score calculation can be seen in the following column, which explains the variability of risk assesment in Constellation's impactful decisions.

	1	2	3	4	5
1	1	1.5	2	2.5	3
2	1.5	2	2.5	3	3.5
3	2	2.5	3	3.5	4
4	2.5	3	3.5	4	4.5
5	3	3.5	4	4.5	5

- 1-2: Low Risk
- 2.5-3.5: Medium Risk
- 4-5: High Risk

Constellation risk matrix ranking system | Source: Constellation

Response Planning

Within our risk register, each item was accompanied by a corresponding response plan. This allowed for individualised mitigation and avoidance strategies based on the risk category:

High Risk – Identified high impact risks carried large ramifications to the project if they occurred. In light of this, both mitigation and avoidance strategies were implemented where possible. Risk mitigation aimed to moderate impact, while avoidance strategies worked to decrease likelihood.

Medium Risk – risks categorised as a medium threat were still considered dangerous to project progress. For risks in this category, either mitigation or avoidance was prioritised if impact or likelihood was ranked higher. As a result, each medium risk event had a personalised response.

Low Risk – Low risk events had negligible project impact potential. One strategy was implemented for each low-risk event since less attention was needed. An extract from our final risk assessment can be seen above.

ENG.1.1	Prototype One deadline not met	2	4	3		x		Car
ENG.1.2	Prototype Two deadline not met	2	4	3		x		Car
ENG.1.3	Prototype Three deadline not met	2	4	3		x		Car
ENG.1.4	Prototype Four deadline not met	2	5	4		x		Car, Portfolios
ENG.1.5	Resignment of design engineer	1	5	3	x	x	x	Car, Portfolios
ENG.1.6	Application / Device crashes	4	3	4		x		Car
ENG.1.7	CAD Subscription Expires	2	5	4		x		Car
ENG.1.8	CAD application is removed off laptop	2	4	3		x		Car
ENG.1.9	CAD software unresponsiveness	3	4	4		x		Car
ENG.1.10	CFD Subscription Expires	2	4	3		x		Car
ENG.1.11	Meshing issues with CFD	3	3	3		x	x	Car
ENG.1.12	Fusion cannot complete desired CAD action	2	3	3			x	Car
ENG.1.13	Fusion will not render	2	2	2		x		Porfolios, Media
ENG.1.15	Designing process causes mental health complications	3	4	4		x	x	Car, Portfolios, Team
ENG.1.16	Internet Outages	3	5	4		x		Car, Portfolios
ENG.1.17	PC catches on fire	2	5	4	x	x		Car, Portfolios
ENG.1.18	Loss of car files	3	5	4		x		Car

Risk Assesment Excerpt | Source: Constellation

Innovation Assessment

We employed an innovation matrix to evaluate benefits of a new, unfamiliar item to the team and the cost, implementation time and risk. This quantified the aforementioned factors to allow a comparison to be set against a standard. A score above 7 warranted investigation, below a score of 5 was not pursued. High risk innovations were also not pursued. This enabled the team to focus on feasible innovations.

Item	Benfit	Feasibilty				Net Assessment
		Cost	Time	Risk	Overall Feasibility	
Wheel Bearing	10.00	2.00	4.00	5.00	3.67	7.89
Instagram marketing assessment	7.00	6.00	7.00	9.00	7.33	7.11
Pit wall trade display	8.00	1.00	4.00	7.00	4.00	6.67
Bearing Testing Device	8.00	6.00	4.00	5.00	5.00	7.00
Race Model	7.00	10.00	3.00	9.00	7.33	7.11
laser alignment system	7.00	7.00	7.00	8.00	7.33	7.11
laser wheel analyser	6.00	4.00	2.00	2.00	2.67	4.89
NFC Porfolios	5.00	7.00	7.00	8.00	7.33	5.78
Nitinol Parts	8.00	3.00	4.00	1.00	2.67	6.22

Innovation Assesment matrix| Source: Constellation

Constellation™ Formula 1® in Schools Team

Communication

constellation WORLD FINALS 2023

SCORECARD CRITERIA: EXECUTING

STAKEHOLDERS

Stakeholder Communication

Within the project, several communication platforms were used, since each platform had its own advantages. The communication platforms we used are below.

PLATFORM NAME	CONTEXT
Microsoft Outlook	Clear communication and information transfer to team members, supervisors, sponsors and mentors on a daily basis.
Microsoft Teams	Organised thread-based messaging, file management and video calls for team members, supervisors, sponsors and mentors, used daily.
Discord	Accessible group messaging, voice and video calls with team members, mentors and supporters on a daily basis.
Instagram (DM)	Relaxed communication and media sharing between team members on a daily basis.
Microsoft OneNote	Collaborative document editing used by team members 3+ times per week.
MailChimp	Detailed newsletter to a shifting follower base of supervisors, sponsors, mentors and supporters, sent quarterly.
Zoom	Video meetings with sponsors and mentors, used fortnightly or in the event of a sponsor meeting.
Google Meet	Alternative video meeting platform for sponsors and mentors, used every 2 months.

Constellation's breakdown of communication methods | Source: Constellation

Communication Plan

With our communication platforms laid out, we set out to define communication plans for each stakeholder category, using our classifications from our Stakeholder Register. Each plan identifies the information communicated, how frequently this communication occurred, and the platforms used to communicate this information.

Since our project was of a relatively small scale, we decided our communication plans should be clear and concise. This allowed for a simple and accessible reference which the whole team could follow, whilst retaining maximal information quality.

In the creation of our communication plans, both our stakeholder list and platform index were used. Our communication plans can be seen below and into the next column.

TEAM MEMBERS	**Frequency:** Daily
Platforms: MS Teams, Discord, Instagram, MS OneNote, MS Outlook	**Information:** Status Reports, Project Data, Project Schedule, Project Scope, Finances, Risk Assessment
SUPERVISORS	**Frequency:** Weekly
Platforms: MS Outlook, MS Teams, Zoom	**Information:** Status Reports, Finances
SPONSORS	**Frequency:** Weekly
Platforms: MS Outlook, MailChimp, Zoom, Google Meet	**Information:** Status Reports, Project Data, Finances
MENTORS	**Frequency:** Weekly
Platforms: MS Outlook, MailChimp, Zoom, Google Meet	**Information:** Status Reports, Project Data, Finances
SUPPORTERS	**Frequency:** Weekly
Platforms: Discord, MailChimp	**Information:** Status Reports

Team communication plans with different groups | Source: Constellation

On top of this, we utilised events to meet and build relationships with existing stakeholders. The following case studies explore two such scenarios.

Australian Grand Prix

Constellation's excursion to the 2023 F1 Australian Grand Prix was focused on engaging with existing stakeholders. One month before the event, we reached out to all existing stakeholders using MailChimp to survey Grand Prix attendance. From this, we heard back from Alfa Romeo and Haas F1 teams, Optus, Tommy Smith from Van Amersfoort Racing, and Walkinshaw Andretti United Supercars team. This allowed us to organise and allocate time for each stakeholder, strengthening relationships and opening up new opportunities.

Team partner meetings at the AUSGP | Source: Constellation/Alfa Romeo F1 Team

Autodesk Converge

In late August of 2023, our Team Engineer and Project Manager were flown to Sydney to present at Autodesk's Converge conference. Through this we were able to notify, invite and network with existing stakeholders using the same methods as for the Grand Prix. Additionally, we used this opportunity to travel to the offices of those stakeholders who couldn't make it to Converge, and were based in Sydney.

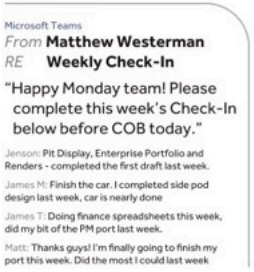
Furthermore, the process of planning for this event required a substantial amount of planning, working together with contacts at Autodesk to organise a professional presentation for viewing by a large industry audience. This provided an insight into corporate communication, and methods of working together with partners and industry to guarantee the best outcome for both parties involved.

Autodesk Converge additionally served as Constellation's 2023 Launch.

Weekly Check-In

Each Monday, a weekly check-in in the form of a Teams post was conducted, where team members would outline their work for the upcoming week. The project manager would compare this to the budgeted Gantt Chart, checking that all tasks are accounted for.

The team also summarised tasks completed in the previous week. This enhanced accountability of tasks, ensuring the project was on track and allowed for any deficiencies to be identified and addressed.


Microsoft Teams
From **Matthew Westerman**
RE **Weekly Check-In**
"Happy Monday team! Please complete this week's Check-In below before COB today."
Jenson: Pit Display, Enterprise Portfolio and Renders - completed the first draft last week.
James M: Finish the car. I completed side pod design last week, car is nearly done
James T: Doing finance spreadsheets this week, did my bit of the PM port last week.
Matt: Thanks guys! I'm finally going to finish my port this week. Did the most I could last week

Constellation Teams Excerpt
Source: Constellation

These check-ins were collated weekly by the Project Manager to ensure a steady track of progress toward the World Finals.

Summary Documents

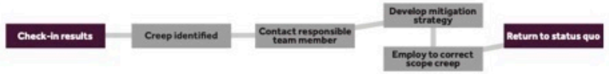
After completing any task or making any progress on a deliverable, progress was recorded in three summary documents, one for Engineering, Enterprise and Project Management. This created a record of all activities and the thinking process to be documented as well to show the rationale behind decisions, sharing insights to team members and for future reference.


Summary Document
Source: Constellation

Scope Creep

Scope creep refers to the gradual expansion of a project's objectives, deliverables, or requirements beyond its original scope. It often occurs when additional features, changes, or requests are added without proper evaluation or control.

To regulate scope creep within our project, the team implemented the aforementioned system of weekly check ins, where each team member would report on Monday the tasks they aimed to complete that week. The buffers set when creating our schedule allowed for potential scope creep, however buffers were only used as a last resort. Our Project Manager then referenced our Gantt Chart, and implemented our management plan if scope creep was observed. This management plan can be observed below in the form of a state flow diagram.



Team State Flow diagram | Source: Constellation

Monitoring and Evaluating

SCORECARD CRITERIA: MONITORING + CONTROLLING

MONITORING

Status Reports

Status reports in project management are essential tools for monitoring and communicating the progress, performance, and challenges of a project. Our fortnightly updates provide a snapshot of key activities, milestones achieved, risks, and any necessary adjustments needed to keep the project on track.

Status reports enable stakeholders to stay informed, make informed decisions, and ensure successful project execution. Our status reports were split into 6 segments: Project Status, Tasks Accomplished, Tasks in Progress, Planned Issues, Issues, and Questions for Discussion.

- **Project Status:** the prevalent segment of our status reports, it provided an at-a-glance overview of different activity's progression within the scope of our project. This segment offered stakeholders an accessible insight into the project advancement.
- **Tasks Accomplished:** within this segment, a bullet point list of the accomplishments made between status report updates. This allowed for stakeholders to comprehensively assess the project rate of progression and analyse the continuous variation over time through graphical interpretations.
- **Tasks in Progress:** in addition to the tasks accomplished, we included a live register of current tasks in progress. This allowed our stakeholders to easily access and reference jobs, and observed an increase in accountability and work efficiency from our National Finals.
- **Planned Issues:** This segment included a list of forthcoming disruptions to scope progression, allowing stakeholders to mitigate disruption.
- **Issues:** below our planned issues, a list of unforeseen issues was included. This allowed for discussions to be held between relevant stakeholders to resolve each issue.
- **Questions for Discussion:** Finally, this segment was included to signpost large questions and discussion points to address during team meetings.

July Status Report
Source: Constellation

EVALUATION

Monthly Reviews

At the end of each month the team sat down with our teachers to analyse team performance in depth. Variance reports were created at the end of each month to compare actual and budgeted performance to easily identify similarities and differences between budgeted performance and actual results. This involved creating spreadsheets comparing resources used and acquired to expected figures, cash inflows and outflows to budgeted cash flows and the completion of tasks and time spent on tasks.

Outflow Varience (AUD)					
Item	Description	Budgeted	Actual	Over(+)/Under(-)budget	Description Actual
Registration	Team member entry fee	$3,162.34	$3,162.34	$0.00	Registration fully paid
Travel	Flights + any transport (location tbd)			$0.00	
Accommodation	any Hotel Fee	$9,149.81		-$9,149.81	Hotel unpaid, pay soon
Food	Food during WF			$0.00	
Pit Display	any costs associated in preparing and transporting TD	$8,000.00		-$8,000.00	Pit Display not paid yet
Car	cost to produce all cars	$1,000.00	$3,162.24	$2,162.24	Wheel Bearing System
Uniform	uniform worn at WF and throughout season			$0.00	
Printing	cost of printing any items	$20.00		-$20.00	No printing Costs
Marketing	cost of promotion of team e.g. website, instagram adds	$50.00	$24.20	-$25.80	Website hosting fee
Merchandise	cost of an business cards, info booklets etc.	$40.00		-$40.00	No Merchandise
Misc - Outflow	other expenses	$30.00		-$30.00	
Buffer	emergency funds			$0.00	
	Total	$21,452.15	$6,348.78	-$15,103.37	

Variance Spreadsheet | Source: Constellation

Consequently, this allowed the team to:

1. **Evaluate Performance** - Team was able to identify areas of underperformance, such as too much cash spent in a particular area or not enough time spent on a specific project element and areas or over performance, too much focus on a particular project element.
2. **Make Informed Mitigations** - Plans were developed to address areas of issue indicated by variance reports. For example, when it was apparent that the team would not have sufficient cash, the team arrange a donation page through the Australian Sports Foundation.
3. **Plan for the future** - New schedules and budgets were created to outline the agenda for the rest of the competition. This allowed more up-to-date, relevant and accurate information to be used, enabling a more accurate prediction of future activities. For example when the location was revealed, and a more accurate flight cost estimation was possible. The new budgets also followed new expectations and strategies of the team, providing a new, more effective structure to the team's workflow for the next month and a base to compare future results against.

Signing off on tasks

Once a task was finished, the responsible and accountable team members would check its quality against the acceptance criteria set during initiation. Then the task would be signed by both team members and the rest of the team informed. The completion would then be recorded in a status report and on the team's live Gantt Chart.

