Tethered Satellite Separation System for TSATT

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Project 22

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EXECUTIVE SUMMARY

The success of the TSATT mission is dependent on a successful tether deployment: a flawless separation without tangling due to interference with the separation system. Separation system benchmarks have been researched to help guide our design and establish a foundation for the separation concept. The ideal heritage-flown separation system called the Lightband is not feasible to separate our two payloads due to the cost exceeding $110,000 and possible tether snag issues. The goal for our ME 450 team is to prove that our laboratory can design, fabricate, and test a separation system that can be integrated for separating the two payloads during the TSATT mission.

We have completed several analyses to refine our design to its final form. We evaluated the preload forces that the pinpullers can withstand, and used the data in our spring selection process. The springs had to comply with the geometric constraints of the design and impart the desired velocity, while also leaving a safety factor on the preload force. We also calculated the safety factor on each pinpuller under the 20g launch loads to be 1.89. Since it is less than 2.0, it will need to undergo testing for flight qualification. Some first-order analysis was done on the thermal expansion of the pins in the bushings, and we determined that the change in dimension will be less than 0.2%, and therefore shouldn't be an issue.

The majority of the prototype parts were machined in the Wilson Student Project Center at the University of Michigan. Because our four-mount system incorporates four pinpuller mounts at four different locations, we need all components to be as close to identical as possible. Consequently, we fabricated every part using the same jig plate on the same Bridgeport CNC mill to reduce part variation. All the parts will have identically spaced holes which press fit onto the dowel pins of the jig plate to exactly match the horizontal axis of the mill's table. The entire separation system has to align itself on four pins, approximately 0.0802" in diameter, which are located in opposite quadrants of the nanosat's interface plates. Therefore, we planned for each pinpuller mount to allow for a small amount of adjustability when aligning the pinpullers and shaft holes of the Vespel bushings. The completion of our prototype was resolved the day of the Design Expo, April 13, 2006, with successful assembly integration. The successful assembly of the prototype was largely due to the replicated, critical components of the separation system being within 0.008" of each other. Furthermore, we were able to validate our concept with one functional test in which two pinpullers located in opposite quadrants of the separation system synchronized retraction allowing one half of the nanosat to fall freely away.

Further validation of our prototype taking place this summer will include developing a circuitry system for safely delivering required power to actuate the four P-5 pinpullers simultaneously, evaluating the entire system's functional capabilities in a thermal chamber, and verifying the load capabilities of the pinpullers. We cannot accurately measure the separation velocity from the spring force prior to the microgravity flights, but we can test basic functionality with an air table and predict that the system can separate independently. Aboard the actual C-9 microgravity flights this summer, S3FL students will be able to measure the tip-off rate and separation velocity. Finally, after all aspects of our separation system design have been proven and all failure points have been corrected, the Four-Mount design will be ready for conversion into a flight ready module for the TSATT mission bound for experimentation in outer space.

TABLE OF CONTENTS

1.0 PROBLEM DESCRIPTION

1.1 Background

TSATT (**T**ethered **SAT**ellite **T**estbed) is a student-managed telemetry satellite project that graduate and undergraduate students work on through the Student Space Systems Fabrication Laboratory (S3FL). The project is sponsored by Professors Brian Gilchrist and Pete Washabaugh. The primary objectives of this project are: testing a new method of evaluating and validating rendezvous and formation flying sensor technologies, and tethered system technologies for distributed spacecraft control. The project is designed to investigate the feasibility of using a tethered spacecraft to provide a low-cost testing platform over variable separations. Completion of the proposed objectives includes the development of a pair of tethered nanosatellites with two lightweight payloads. The two payloads will house the necessary equipment to test telemetry technology, secure the tether and deployment mechanisms, and record required data with computer technology and photographs. A well-designed separation system is paramount to mission success.

1.2 Other Attempts

Prior to this project, no measures had been taken to solve the problem of a suitable separation system for the payloads. Preliminary research conducted through S3FL established a foundation upon which to build, but very little design work had been done. Currently a Lightband System is set for use as the separation system between the payloads and the Delta rocket. However, as this system costs in excess of $100,000, there is not sufficient funding to use a second Lightband between the payloads. Under consideration were: separation nuts, a Qwksys clampband, and pinpullers. Pinpullers, which were eventually incorporated into our final design, were the front-runner as they are light, inexpensive, reusable, impart low shock, and most importantly recommended in a design review by Lockheed Martin.

