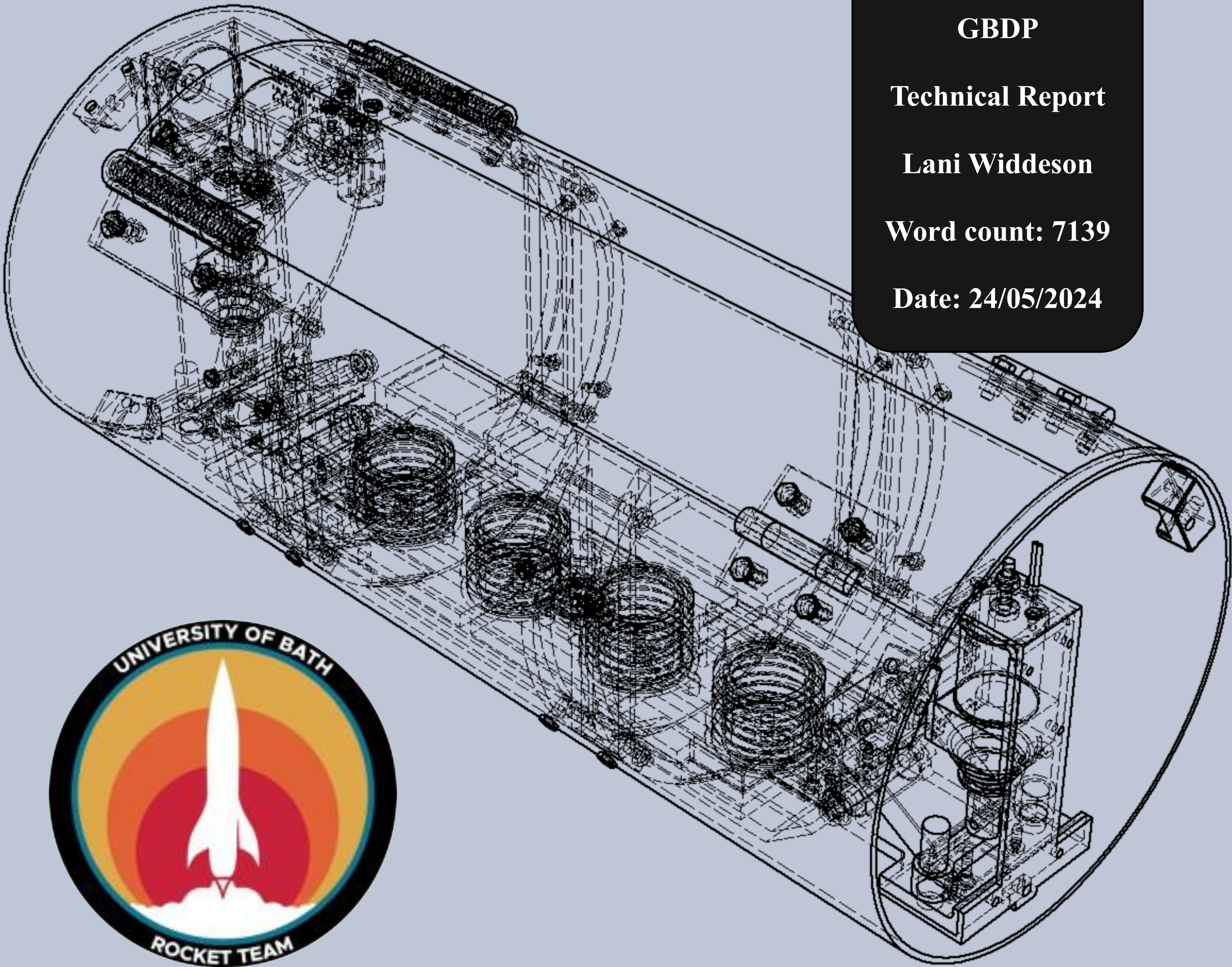

GBDP

Technical Report

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Rocket Payload Ejection: Design and Development of an Electro-Mechanical Payload Bay

Summary

This report details the design, development, and validation process of a rocket Payload Bay. The rocket was designed to carry either a standard two CubeSat sized payload - for competition purposes - or a high spec drone. This was in order to meet the business case developed by the team to use the rocket to launch a drone at high altitude (3000 m) for military purposes. The Payload Bay had to fit into the rocket both in dimensions and in weight while providing ejection capabilities to the payload.

It was determined the payload would be ejected out of the side of the rocket; the doors would be held shut by a solenoid and opened by sprung hinges; the bed would be restrained by solenoid driven latches and guided by rails on two sides; and the payload would be ejected by springs placed underneath the bed. A full assembly of this system was created in Autodesk Inventor and drawings of each sub-system were generated for clarity (see Appendix 5). To ensure these parts would successfully eject the payload, calculations were completed to give the following results: two sprung door hinges should provide an opening moment of at least 0.7334 Nm each; the door solenoid should provide at least 27.26 N of pulling force; the Latch solenoid should provide at least 43.31 N of pulling force; and the bed (compression) springs should provide a minimum force of 1411.76 N in total (which with four springs is 352.94 N each). The trajectory of the payload after ejection was also modelled to ensure it would not collide or interfere with the rocket or its recovery system after deployment.

These calculations were then used to source the Commercial Off the Shelf (COTS) components to their required specifications and validate the designs of the bespoke components. Validation was conducted using Finite Element Analysis (FEA) at a mesh size deemed appropriate by results of convergence studies (detailed in Appendix 6). Each bespoke part expected to bare a significant load during launch or ejection was modelled and analysed for maximum stress and deformation, and changes were made to the design where necessary. The cost of the Payload Bay was estimated to be £571.63 total with the COTS components costing £484.46 and the bespoke component materials costing £87.01 disregarding transport and machining costs.

Redundancy was also considered with the top priority to be protecting the payload. This meant that measures were implemented to ensure the payload's safety over the success of its ejection. If the ejection was likely to fail or damage the payload then the payload would remain inside the rocket so it could land, and launch could be re-attempted. In addition to this, all parts were designed with a safety factor of at least 1.5 to minimise the risk of component failure.

The main constraint factor when designing the Payload Bay was space as the rocket internal diameter was only 157 mm. This left very limited space around the rocket in which to fit the sub-systems necessary to eject the payload. In the future, the Payload Bay should be optimised to reduce weight by reducing the thickness of components and using less dense materials (where possible) while maintaining

the performance of the parts. This would increase the efficiency of the rocket. If the rocket was required to eject a heavier payload (>1 kg), the payload bay would need to be increased in size to accommodate more forceful springs and solenoids, or a combination method of ejection would need to be developed (e.g., the majority of the power to come from springs with an extra portion coming from a small amount of black powder/explosive charge).

Contents

Table of Symbols

Variable	Abbreviation	Units
Radius	r	m
Thickness	t	m
Diameter	d	m
Chord length	c	m
Angle	θ or α	Degrees (°)
Weight	W	N
Moment	M	Nm
Mass	m	kg
Mass of Door	m_d	kg
Gravity	g	m/s^2
Air Density	ρ_a	Kg/m^3
Area	A	m^2
(Final) Velocity	v	m/s
Force on plate area of Door	W_d	N
Force on cross-sectional area of Door	W_c	N
Coefficient of friction	μ	
Force	F	N
Acceleration	a	m/s^2
Drag	D	N
Coefficient of Drag	C_D	
Initial Velocity	u	m/s
Distance Travelled	s	m
Spring Energy	E_s	J
Kinetic Energy	E_k	J
Potential Energy	E_p	J
Distance/Extension	x	m
Spring Constant	k	N/m

Table of Abbreviations

Abbreviation	Meaning
BRT	Bath Rocket Team
CNC	Computer Numerical Control
COTS	Commercial Off the Shelf
EuRoC	European Rocketry Competition
FEA	Finite Element Analysis
GBDP	Group Business Design Project
MCDA	Multi Criteria Decision Analysis

Table of Figures

Table of Tables

1 Introduction

This technical report details the design of a rocket Payload Bay and ejection system to deploy a payload at 3000 m. The rocket had 2 purposes: to enter the annual European Rocketry Competition (EuRoC) for university rocket teams; and to satisfy the business case chosen by the team. The business case was to rapidly deploy a drone at 3000 m for military purposes. Due to the requirement that the payload would be ejected, the system involved the following sub-systems: Payload bed ejection, Payload Bay doors, and Payload bed latching system.

As the rocket was designed for both the competition and the business case, the Payload Bay had to be designed to contain either a CubeSat dimensioned payload (with an individual parachute to meet competition regulations) or a high spec drone (which had been selected by the team).

1.1 Rocket Overview

The rocket was named 'SULIS' and divided into 6 sections: Aerostructure, Recovery, Avionics, Payload, Airbrakes, and Hybrid engine. These systems were developed simultaneously with close collaboration between all sections. With regards to the Payload Bay (seen in the dashed blue box in Figure 1), cooperation with Avionics (positioned above Payload and responsible for integrating electrical components), Airbrakes (positioned below Payload), and Aerostructures (responsible for the skin and bulkheads) was essential. It was decided the rocket would have a hybrid motor, a custom parachute ejection system and nose cone, and fully electro-mechanical recovery and payload systems. See Appendix 5.4 for the overall rocket assembly drawing (Koval, 2024).

1.2 Spec

The specification of this project was defined by both the competition rules (set by EuRoC) and restrictions established by the team in order to satisfy the business case.

1.2.1 EUROC Regulations Relating to Payload

EuRoC regulations specified the size, mass, and recovery system requirements of the payload, as well as restrictions for the energetics inside the payload. No specifications were made for the Payload Bay mechanisms specifically. See Appendix 1.1 for a comprehensive list of regulations from the EuRoC organising body relating to the payload.

1.2.2 Business Case Restrictions

Since the payload was a high spec military drone, there were some other requirements implemented for its protection. These included reducing the movement of the drone whilst inside the rocket (pre-deployment); limiting the heat and explosive forces the drone was subjected to; and decreasing the volume of the payload section to optimise flight dynamics of the rocket.

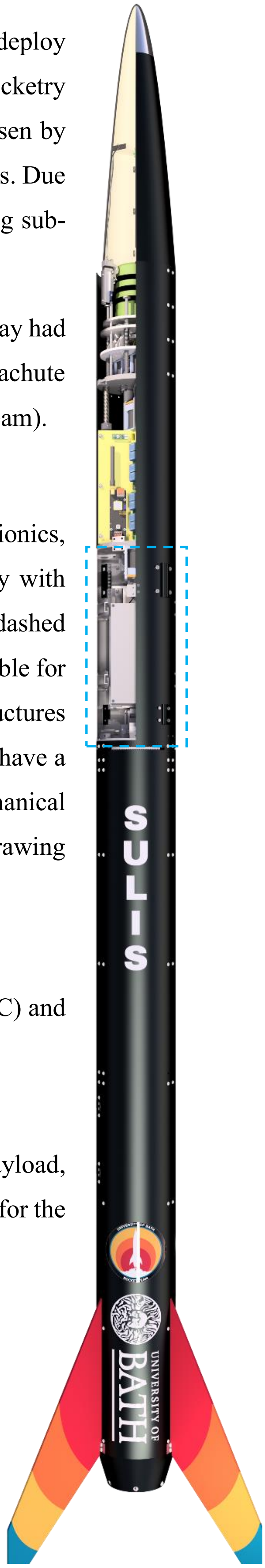


Figure 1: Rocket 'SULIS' section view (University of Bath GBDP BRT Team 2024, 24AD).

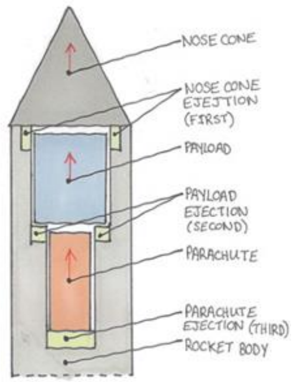
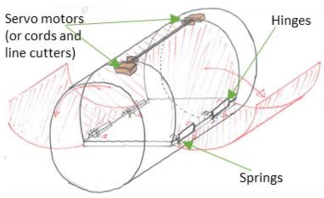
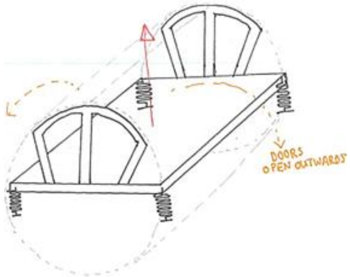
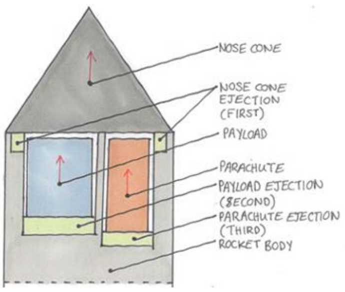
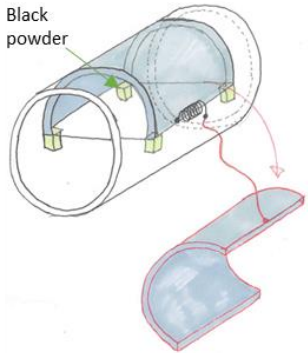
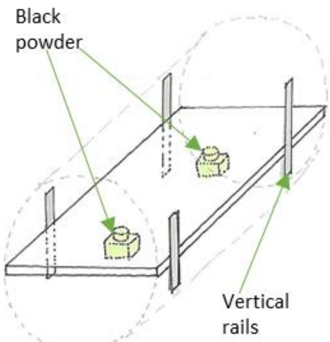
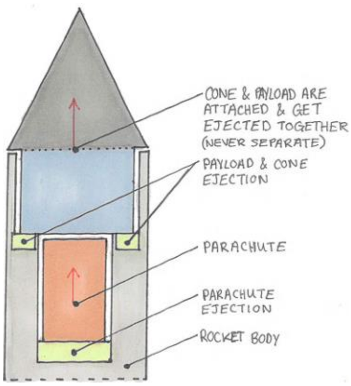
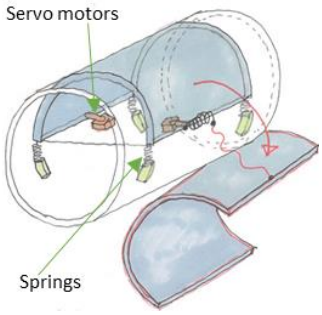
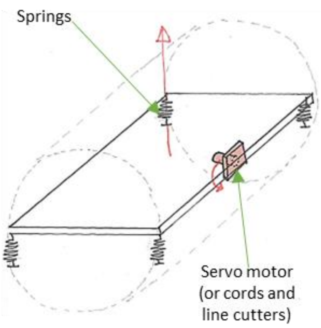
2 Concept phase

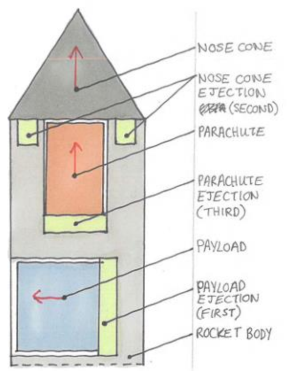
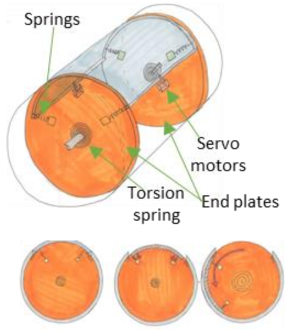
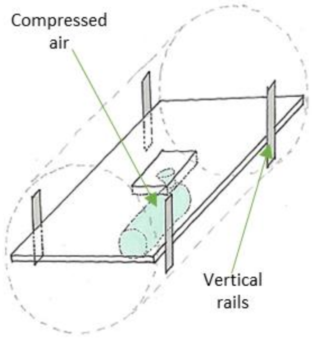
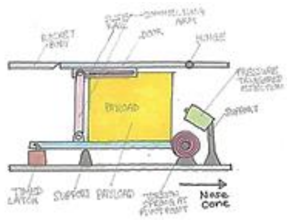
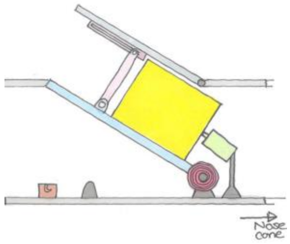
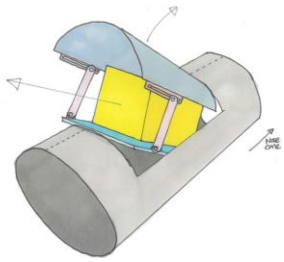
Two concept phases were completed to select the systems that were be used within the Payload Bay.