Constellation sign-off process documentation diagram | Source: Constellation

After completion of project elements the whole team and supervising teachers would assess quality against acceptance criteria before signing off to verify the completion of the item and approve it to be competition ready.

Case Study - Management of Wheels

The teams wheel-bearing system was first assessed through the innovation assessment scoring 8 and thus the team saw reason in pursuing the system. The task was then assigned using our RACI matrix (see exert below) to appropriate team members. Acceptance Criteria was also defined for the wheels, which was that the wheels had to be less than 1.3g each and perform better on track testing than previous wheels. The risk of the wheels being inadequate was substantial so we prepared alternative wheels as a contingency.

	Matt W	James M	James T	Jenson G
Wheel Development	Consulted	Responsible	Consulted	Informed

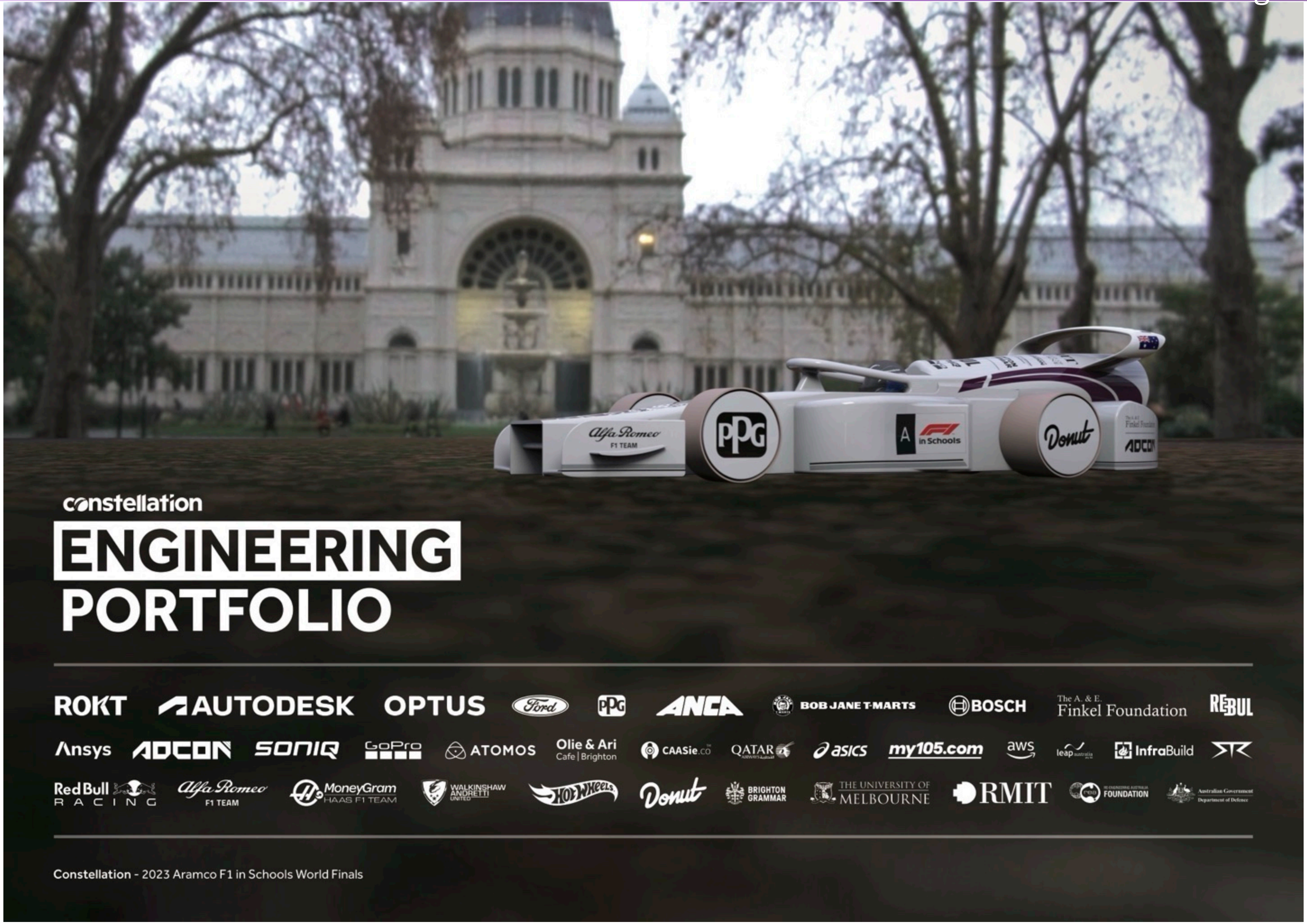
RACI matrix for Wheel Development | Source: Constellation

It was then estimated that there would be a long lead time for production, thus the wheels were prioritised in the car design process to ensure the project could be completed on time. The amount and cost of wheels were added to the next budgets and timeframe added to the Gantt Chart. Coordination with our supplier followed our communications plan, using Microsoft Outlook for primary communication and Zoom for video calls.

All progress on the wheel-bearing system, including designing, manufacturing and testing, was recorded in the engineering summary document and status reports to ensure stakeholders are informed and the creating of the wheels were on schedule. This allowed any issues to be identified early and addressed. It was noticed that quality of manufacturing could not be assessed. Thus we requested, through Microsoft Outlook, that our supplier send images and videos of the entire production process.

Example of Constellation's innovative and brand new wheel system
Source: Constellation/ DGYQ Bearings

During Monthly Reviews, progress of the wheels were assessed in-depth between the whole team. During the review at the end of May, the team, although pleased with the manufacturing progress, realised through extensive bearing testing, that bearings will always vary and thus a larger order was suggested to increase the amount of "good" bearings. New budgets were created to allow for the additional bearing cost and the slightly extended time frame of manufacturing completion. After the wheels were received and passed the acceptance criteria (the wheels were 1.124g, 0.176g lighter than required and 0.083 seconds faster on average than our old wheels), the team signed off on the process and could then start manufacturing.


constellation
ENGINEERING
PORTFOLIO
ROKT
AUTODESK
OPTUS
Ford
PPG
ANCA
BOB JANE T-MARTS
BOSCH
The A. & E. Finkel Foundation
Ansys
ADCON
SONIQ
GoPro
ATOMOS
Olie & Ari
Cafe | Brighton
CAASie.co
QATAR
asics
my105.com
aws
InfraBuild
Red Bull RACING
Alfa Romeo F1 TEAM
MoneyGram HAAS F1 TEAM
WALKINSHAW ANDRETTI UNITED
HOT WHEELS
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Constellation - 2023 Aramco F1 in Schools World Finals

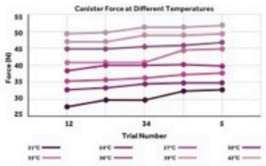
Uncontrollable Factors, Wheels & Bearings

Canister Efficiency

Canister efficiency refers to the effectiveness of converting CO2 during launch into kinetic energy that propels the car forward, while minimizing energy wastage into the environment.

Canister Temperature Testing

Heating a CO2 canister raises gas temperature, causing expansion due to the Ideal Gas Law. Molecules move faster, increasing collisions and pressure. The expanded gas occupies more volume, leading to a stronger force on the car's propulsion system. This increase in force translates to higher maximum force and average force values in the data, indicating the enhanced propulsive capacity of the heated canister.



Through use of the Ideal Gas Law, the pressure at 21°C was calculated to be 43.33kPa, and 46.43kPa at 42°C. This resulted in an increase of 3.10kPa, or 7.14%.

This was seen when we tested the theory. The analysis of the data reveals notable differences in the measured variables when comparing different temperature levels. For instance, when comparing the maximum force data points between 21°C and 42°C, there was a significant difference of 14.34N. Similarly, the average acceleration exhibited a substantial difference of 53.7977 m/s^2 between these temperature levels. However, the increases in force and acceleration did not translate to race time data, as there was an observed difference of 0.055 seconds between the average race time at 21°C and 42°C.

Canister Hole/Force Testing

As a part of our physical testing, we sought to determine the thrust provided by the compressed gas canisters and acting on our car. By determining this force and its variance, we could apply this knowledge to our race model, and understand one of the factors affecting variation in a car's performance. This was done using the set-up shown in [diagram]. Through this testing we observed an average force of 10.14N, and a variance of 6.19N across the canisters.

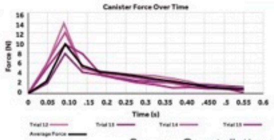
We've seen a variety of canister types effect car launches over the course of five years of racing. End caps in Sets A (silver) and B (gold) have different hole sizes and positioning patterns. The mean hole diameter for Set A is 1.018 mm (range: 0.907 mm to 1.160 mm), while the mean for Set B is 0.526 mm (range: 0.461 mm to 0.598 mm). The majority of the holes in both sets are off-center, which could be related to manufacturing, causing torque on the car during launch due to misalignment thrust and centre of mass. As the race distance rises, the automobile will swing about its centre of mass, generating avenues for energy loss as the thrust vector creates torque, as explained in stability. Some holes are also partially obstructed by puncture burrs on the end caps' inner sides, affecting gas flow and potentially causing force imbalances.

Silver Canister		
Hole #	Dia. (mm)	Hole Location in End Cap
1	1.160	off centre
2	0.973	off centre
3	0.953	close to edge
4	1.102	near centre
5	0.943	off centre
6	0.919	close to edge
7	1.117	off centre
8	1.137	near centre
9	1.012	close to edge
10	0.965	off centre
11	0.907	off centre
12	0.913	near centre
13	1.122	off centre
14	1.029	near centre

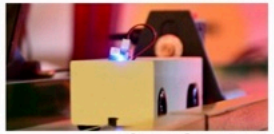
Gold Canister		
Hole #	Dia. (mm)	Hole Location in End Cap
1	0.482	near centre
2	0.527	off centre
3	0.493	near centre
4	0.584	off centre
5	0.476	off centre
6	0.550	off centre
7	0.504	off centre
8	0.567	off centre
9	0.461	near centre
10	0.598	close to edge
11	0.482	off centre
12	0.563	off centre
13	0.576	close to edge
14	0.503	near centre

Source: Constellation

Furthermore, differences in hole diameters within each set may be related to end cap thickness. Thickness differences between Sets A and B could explain variances in hole size, influencing thrust characteristics. A comparison of force curves revealed that Set B had a smaller peak force but a similar impulse area, demonstrating that force output varied due to differing release times. This led us to the conclusion that larger canister holes provide greater thrust force during the thrust phase, resulting in faster timings.



Source: Constellation

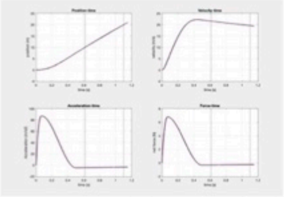


Source: Constellation

L: Canister Puncture Test images R: Force Test rig | Source: Constellation

Mathematical Modelling

To aid in the development of different aspects of the car, we developed a mathematical model in MATLAB to analyse virtual laps. However, as identified above, there are a large number of unpredictable and uncontrollable factors which affect lap time. Therefore, we opted to utilise our model to compare design choices while keeping other variables constant. By using an experimentally designed force curve for thrust and accounting for the mass of the car and canister, the change in mass, canister temperature, and the drag force, we could keep certain factors constant to analyse the impact of changing one of these factors.



Mathematical Race Model
Source: Constellation

On top of this, we developed code to aid in simple tasks like choosing a foam block to mill. Since the foam blocks had slightly different weights, we were able to input the volume of the car, and receive an output stating the mass of the foam block needed for a 50g car. This calculation factored in the masses of all 3D printed parts, wheels, and tether guides.

Final Car Objectives

We developed the following set of primary design goals, sorted in order of significance, as a result of our research and testing:

- **Mass** - Develop a car that weights minimum of 50g with a tolerance of +0.2g.
- **Durability** - The car must be able to race the minimum of 4 automatic and 4 reaction races as well as 48 team knockout bracket without breaking or getting damaged.
- **Compliance** - The cars must be fully compliant and not break any of the 2023 Technical Regulations
- **Friction** - The car must be manufactured to have a smooth glossy surface finish to reduce the surface friction
- **Aerodynamics:** Develop pressure gradients in the halo pocket and the 45 degree front of rear wheels exclusion zone, redirect any airflow away from rotating surfaces like the front and rear wheels, don't have any extreme deviations in the body which causes airflow separation, try and reduce any effects caused by the horseshoe vortex, given technical constraints, try to achieve the lowest feasible drag value.
- **Centre of Gravity** - Position our centre of gravity inline with our centre of thrust even if the canister has a ±3 degree angle on it.
- **Canister Efficiency** - Try and reconnect as much air as close to the tip of the canister as possible to help improve the efficiency of the canister.

WHEELS & BEARINGS

WHEEL AND BEARING DESIGN

National Finals Review

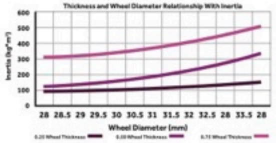
In previous competitions, we encountered many problems with our wheel system. Most noticeably of these was the improper fixation of the bearing into the PEEK wheel when attempting to pressure fit the bearing into the wheel. The slight deformation in the bearing's outer ring reduced its diameter, increasing stress on the balls and resulting in higher friction, and a higher likelihood of breakage. We also knew that pressure fitting the bearing to the axle increased the diameter of the inner ring, and further increased stress on the balls.

In previous competitions, we also experimented with not pressure fitting the wheels and instead using caps on both ends to prevent the bearing from falling out. However, this led to excessive side-to-side movement of the wheel during races, making the car highly unstable. Additionally, when attempting to glue the bearings in place, the glue seeped into the bearing and destroyed it entirely. Consequently, we had to avoid using glue altogether.

In addition to these issues, the introduction of new technical regulations brought with it article T7.13, the wheel safety test. With the inclusion of this new regulation, we were immediately cautious of our current wheel system, knowing the issues previously mentioned. Therefore, we opted to develop a new wheel system, where the bearing was built into the wheel. By doing this, we were able to introduce a high level of customisation into every aspect of wheel system development, and remove the performance inhibitors previously mentioned.