1.3 Project Goals

The main goals for this project are to develop, design, and fabricate the separation system for TSATT. The team will use information already gathered by members of S3FL, and Lockheed Martin as a resource for advice. Successful implementation of the separation system includes compliance with TSATT constraints and functioning in various inertial orientations. Successful tether deployment is also contingent upon flawless separation without interference or tangling due to problems with the separation system.

2.0 BENCHMARKING

There are two general categories of satellite separation systems in operation today: mechanical and pyrotechnic. The first type of system uses a moving clamp system to secure the bodies, and springs to propel them apart. The second type of system uses explosive charges to cut the links between the bodies and to propel them apart. Mechanical systems can be purchased as standalone systems, or separately as components. Pyrotechnic systems are generally purchased as separate components. We will concentrate on the mechanical systems as they are less dangerous to design and operate, are reusable, and impart less shock to the satellites.

2.1 Mechanical Systems

Standalone mechanical systems available today are largely of the clamp and spring design. The two bodies are held together with clamps which can be released simultaneously through a few different mechanisms and the bodies are propelled apart by compressed springs.

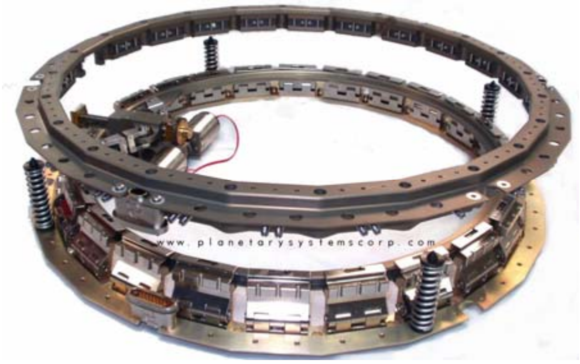


Figure 2.1.1: Lightband Separation System

The Lightband satellite separation system is built by Planetary Systems Corporation. It is the current stand-alone system of choice, and will be used to propel TSATT away from the Delta rocket. There are two Lightband systems available. The Standard Lightband system has clamps on the outer ring, held together by a tensioned wire. The clamps are released by cutting the wire with a heating element. The Motorized Lightband, shown in Figure 2.1.1, has clamps on the inner ring, and these are pulled back by their attachment to a retracting metal ring. Since there is no wire being cut, the Motorized Lightband is reusable. The Lightband system has flying heritage, but is prohibitively expensive [4].

There are several other systems that use the same basic principles as the Lightband. The Saab Ericsson family of satellite separation devices is extremely customizable. It operates on a clamp and spring system similar to the Lightband. The system can be operated pyrotechnically or mechanically. Different spring sets can impart the required velocity and spin to the satellite [5]. Starsys Corporation also manufactures a standalone clampband system called Qwksys [6]. A third system, the Marmon Clampband, also uses springs to push the two halves apart. The clampband consists of two flanges held together by shoes and secured by a belt. The belt is cut either mechanically or by an explosive device, releasing the shoes and the satellite [1].

2.2 Mechanical Components

In addition to the Lightband-type standalone systems, a few other types of actuators exist that can be integrated into a separation system.

- Electronically actuated Pinpullers: Solenoid moves a pin through magnetic effects. [6]
- Heated Paraffin or Nitinol Pinpullers: Piston and cylinder contains a substance that sublimates when heated, creating pressure on the piston to move the connected pin. [1,6]
- Bolt / Wire Cutters: Severs a retaining wire either mechanically or through chemical decomposition by heating a heat sensitive wire. [1]
- Split Spool Release Device: Rotary cam device capable of holding a bolt end
- Qwknut: Rotary cam device which holds onto a hollow tube with a matching cam on the exterior. [6]
- Clamps: Can be retained mechanically by pin pullers or a retaining wire, allows the load path to be moved.
- Springs: Primary mechanism for separation.