2.1 Primary Concept Phase

2.1.1 Pugh's Matrix 1

Table 1: Primary concepts Pugh's matrix

	Config Layout (Payload and Recovery systems)	Payload Rocket Doors	Payload Ejection Method
Design 1			
Design 2			
Design 3			

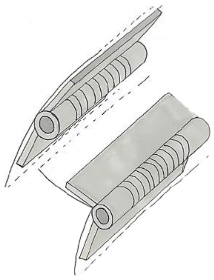
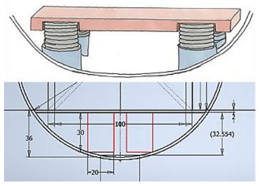
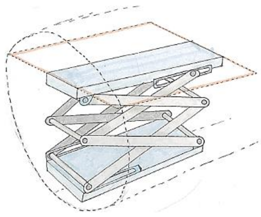
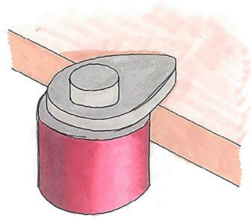
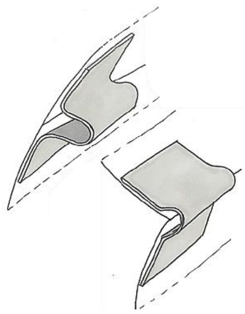
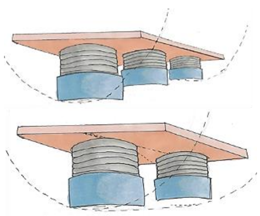
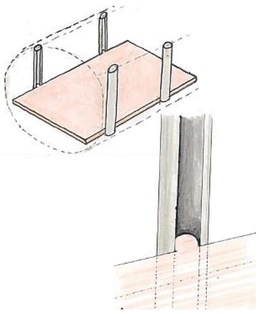
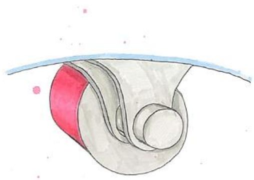
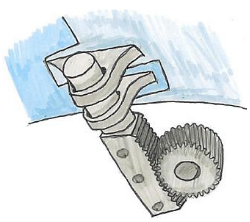
Design 4			
Design 5			

** Design 4 explanation: The door would begin in-line with the rest of the rocket body, so the overall exterior shape would be a smooth cylinder. The servo motors would be engaged, holding the door outwards to be in-line with the rest of the body. With the door held outwards, it would be fully constrained in all directions, preventing the plates from spinning, as they would be inclined to do by the torsion springs. The servo motors would disengage releasing the door which would be drawn inwards by the springs attached to the end plates. Drawing it inwards would create a small clearance between the outer face of the door and the inner face of the rocket body. As the door would move downwards it would no longer be constrained in all directions allowing the force from the torsion springs to spin the endplates. As the endplates would be attached to the door, it would also spin to end up under the surface of the rocket body. With the door rotated inside, the doorway would be open, and the drone would exit.

2.1.2 Pugh's Matrix 1 Explanation

See Appendix 2 for the full MCDA matrix detailing the assessment criteria and results of each of the concept designs in Table 1. Analysis of these concepts using the MCDA matrix revealed that design 4 should be used as the config layout for recovery and payload systems. This was largely due to the design allowing the sections to be completely separate entities within the rocket (with another system in between if required). Also, space constraints inflicted to minimise the rocket diameter resulted in the need to maximise space around the payload, which ejecting the payload out of the side of the rocket achieved. Design 1 was chosen for the Payload Bay doors. The reduced complexity and number of moving parts in this system were a deciding factor in the selection process as this reduced the weight of the system and increased its reliability. For the payload ejection method, design 3 was chosen. This method allowed for control of when the bed was released, regardless of when the doors opened, and did not require explosive or single use components. Explosives such as black powder were undesirable as they produce excessive heat which could damage the payload and they are not sustainable or re-usable. Compressed air was not desirable as the rocket was required to be reusable in a military scenario (as per the business case) and refilling a tank with compressed air before launch would take excessive time and resources.

2.1.3 Pugh's Matrix 2

	Hinges	Bed springs	Bed alignment	Latch systems
Design 1	Sprung hinges 	Four springs at the bottom of the bed. Min compressed length of springs: 30 mm. 	Scissor lift 	Slide on servo motor 
Design 2	Flat hinge 	Springs in-line 2 to 4 springs (depending on strength in a linear arrangement) 	Rails 	Solenoid pin inserted through a fixing on each door. 
Design 3				Rack and pinion with pin inserted through a fixing on each door. 

2.1.4 Pugh's Matrix 2 Explanation

See Appendix 3 for full analysis and MCDA matrix detailing the process of ranking these concepts. Design 1 was chosen for the hinges due to its ease of sourcing and sizing, and the expectation that it would be more difficult to achieve a consistent force from design 2. Due to space constraints (dictated by the diameter of the rocket), design 2 was chosen for the bed ejection method. Spring calculations were completed (detailed in Section 3.5.4) to determine that 4 springs were needed. Also due to space constraints, design 2 was chosen for the bed alignment system as it was determined that with springs underneath the bed there would be no additional space for a scissor lift system. Finally, for the latching systems, design 2 was chosen for both the bed and door latches. The solenoid was found to be the most simplistic and compact method, while reducing the required force.

3 Design Phase

3.1 Final Labelled Diagram

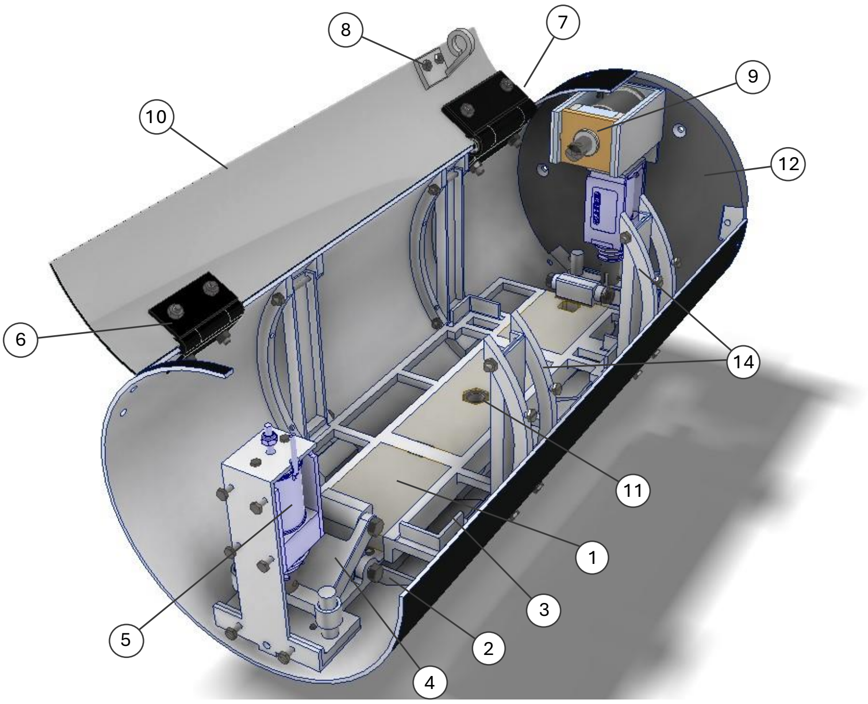


Figure 2: Labelled diagram front view of the Payload Bay (with a quarter section applied to the skin and one door removed) without the payload present.

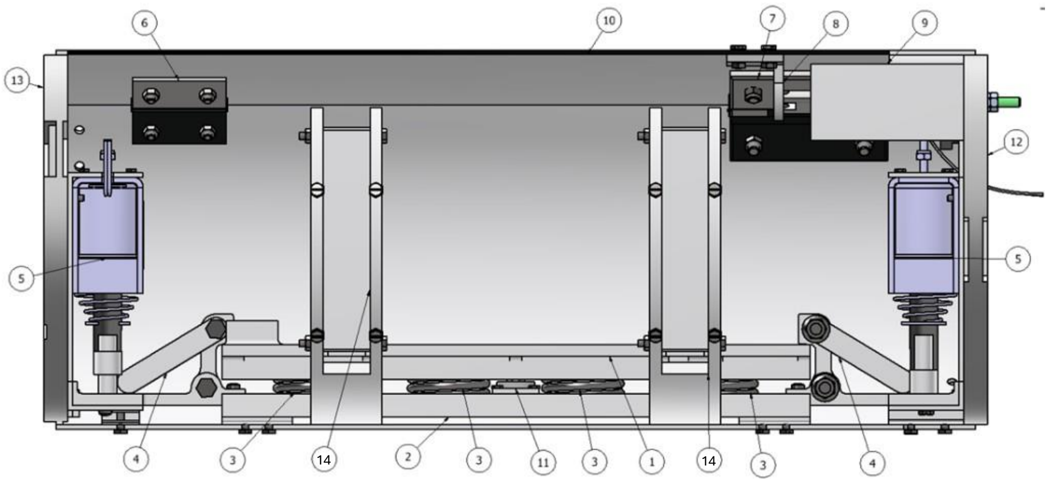


Figure 3: Labelled diagram side view of the Payload Bay (with a half section applied to the skin and one door removed) without the payload present

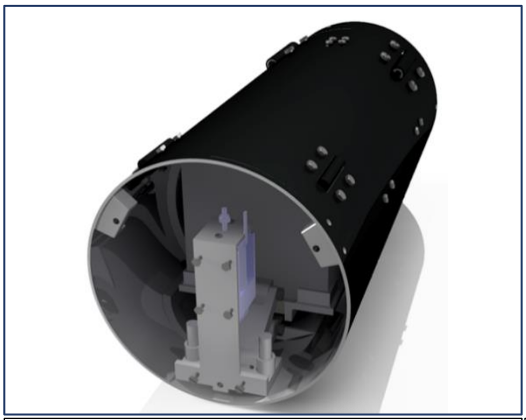
Table 2:Bubble references for Figures 2 and 3.

Bubble reference	Component(s)	Sub-system
1	Payload Bed	Bed system
2	Bed Base	Bed system
3	Bed Spring	Bed system
4	Latch System	Latch system
5	Latch Solenoid	Latch system
6	Hinge (not sprung)	Door system
7	Sprung Hinge	Door system
8	Door Hook	Door system
9	Door Solenoid	Door system
10	Door	Door system
11	Ratchet Connection System	Ratchet system
12	Avionics-Payload Bulkhead	Skin system
13	Payload-Airbrakes Bulkhead	Skin system

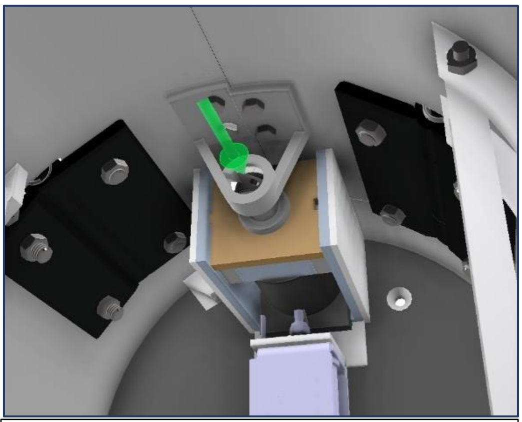
3.2 Final Configuration of the Payload Bay

For sub-system drawings see Appendix 5. The payload sat on a bed with its movement (in plane with the bed) constrained by locators attached to the bed at each corner. The payloads movement perpendicular to the bed was constrained by the bed on one side and the skin doors on the other. The bed's motion was constrained by 4 rails keeping it level and only allowing movement perpendicular to the plane of the bed. Underneath the bed were four in-line springs which made up the ejection system. The bed springs were held in compression during launch (until ejection) by a latch on either side controlled by a solenoid. The Payload Bay doors were attached by two hinges per door. On each door, one of these hinges was sprung and the other was standard. During launch the doors were held shut by a solenoid attached to the body which passed through a hook on each door at one end only. The hooks and the solenoid which passes through them are all located at the same end of the doors as the sprung hinges (instead of the standard hinges) to reduce moment out of the plane of motion of the doors, and to reduce the force required by the solenoid. CAD for the latch solenoids was sourced from 'Solenoid Ninja' (Solenoid Ninja, n.d.) and the CAD for the door solenoid was sourced from 'NAFSA' (Nafsa, n.d.).

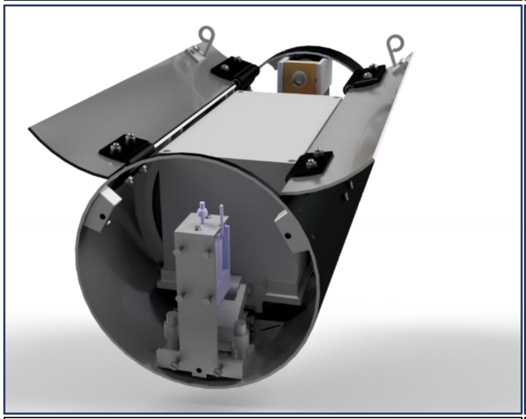
3.3 Storyboard



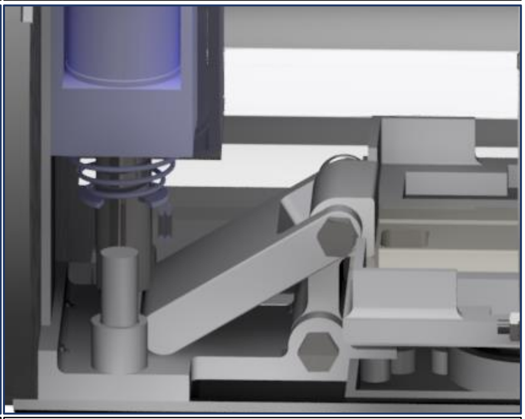
Stage 1: Launch position. The doors are closed, the bed springs are compressed, and all the latches are secured.



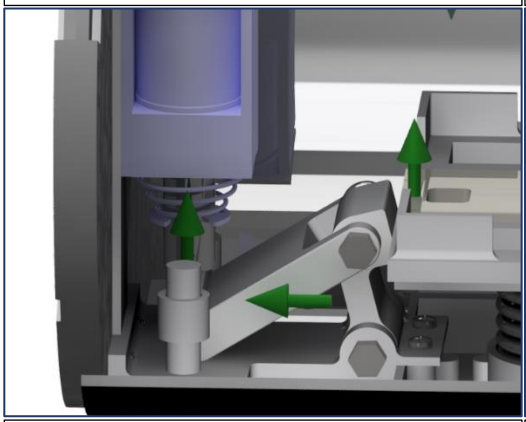
Stage 2: the solenoid acting as a latching mechanism retracts from the two hooks attached to the doors, releasing the doors.



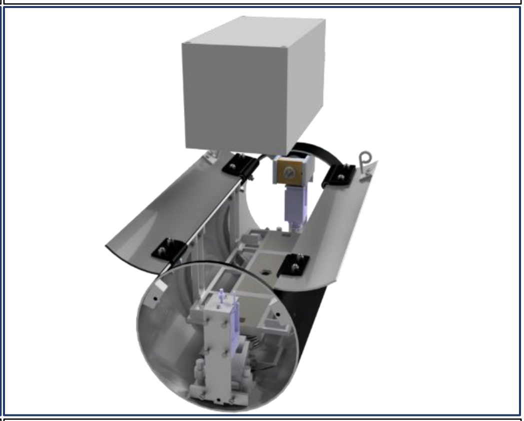
Stage 3: the sprung hinges force the doors open as they are no longer secured by the latch/hooks.



In launch position, the solenoid is extended, the blocking bar is down, the slider is blocked, and the latch is prevented from rotating, which keeps the bed down.



Stage 4: The solenoid retracts pulling the bar upwards clear of the slider. The springs under the bed push on the latch which can now rotate backwards as the slider is able to move.



Stage 5: the bed is forced upwards by the springs (and guided by the rails) ejecting the payload at a speed of 7.35 m/s to a distance of at least 2.5 m away from the rocket.

3.4 Detailed design

3.4.1 Door System

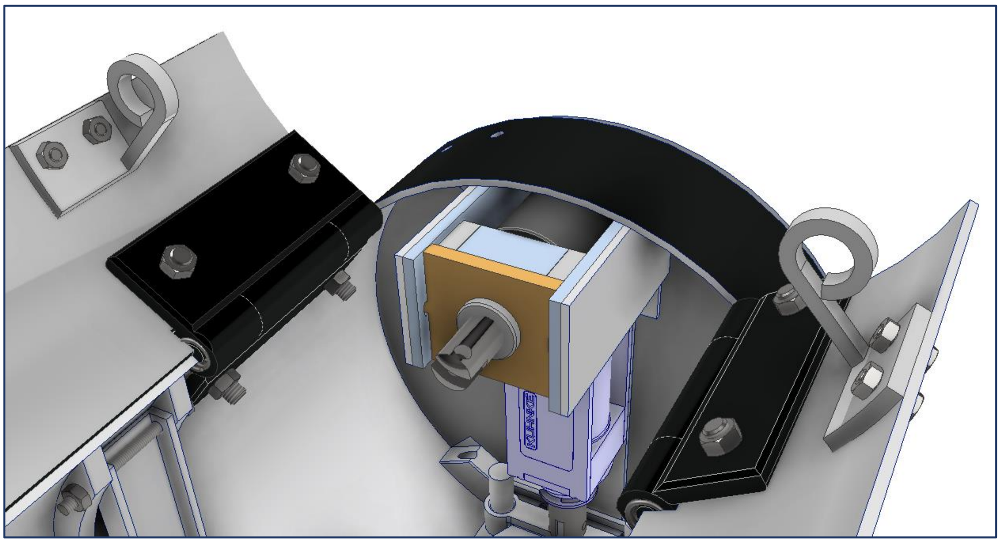


Figure 4: View of door latching system when doors are open.