Moment of Inertia

Moment of inertia is a body's resistance to angular acceleration. When the car accelerates after launch, the wheels must rapidly accelerate to over 1400 rad/s to allow the car to reach top speed as quickly as possible. For the wheels to accelerate so quickly, the least amount of resistance to angular acceleration is desirable, meaning that we aimed to minimise the moment of inertia of the wheels, using the elements of $I = k \cdot MR^2$ as guidelines.



Source: Constellation

To ensure we minimised the moment of inertia we had to investigate effects of mass and radius on our wheels. Moment of inertia was calculated directly in Fusion 360, over the range of legal dimensions. Fusion 360 was chosen for the application of wheel development as it allowed rapid and simple FEA testing and moment of inertia tools. To investigate the effects of mass, we chose to test the outer wall

Wheels & Bearings, Car Development

thickness of the wheel.

Increases in both outer wall thickness and wheel diameter resulted in increased moment of inertia, with wheel radius affecting moment of inertia in a quadratic relationship and wall thickness increasing inertia linearly. For this reason, we designed our wheels to be as close to the minimum legal wheel radius, while allowing for tolerance, and aimed to have the thinnest outer walls while satisfying our structural goals.

Yield Strength

The yield strength is the stress at which deformation changes from elastic deformation to plastic deformation, or a permanent change in the material's size and/or shape occurs. As our wheels needed to be reusable, we aimed to limit all deformation to elastic deformation, and thus keep all stresses below the yield strength of the chosen materials. We decided to aim for a peak stress of 60% of the yield strength, allowing a safety factor of approximately 9.5. The force at which wheels were tested was 50N, 100 times higher than the normal force experienced on the car, and an approximation of the highest force which the wheels would need to withstand during manufacturing and handling.

Deformation and Contact Area

Rolling resistance develops as a result of wheel-track surface contact, and it increases with increased deformation owing to hysteresis loss. As a result, we concentrated on reducing hysteresis loss, which involves energy dissipation during cyclic loading and unloading. This was accomplished by reducing the track contact area and designing stiff wheels with little distortion.

Bearing Size

To ensure the best performance from our wheel system, we knew the size of our bearing would have an impact. The most important thing we focused on was the inertia of the bearing, knowing this would most inhibit race time. However, as a result of T7.13's introduction, we also had to consider the axial load capacity for our bearing size. If our bearings were to break during this load test, our race times would take a large hit.

Therefore, when choosing the bearing size, we looked at the axial load that deep groove ball bearings (DGBBs) could support. This is because the magnitude of force that can be supported depends on the internal geometry and curvature ratio. One cannot define an axial load capacity for bearings unless they are designed to be axial (thrust) bearings, however a rule of thumb for small DGBB is that they can handle up to around 25% of their static load capacity (C0r) as pure axial load (Fa). Thus, we collaborated with Schaeffler to develop our bearings. We employed the below table to work out the axial load and overall, which bearing size we were going to use.

To work out the axial load of the 3*7*3mm bearing we took the static capacity of the bearing from the table above. C0r = 112N. Then we worked out the theoretical maximum axial load by calculating 25% of the C0r (Fa = 0.25 · 112 = 28N). therefore, a 3*7*3mm bearing could handle the stress of our wheel with no issue.

However, next we had to factor in material choice on the axial load. Given that we had the option of using a plastic for our wheel, we had to calculate the axial load capacity, which will be lower. We assumed that the plastic bearing has much lower static capacity, 25% of the production bearing made of steel. Working with 28N as our static radial capacity, we also assumed that our bearing also cannot handle quite as much axial load as a result of our curvature ratio, so we will only allow for 20% of the static capacity to be supported axially (0.2 · 28 = 5.6N). Accounting for this worst case scenario, with our bearing being much less strong than a catalogue bearing, and with these assumptions, we would still have a safety factor of over 5 from the 1N force applied by T7.13. Using this information, we chose to minimise bearing size and employ 3*7*3mm bearings.

Material Selection

During material research for our wheels we identified relevant material properties which affected how well the wheels satisfied our goals. We compared the following materials using Multi Criteria Decision Analysis as seen below. This allowed us to critically analyse material choice and find the best material for our wheels.For the material selection of the balls in our bearings, the same process was used.

Wheel Material						
Material	Density (g/cm^3)	Coefficient of static friction (N)	Tensile Strength, Yield (Mpa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Manufacture Method
Steel 440	7.74	0.32	1280	1850	200	CNC Machined
PEEK	1.32	0.171	97.5	44.9	3.44	CNC Machined
Nylon / PA	1.14	0.222	74	89.4	1.71	CNC Machined
Acetal / Delrin	1.46	0.276	71.5	156	10.1	CNC Machined
Aluminium - 6061	2.88	0.61	75	299	68.9	CNC Machined

Material	Density (g/cm^3)	Coefficient of Friction (N)	Tensile Strength (Mpa)	ABEC Rating	Heat deflection temperature (°C @ 271 psi)	Water absorption (% @ 50°C)
Stainless Steel 440	7.74	0.58	1790	77	60	0.3
Silicon nitride Si3N43	.170	.051	5867		1490	2
Aluminium oxide Al2O3	3.98	0.72	69	51	0804	5
Zirconium dioxide ZrO25	.220	.751	38	51	1703	4
Soda-lime glass2	.5	0.51	82	39	00	0.08
Borosilicate glass2	.7	0.68	81	37	00	0.1

Wheel + Ball Material Selection Spreadsheets | Source: Constellation

Bearing Design

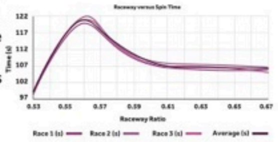
In the development of our bearings, we also needed to consider bearing geometry, lubrication and the inclusion of dust shields and a bearing cage.

The main focus of our development was bearing geometry, since this can greatly affect performance. By manipulating the ratio between bearing raceway radius and ball diameter, we could prioritise load capacity or friction. Calculated by *curvature ratio=raceway radius/ball diameter* , a ratio of 0.5 means the ball is in contact with the raceway for its whole circumference, and a larger ratio has reduced contact. Typically, DGBBs have a curvature ratio of 0.52-0.58, where a lower value favours load capacity and a higher value values low friction. Within our application, we settled on a ratio of 0.56 to minimise rolling resistance while still providing enough load capacity to support the car through a race.

Race Way Ratio Choice

To optimize our wheel and bearing design, we developed a specialized system to automate data collection and eliminate measurement errors. Utilizing a laser sensor connected to an Arduino, we measured the RPM of a three-spoke wheel by counting laser interruptions per second, with a calculation to determine the RPM. Our setup spun the wheel at around 12,000 RPM and recorded the subsequent RPM drop over time, creating a data table plotted on an Excel graph.

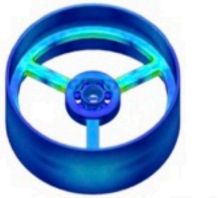
We investigated several raceway ratios using this system, focusing on the relationship between raceway radii and rolling element size. This factor is critical in bearing design since it has a major impact on performance. The raceway curvature ratio of a typical ball bearing ranges between 0.52 and 0.58 (raceway radius/ball diameter), with lower ratios increasing rolling resistance due to closer ball-raceway contact and increased friction. We created special wheels and bearings with raceway ratios ranging from 0.50 to 0.65, and testing revealed that larger ratios were often associated with longer running timings.



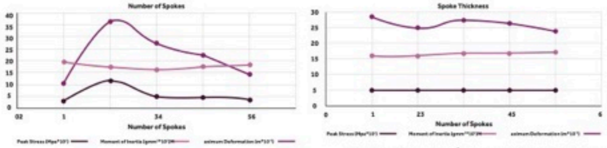
Source: Constellation

Outer Rim Wheel Design

When designing our outer rim which also acted as our wheel design, we first started by choosing the optimum spoke number. Once the spoke number was chosen, we then decided to see the spoke thickness. The factors that influenced our decision with both wheels spoke number and spoke thickness was weight maximum deformation, peak stress and where the peak stress is located. Please see QR code for all wheel options.



FEA Snapshot of Wheel
Source: Constellation



Spoke diagrams | Source: Constellation

WHEEL EVALUATION

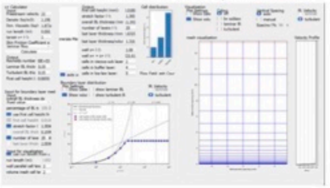
We discovered that our 3-spoke wheel design, with 2mm spoke width and 0.5mm wheel width, surpassed all other designs after rigors testing and careful evaluation of outcomes versus our objectives. This design matched all of our criteria, whether in front or rear wheel configurations, and had the lowest moment of inertia of any of the wheels we evaluated. As a result, we confidently chose this design as our best option, knowing that it would deliver the best performance for our car.

CAR DEVELOPMENT REVIEW

For more info, SCAN QR CODE

Our team worked closely with numerous engineers in the Formula One sector, especially Alfa Romeo, in order to prepare for designing our cars. We ascertained the relative significance of factors affecting the performance of the car by combining their experience with our own. The weight of the car is the most important aspect, followed by the wheel system and finally aerodynamics, according to the engineers. We had to take aerodynamic adjustments into account even though they had a minimal effect on the performance of the small-scale F1 in Schools car.

We customised our car's design direction in accordance with this helpful advice, taking into consideration earlier competition discoveries and advancements. This enabled us to improve upon earlier designs while still adhering to the new World Finals rules. We used computer-based analyses to evaluate the aerodynamics, concentrating on changing one component or factor between tests. We were able to accurately determine how each



Jonas Pangerl Software
Source: Constellation/Jonas Pangerl

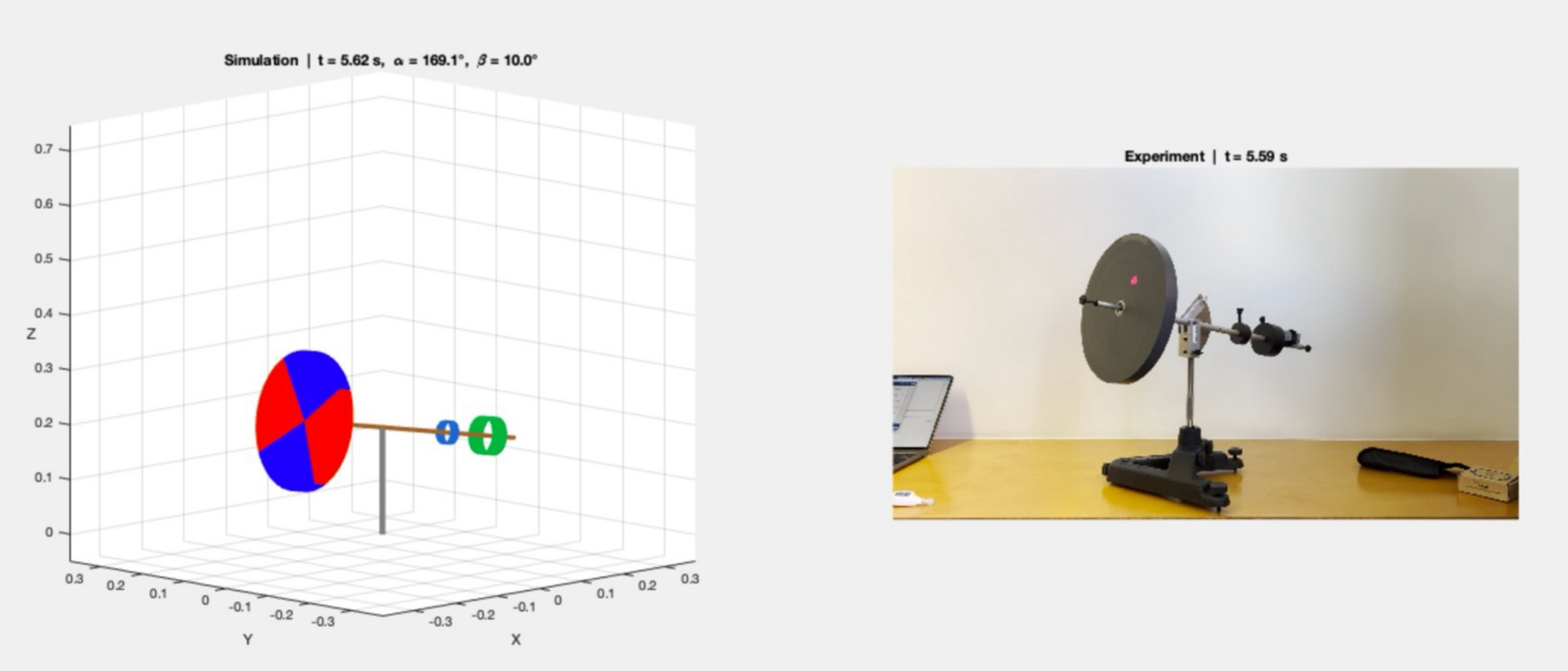
Dynamics MCEN90038

As a part of this subject, we were asked to model a gyroscope with three degrees of freedom, demonstrating both precession and nutation.

This involved determining rotation frames, angular velocities, inertia tensors for each gyroscope body and constraint forces at each joint, then writing Newton-Euler expressions to determine the equations of motion. Solving for the angular positions and velocities used MATLAB to create a state-space representation of the equations of motion and the ode45 function to solve for the positions and velocities. With these values, we could also create a simple animation to compare our model against a video of the gyroscope. Accuracy was determined by plotting the model outputs against experimentally determined sensor data.

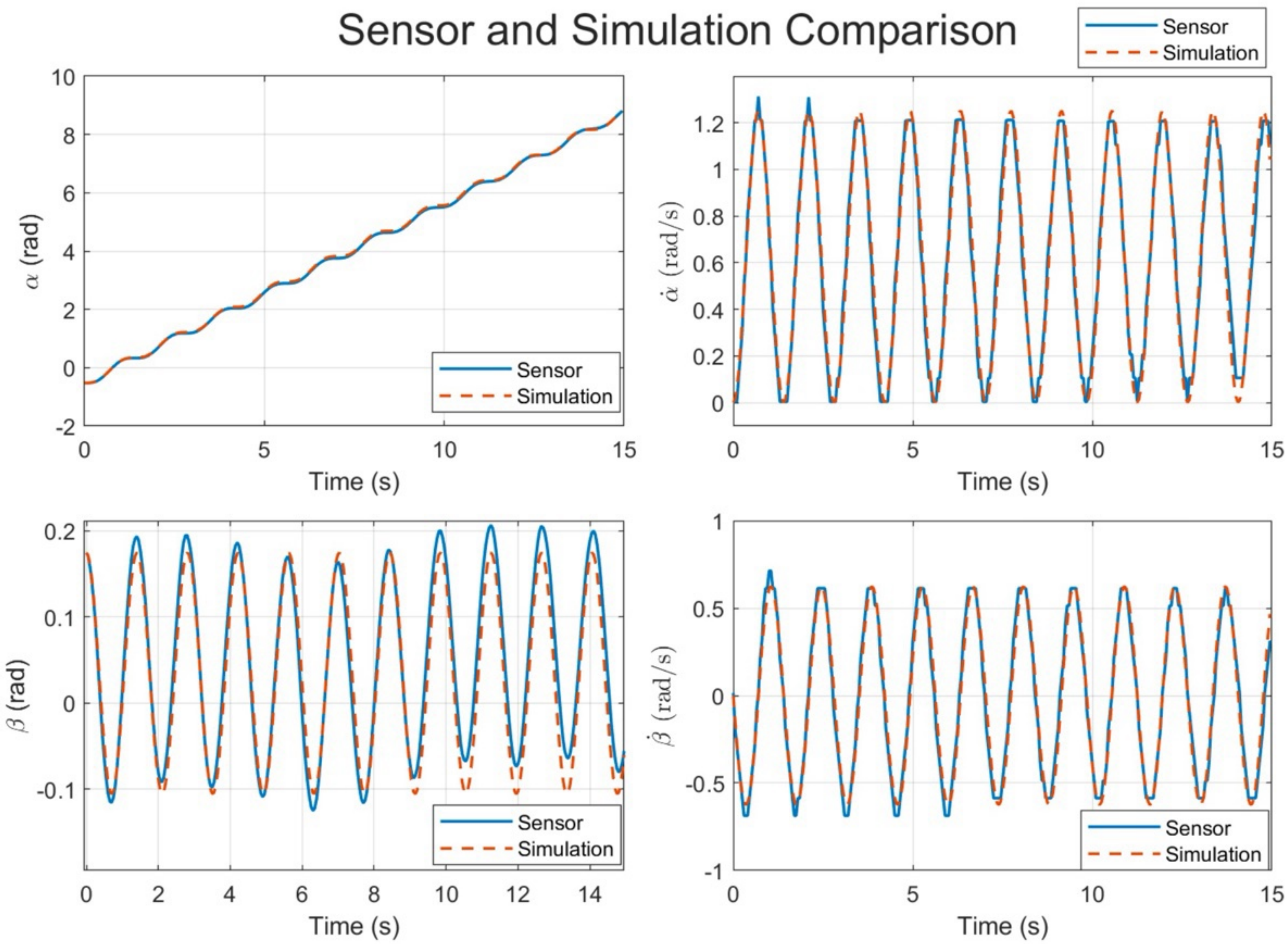
In order to model the system, reasonable assumptions had to be made for simplification. Although immediate correlation was quite high between the physical and mathematical models, these assumptions meant that the models began to diverge across longer time windows. Primarily, assuming a lack of bearing friction and constant rotor speed in the model meant that it would never slow down compared to the physical model

The following slides contain MATLAB outputs visualising the correlation between my experimental setup and mathematical model.



MATLAB output comparing animation with video

Graphical comparison of model output with sensor data



Mechanical Systems Design MCEN30021

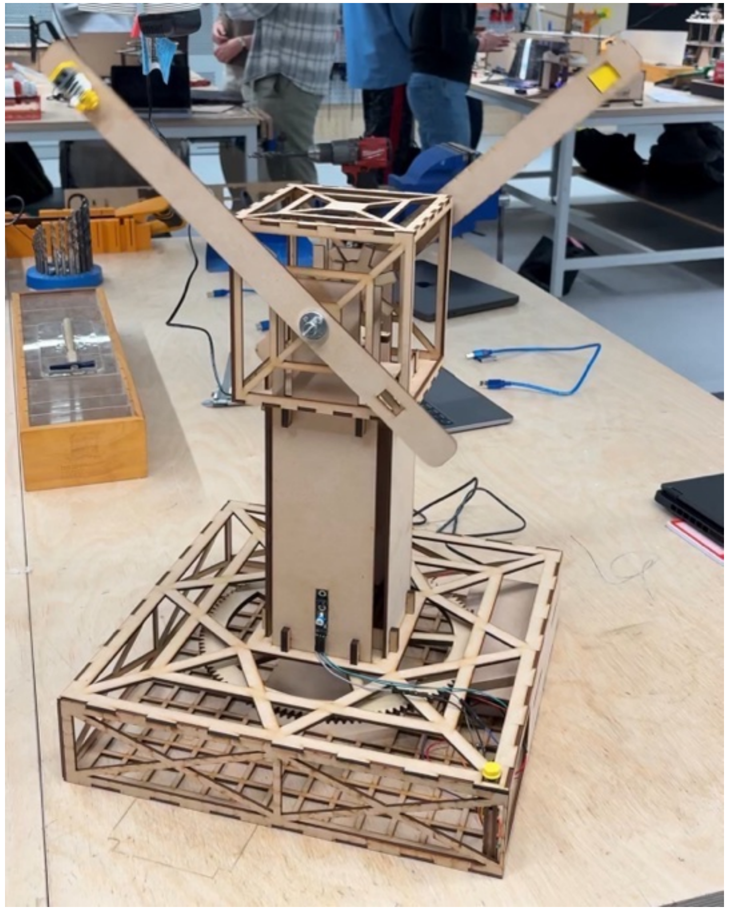
Through this subject we were put into groups of three, and tasked with designing and constructing an amusement park ride for 2 LEGO figures.

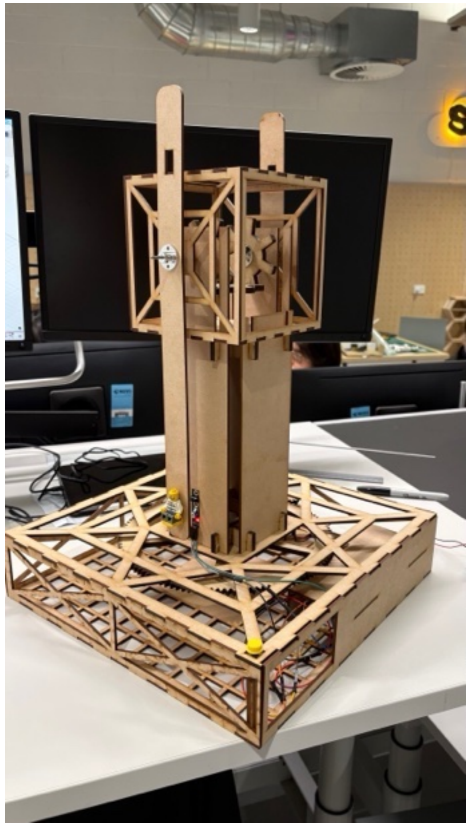
My group built a variation of a “dual pendulum” ride, where two arms swing back and forth in opposing directions. Upon starting with a button, an infrared sensor detects when the arms are in a vertical position and sends a signal to the motor to pulse for a short period to inject speed into the arms. This leads to a natural swing pattern, allowing the 2 LEGO riders to fall under the force of gravity before being sped up and pushed higher by the motor. The ride can be stopped via the same button, and if the ride arms experiences speeds higher than intended, it will automatically shut off the motor and allow the arms to come to rest in a controlled manner.

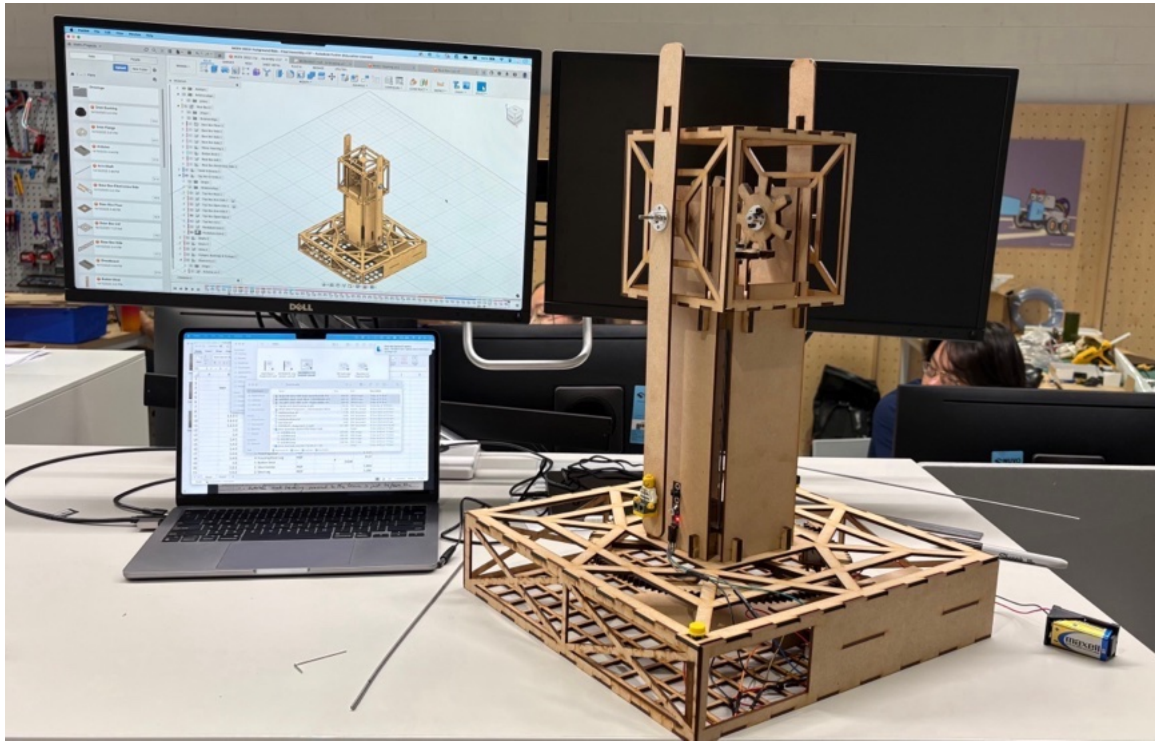
All team members were expected to understand every design aspect, including Computer Aided Design (CAD), manufacturing, circuit building, and Arduino code logic. We determined that, while each member would learn all design aspects, splitting responsibilities would be the best use of resources. I focused on designing the ride in CAD, as well as elements of manufacturing.

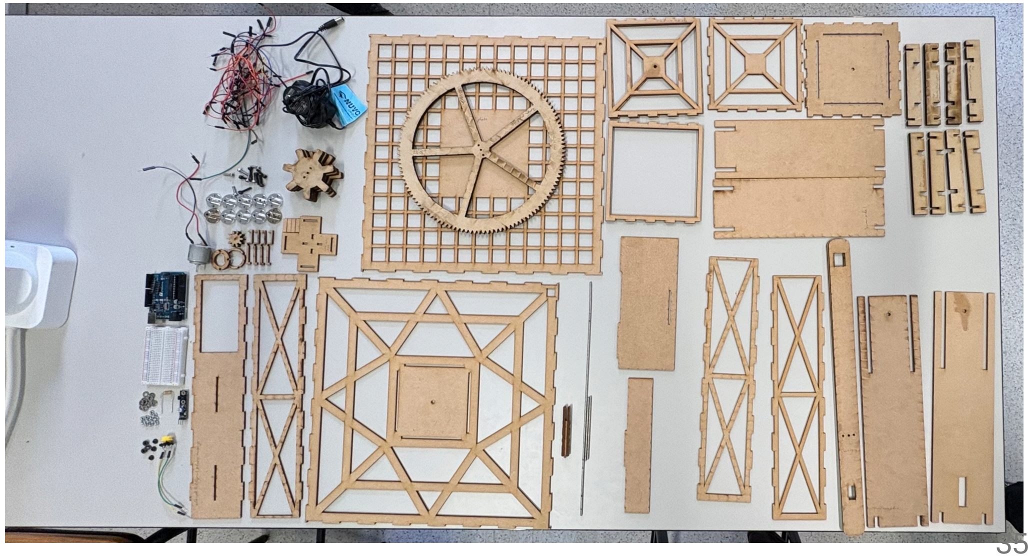
The following slides contain photos of the final assembly and some of the engineering drawings I produced for our final report, along with an exploded view and bill of materials