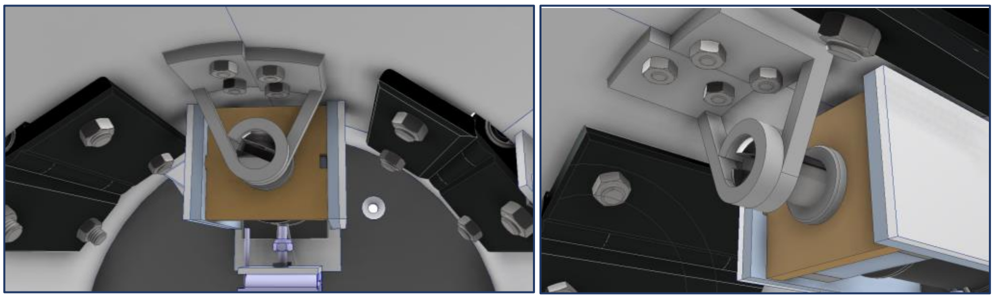


Figure 5: Close up views from inside the Payload Bay of door latching system when doors are closed.

The door system (shown in Figure 4 and Figure 5) was made up of several compontents including the (unsprung) hinges, sprung hinges, hooks, solenoid, and aluminium doors (labelled in Figure 2 as parts 6, 7, 8, 9, and 10 respectively). During launch, the doors were secured shut as the solenoid pin passed through the hook on each door. When the rocket reached apogee and the payload needed to be ejected, the solenoid retracted which released the hooks and the sprung hinges forced the doors open. The hinges and solenoid were COTS components. The hooks and doors were bespoke components made from cut and bent aluminium due to its high strength to weight ratio, easy of manufacture, availability, and recyclability.

See Appendix 5.2 for the assembly drawing and parts list of the door system.

3.4.2 Latch System

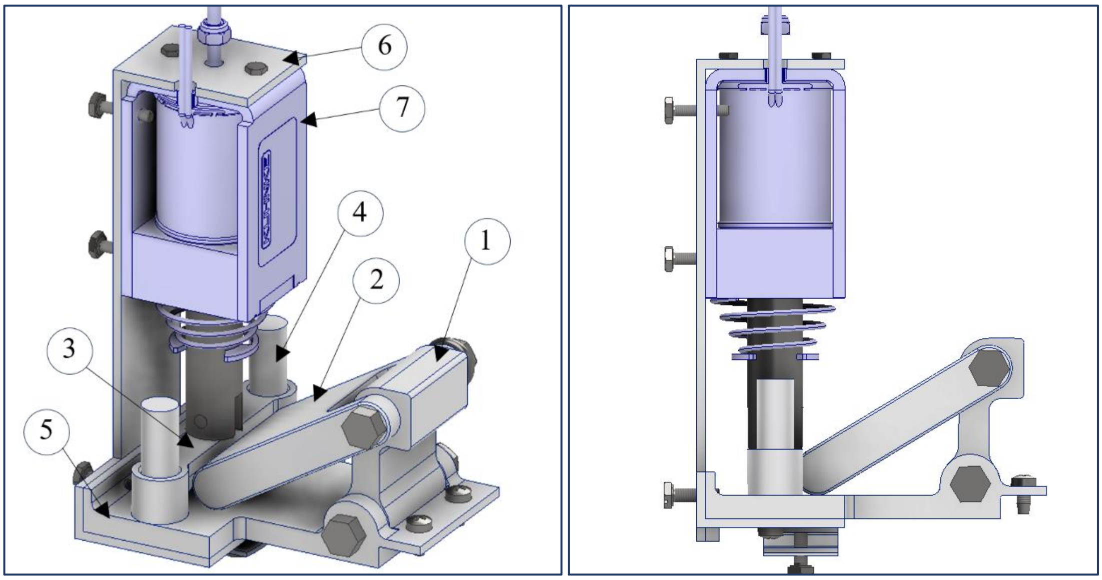


Figure 6: Latch System

The latch system (Figure 6) was comprised of several parts. All of the bespoke components were machined from Aluminium as this was deemed to have a great enough stiffness to resist bending under the force of the bed springs. The latch, slider arm, and bar (labelled as 1, 2, and 3 respectively in Figure 6) were produced using minimal machining from billets. The pins (4) were sections of cut billet inserted into holes in the latch base with an interference fit. The latch base (5) and backplate (6) (which secures the solenoid (7)) were made from bent aluminium sheets with additional machining in some places. Aluminium was chosen for these parts for the same reasons as listed in Section 3.4.1.

See Appendix 5.1 for the assembly drawing and parts list of the latch system.

3.4.3 Bed System

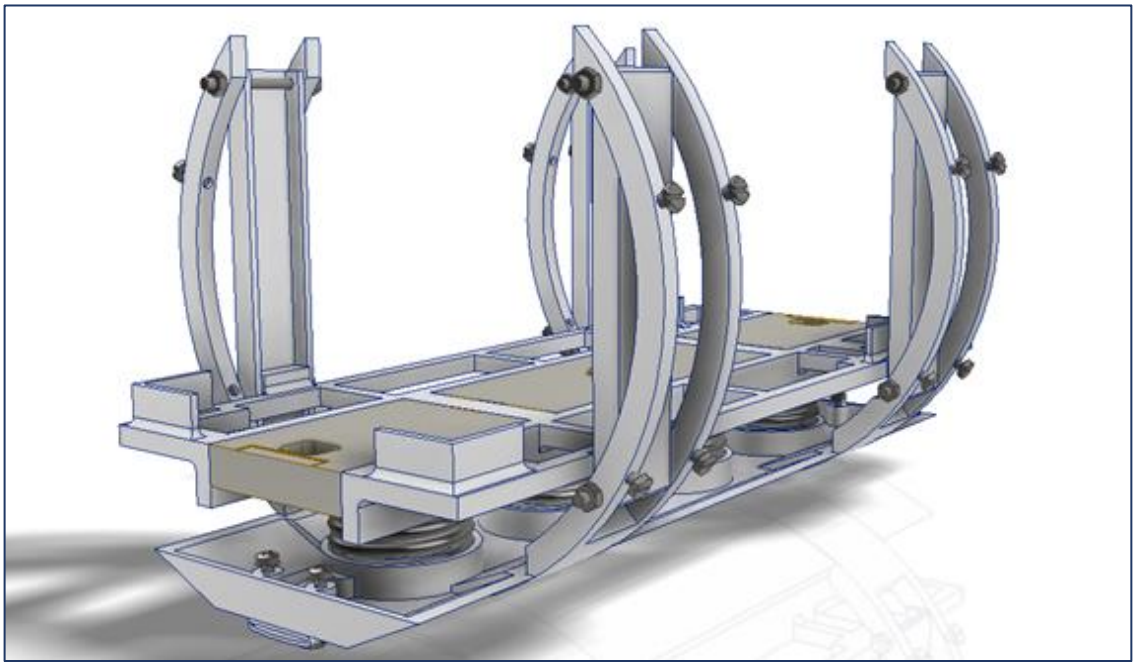


Figure 7: Bed System.

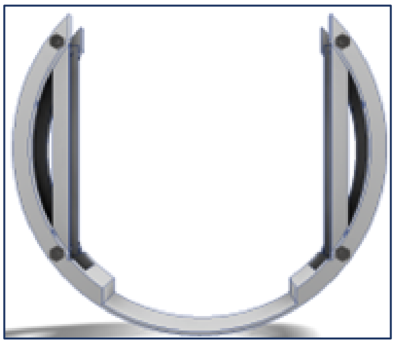


Figure 8: Rail Sub-System.

Figure 9: Bed.

Figure 10: Base with springs.

The bed system (Figure 7) comprised of the bed, the base, the rails, and the springs. The minor parts of the system consisted of nuts and bolts, spring guides, and spacers to secure the base to the skin of the Payload Bay. The rail sub-system (Figure 8) was made up of three parts: two rails (one on either side) and the curved frame which connected them to the skin. The protrusions on the sides of the bed fitted into the rails to restrain the bed from rotating or moving any direction except up and down (reletive to the orientation in Figure 8). The top of the bed is shown in Figure 7 and the underside is show in Figure 9. On the top of the bed, there were extruded corners which restrain the movement of the payload once it was on the bed. On the underneath of the bed, grooves were present to house the tops of the springs. The bed was made from two parts which have been manufactured using Computer Numerical Control (CNC) machining and welded together. The middle section (coloured in gold in Figures 7 and 9) was made from titanuim to increase the strength of the part so it didn't bend due to the force of the springs. The wider section (in silver) was made from aluminium to be wide enough to hold the payload. Grooves and holes were included in the bed to minimise mass. The base (in Figure 10) was made from CNC machined aluminium as a shell of the necessary geometry (to mimimise mass) to contain the springs and restrain the system. The spring guides also fitted into the base, these are hollow tubes that ran inside the springs to ensure they did not buckle and remained verticle.

See Appendix 5.3 for the assembly drawing and parts list of the bed system.

3.5 Calculations

3.5.1 Door System: Hinges

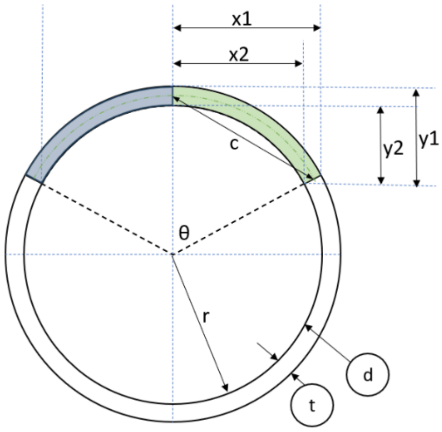
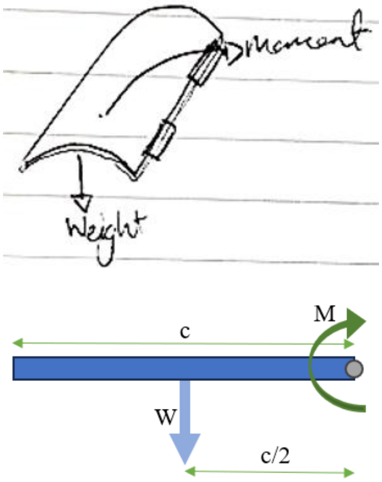
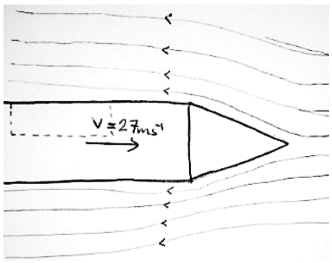
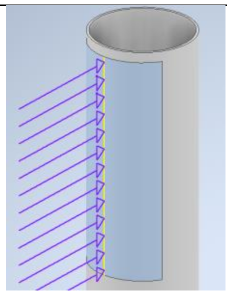
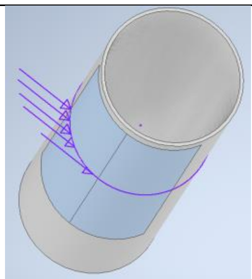
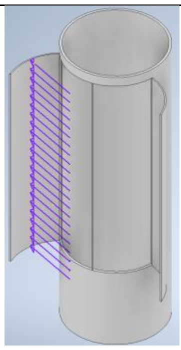
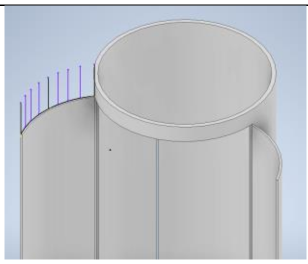
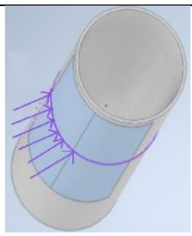


Figure 11: End section view of the payload skin/tube showing the overall dimensions of the doors. In this sketch, one door is green, and the other is blue with the rest of the tube in white.

There were several loading conditions to be considered for the door hinges. These are detailed in Table 3 below. Each door needed at least one sprung hinge for the doors to both be forced open when the latch was released, so the spring torques needed to be sourced with this in mind. Minimising the number of sprung hinges decreased cost and the size of the protrusions outside of the skin cause by the hinges, so this was preferable.

Table 3: Door hinge forces

Name	Description	Image	Equation for required value	Value	Unit
M1	Moment to lift the weight of the doors		$> \frac{c m_d g}{2}$	0.2439	Nm
M2	Pressure difference direct on both doors due to velocity of free stream air on outside.		$\frac{\rho_a A c(v_1^2 - v_2^2)}{4}$	0.1194	Nm
M3	Direct cross wind on closed doors while traveling at velocity		$W_d c^2 * \frac{\sin(\alpha)}{2}$	0.003122	Nm
M4	Perpendicular cross wind on closed doors while travelling at velocity.		$W_d c^2 * \frac{\sin(\theta)}{2}$	0.001277	Nm

M5	Cross wind on inside of open doors while traveling at velocity.		$\frac{W_d c^2}{2}$	0.003373	Nm
M6	Moment from air on door cross-section while travelling at velocity.		$\frac{W_c c^2}{2}$	3.000e-6	Nm
M7	Cross wind on centre of each closed door while travelling at velocity.		$\frac{W_d c^2}{2}$	0.003373	Nm

From Table 3, the following minimum/maximum moments the hinges needed to provide/withstand were obtained:

$$\text{Minimum moment hinges need to provide per door} = M1 + M2 + MAX\{M3, M4, M7\}$$
$$= 0.3667\ Nm$$

$$\text{Parallel moment each hinge must withtand whilst open} = M5 = 0.003373\ Nm$$

$$\text{Perpendicular moment each hinge will need to withstand} = M6 = 3 \times 10^{-6}\ Nm$$

Since these were relatively low moments, only one of the two hinges on each door needed to be sprung. This sprung hinge needed to provide a moment of at least 0.7334 Nm as a safety factor of 2 was applied to the calculated 'Minimum moment hinges need to provide per door'.

3.5.2 Door System: Hinge Latch Solenoid

The Hinge solenoid needed to produce enough force to overcome the friction with the hinge hooks while the sprung hinges provided a moment outward on the doors. The outward force on the doors at the latches was determined by the moment from the sprung hinges and the chord length of the curved face of the doors. Note: chord length refers to the dimension labelled 'c' in Figure 11.

$$\text{Force from both doors} = \text{Moment from both doors} * \text{chord length}$$

$$\text{Force from both doors} = 0.8 * 0.059 = 13.46\ N$$

The force required from the solenoid was determined by the coefficient of friction of the aluminium latches on the solenoid (un-lubricated this is 1.35 (Engineering ToolBox, 2004):

$$\text{Force from solenoid} = \mu * \text{Force from both doors}$$

$$\text{Force from solenoid} = 1.35 * 13.46 = 18.18\ N$$

A safety factor of 1.5 was considered for this system as it was integral to the ejection success of the payload:

$$\text{Total force from solenoid} = \text{Force from solenoid} * 1.5$$

$$\text{Total force from solenoid} = 18.18 * 1.5 = 27.26\ N$$

3.5.3 Latch System: Forces

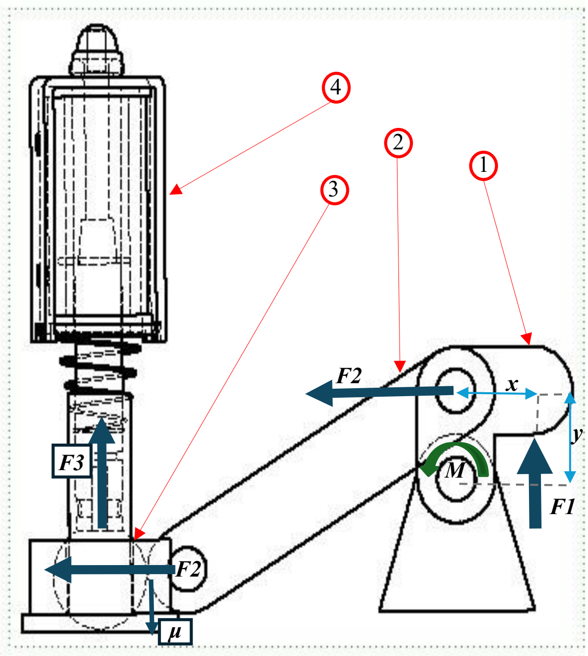


Figure 12: FBD of forces acting on latch mechanism.

Figure 12 was used alongside the following calculations to determine the required pull force from solenoid (4) to lift the bar (3) out of the way of the latch slider arm (2).

The upwards force from the sprung bed on the latch (1) is labelled in Figure 12 as F1, this was equal to half of the force applied by the springs (as there are two latches). Due to the lever effect created by the dimensions of the latch (1) - intended to decease the force transmitted horizontally through the latch (1) - the force F2 was found by (for x and y see Figure 12):

$$F2 = F1 * \left(\frac{x}{y}\right) \tag{21}$$

$$F2 = \left(\frac{1443.52}{2}\right) * \left(\frac{0.005}{0.025}\right) = 144.35\ N$$

F2 was transferred directly through the latch arm (2) as it was held in place whilst the solenoid extended and exerted a force on the bar (3). This force had to be overcome with respect to the coefficient of friction of the arm (2) against the bar (3) by the solenoid to pull the bar upwards (out of the way of the bar). The coefficient of friction of two aluminium parts when lubricated is 0.3 (Engineering ToolBox, 2004), therefore, the force (F3) required from the solenoid (4) was as follows:

$$F3 = \mu * F2 \tag{22}$$

$$F3 = 0.3 * 144.35 = 43.31\ N$$

3.5.4 Ejection/Bed System Forces

The ejection mechanism was required to eject to payload a distance of at least 2.5 m away from the rocket in its 'worst case scenario' orientation. This was to ensure the payload would not interfere with the rocket or the rocket recovery system during or immediately after ejection. The 'worst case scenario' for this system was when the rocket was horizontal in the air with the payload doors facing upwards, this condition required the greatest force from the springs for the payload to be ejected 2.5 m upwards.

To find the force required from the springs, first the velocity of the payload as it exited the rocket (at the moment it leaves contact with the sprung bed) was found:

$$F = ma \tag{1}$$

FBD:

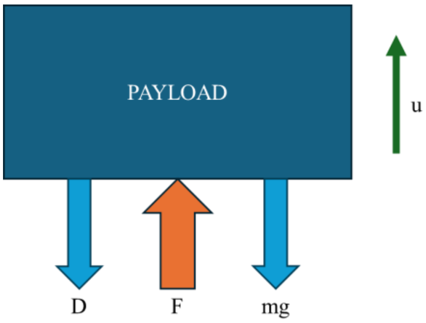


Figure 13: FBD of forces on the payload during ejection.

$$\therefore F = -D - mg \tag{2}$$

Eq. 1 and Eq. 2 were combined:

$$-(D + mg) = ma \tag{3}$$

Eq. 3 rearranged:

$$a = \frac{-D}{m} - g \tag{4}$$

The equation for drag on a cuboid body is as follows:

$$D = 0.5\,\rho u^2 C_D A \tag{5}$$

Therefore, combining Eq. 4 and Eq. 5 gave an equation for the initial acceleration of the payload:

$$a = \left(\frac{-0.5\rho u^2 C_D A}{m} - g\right) \tag{6}$$

To find the initial velocity of the payload Eq. 7 was required:

$$v^2 = u^2 + 2as \tag{7}$$

Eq. 6 and Eq. 7 were combined:

$$v^2 = u^2 + 2s\left(\frac{-0.5\rho u^2 C_D A}{m} - g\right) = u^2 - \frac{s\rho u^2 C_D A}{m} - 2sg \tag{8}$$

Rearranging Eq. 8:

$$\boldsymbol{u = \sqrt{\frac{2sg}{1 - \frac{s\rho C_D A}{m}}}} \tag{9}$$

The Energy required to reach the final ejection velocity was found by:

$$E_s = E_k + E_p \tag{10}$$

From the equation for total energy (Eq. 10) it was be determined that (where x was the distance moved upwards by the bed whilst it was in contact with the payload):

$$\frac{1}{2}kx^2 = \frac{1}{2}mu^2 + mgx \tag{11}$$

The equation for force of a spring is as follows:

$$F = kx \tag{12}$$

Eq. 11 was combined with Eq. 12 to produce Eq. 13:

$$\frac{1}{2}Fx = \frac{1}{2}mu^2 + mgx \tag{13}$$

Rearranged, Eq. 13 gave an equation for the force required of the springs with respect to mass, velocity of payload at ejection (when it ceased contact with the bed), gravitational acceleration, and the extension of the springs (equivalent to the distance the bed moved whilst it was in contact with the payload):

$$\boldsymbol{F = m\left(\frac{u^2}{x} + 2g\right)} \tag{14}$$

Therefore (where all values are as defined in the Table of Symbols):

$$u = \sqrt{\frac{2*2.5*9.81}{1-\frac{2.5*0.909*2.1*0.020}{1.04}}} = 7.35 \text{ m/s}$$

$$F = 1.04 * \left(\frac{7.35^2}{x} + 2 * 9.81\right)$$

Where x was determined by the chosen spring(s). The springs were chosen by trialling numerous combinations of available springs' spring constants and extensions, and the extension of the springs sourced was 61 mm.

Therefore:

$$F = 941.17\ N$$

A safety factor of 1.5 was applied to ensure the payload travelled at least 2.5 m away from the rocket, meaning the final required force from the springs underneath the bed was:

$$\boldsymbol{F = 1411.76\ N}$$

Since the final design required four springs in line underneath the bed, each spring was required to provide at least 352.94 N of force.

3.5.5 Trajectory

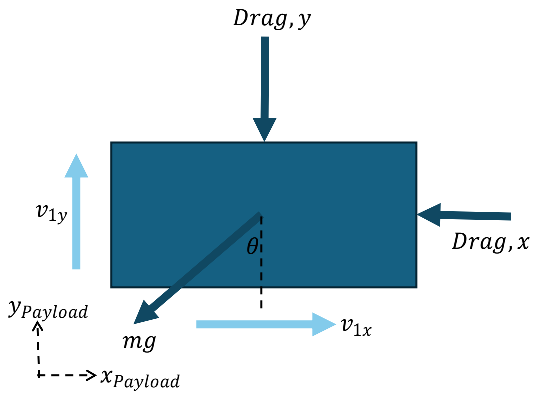


Figure 14: FBD of Payload Bay at beginning of payload ejection.

Velocity in the $y_{Payload}$ direction:

$$F = ma \tag{15}$$

From Eq. 15 and the FBD in Figure 14:

$$ma_y = -D_y - mg * \cos\theta \tag{16}$$

Combining Eq. 7 and Eq. 16:

$$m\left(\frac{v_{1y}^2 - u_{1y}^2}{2s_y}\right) = -D_y - mg * \cos\theta \tag{17}$$

Rearranging Eq.17:

$$v_{1y}^2 = \frac{m(u_{1y}^2 - 2s_y g * \cos\theta)}{m + s_y C_D \rho A} \tag{18}$$

$$v_{1y} = \sqrt{\frac{m(u_{1y}^2 - 2s_y g * \cos\theta)}{m + s_y C_D \rho A}} \tag{19}$$

The same calculations were done as above to result in the following equation for velocity in the $x_{Payload}$ direction:

$$v_{1x} = \sqrt{\frac{m(u_{1x}^2 - 2s_x g * \sin\theta)}{m + s_x C_D \rho A}} \tag{20}$$

The equations for v_{1y} and v_{1x} represent the trajectory of the payload from immediately after it left the bed. Figure 15 (below) shows that with an initial y direction ejection velocity of 7.35 m/s (as found in Eq. 9), the payload will be ejected a maximum vertical distance of 2.75 m from the rocket. This is an acceptable distance.

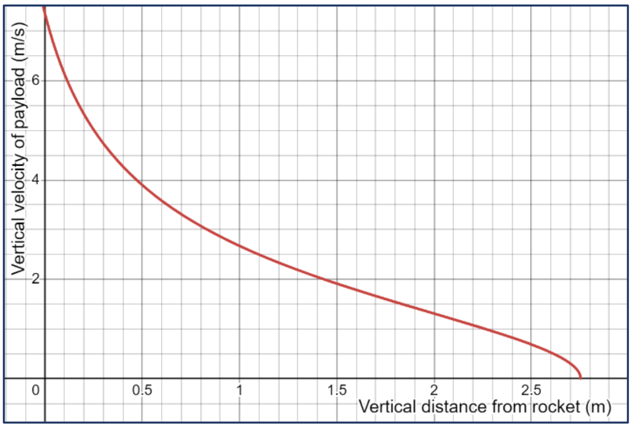


Figure 15: Graph representing the vertical motion of the payload after ejection with initial. vertical velocity of 7.35 m/s (determined by eq. 9).

4 Sourcing

Table 4 details which supplier parts were sourced for the most important COTS components in the Payload Bay. These were defined as parts that were required to meet certain tolerance or performance specifications determined by the calculations in Section 3. The avionics team were consulted to ensure the solenoids were of the correct ratings (voltage, current, etc) to be compatible with the rest of the rocket. This consultation also resulted in the decision to source bi-stable solenoids only as these do not require power to hold their standby position as power is only required during movement.

In general, when sourcing components, three main requirements were assessed in the following order: calculations (Section 3), dimensions and mass, and cost. The ability of the part to meet the requirement specified by the calculated results in Section 3 was given top priority as this was integral to the performance of the system. The size of the part was considered next as a very high priority requirement. Many possible COTS parts where rejected due to their overall dimensions since, as mentioned before, space within the Payload Bay was severely limited. Each part had to fit comfortably within its designated envelope with clearance on all appropriate sides. For some components this led to a greatly increased cost (namely the latch solenoid) as the part needed to be both forceful and compact. A list of supplier parts that met these first two requirements was created and cost was used as the deciding factor to determine the final part that would be used in the rocket.

Table 4: Sourcing details of main Payload Bay COTS components

System	Part	Requirement	Sourced Part Name/Info	Supplier	Cost (each)	Reference
Door System	Sprung Hinges	0.7334 Nm moment each (Section 3.5.1).	Pinet Aluminium Spring Hinge, Screw Fixing, 67mm x 55mm x 4.5mm RS Stock No.: 917-4589 Mfr. Part No.: 72-1-4260	RS Components Brand: Pinet	£17.60	(uk.rs-online.com, n.d.)
Door System	Standard Hinges	Withstand M5 and M6 moments detailed in Section 3.5.1.	RS PRO Stainless Steel Butt Hinge, Screw Fixing, 40mm x 40mm x 2mm RS Stock No.: 726-4129	RS Components Brand: RS PRO	£3.97	(uk.rs-online.com, n.d.)
Door System	Door Solenoid	27.26 N pulling forces (Section 3.5.2).	ERB 50/N TYPE Ordering code: ERB50/N --V ED20% - Spring	NAFSA	£80.19	(Nafsa, n.d.)
Latch System	Latch Solenoid	43.31 N of force each (Section 3.5.3).	Latching Frame Solenoid, 24V DC, 8mm - 94135 - BI 34 Part Number: 94135	Solenoid Ninja	£146	(Solenoid Ninja, n.d.)
Bed System	Bed Springs	352.9 N of force each (Section 3.5.4).	Compression Spring 13440 Music Wire	Sodemann Industrial Springs	£10.84	(Sodemann Industrial Springs, n.d.)

5 Validation

The abilities of the bespoke components to resist bending caused concern during the design process. Therefore, FEA was carried out to validate the designs. Both Autodesk Inventor Nastran and Ansys were used to create FEA models due to the different sizes of the components (Nastran could only handle smaller components) and the availability of the programmes (Ansys could not be accessed throughout the entire time frame of the project). Convergence studies are detailed in Appendix 6, these were used to determine the maximum mesh size appropriate for each part to decrease programme run time while maintaining accuracy.

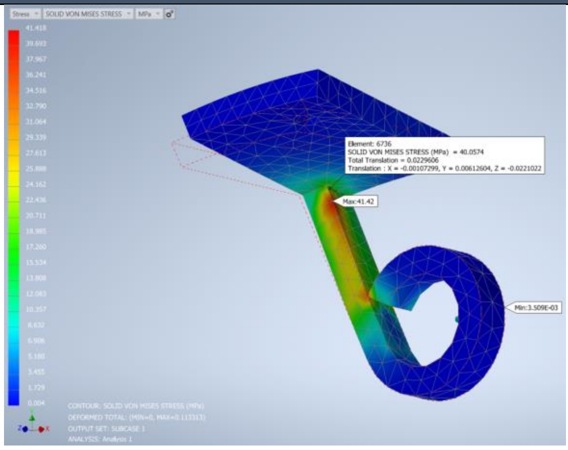
Note: The yield stress of aluminium 6061 is 241 MPa (Engineeringtoolbox.com, 2014).

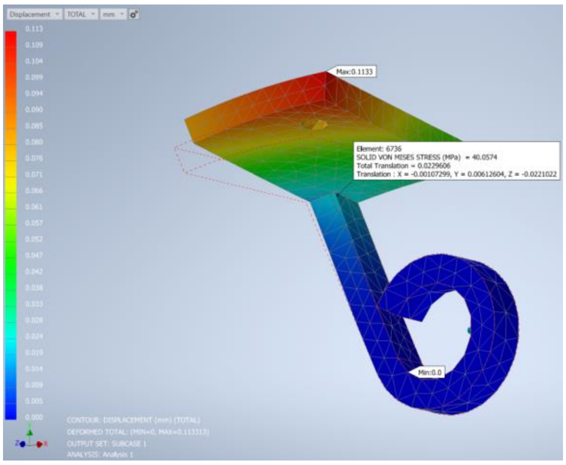
5.1 Door System Components

All of the door hinges were COTS components, so the strength of these parts was validated with calculations (detailed in Section 3.5) and information provided by the manufacturer. However, the hooks were essential bespoke components with forces applied so had to be analysed closely.

In the model for the door hook, a load of 16.83 N was applied in the positive y direction (derived from the moment applied by the hinges on the doors and the distance between the door hinge and the hook), and the looped part of the component was constrained as it would be by the solenoid when in stand by position. Table 5 (below) validates the design of the hinge hook as it did not yield or deform to an unacceptable level.

Table 5: Door Components FEA

<table>
<tr><th>Part</th><th>FEA</th><th>Max stress</th><th>Max Deformation</th><th>Mesh size</th></tr>
<tr><td>Door Hook</td><td>




</td><td>41.42 MPa

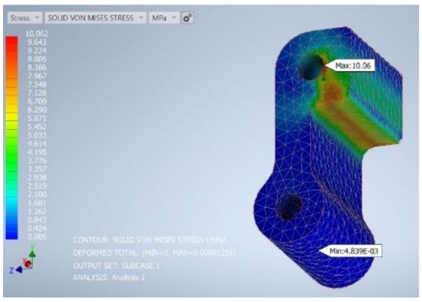
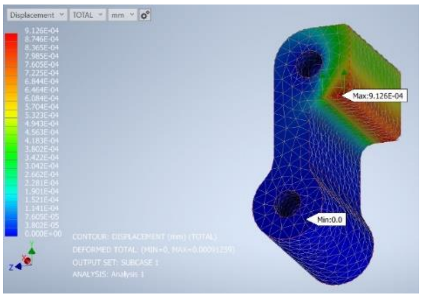
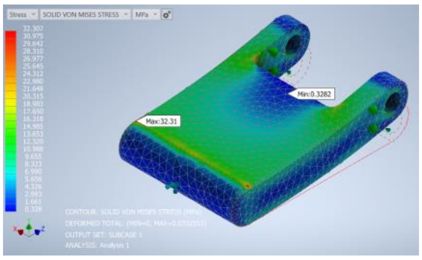
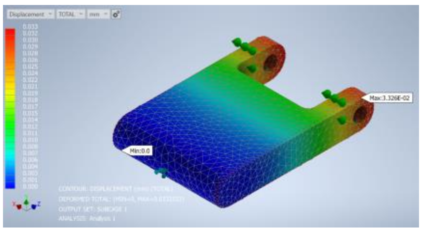
Below aluminium 6061 yield stress.</td><td>0.1133 mm

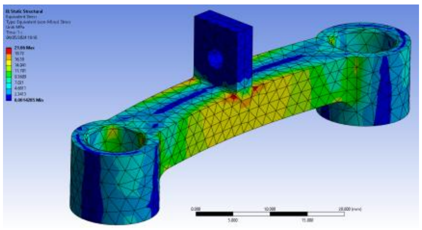
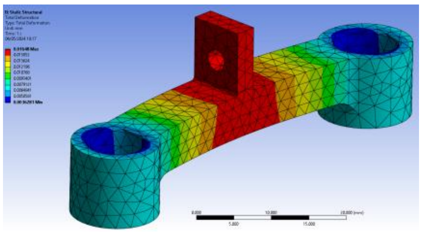
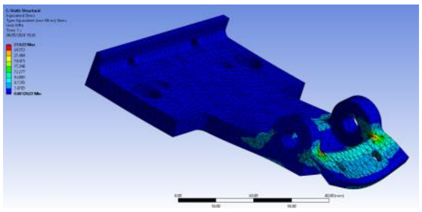
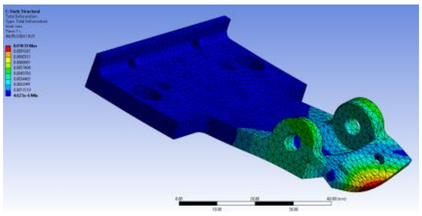
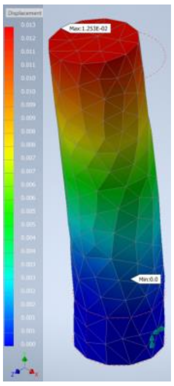
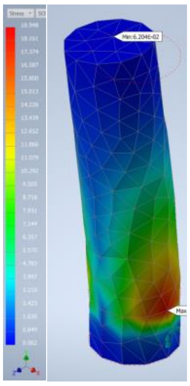
This is an acceptable level deformation for the part relative to its size.</td><td>2 mm</td></tr>
</table>

5.2 Latch System Components

In the models for the latch parts, forces were applied as derived in the calculations section of this report. Each part was simulated and constrained separately to improve the accuracy of the results by reducing the number of assumptions made. Table 6 validates the designs of all bespoke latch parts as they all experienced no more than an acceptable level of stress and deformation.