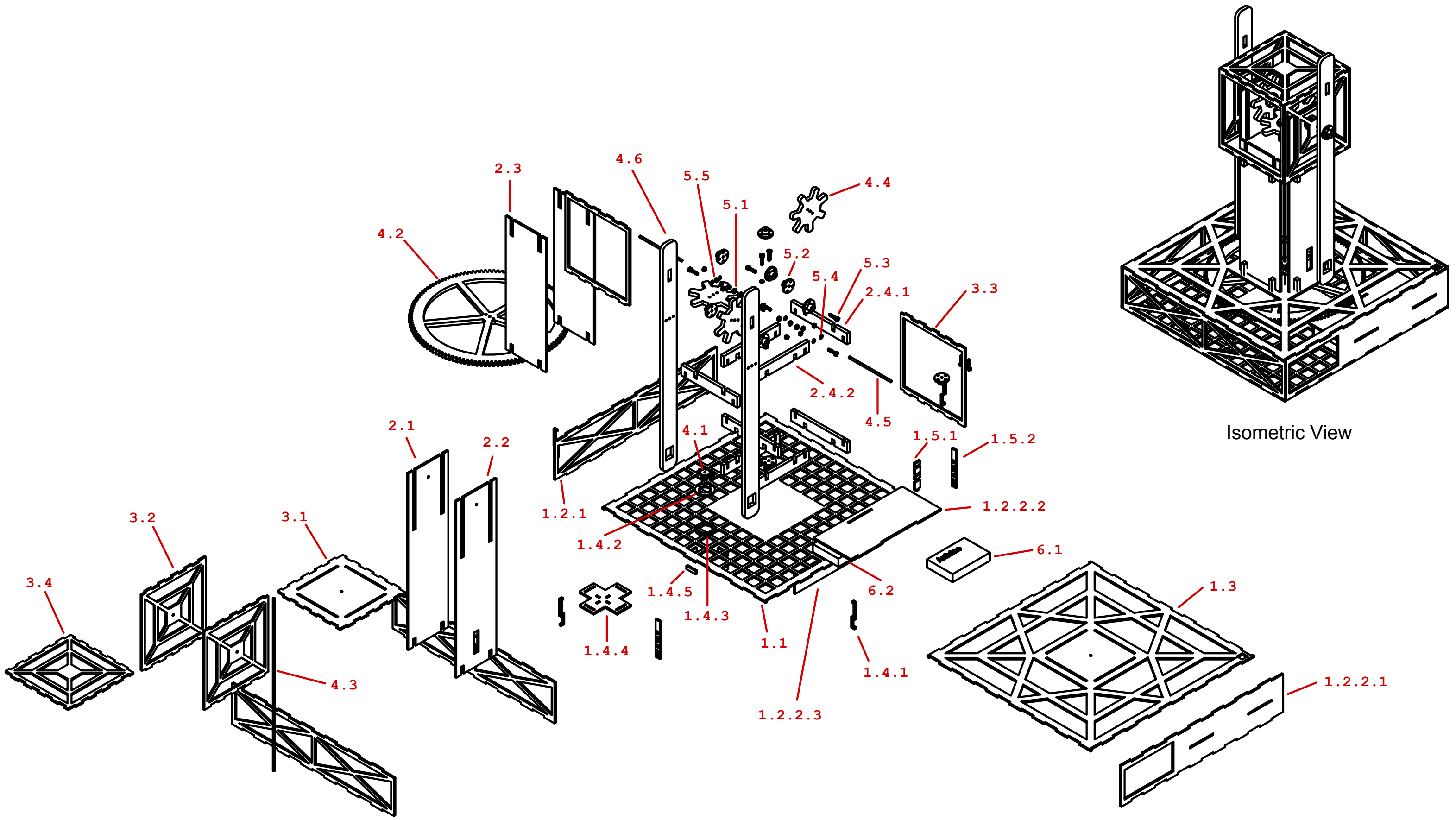
“LEGO Scissors” ride











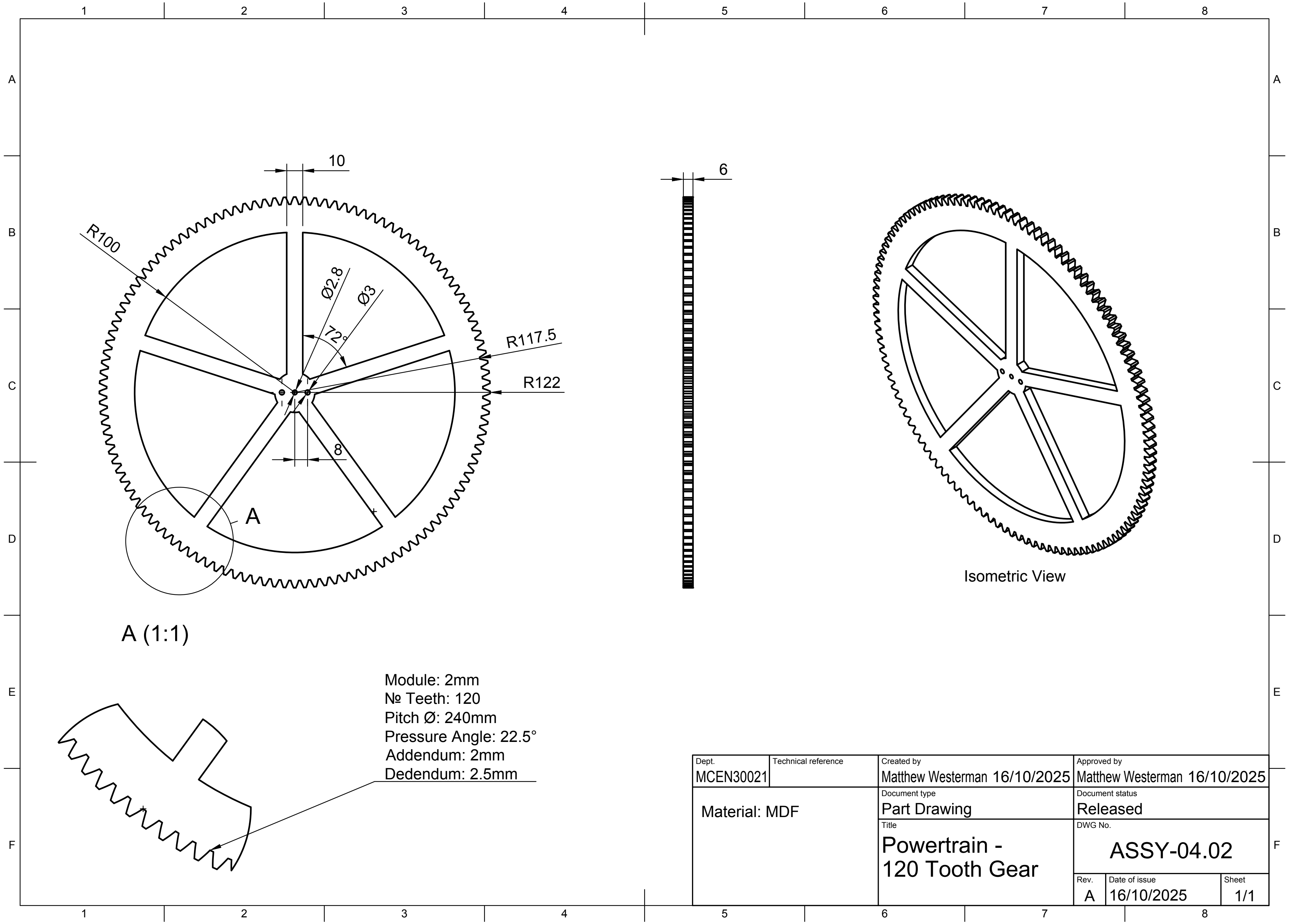
Dept.	Technical reference	Created by	Approved by
MCEN30021		Matthew Westerman 16/10/2025	Matthew Westerman 16/10/2025
		Document type: Exploded View	Document status: Released
		Title: Fairground Ride Full Assembly	DWG No.: ASSY-FULL
			Rev.: A; Date of issue: 16/10/2025; Sheet: 1/1

Bill of Materials:

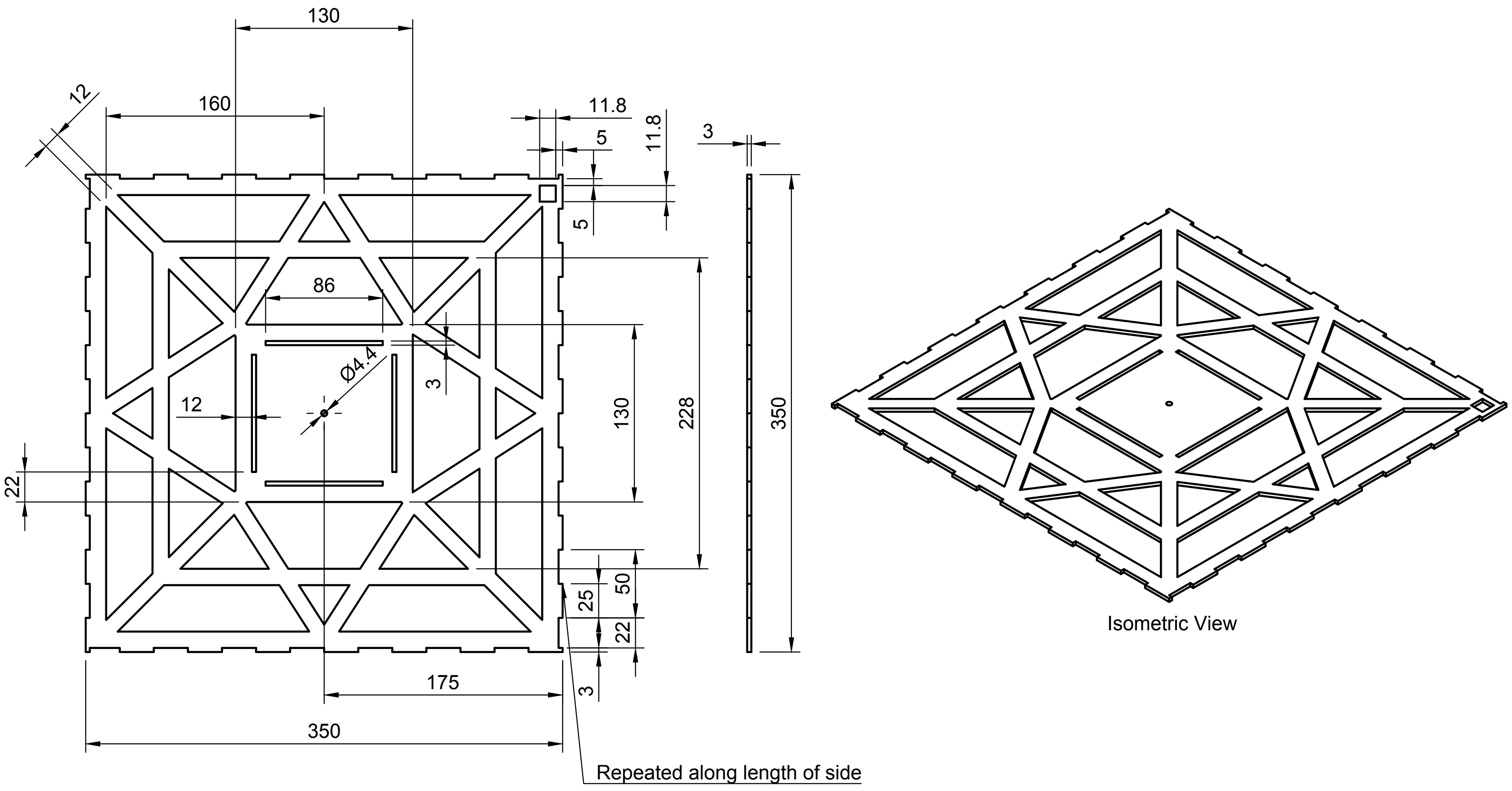
Item	Qty	Part Name	Material	Weight (g)
1	-	Base Box	-	**483.55**
1.1	1	Base Box Floor	MDF	150.78
1.2	1	Base Box Sides	-	172.92
1.2.1	3	Light Side	MDF	*24.52*
1.2.2	1	Electronics Side	-	*99.35*
1.2.2.1	1	Electronics Side Panel	MDF	*46.19*
1.2.2.2	1	Electronics Side Box Top	MDF	*36.84*
1.2.2.3	1	Electronics Side Box Side	MDF	*16.32*
1.3	1	Base Box Lid	MDF	*143.35*
1.4	1	Motor Housing	-	12.85
1.4.1	4	Housing Arm	MDF	*0.38*
1.4.2	1	Housing Top Ring	MDF	*1.00*
1.4.3	1	Housing Bottom Ring	MDF	*0.57*
1.4.4	1	Housing Base	MDF	*8.69*
1.4.5	4	Housing Base Leg	MDF	*0.27*
1.5	1	Button Strut	-	3.65
1.5.1	1	Strut Centre	MDF	*1.06*
1.5.2	2	Strut Leg	MDF	*1.29*
2	-	Tower	-	**311.41**
2.1	1	Tall Tower	MDF	63.88
2.2	1	Tall Tower - IR Cutout	MDF	62.92
2.3	2	Short Tower	MDF	49.68
2.4	2	Brace	-	42.62
2.4.1	2	Brace - S Arm	MDF	*10.66*
2.4.2	2	Brace - E Arm	MDF	*10.66*

Item	Qty	Part Name	Material	Weight (g)
3	-	Top Box	-	**116.55**
3.1	1	Top Box Floor	MDF	42.53
3.2	2	Top Box - Arm Side	MDF	18.68
3.3	2	Top Box - Open Side	MDF	8.64
3.4	1	Top Box Lid	MDF	19.38
4	-	Powertrain	-	**261.86**
4.1	1	10 Tooth Gear	MDF	1.42
4.2	1	120 Tooth Gear	MDF	89.26
4.3	1	Driveshaft	Steel	17.76
4.4	3	Top Paddle	MDF	12.57
4.5	2	Arm Shafts	Steel	4.99
4.6	2	Pendulum Arm	MDF	52.86
5	-	Fastenings	-	**57.77**
5.1	6	Bushing	Plastic	0.15
5.2	9	Flange	Aluminium	4.14
5.3	12	M3x10 12.9 SHCS Screw	Steel	1.15
5.4	12	M3 Washer	Steel	0.10
5.5	12	M3 Nut	Steel	0.38
6	-	Electrical Components	-	**160.00**
6.1	1	Arduino	Various	-
6.2	1	3V DC Motor	Various	-
6.3	1	Small Breadboard	Various	-
6.3.1	36	Wires	Various	-
6.3.2	1	Infrared Sensor	Various	-
6.3.3	1	H-Bridge L293D	Various	-
6.3.4	1	Push Button	Various	-
6.4	1	9V Battery Holder	Various	-
6.5	1	9V Battery	Various	-