Table 6: Latch Components FEA

Part	FEA	Max stress	Max Deformation	Mesh size
Latch	Von Mises Stress:  Deformation: 	10.06 MPa Below aluminium 6061 yield stress.	0.00091 mm This is an acceptable level deformation for the part relative to its size.	2 mm
Latch Arm	Von Mises Stress:  Deformation: 	20.63 MPa Below aluminium 6061 yield stress. (The label on the top image to the left shows a singularity stress point, not the true maximum stress.)	0.033 mm This is an acceptable level deformation for the part relative to its size. (Deformation is exaggerated in the images to the left)	2 mm

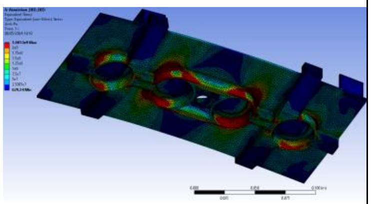
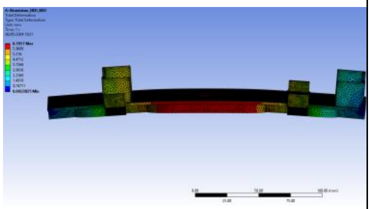
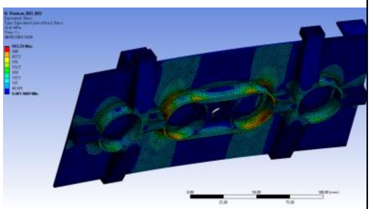
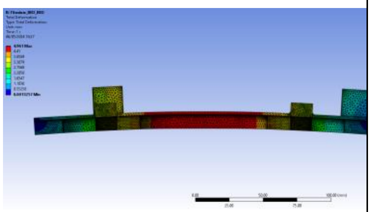
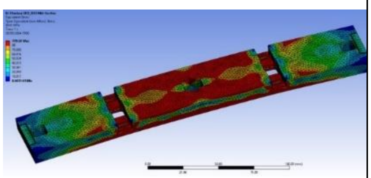
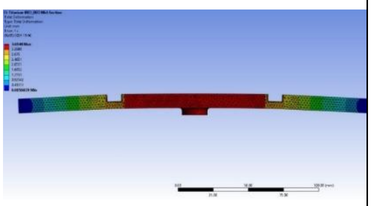
Latch Slider	Von Mises Stress:  Deformation: 	21.06 MPa Below aluminium 6061 yield stress.	0.016 mm This is an acceptable level deformation for the part relative to its size. (Deformation is exaggerated in the images to the left)	2 mm
Latch Base	Von Mises Stress:  Deformation: 	27.62 MPa Below aluminium 6061 yield stress.	0.010 mm This is an acceptable level deformation for the part relative to its size. (Deformation is exaggerated in the images to the left)	2 mm
Latch Slider Pin	Von Mises stress:  Deformation: 	27.62 MPa Below aluminium 6061 yield stress.	0.013 mm This is an acceptable level deformation for the part relative to its size. (Deformation is exaggerated in the images to the left)	2 mm

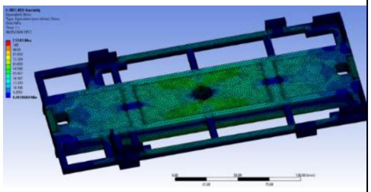
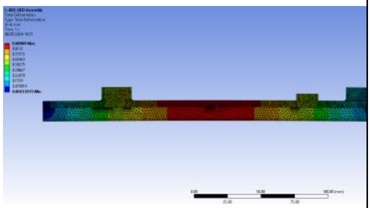
5.3 Bed System Components

The FEA simulations in Table 7 were create using the values derived in Section 3.5 of this report. The bed was initially designed as a solid aluminium part, however as demonstrated in the FEA model in the first row of Table 7 it was found that this would not be of sufficient strength to prevent the bed from yielding under the force of the springs. Therefore, other designs were tested (as detailed in Table 7) to find a solution where the bed did not buckle or deform more than an acceptable amount. The selected design included two parts which were welded together: An aluminium frame the correct dimensions to hold and constrain the payload, and a titanium alloy centre beam to strengthen the part and withstand the force of the springs when clamped by the latches. Welding Aluminium and titanium is not usually desirable but was possible for this assembly as only spot welding was needed (Hernandez, 2020). The aluminium frame was 2 mm thick throughout most of its geometry and was minimised in volume by cutting sections and holes throughout in order to decrease its mass. The titanium alloy beam that strengthened the centre of the bed was manufactured from a rectangular section billet with a thickness of 10 mm. Grooves were cut into it in places that allowed a thinner cross-section to reduce mass while maintain strength. As shown in the final row of Table 7 (Bed final assembly: Titanium alloy mid-section and reduced volume aluminium frame), this configuration of an aluminium bed frame welded to a titanium alloy mid-section adequately supported the force of the springs with acceptable stress on the parts and an acceptable level of deformation relative to the part size.

Note: The yield stress of titanium alloy is 730 MPa (Engineering ToolBox, 2003).

Table 7: Bed Components FEA

Part	**FEA**	**Max stress**	**Max Deformation**	**Mesh size**
One-piece Aluminium bed	Von Mises Stress:  Deformation: 	>1000 MPa This is not an acceptable amount of stress as it far surpasses the yield stress of aluminium.	6.71 mm This is an unacceptable level of deformation relative to the part's thickness (minimum of 2mm).	2 mm (1 mm mesh on small surfaces)
One piece titanium alloy bed	Von Mises Stress  Deformation: 	993 MPa This is an unacceptable amount of stress as the yield stress. However, it is over a smaller area of the bed.	4.96 mm This is an unacceptable level of deformation relative to the part's thickness (minimum of 2mm).	2 mm (1 mm mesh on small surfaces)
Bed titanium alloy mid-section	Von Mises Stress:  Deformation: 	710 MPa This is below the yield stress of titanium, but not ideal as it is very close to the yield stress.	3.7 mm This is an undesirable amount of deformation.	2 mm

Bed final assembly: Titanium alloy mid-section and reduced volume aluminium frame	Von Mises Stress:  Deformation: 	233 MPa This is an acceptable level of stress as it is below the yield stresses of both Aluminium and titanium.	0.69 mm This is an acceptable level of deformation relative to the average thickness of the bed.	2 mm

6 Ratchet System

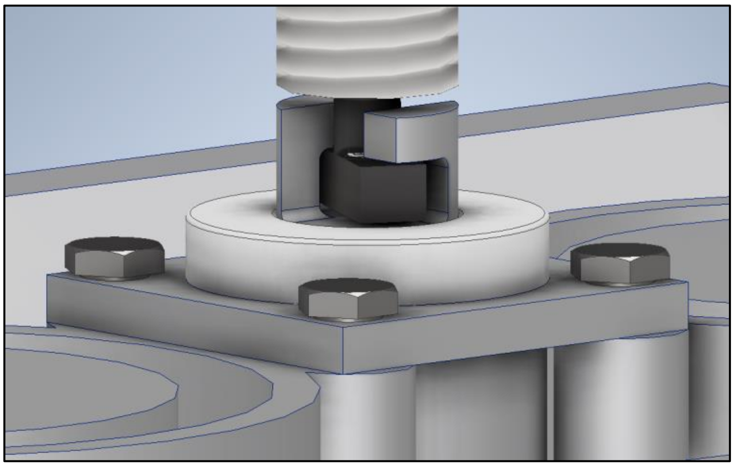


Figure 16: Close up view of ratchet system base hook and ratchet attachment. View of the middle of the base, below the bed.

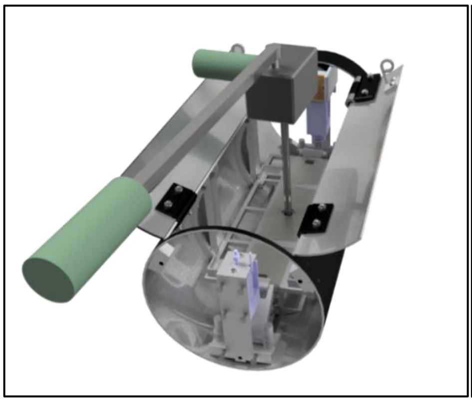


Figure 17: Wide view of Payload Bay with ratchet system engaged.

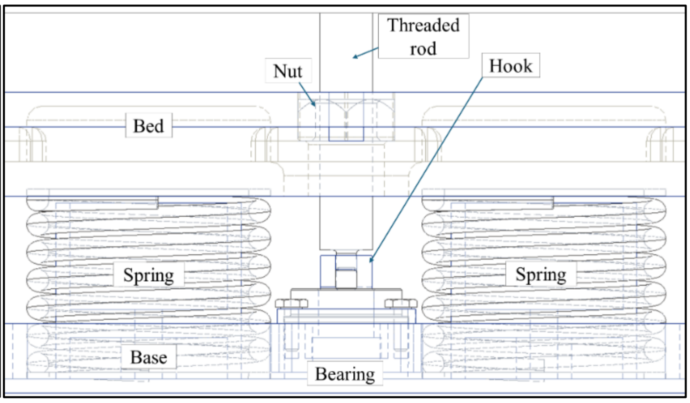


Figure 18: Labelled wire diagram of ratchet system passing through bed and into base.

The compression springs under the bed provided a total force of 1443 N to eject the payload out of the rocket at apogee. These springs were sourced as they provided only slightly more force than calculated as necessary in Section 3.5 and the were sufficiently compact. This meant that compressing the springs to set the bed in its launch (lowest) position required 1443 N of force acting down on it. This was an unrealistic requirement for one or two people to provide manually, especially since the bed had to be compressed whilst inside the rocket (unlike other systems, including recovery, that could be set to stand-by position first and then placed inside the rocket). Therefore, an external bespoke ratchet system was used to lower the bed into the Payload Bay, simultaneously compressing the springs. A latching part was connected to a bearing embedded in the base, and a nut was embedded in the bed. The ratchet tool was inserted through the nut in the bed and attached to the latch/hook on the base. Then when the tool was turned, using a long handle to reduce the force required, the bed nut interacted with the tool's threaded rod forcing it downwards towards the base.

7 Sensors

Sensors were needed in the Payload Bay to ensure all systems happened in the correct sequence. They also ensured if one system failed, the following systems actions were cancelled. This prevented a scenario such as the bed ejecting the payload before the doors were open which would cause damage to both the rocket and the payload. There was a contact sensor between the two doors to communicate to the central avionics system when the doors had opened. There was also a contact sensor on the bed to relay to the central avionics system when the bed had ejected the payload (this also gave information as to whether the bed latches had released).

8 Redundancy and Risks

The Payload Bay had been designed with a high level of redundancy. This was to prevent the payload and the rocket from being damaged at any point in the ejection as this would have incurred significant costs. It was decided by the rocket team lead that in the case any part should become non-functional during launch or ejection, ejection of the payload should be abandoned in favour or retaining the payload inside the rocket throughout its flight. As the rocket itself has a parachute, the drone would be safe to return back to the ground and could be reused for a second attempt.

Redundancy measures:

- All parts and systems were designed with a safety factor of at least 1.5 to ensure any forces inflicted on them could be withstood with high confidence and tolerance.
- If one or both of the rocket doors failed to open, the bed latches would remain in their closed position so the bed would not be released or eject the payload.
- When only one door was open there would not be space for the payload to exit the rocket so it would remain inside.
- If one latch did not release, the bed was strong enough to force it open as long as the other latch had opened successfully. This would cause damage to one part of the failed latch as the arm would bend, however since it is only a single part it could be replaced at a lower cost than relaunching the rocket for a second attempt.
- If both latches did not release, the payload would still fall from the rocket as it spins, since the doors would already be open. The velocity of the payload would not be as high as desired (which the springs would usually provide) so this would not be an ideal situation. However, once the drone had fallen an appropriate distance from the rocket it could still activate in the air. Although the payload's height at activation may have to be lower than anticipated, it would still remain functional and could return to the ground to be relaunched.

9 Sustainability

A rocket is inherently non-sustainable as the hybrid engine the team designed uses environmentally damaging fuels and had to be refuelled every launch. For this reason, the body of the rocket was designed with sustainability/reusability in mind, but this has not been considered a restrictive factor to the design. The majority of the bespoke parts in the Payload Bay were manufacture from aluminium. Aluminium as a material is 'infinitely recyclable' and more sustainable than other materials as it takes less energy to manufacture and process (The Aluminum Association, 2021). Most of the parts in the Payload Bay were bespoke components which is usually less ecofriendly than using COTS components in small quantities. This is because COTS components are often manufactured in large quantities which minimises the energy used by the tools and manufacturing equipment. However, since so many of the payload parts were of specific and highly constrained geometry, it was not plausible to use COTS Components only. In another revision of the rocket, this could be improved by using larger more standard geometries for the rocket body, and simplified systems (such as explosive or compressed air systems).

10 Cost estimation

Thorough cost analysis for every part in the Payload Bay can be found in Appendix 4. Bespoke components are detailed in Appendix 4.1 and COTS components are detailed in Appendix 4.2.

The costs of all COTS components totalled to £484.63. This price was assuming some parts would be bought in bulk (for example nuts and bolts) which would be the case in a business setting and may also be applicable for the competition rocket as other sections utilise many of the same sized fasteners. The majority of this cost came from the solenoids as the two bed latch solenoids cost £292 each and the hinge solenoid costed £80.19. The bed springs contributed the next highest cost to the Payload Bay with four costing £43.40. The rest of the total cost was from other COTS components (e.g., fasteners).

The cost of all bespoke components materials was £87.01. This was not including the manufacturing costs after the materials had been procured as this was done in house using university machinery. This cost was calculated using a minimal number of metal sheets by cutting many parts from the same sheet. The price of manufacturing could be calculated by combining the depreciation cost of the machinery, electricity, and labour costs.

The total price of combined COTS and bespoke parts for the Payload Bay was £571.63. This figure did not include the cost of manufacturing or transporting parts or materials. When producing batches of the rocket in the order of dozens or hundreds, the price would decrease as parts could be bought in bulk for a lower cost and machining could be completed on mass.

11 Future development/improvements

Improvements to the design could be conceptualised and developed with additional time and resources. The most prominent issues that arose during the design process of the Payload Bay were related to space constraints and the forces put on the system. The size constraints were inflicted due to aero dynamic analysis of the rocket and apogee - in relation to the engine thrust - which concluded the upper bound of the external diameter of the rocket would be 161 mm. Since the payload itself is a box the size of two CubeSats (totalling 100 mm x 100 mm x 200 mm), the with payload inside the body of the rocket there was minimal space left around it to fit the various launch mechanisms. In future developments, the rocket may be required to carry a larger payload in volume and/or mass. For either of these cases the rocket body size would need to be increased (and therefore the engine would need to be increased in power) to either accommodate the larger dimensions of the payload, or to allow space for more powerful mechanisms to fit around the payload.

In order to eject the payload a sufficient distance from the rocket so that it wouldn't interfere with the rocket recovery system, the forces provided by the ejection mechanism had to be very high. This made sourcing the COTS components difficult which, since the options for suitable components was limited, increased the cost of the system. This applied to the springs under the bed used to eject the payload, and the solenoids holding the bed latches down as they had to overcome the friction caused by the springs within the latch system to release the bed. If the rocket were to be scaled up in the future, alternative methods for bed ejection would need to be considered. This is because springs would likely not be able to provide sufficient force to launch a much larger/heavier payload an appropriate distance whilst maintaining a small enough spring size to fit underneath the bed. The spring system could either be replaced by a pyrotechnic or pneumatic system, or the springs could remain, and another less powerful ejection system could be added in parallel.

The Payload Bay could also be improved by reducing its total mass, which would increase the efficiency of the rocket. To do this, both the materials used, and the thickness/dimensions of the parts could be optimised. Software packages such as Ansys Granta Edu Pack could be utilised using merit indices to compare material properties, such as density and yield strength, with required part thickness to find the optimal minimum mass model of each part. A cost component would also be considered with the goal to minimise mass while maintaining a limit on maximum cost.

12 Conclusion

The Payload Bay was designed to eject a payload at a speed of 7.35 m/s when the rocket is at an apogee of 3000 m. This was done using sprung hinges and a solenoid to operate the Payload Bay doors; latch systems driven by solenoids to restrain the bed; and stiff compression springs under the bed to eject the payload. All of the parts have been sized to withstand the loads inflicted upon them with respect to the material from which they were made. Each bespoke component was made from aluminium due to its high strength to weight ratio, except the bed which was made from both aluminium and titanium alloy to provide additional stiffness. The total cost of the payload bay came to £571.63 not including the manufacturing of bespoke components or transport costs of materials or COTS components. Sustainability is difficult to achieve in a rocket, however this was attempted by utilising recyclable materials (such as aluminium) and avoiding explosive devices which harm the environment (such as black powder to eject the payload).

It was determined that the payload should be treated as a non-disposable and highly valuable commodity since it was the purpose for the rocket's launch. Therefore, redundancy measures were implemented to ensure its safety. These included a fail-safe measure which specified the payload should not be ejected if ejection was likely to fail or damage the payload.

It has been determined that space/size constraints are the most challenging factor when designing a Payload Bay and thus compactness of the systems within the Bay is of utmost importance. This was achieved by using multiple springs (reducing the necessary extension length of each spring) in parallel underneath the bed to eject the payload, and elongating the length of the Payload Bay so the latch and door mechanisms could fit either end of the bed, instead of being positioned alongside it.

This report has confirmed the possibility of designing a fully electro-mechanical Payload Bay to eject the payload to meet both the competition and business case specifications. More iterations of the design should be completed in order to optimise its performance before manufacture occurs. If the use case were to change the Payload Bay could be scaled to fit new requirements with minor changes and compromises to be made to the bed ejection system.

13 Acknowledgements

LW thanks James Scobie and Michael Carley for their guidance for the duration of this project. Also, thanks to Cedric Bridger for his management of the project as a whole and the rest of Bath Rocket Team GDBP group for their support and collaboration.

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GenAI Acknowledgement Statement

GenAI was not used in the preparation of this assignment.

Appendices

Appendix 1

1.1 EuRoC Payload requirements

Number	Requirement	Detailed Notes	Related Regulation
3.1	Payload definition	The payload is defined as an independent component that is replaced by a ballast of the same mass, with no change in the vehicle's functionality and trajectory in reaching the target apogee, or its successful recovery.	EuRoC_RR_V04 7.2
3.2		Pay load shall be recoverable.	EuRoC_RR_V04 7.3
3.3		Payload shall not be part of the vehicle functionality.	EuRoC_RR_V04 7.7
3.5		Payload shall not contain significant quantities of lead or any other hazardous materials or any radioactive materials.	EuRoC_RR_V04 7.9
3.6	Payload form factor	Payload basic form factor: • CanSat: Cylinder with 115mm height and 66mm diameter. • CubeSat: Cubic shape with one cube sat Unit (1U) defined as 100mm x 100mm x 100mm cube. • PocketSta: Cubic shape 50mm x 50mm x 50mm. • Volume of the payload may be a multiple of the basic form factor.	
3.7.1	Payload mass	Launch vehicle carries no less than 1000g of payload.	EuRoC_RR_V04 7.5
3.7.2		Mass requirements: • A single CanSat: 300g to 350g • A single CubeSat: 1000g to 1330g • A single PocketSat: 200g to 250g	EuRoC_RR_V04 7.5

3.8.1	Payload Recovery	Deployable pay load shall have an independent recovery system that reduces the payloads descent velocity to less than 9m/s before it descends through an altitude of 450m AGL.	EuRoC_RR_V04 7.1
3.9	Payload Energetics	Energetics: • Shall be "safed" until the rocket is in the launch position, at which point they may be "armed". • Energetic devise arming features shall be externally accessible/controllable.	EuRoC_RR_V04 7.2

Appendix 2: Selection – MCDA

2.1 Ranking table:

Rating score	Meaning
1	Needs re-thinking entirely
2	Poor
3	Sufficient
4	Good
5	Really Good

2.2 Ranking criteria:

Letter	Criteria	Definition	Weight
A	Ease of assembly	Is it dangerous? Can it be assembled under pressure? When does it have to be assembled (day before, right before launch etc…)	3
B	Simplicity	How many moving parts/systems does it have?	2
C	Weight	Is it a relatively heavy system?	4
D	Cost	How expensive is the system?	1
E	Relevance	How closely does it link to the Business Case?	4
F	Compactness	How much space does it take up in the Rocket?	4
G	Redundancy	How "fail safe" is the design?	5
H	Reusability	Can it be reused without additional components (eg Black powder restore etc)	3
I	Avionics Impact	Difficulty for Avionics design	1
J	Structural impact	Difficulty for Aerostructures design	5

2.3 Criteria weightings table:

	A	B	C	D	E	F	G	H	I	J	Row Totals	Weight
A	0	1	0	1	0.5	0	1	1	0.5	0	5	3
B	0	0	0	1	0	0	0	0	1	0	2	2
C	1	1	0	1	0	0.5	0	1	1	0.5	6	4
D	0	0	0	0	0	0	0	0	1	0	1	1
E	0.5	1	1	1	0	1	0	1	1	0	6.5	4
F	1	1	0.5	1	0	0	0	1	1	0.5	6	4
G	0	1	1	1	1	1	0	1	1	0.5	7.5	5
H	0	1	0	1	0	0	0	0	1	0	3	3
I	0.5	0	0	0	0	0	0	0	0	0	0.5	1
J	1	1	0.5	1	1	0.5	0.5	1	1	0	7.5	5

2.4 Scoring and ranking of concepts for Payload Bay doors system:

	1		2		3		4		5	
	Payload Rocket Doors		**Payload Rocket Doors**		**Payload Rocket Doors**		**Payload Rocket Doors**		**Payload Rocket Doors**	
Criteria	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Easy to assemble	5	15	1	3	4	12	5	15	5	15
Simplicity	3	6	4	8	2	4	1	2	2	4
Weight	4	16	5	20	3	12	1	4	3	12
Cost	4	4	4	4	2	2	2	2	4	4
Relevance	4	16	1	4	3	12	4	16	5	20
Compactness	5	20	4	16	3	12	2	8	4	16
Redundancy	5	25	2	10	4	20	2	10	2	10
Reusability	5	15	1	3	5	15	5	15	5	15
Avionics Impact	3	3	4	4	3	3	3	3	4	4
Structural impact	3	15	1	5	2	10	3	15	3	15
	Total	135	**Total**	77	**Total**	102	**Total**	90	**Total**	115
	Rank	1	**Rank**	5	**Rank**	3	**Rank**	4	**Rank**	2
	Percentage	26%	**Percentage**	15%	**Percentage**	20%	**Percentage**	**17%**	**Percentage**	**22%**

2.5 Scoring and ranking of concepts for Payload Bay ejection system:

	1		**2**		**3**		**4**	
	Payload Ejection Method		**Payload Ejection Method**		**Payload Ejection Method**		**Payload Ejection Method**	
Criteria	**Rating**	**Weighted Score**	**Rating**	**Weighted score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Easy to assemble	4	12	1	3	5	15	1	3
Simplicity	2	4	5	10	5	10	3	6
Weight	3	12	4	16	4	16	1	4
Cost	3	3	4	4	3	3	3	3
Relevance	4	16	1	4	4	16	1	4
Compactness	3	12	5	20	5	20	1	4
Redundancy	4	20	3	15	5	25	3	15
Reusability	5	15	1	3	5	15	2	6
Avionics Impact	5	5	4	4	3	3	3	3
Structural impact	1	5	1	5	4	20	4	20
	Total	104	**Total**	84	**Total**	143	**Total**	68
	Rank	2	**Rank**	3	**Rank**	1	**Rank**	**4**
	Percentage	26%	**Percentage**	21%	**Percentage**	36%	**Percentage**	17%

Appendix 3: Selection – MCDA 2

Same weightings and rankings as for the previous phase.

3.1 Scoring and ranking of secondary concepts for payloads doors system, payload ejection system, payload be alignment system, and latching systems:

	1		**2**		**4**		**5**		**6**		**7**		**8**		**9**		**10**	
	Hinge Design		**Hinge Design**		**Bed Springs (corners)**		**Bed Springs (in line)**		**Bed Align-ment**		**Bed Align-ment**		**Latch System**		**Latch System**		**Latch System**	
Criteria	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Easy to assemble	5	15	5	15	3	9	4	12	4	12	4	12	4	12	3	9	2	6
Simplicity	4	8	5	10	3	6	4	8	3	6	5	10	4	8	3	6	2	4
Weight	5	20	5	20	4	16	4	16	3	12	5	20	5	20	4	16	3	12
Cost	5	5	5	5	4	4	4	4	3	3	5	5	4	4	5	5	3	3

Relevance	5	20	5	20	5	20	5	20	5	20	5	20	4	16	5	20	3	12
Compact- ness	4	16	5	20	3	12	4	16	1	4	3	12	3	12	3	12	2	8
Redund- ancy	4	20	2	10	4	20	4	20	2	10	5	25	4	20	5	25	4	20
Reusabil- ity	5	15	5	15	5	15	5	15	5	15	5	15	5	15	5	15	3	9
Avionics Impact	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4	4
Structural impact	3	15	3	15	3	15	2	10	3	15	4	20	3	15	3	15	3	15
	Total	139	**Total**	135	**Total**	122	**Total**	126	**Total**	102	**Total**	144	**Total**	126	**Total**	127	**Total**	93

Appendix 4: Cost breakdown of Payload Bay and payload box

4.1 Bespoke components

BESPOKE COMPONENTS						Material only				
CAD Directory File Name	**Description**	**Sub Assembly**	**Mass (kg)**	**Unit Price (GBP)**	**Quantity Required**	**Total Cost**	**Material Manufacturer/Source Name**	**Source URL**	**Notes**	**Entry By**
PYL_001_SKIN_BODY	ALUMINIUM TUBE (BENT/CURVED SHEET METAL)	001_SKIN	0.790	5.42	1	£5.42	2mm Aluminium Sheet - 500mm x 300mm	https://www.1stchoicemetals.co.uk/product/2mm-3/		
PYL_001_SKIN_DOOR_1	CURVED ALUMINIUM	001_SKIN	0.107	1.085	1	£1.09	2mm Aluminium Sheet - half of a 300mm x 200mm sheet	https://www.1stchoicemetals.co.uk/product/2mm-3/	Both doors will be cut from the same sheet	
PYL_001_SKIN_DOOR_2	CURVED ALUMINIUM	001_SKIN	0.107	1.085	1	£1.09	2mm Aluminium Sheet - half of a 300mm x 200mm sheet		Both doors will be cut from the same sheet	
PYL_002_BED_BASE	CNC ALUMINIUM BLOCK	002_BED	0.173	20.49	1	£20.49	19mm (3/4″) Aluminium Plate 6082T6	https://www.1stchoicemetals.co.uk/product/34-19-05mm-5/		
PYL_002_BED_BED_INNER	CNC TITANIUM BLOCK	002_BED	0.279	19.3	1	£19.30	Titanium Grade 1 ASTM B265 plate	https://www.titaniummetals.co.uk/		

PYL_002_BED_BED_OUTER	CNC ALUMINIUM BLOCK	002_BED	0.200	9.02	1	£9.02	10mm Aluminium Plate 6082T6	https://www.1stchoicemetals.co.uk/product/10mm-3/	The guides for the payload to sit in should be cut and bent seperately the slotted into place on the bed into CNCed slots	
PYL_002_BED_RATCHED_FLANGED_BEARING_CAP	SMALL MACHINED ALUMINIUM PLATE	002_BED	0.001		1	£0.00			This will be mad from the same sheet as PYL_002_BED_BED	
PYL_002_BED_SPRING_GUIDE	ALUMINIUM TUBE WITH PLATE ON ONE END	002_BED	0.009	0.6	4	£2.40	28.6mm x 3.2mm Aluminium Round Tube (1.1/8″ x 10swg)	https://www.1stchoicemetals.co.uk/product/1-18-x-10s wg-28-58mm-x-3-26mm/	The plate on the end will be mad from the same sheet as PYL_002_BED_BED. The OD will be machined slightly smaller.	
PYL_003_RAIL	ALUMINIUM BENT SHEET METAL	003_RAIL	0.015	0.3175	4	£1.27	2mm Aluminium Sheet	https://www.1stchoicemetals.co.uk/product/2mm-3/		
PYL_003_RAIL_FRAME	ALUMINIUM BENT/CURVED SHEET METAL	003_RAIL	0.068	5.55	2	£11.10	8mm Aluminium Plate Grade 6082T6	https://www.1stchoicemetals.co.uk/product/8mm-aluminium-plate/		
PYL_004_LATCH_ARM	ALUMINIUM SLIDING PART OF LEVER LATCH MECHANISM	004_LATCH	0.035	0.708	2	£1.42	19mm (3/4″) Aluminium Plate 6082T6	https://www.1stchoicemetals.co.uk/product/34-19-05mm-5/	Same sheet as PYL_004_LATCH_LATCH	
PYL_004_LATCH_BACK_PLATE_1	ALUMINIUM SHEET METAL BENT INTO BRACKET TO HOLD 1 LATCH	004_LATCH	0.030	0.82	1	£0.82	2mm Aluminium Sheet	https://www.1stchoicemetals.co.uk/product/2mm-3/		
PYL_004_LATCH_BACK_PLATE_2_FOR SOLENOID	ALUMINIUM SHEET METAL BENT INTO BRACKET TO HOLD 1 LATCH	004_LATCH	0.063	0.82	1	£0.82			Same sheet used as above (PYL_004_LATCH_BACK_PLATE_1)	

PYL_004_LATCH_BASE	ALUMINIUM BASE FOR LATCHING MECHANISM CONNECTING LATCH TO	004_LATCH	0.049	1.355	2	£2.71	5mm Aluminium Plate 6082T6	https://www.1stchoicemetals.co.uk/product/5mm/?doing_wp_cron=1714049985.1761250495910644531250	THIS PART WILL BE LASER CUT AND BENT	
PYL_004_LATCH_BASE_SPACER	ALUMINIUM FOLDED SHEET METAL TO ATTACH LATCH MECHANISM TO	004_LATCH	0.040	0.2675	2	£0.54	1mm Aluminium Sheet	https://www.1stchoicemetals.co.uk/product/1mm/	PYL_003_BED_BASE_SPACER will also come from this sheet	
PYL_004_LATCH_LATCH	ALUMINIUM LATCH TO HOLD BED DOWN	004_LATCH	0.022	0.708	2	£1.42	19mm (3/4″) Aluminium Plate 6082T6	https://www.1stchoicemetals.co.uk/product/34-19-05mm-5/		
PYL_004_LATCH_SHOULDERED_BOLT	MILD STEEL PIVOT POINT BETWEEN BOTTOM OF LATCH_LATCH TO LATCH_BASE, AND	004_LATCH	0.008		4	£0.00				
PYL_004_LATCH_SLIDER_BAR	ALUMINIUM BAR ATTACHED TO LATCH SOLENOID TO HOLD THE LATCH_ARM IN	004_LATCH	0.010	0.708	2	£1.42	19mm (3/4″) Aluminium Plate 6082T6	https://www.1stchoicemetals.co.uk/product/34-19-05mm-5/	Same sheet as PYL_004_LATCH_LATCH	
PYL_004_LATCH_SLIDER_PIN	ALUMINIUM PIN THAT SCREWS INTO LATCH_BASE FOR LATCH_SLIDER_BA	004_LATCH	0.004	0.6	4	£2.40	M5 x 40mm Plain Hexagon Bolts (DIN 931) - Marine Stainless	https://www.accu.co.uk/metric-hexagon-bolts/18042-SEB-M5-40-A4		
PYL_006_HINGE_HOOK_1	HOOK FOR HINGE_SOLENOID TO LATCH ONTO FOR DOOR_2	005_HINGE	0.002	0.825	1	£0.83	4mm Aluminium Sheet	https://www.1stchoicemetals.co.uk/product/4mm/?doing_wp_cron=1714056107.7018809318542480468750		
PYL_006_HINGE_HOOK_2	HOOK FOR HINGE_SOLENOID TO LATCH ONTO FOR DOOR_1	005_HINGE	0.002	0.825	1	£0.83	4mm Aluminium Sheet	https://www.1stchoicemetals.co.uk/product/4mm/?doing_wp_cron=1714056107.7018809318542480468750		

PYL_002_BED_RATCHET_BEARING PIN	ROTATING ALUMINIUM PART	002_ BED	0.002	2.12	1	£2.12	10mm Aluminium Round Bar	https://www.1stchoicemetals.co.uk/product/10mm-aluminium-round-bar/?doing_wp_cron=1714056300.363604 0687561035156250		
PYL_003_BED_BASE_SPACER	ALUMINIUM FOLDED SHEET METAL TO ATTACH BED_BASE TO TUBE	003_BED	0.003	0.2675	2	£0.54	1mm Aluminium Sheet	https://www.1stchoicemetals.co.uk/product/1mm/	PYL_004_LATCH_BASE_SPACER will also come from this sheet	