Total Weight: **1391.14** g

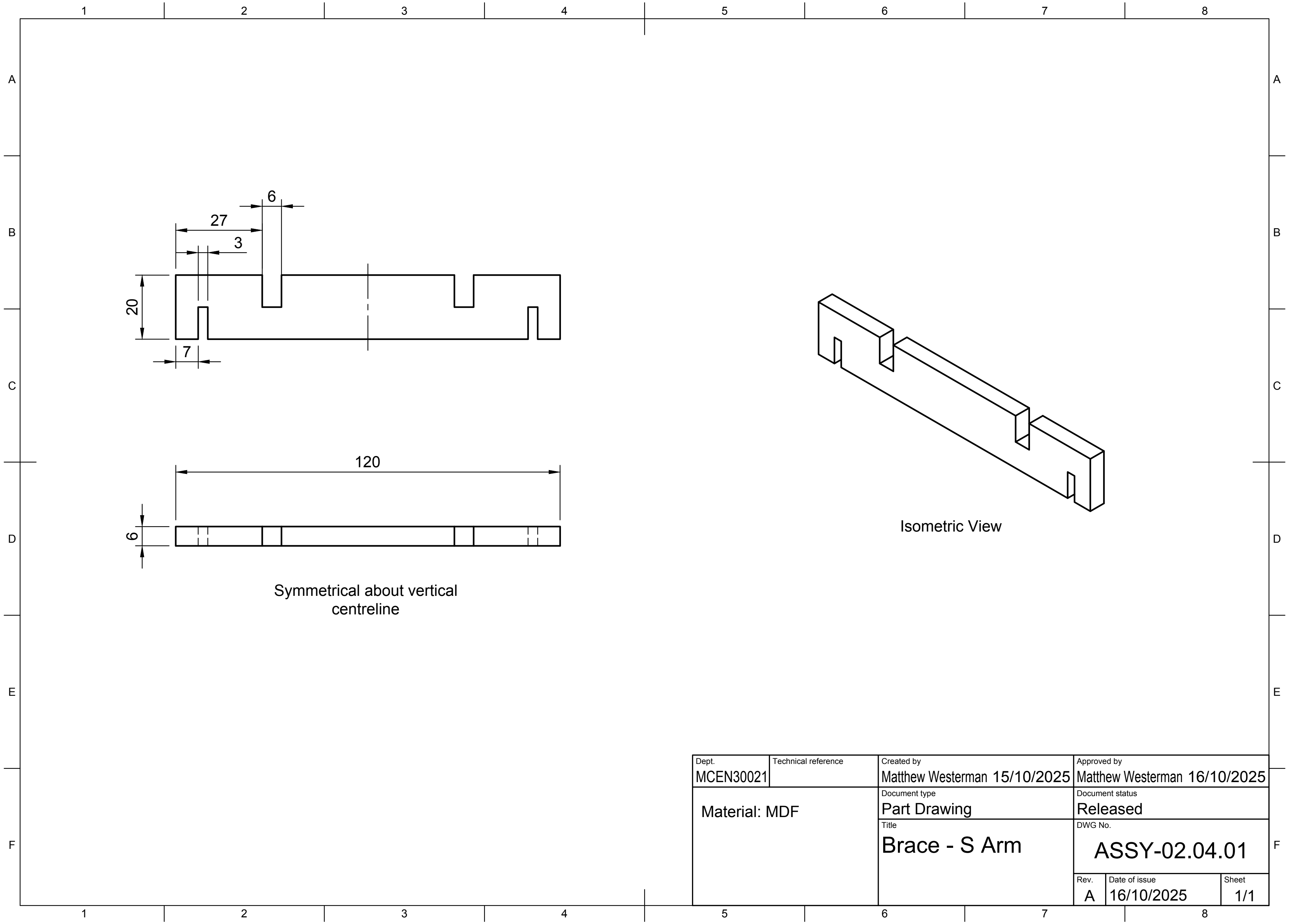


Dept.	Technical reference	Created by	Approved by
MCEN30021		Matthew Westerman 16/10/2025	Matthew Westerman 16/10/2025
Material: MDF		Document type: Part Drawing	Document status: Released
		Title: Powertrain - 120 Tooth Gear	DWG No.: ASSY-04.02
			Rev.: A; Date of issue: 16/10/2025; Sheet: 1/1

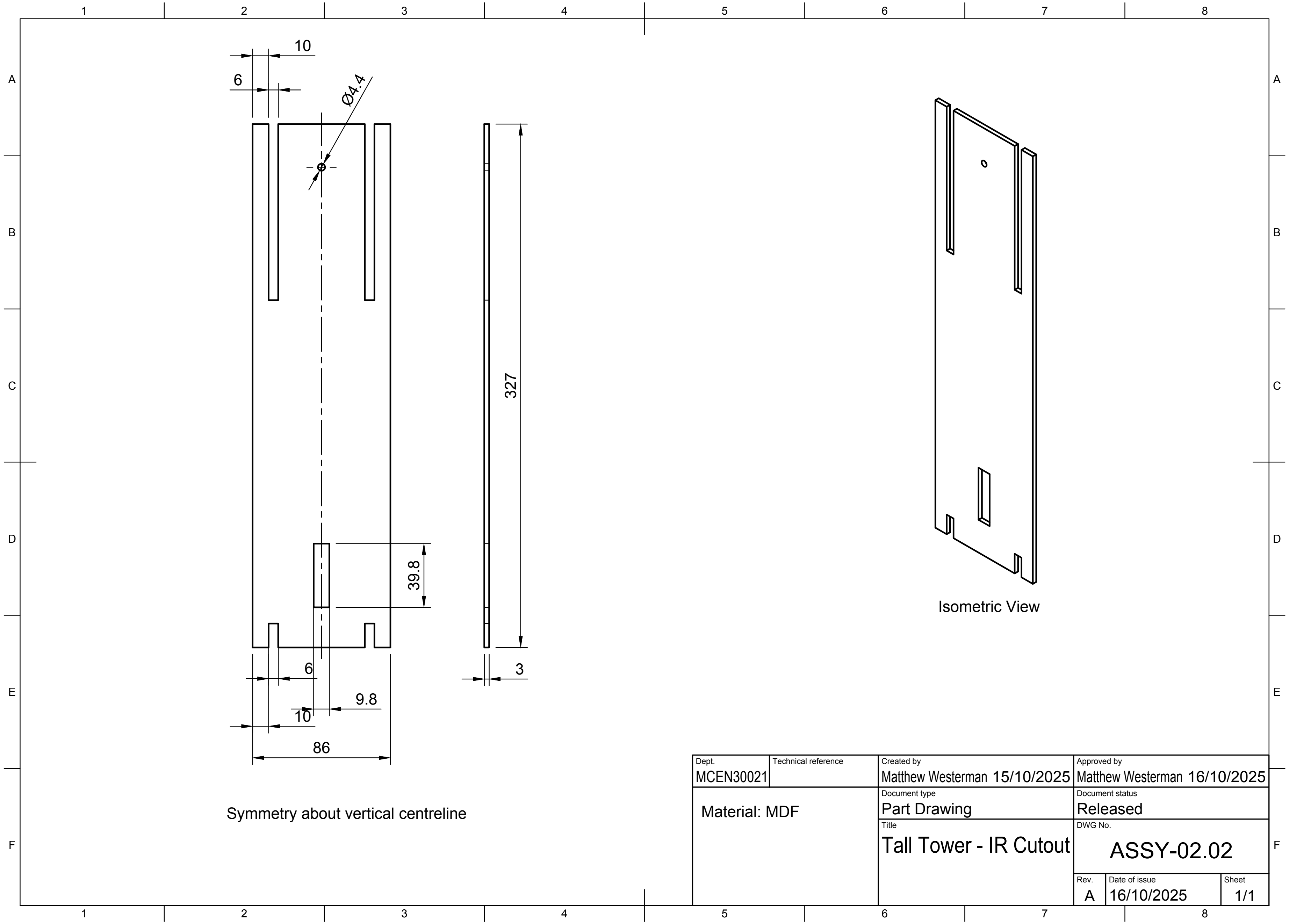


Rotational symmetry of outer teeth
and inner slots

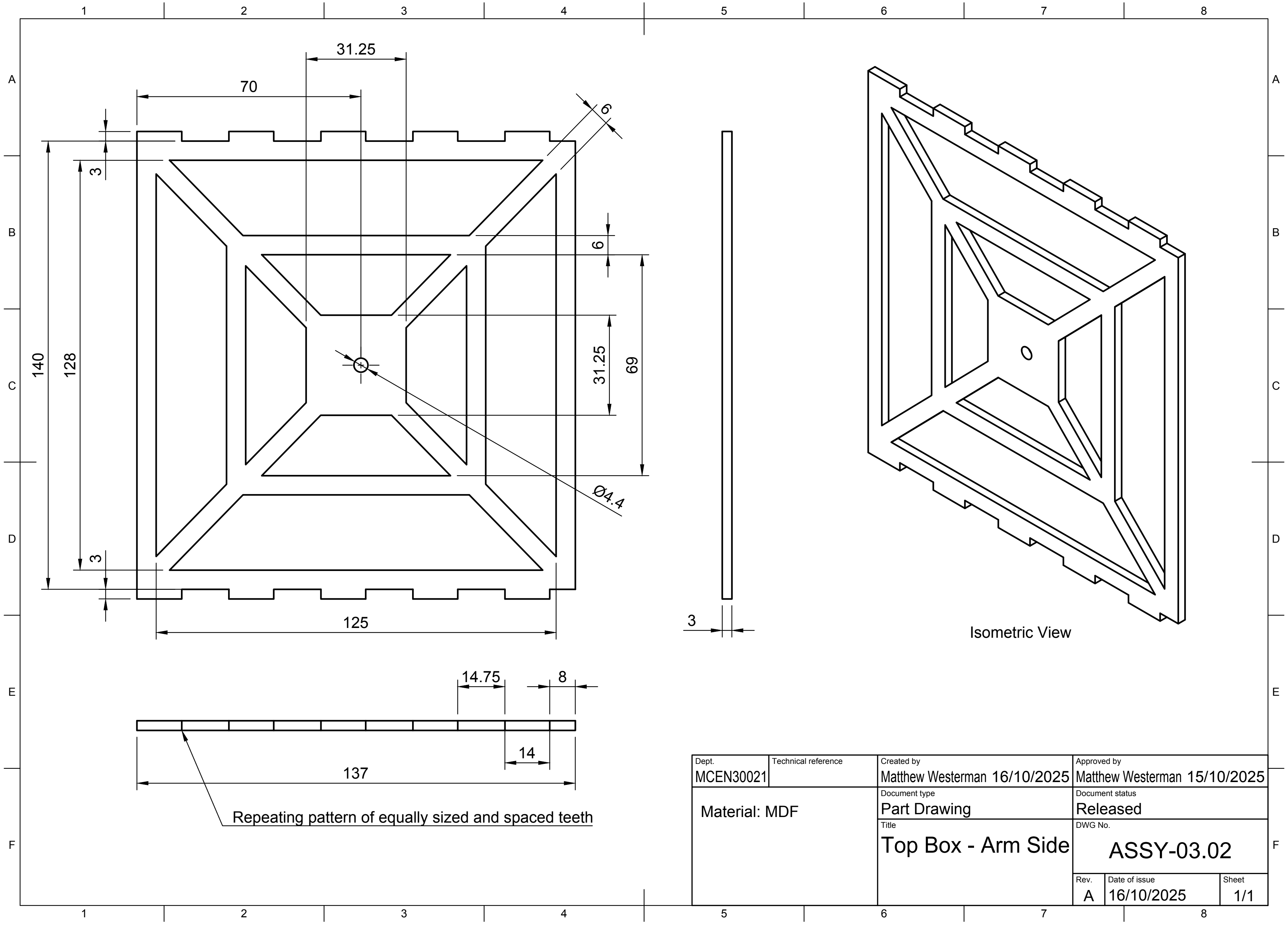
Dept.	Technical reference	Created by	Approved by
MCEN30021		Matthew Westerman 16/10/2025	Matthew Westerman 16/10/2025
Material: MDF		Document type: Part Drawing	Document status: Released
		Title: Base Box Lid	DWG No.: ASSY-01.03
			Rev.: A / Date of issue: 16/10/2025 / Sheet: 1/1



6
27
3
20
7
120
6
Symmetrical about vertical centreline
Isometric View
Dept.
MCEN30021
Technical reference
Created by
Matthew Westerman 15/10/2025
Approved by
Matthew Westerman 16/10/2025
Material: MDF
Document type
Part Drawing
Document status
Released
Title
Brace - S Arm
DWG No.
ASSY-02.04.01
Rev.
A
Date of issue
16/10/2025
Sheet
1/1



10
6
Ø4.4
327
39.8
6
3
9.8
10
86
Isometric View
Symmetry about vertical centreline
Dept.
MCEN30021
Technical reference
Created by
Matthew Westerman 15/10/2025
Approved by
Matthew Westerman 16/10/2025
Material: MDF
Document type
Part Drawing
Document status
Released
Title
Tall Tower - IR Cutout
DWG No.
ASSY-02.02
Rev.
A
Date of issue
16/10/2025
Sheet
1/1



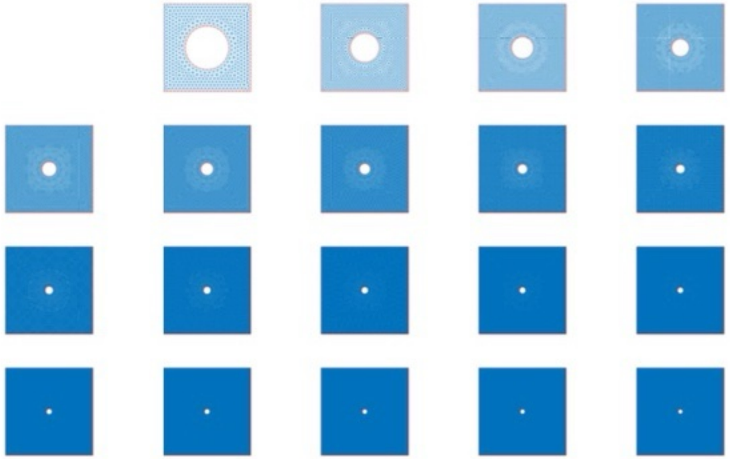
Dept.: MCEN30021	Technical reference	Created by: Matthew Westerman 16/10/2025	Approved by: Matthew Westerman 15/10/2025
Material: MDF		Document type: Part Drawing	Document status: Released
		Title: Top Box - Arm Side	DWG No.: ASSY-03.02
			Rev.: A; Date of issue: 16/10/2025; Sheet: 1/1

Mechanics and Materials MCEN30017

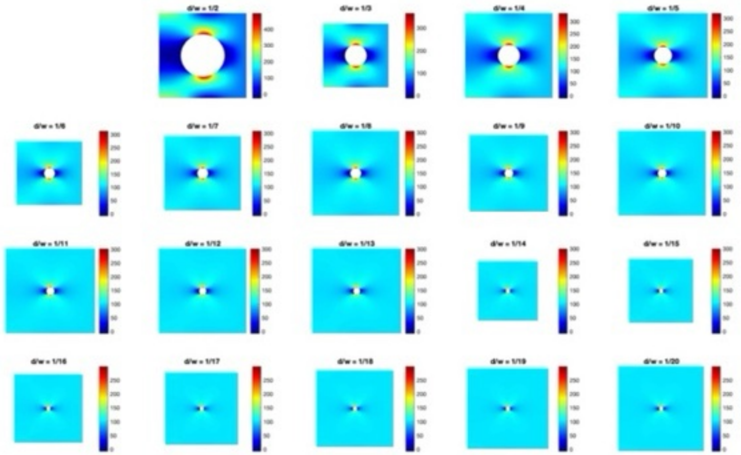
The largest assessment task of this subject was on the theory and application of Finite Element Analysis. FEA theory was explored through first principles hand calculations and a numerical MATLAB based simulation, and then practiced at full scale through the design, meshing, loading, and optimisation of a hip implant in SolidWorks.