4.2 COTS components

COTS Components **CAD Directory File Name**	**Description**	**Sub Assembly**	**Mass (kg)**	**Unit Price (GBP)**	**Quantity Required**	**Total Cost**	**Manufacturer Part Name**	**Source URL**	**Notes**	**Entry By**
PYL_002_BED_RATCHED_FLANGED_BEARING	8mm bore, 16mm OD, sealed flanged bearing for ratchet system	002_BED	0.006	3.54	1	£3.54	F688-2RS	https://www.smbbearings.com/products/flanged-miniature-bearings.html		
PYL_002_BED_SPRING	Spring under bed to eject payload	002_BED	0.046	10.85	4	£43.40	13440	https://www.industrial-springs.com/13440		
Nut GB/T 6170-2000 M3	Nut for ...RAIL_M3_BOLT_35MM...	003_RAIL	0.000	0.14	8	£1.12	M3 Thin Hexagon Nuts (DIN 439) - Stainless Steel (A2)	https://www.accu.co.uk/thin-hexagon-nuts/73054-HFN-M3-A2		
Bolt GB/T 29.2 M3x8	Bolt connecting rail frams to skin	003_RAIL	0.001	0.17	16	£2.72	M3 x 8mm Full Thread Hexagon Bolts (DIN 933) - Stainless Steel (A2)	https://www.accu.co.uk/full-thread-hexagon-bolts/18800-SEBF-M3-8-A2		
PYL_003_RAIL_M3_BOLT_35MM_ (2mm shoulder)	BOLT CONNECTING RAIL TO FRAME	003_RAIL	0.002		8	£0.00				
Bolt GB/T 29.2 M3x8	Bolt connecting bottom of […] LATCH_BACK_PLATE_1/2 to […] LATCH_BASE	003_RAIL	0.001	0.17	4	£0.68	M3 x 8mm Full Thread Hexagon Bolts (DIN 933) - Stainless Steel (A2)	https://www.accu.co.uk/full-thread-hexagon-bolts/18800-SEBF-M3-8-A2		
Nut GB/T 6177.1-2000 M5	Flanged nut securing LATCH-SHOULDERED_BOLT	004_LATCH	0.002	0.64	4	£2.56	M5 Non-Serrated Flanged Nylon Locking Nuts (DIN 6926) - Stainless Steel (A2)	https://www.accu.co.uk/flanged-nylon-locking-nuts/409673-HNFFN-M5-A2		
PYL_004_LATCH_SOLENOID_PIN	Pin that attaches Latch solenoid to LATCH_SLIDER_BAR		0.001		2	£0.00				
PYL_005_BED_SOLENOID_IMPORTED_Huelle_BODY	SOLENOID THAT RELEASES BED LATCHING MECHANISM	005_BED	0.256	146	2	£292.00	Latching Frame Solenoid, 24V DC, 8mm - 94135 - BI 34	https://solenoid-ninja.com/latching-frame-solenoid-24v-dc-8mm-94135-bi-34/	ALL OF THESE PARTS ARE SOLD TOGETHER UNDER	

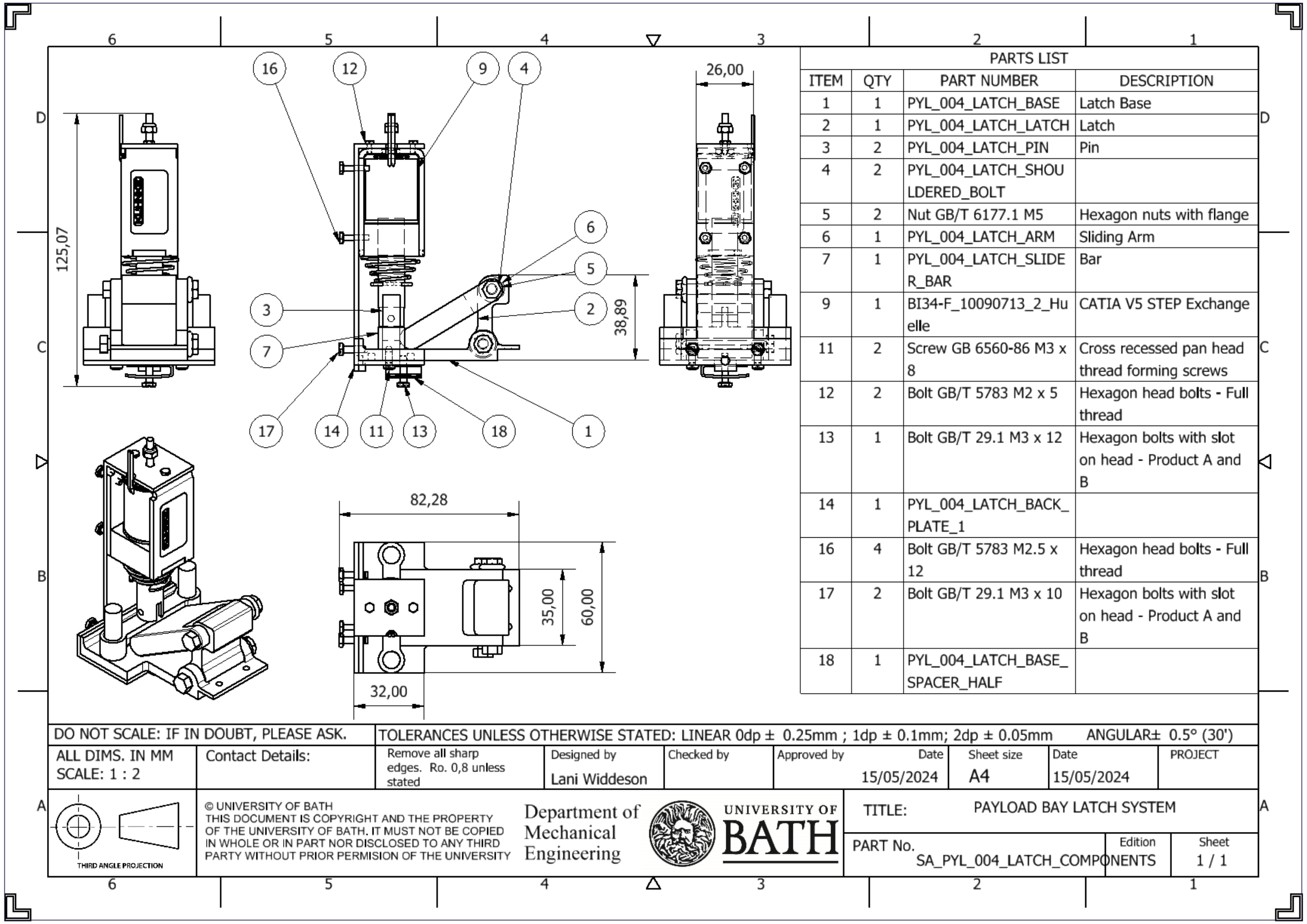
									ONE TOTAL PRICE	
PYL_005_BED_SOLENOID_IMPORTED_Huelle_PIN	SOLENOID PIN THAT RELEASES BED LATCHING SYSTEM	005_BED	0.041		2	£0.00				
Bolt GB/T 29.2 M3x8	Bolts to attach HINGE_HOOK to SKIN_DOOR	006_HINGE	0.001	0.17	4	£0.68	M3 x 8mm Full Thread Hexagon Bolts (DIN 933) - Stainless Steel (A2)	https://www.accu.co.uk/full-thread-hexagon-bolts/18800-SEBF-M3-8-A2		
Nut GB/T 6170-2000 M3	Nut to secure bolt connecting HINGE_HOOK to SKIN_DOOR	006_HINGE	0.000	0.14	4	£0.56	M3 Thin Hexagon Nuts (DIN 439) - Stainless Steel (A2)	https://www.accu.co.uk/thin-hexagon-nuts/73054-HFN-M3-A2		
PYL_006_HINGE_INNER_WING	Half of the hinge for the door	006_HINGE			2	£0.00		https://uk.rs-online.com/web/p/hinges/9174589?gb=s		
PYL_006_HINGE_OUTER_WING	Half of the hinge for the door	006_HINGE	0.067	17.595	2	£35.19	Spring hinges - aluminium profile 1.3 N.m	https://docs.rs-online.com/8806/0900766b814daee9.pdf	ALL OF THESE PARTS ARE SOLD TOGETHER UNDER ONE TOTAL PRICE AND WEIGHT	
PYL_006_HINGE_SPRING	Spring that goes insed 2 of the 4 door hinges	006_HINGE			2	£0.00				
Bolt GB/T 29.1-1988 M5x12	Bolt for sprung hinge attachment to skin	006_HINGE	0.003	0.26	8	£2.08	M5 x 12mm Full Thread Hexagon Bolts (DIN 933) - Stainless Steel (A2)	https://www.accu.co.uk/full-thread-hexagon-bolts/18841-SEBF-M5-12-A2		

Nut GB/T 6170-2000 M4	Nut for sprung hinge attachment to skin	006_HINGE	0.001	0.24	8	£1.92	M5 Hexagon Nuts (DIN 934) - Stainless Steel (A2)	https://www.accu.co.uk/hexagon-nuts/7891-HPN-M5-A2
PYL_006_HINGE_M5_WASHER	WASHER TO POSITION HINGE ON DOOR	006_HINGE	0.000	0.15	8	£1.20	M5 Rectangular Profile Spring Washers (DIN 127B) - Marine Stainless Steel (A4)	https://www.accu.co.uk/rectangular-profile-spring-washers/62561-HRSW-M5-A4
PYL_006_HINGE_SMALL_OUTER_WING	Half of the unsprung small hinge for the doors	006_HINGE	0.020	3.972 5	2	£7.95	RS PRO Stainless Steel Butt Hinge, Screw Fixing, 40mm x 40mm x 2mm	https://uk.rs-online.com/web/p/hinges/7264129
PYL_006_HINGE_SMALL_INNER_WING	Half of the unsprung small highe for the doors	006_HINGE	0.020	0	2	£0.00		
Bolt GB/T 5783-2000 M3.5x10	Bolt for small hinge attachment to skin	006_HINGE	0.001	0.12	8	£0.96	M3.5 x 10mm Full Thread Slotted Hexagon Bolts - Polyamide	https://www.accu.co.uk/slotted-hexagon-bolts/588277-SFEBF-M3-5-10-PA
Nut GB/T 6170-2000 M3.5	Nut for small hinge attachment to skin	006_HINGE	0.001	0.15	8	£1.20	M3.5 Hexagon Nuts (DIN 934) - Stainless Steel (A2)	https://www.accu.co.uk/hexagon-nuts/7889-HPN-M3-5-A2
NAFSA_ERB50_N (carrera=0mm)	Solenoid that retracts to release doors	006_HINGE	0.365	80.19	1	£80.19	ERB 50/N TYPE	https://nafsa-solenoids.com/producto/erb-serie/
PYL_006_HINGE_SOLENOID_PIN	Pin in solenoid that retracts to release doors	006_HINGE	0.071		1	£0.00		
PN-85/M-82105 Product grade B M 3.5 x 6.1	Bolt to connect LATCH_BACK_PLATE_2_FOR_SOLENOID to NAFSA_ERB50_N (carrera=0mm)	006_HINGE	0.001	0.06	2	£0.12	M3.5 x 6mm Full Thread Slotted Hexagon Bolts - Polyamide	https://www.accu.co.uk/slotted-hexagon-bolts/588275-SFEBF-M3-5-6-PA
Bolt GB/T 5783-2000 M2.5 x 12	Bolt to connect LATCH_BACK_PLATE_1/2 to PYL_005_BED_SOLENOID_IMPORTED_Huelle_BODY	004_LATCH	0.000	0.49	8	£3.92	M2.5 x 12mm Full Thread Hexagon Bolts (DIN 933) - Stainless Steel (A2)	https://www.accu.co.uk/full-thread-hexagon-bolts/18791-SEBF-M2-5-12-A2

Bolt GB/T 29.1 M3x10	Bolt connecting bottom of […] LATCH_BACK_PLATE_1/2 to […] LATCH_BASE	004_LATCH	0.001	0.66	4	£2.64	M3 x 10mm Full Thread Hexagon Bolts (DIN 933) - Stainless Steel (A2)	https://www.accu.co.uk/full-thread-hexagon-bolts/18801-SEBF-M3-10-A2

Appendix 5: Sub-Assembly Drawings

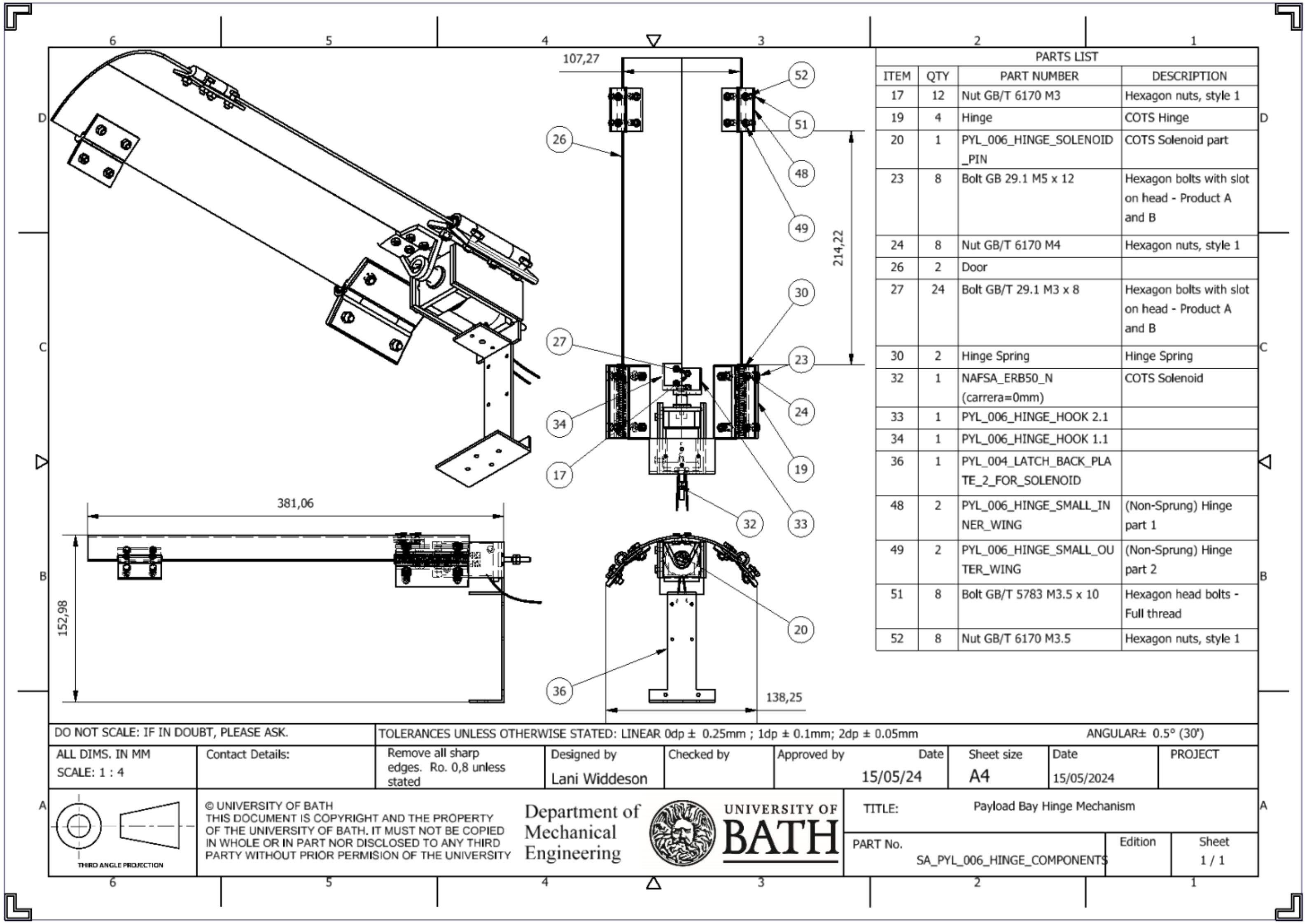
5.1 Latch assembly drawing



PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	PYL_004_LATCH_BASE	Latch Base
2	1	PYL_004_LATCH_LATCH	Latch
3	2	PYL_004_LATCH_PIN	Pin
4	2	PYL_004_LATCH_SHOULDERED_BOLT	
5	2	Nut GB/T 6177.1 M5	Hexagon nuts with flange
6	1	PYL_004_LATCH_ARM	Sliding Arm
7	1	PYL_004_LATCH_SLIDER_BAR	Bar
9	1	BI34-F_10090713_2_Huelle	CATIA V5 STEP Exchange
11	2	Screw GB 6560-86 M3 x 8	Cross recessed pan head thread forming screws
12	2	Bolt GB/T 5783 M2 x 5	Hexagon head bolts - Full thread
13	1	Bolt GB/T 29.1 M3 x 12	Hexagon bolts with slot on head - Product A and B
14	1	PYL_004_LATCH_BACK_PLATE_1	
16	4	Bolt GB/T 5783 M2.5 x 12	Hexagon head bolts - Full thread
17	2	Bolt GB/T 29.1 M3 x 10	Hexagon bolts with slot on head - Product A and B
18	1	PYL_004_LATCH_BASE_SPACER_HALF	

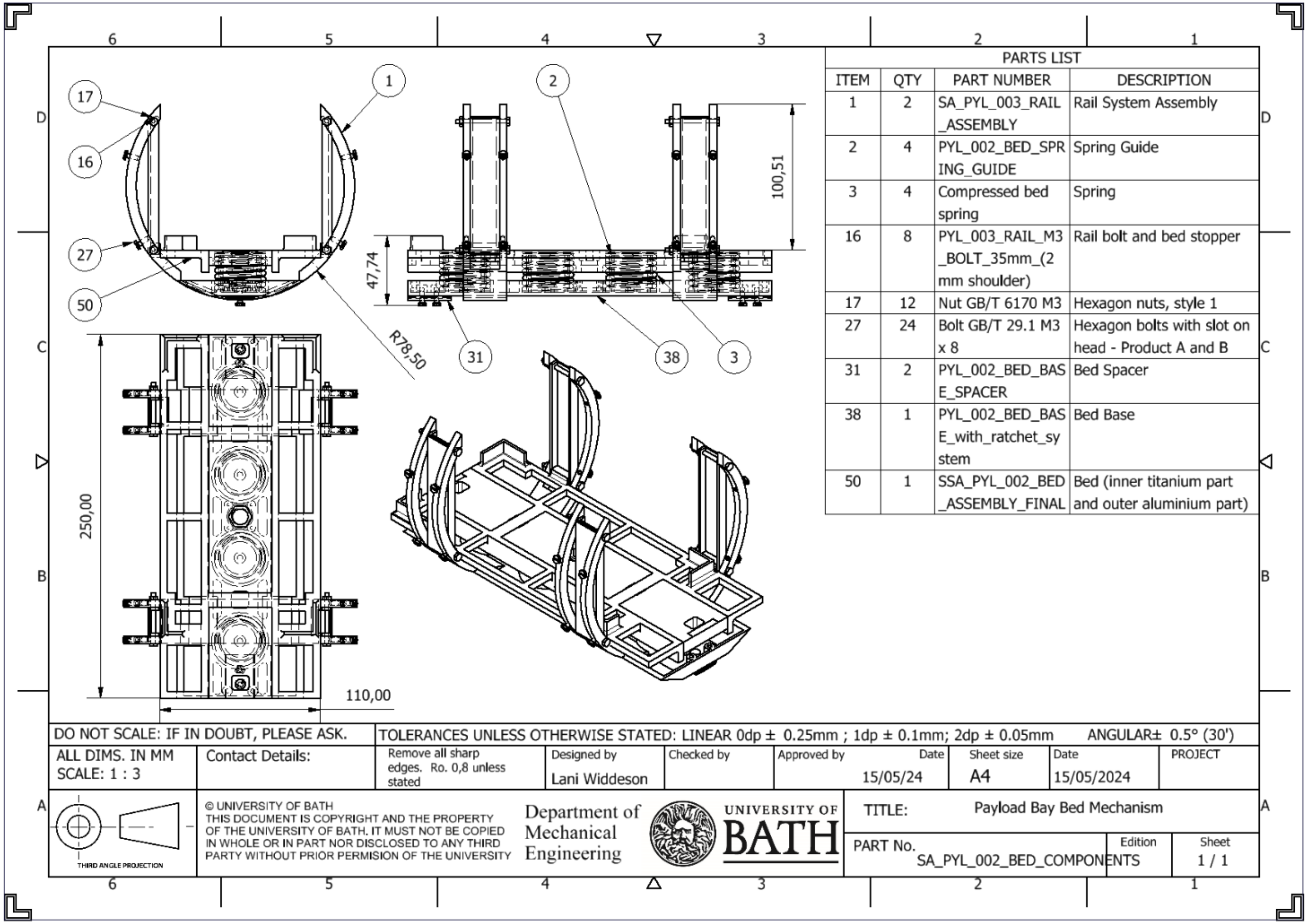
5.2 Hinge assembly drawing



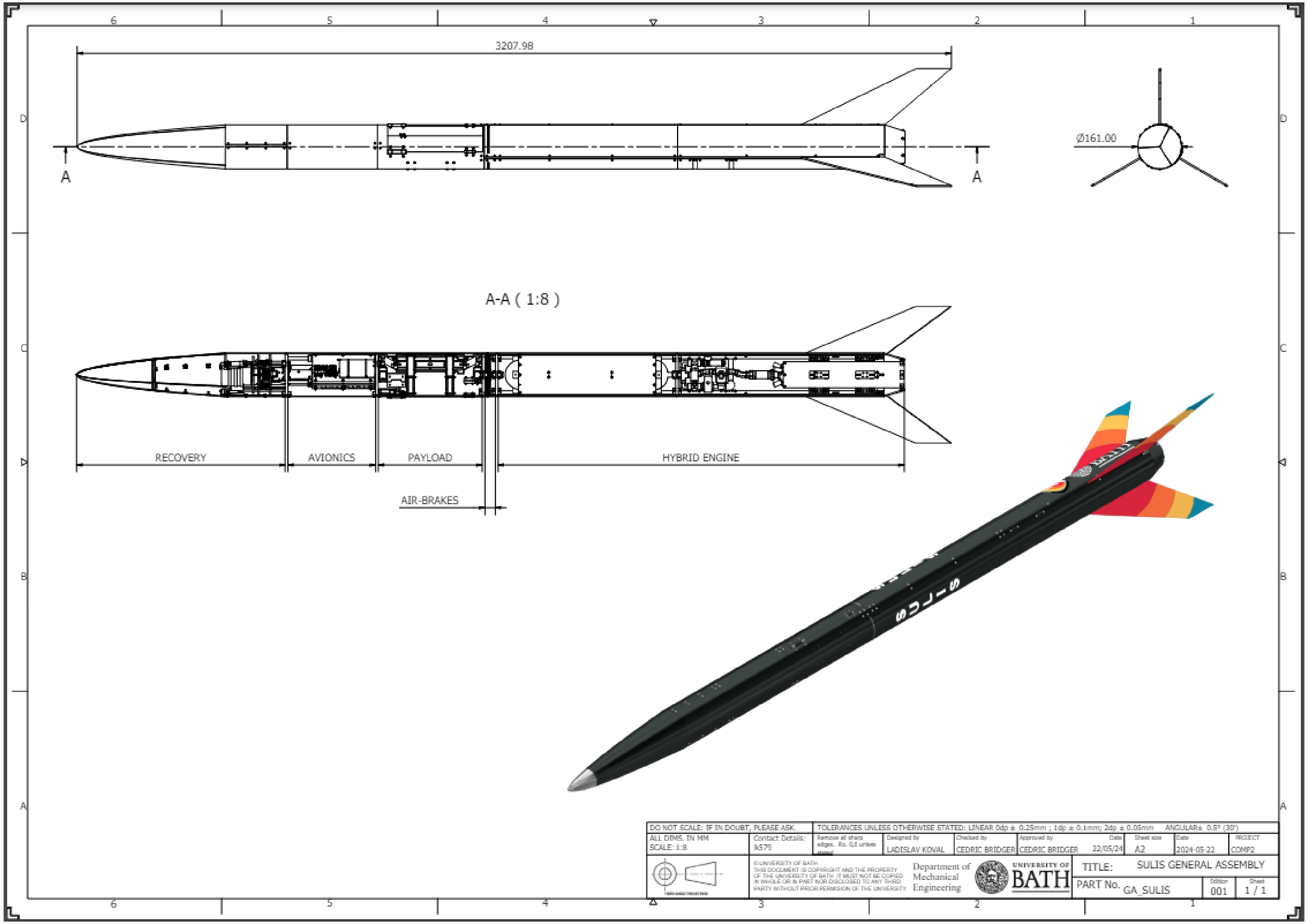
PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
17	12	Nut GB/T 6170 M3	Hexagon nuts, style 1
19	4	Hinge	COTS Hinge
20	1	PYL_006_HINGE_SOLENOID _PIN	COTS Solenoid part
23	8	Bolt GB 29.1 M5 x 12	Hexagon bolts with slot on head - Product A and B
24	8	Nut GB/T 6170 M4	Hexagon nuts, style 1
26	2	Door	
27	24	Bolt GB/T 29.1 M3 x 8	Hexagon bolts with slot on head - Product A and B
30	2	Hinge Spring	Hinge Spring
32	1	NAFSA_ERB50_N (carrera=0mm)	COTS Solenoid
33	1	PYL_006_HINGE_HOOK 2.1	
34	1	PYL_006_HINGE_HOOK 1.1	
36	1	PYL_004_LATCH_BACK_PLA TE_2_FOR_SOLENOID	
48	2	PYL_006_HINGE_SMALL_IN NER_WING	(Non-Sprung) Hinge part 1
49	2	PYL_006_HINGE_SMALL_OU TER_WING	(Non-Sprung) Hinge part 2
51	8	Bolt GB/T 5783 M3.5 x 10	Hexagon head bolts - Full thread
52	8	Nut GB/T 6170 M3.5	Hexagon nuts, style 1

5.3 Bed assembly drawing



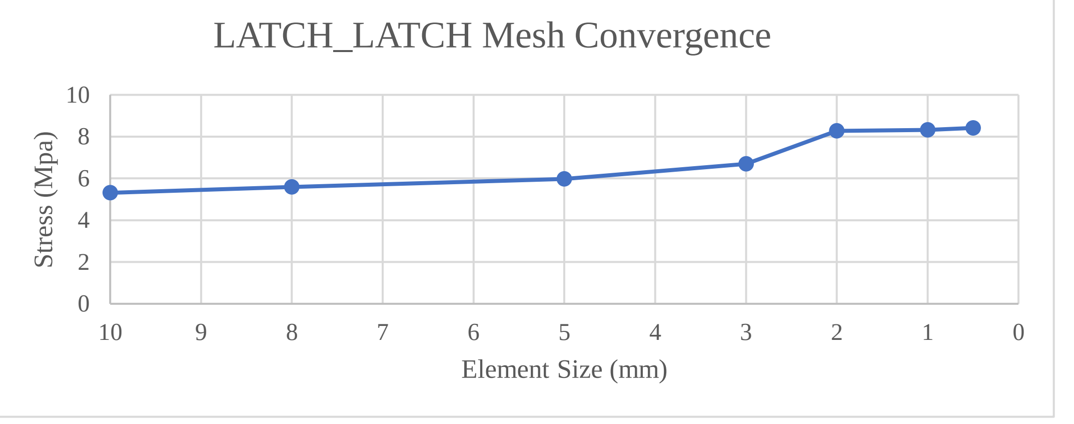
5.4 Rocket General Assembly Drawing (Koval, 2024)



Appendix 6: Convergence Studies

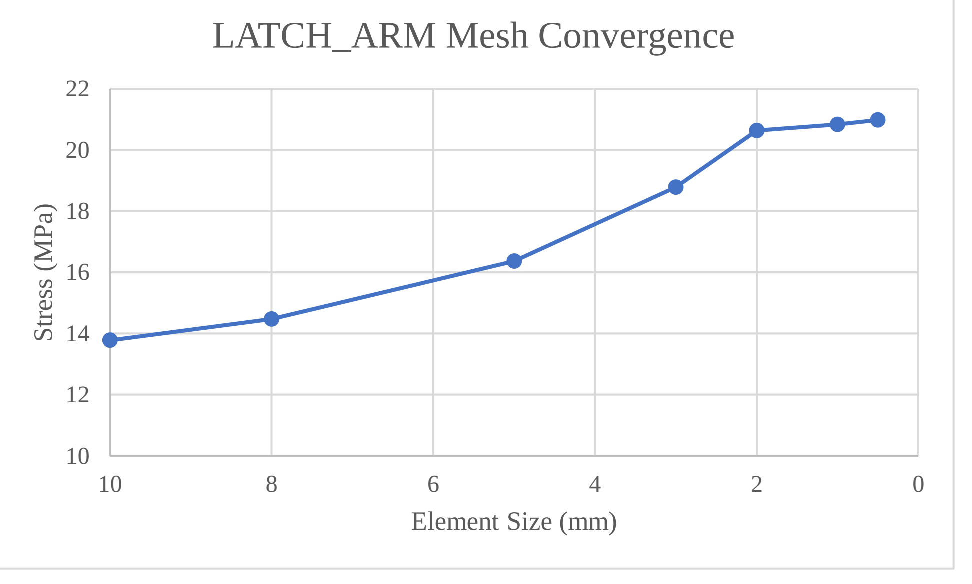
Appendix 6.1: Latch convergence (part labelled 1 in Figure 6)

Element Size (mm)	Stress (MPa)
10	5.31
8	5.588
5	5.978
3	6.7
2	8.271
1	8.323
0.5	8.417



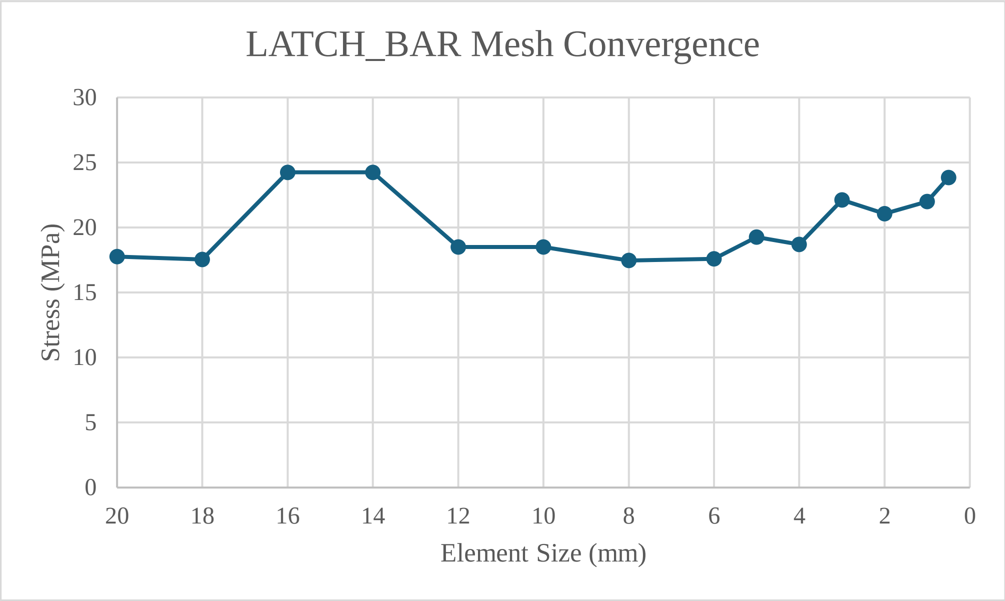
Appendix 6.2: Latch Slider Arm convergence (part labelled 2 in Figure 6)

Element size (mm)	Stress (MPa)
10	13.7746
8	14.4682
5	16.3603
3	18.7857
2	20.6298
1	20.8349
0.5	20.9797



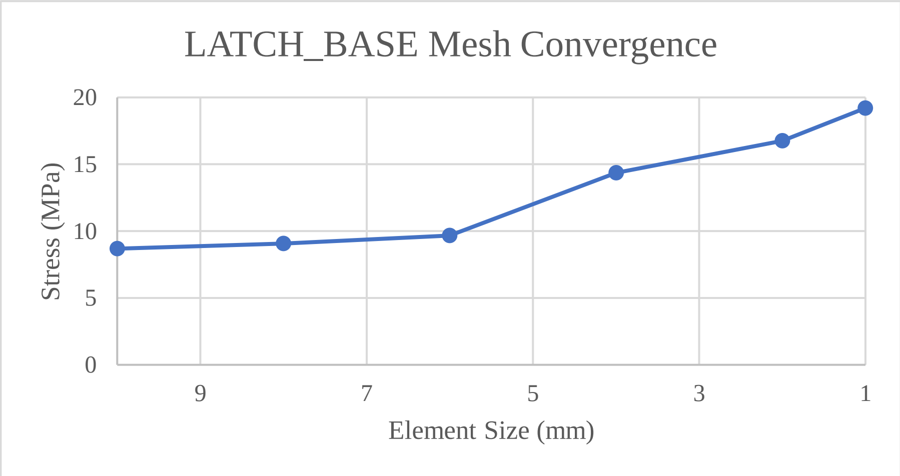
Appendix 6.3: Latch Bar convergence (part labelled 3 in Figure 6)

Element size (mm)	Max Stress (MPa)
20	17.756
18	17.531
16	24.246
14	24.246
12	18.505
10	18.496
8	17.46
6	17.578
5	19.266
4	18.696
3	22.113
2	21.06
1	21.985
0.5	23.834



Appendix 6.4: Latch Base convergence (part labelled 5 in Figure 6)

Element size (mm)	Stress (MPa)
10	8.6864
8	9.0681
6	9.6594
4	14.366
2	16.757
1	19.203



Appendix 6.5: Hinge Hook convergence

Element size (mm)	Max Stress (MPa)
6	34.64
4	34.53
3	34.92
2	41.59
1	40.0574