The analytical component developed a first principles understanding of FEM by deriving element stiffness matrices, assembling the global system, and solving for nodal displacements and axial stresses in selected truss members, with MATLAB used to verify the numerical results. The numerical PDE study extended this into a continuum setting through a parameterised MATLAB model of a square plate with a central hole. The aim was to identify the d/w ratio at which the numerical stress concentration matched the analytical 3:1 value, achieved by generating geometries, automating meshing, extracting stress fields across widths from 2 to 20 mm, and validating the result against a 3D SolidWorks simulation.

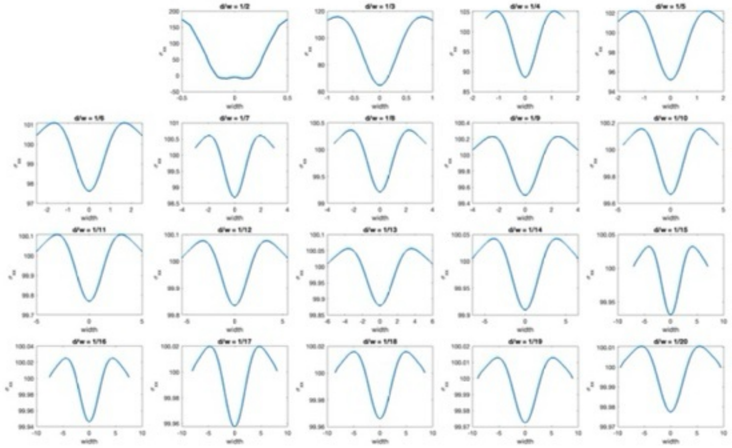
The design and simulation task applied FEA to a biomedical implant by constructing a full 3D hip implant model in SolidWorks from engineering drawings, assigning material properties, and applying a 1500 N load to simulate walking. Mesh sensitivity analysis identified the neck as the critical region and established a 0.3 mm local mesh as optimal. Stress visualisation isolated a neck hotspot, and a design study reduced peak stress through targeted geometric changes.



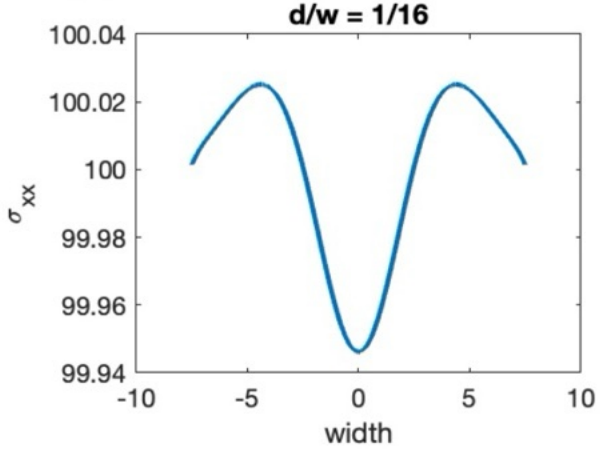
(a) Mesh for each width



(b) Contours for each width

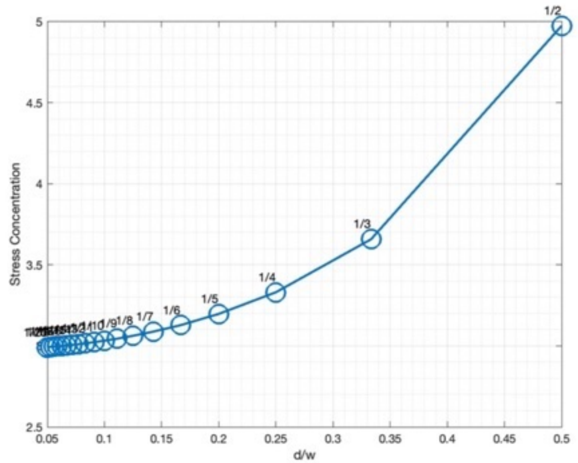


(c) Stress curves for each width

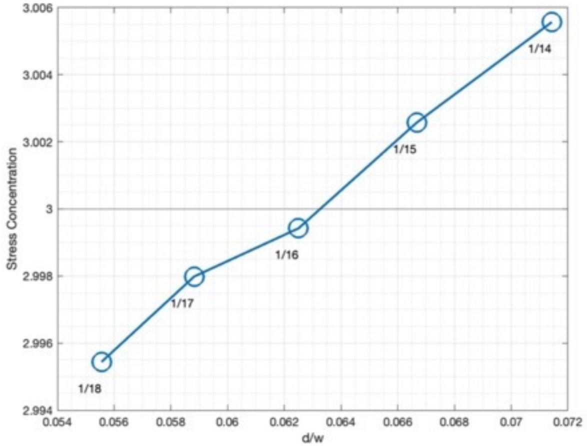


(d) Stress curve for $w = 16\,\mathrm{mm}$

Figure 1: MATLAB graphical outputs

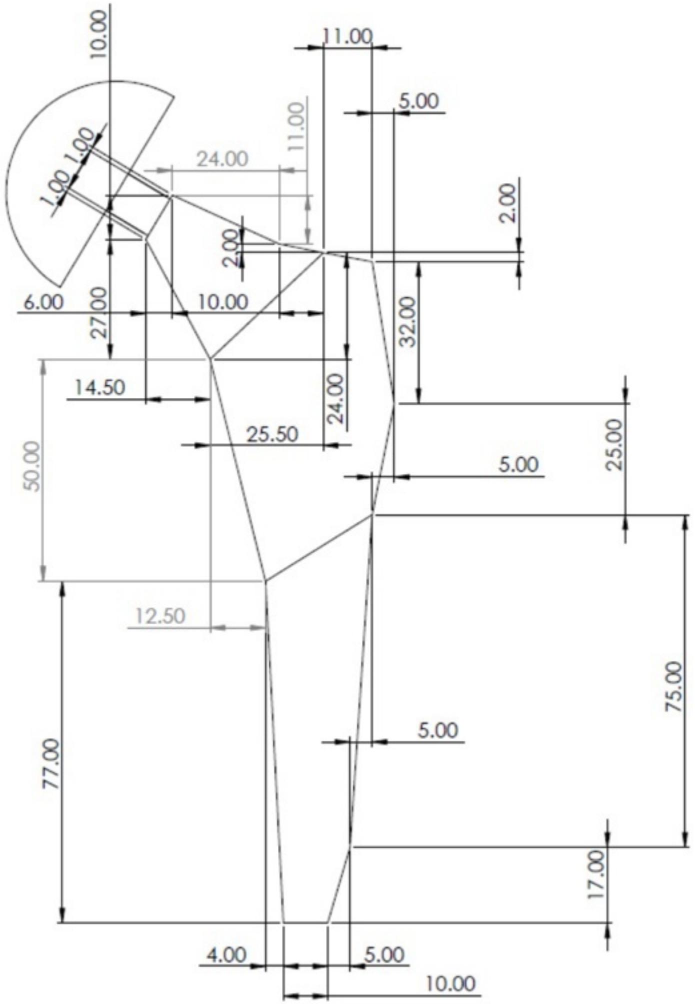


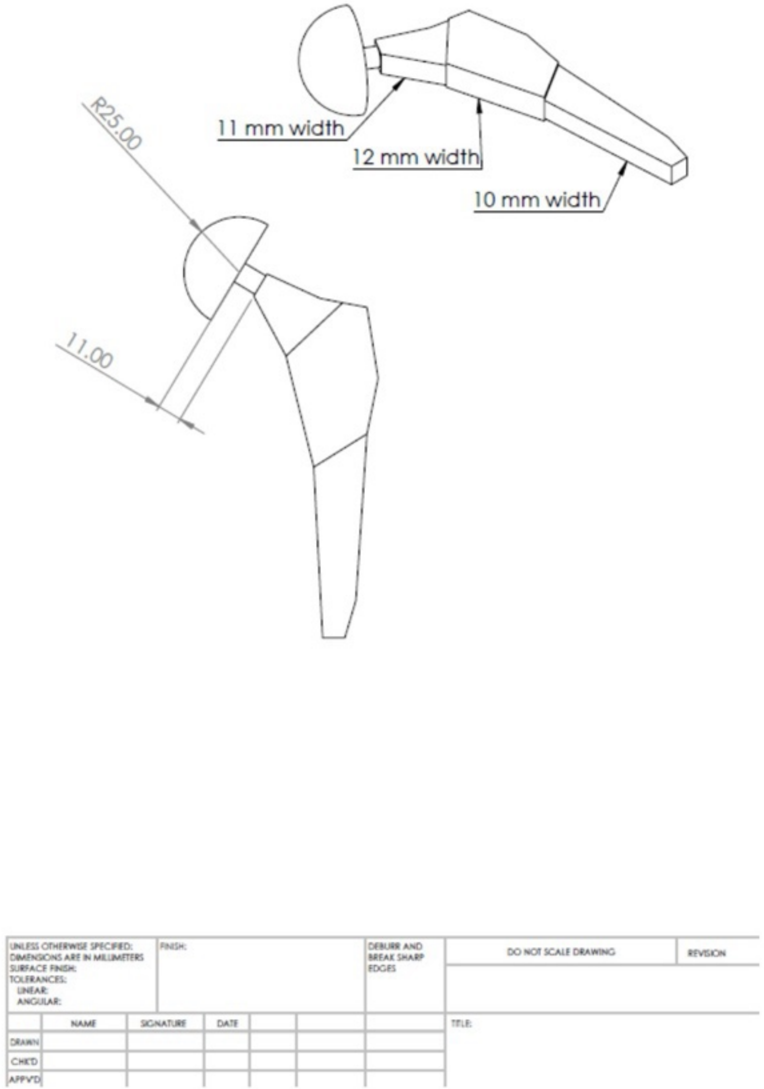
(a) Relationship between stress ratio and d/w



(b) Isolating w=16 as closest to 3:1 ratio

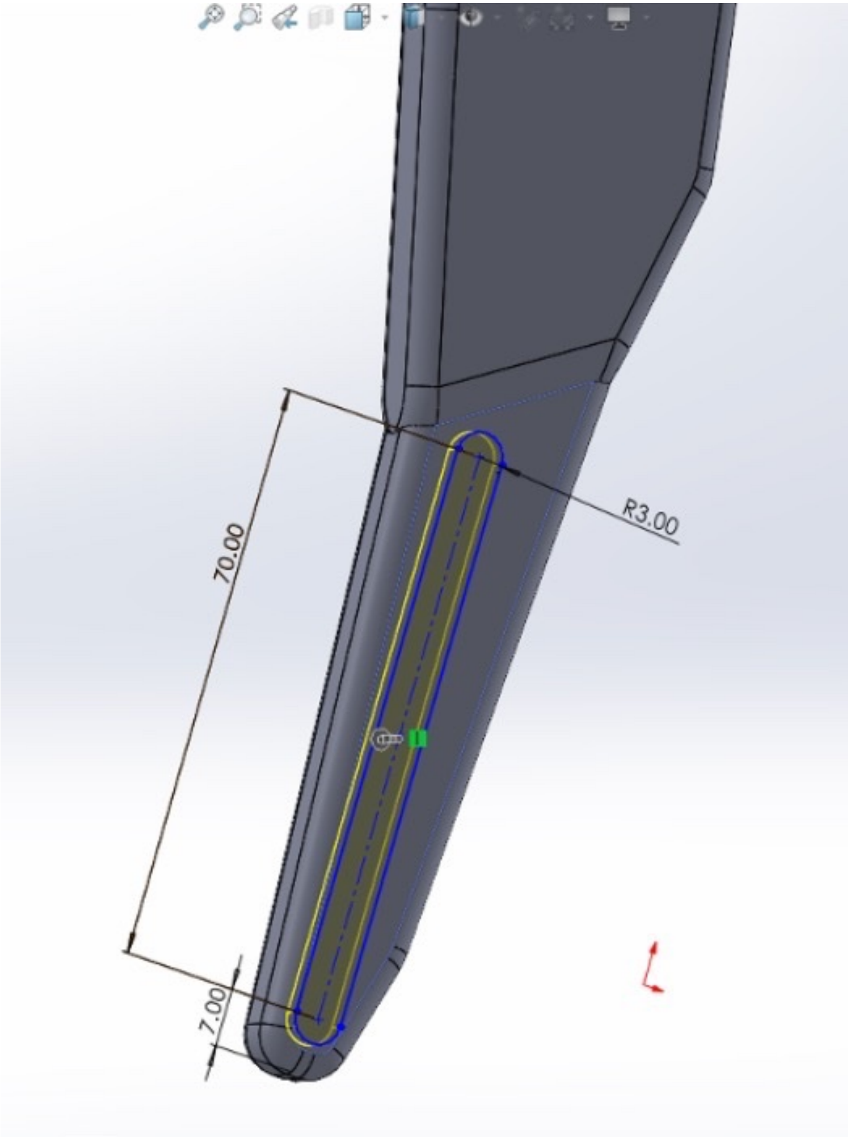
Figure 2: MATLAB Stress vs d/w Curves

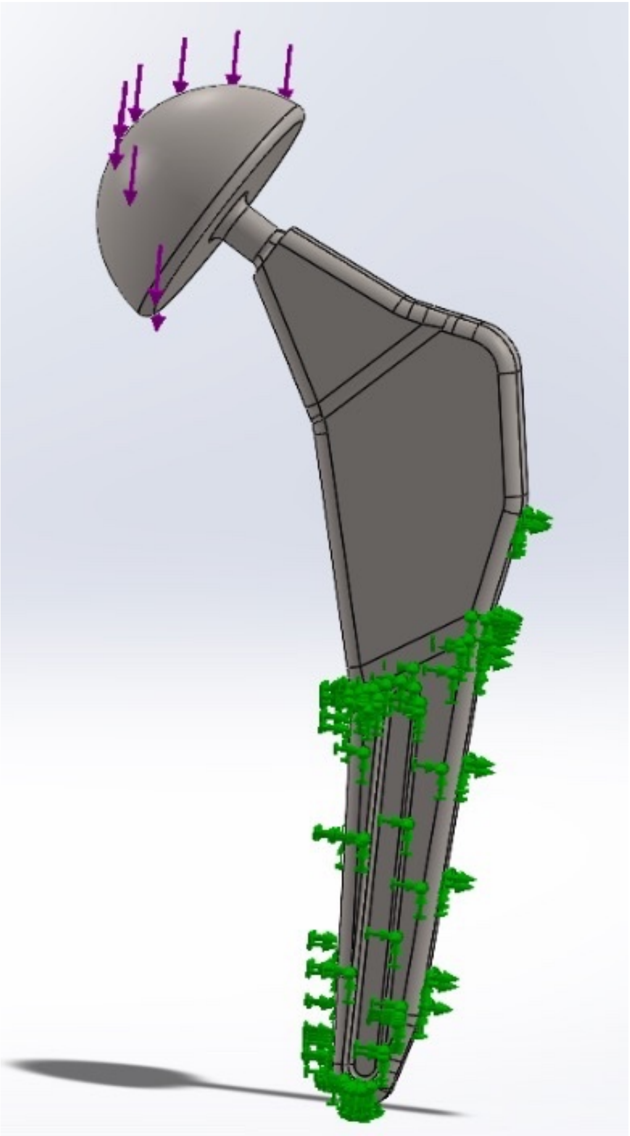


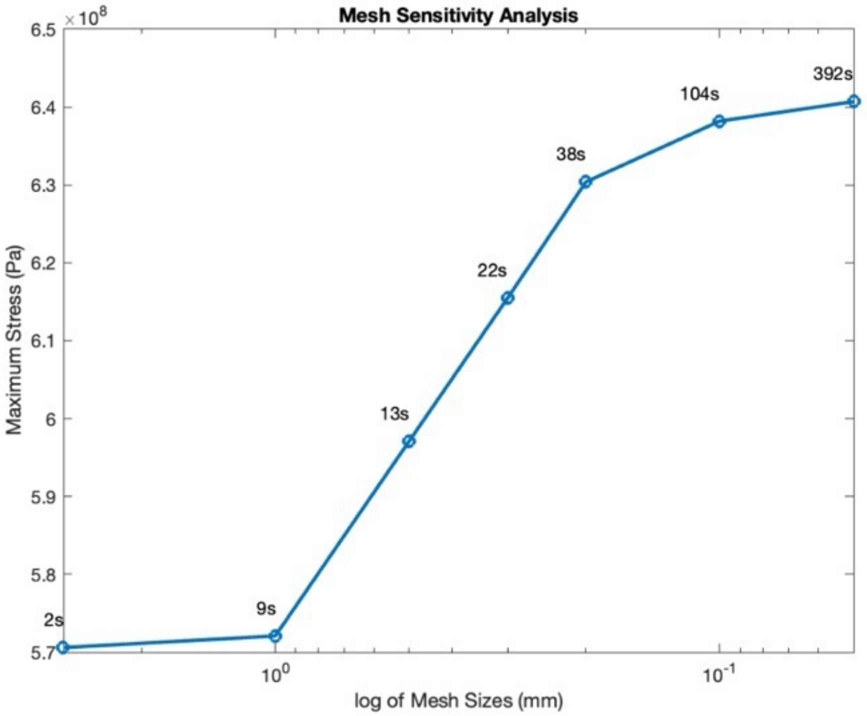


Provided engineering drawings for hip implant design

CAD model built from provided engineering drawings







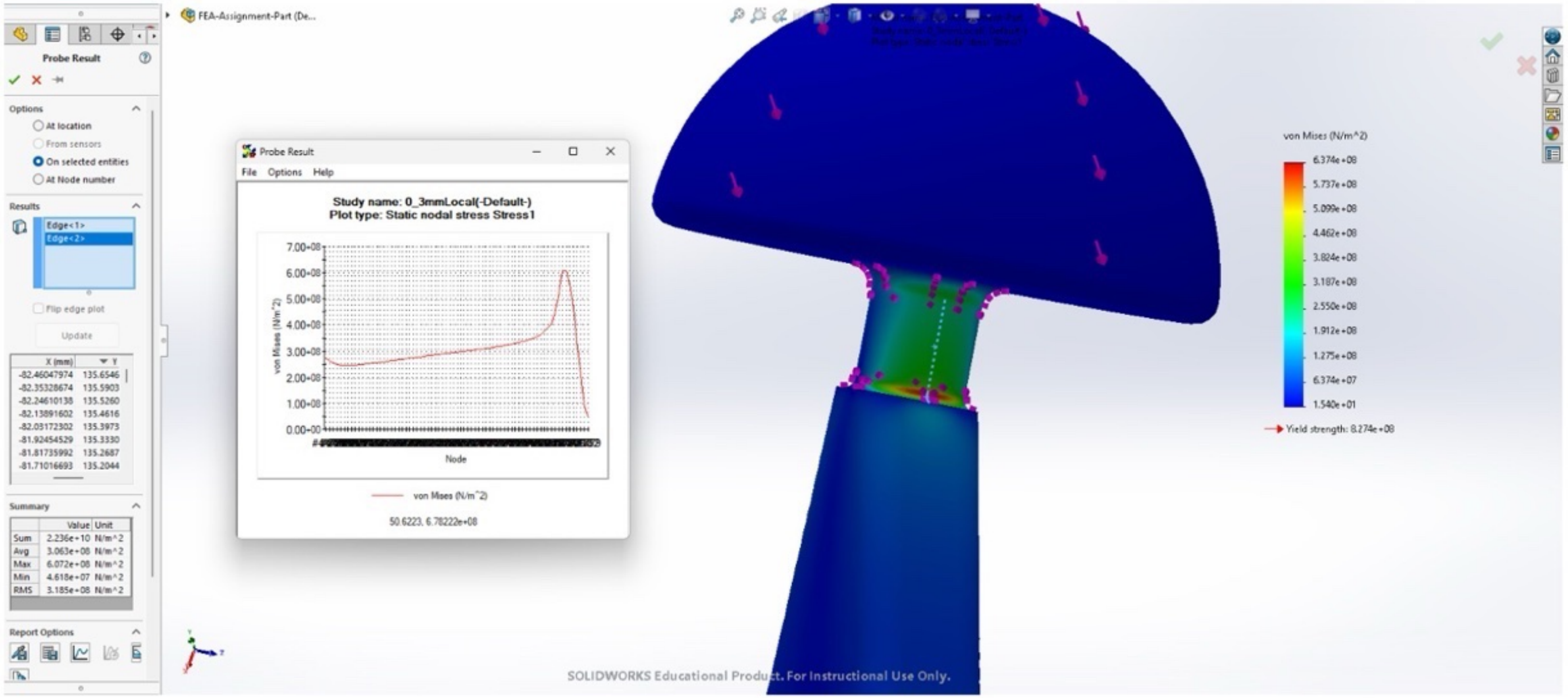


Figure 15: Stress Plot for Local Mesh of 0.3mm (run time 22s)

Mesh Sensitivity Analysis for implant neck – 0.3mm selected as balance between run time and accuracy

Design study assessing optimal neck thickness & fillet size for minimal stress

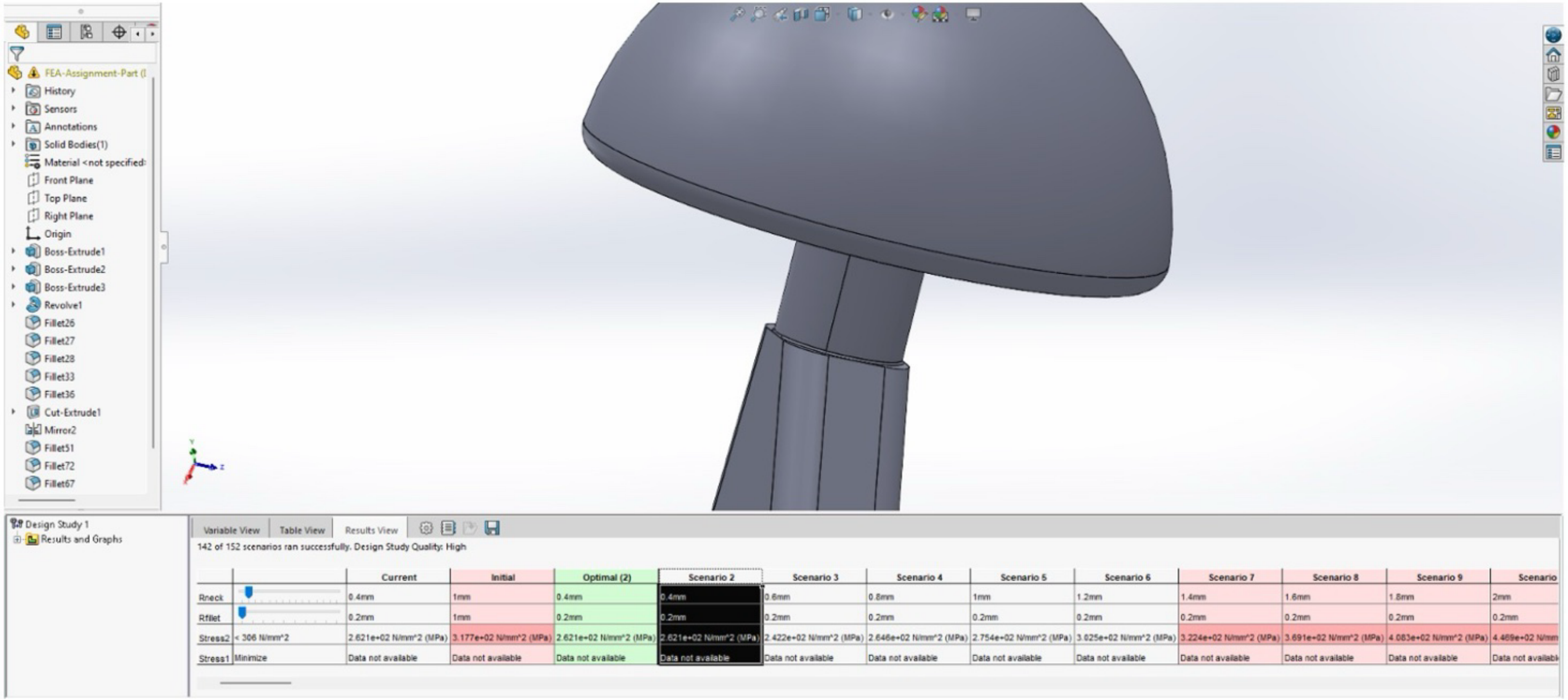


Figure 17: Design Study Results and Optimal Dimensions

1. The original flight controller was a proprietary, undocumented PCB with no exposed programming interface. Reusing it would have introduced unknown dynamics, hidden firmware behaviour, and unquantifiable timing constraints.

To maintain model–implementation traceability, the controller was replaced with a custom-designed board with a known MCU, IMU, and power architecture.

2. Initial investigation explored retrofitting autonomy onto a coaxial helicopter airframe. Mechanical stabilisation, limited control authority, and sensor packaging constraints motivated a platform change. A quadrotor airframe was selected to align vehicle dynamics with the desired autonomous mission, while retaining a fully custom control system and electronics design.

3. A commercial quadrotor platform was used as a mechanical testbed. The stock flight controller was replaced due to undocumented firmware, unknown con logic, and lack of sensor access. A custom controller wa designed to enable full model-based control and onboa autonomy

Mission definition: The vehicle is required to execute a fixed, closed set of behaviours in sequence, with no expansion of scope. These behaviours are takeoff to a controlled height, steady hover, a yaw spin in place, a square trajectory defined by commanded horizontal velocity combined with a yaw profile, a figure-eight trajectory with coupled velocity and yaw shaping, and a controlled landing. No additional manoeuvres, recovery modes, or autonomy features are included beyond this sequence.

Sensing stack: An IMU provides attitude estimation and yaw rate, a time-of-flight sensor provides altitude above ground, and a PMW3901 optical flow sensor provides horizontal velocity relative to the ground. There is no absolute position measurement in x or y, position exists only implicitly through time integration of velocity, and no external references such as GPS, beacons, or vision-based mapping are part of the architecture.

Actuation architecture: The platform uses four brushed DC motors driven via low-side MOSFETs. Motor control is unidirectional only, with no reverse capability, and no electronic speed controllers are used. All control authority is achieved through differential thrust modulation within these constraints, and no changes to this actuation approach are permitted once this phase is complete.