- Vespel Bushings and Coatings: Teflon-based plastic available in bushing form and in sheet form. This material can be inserted into a pin joint or between two surfaces to reduce friction and reduce the probability of cold-weld.

2.3 Explosive Components

- Separation Bolt: An explosive is fired within a piston and cylinder arrangement, the piston is within the bolt. The force breaks the weakened sides of the bolt and pushes the other half of the bolt away (Figure 2.3.1). [3]
- Bolt / Wire Cutters: Explosives fired within a piston and cylinder arrangement, the piston actuates a wire cutter. [1,2]
- Pin Pullers: Explosives fired within a piston and cylinder arrangement, the piston actuates a pin puller. [2]

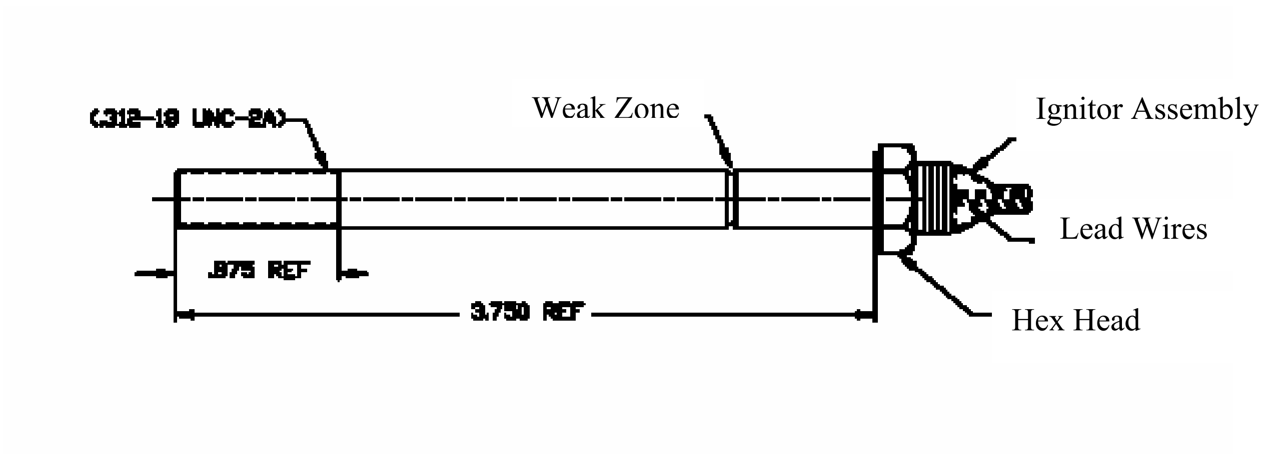


Figure 2.3.1: Pyrotechnic Separation Bolt

3.0 REQUIREMENTS AND SPECIFICATIONS

3.1 Requirements

A fully functional separation system is composed of a system of mechanisms or pyrotechnics that are capable of keeping the satellite intact before, during, and after launch and still have the capability to separate the satellite post-entry into the space environment. After TSATT separates from the primary spacecraft, our separation system will have to separate our internal payloads from each other in order for the mission to proceed with its objectives. Our requirements contain very few soft customer wants; the system must work, and must follow the Air Force regulations, or the entire TSATT mission fails. Most of the engineering specifications for the project were either dictated by the AFRL Nanosat 4 Program [7] guidelines, or given to us by the TSATT team. The specifications from the Nanosat 4 guidelines and the internal requirements from the TSATT team were used to determine our own customer requirements. The requirements are shown in Table 3.1.1, along with the weights showing their relative importance. An asterisk designates a requirement that must be met, and has essentially infinite weight.

Table 3.1.1: Requirements

Requirements	Weights
No premature separation	*
Space qualified materials	*
Reliable	10
Minimize potential tether snags	10
Low cost	10
Reusable	9
Low power consumption	9
Large separation distance	8
Low mass	7
Straight separation	6
Small volume envelope	5
Large temperature range	4

The first two requirements are needs that must be met for the separation system to fly on TSATT. A battery of tests must be performed before flight, and the TSATT team is requiring a safety circuit to prevent premature actuation. However, the use of space qualified materials is not required for the C-9 mission; therefore, our alpha prototype can save a significant amount of money by using some equivalent non-space qualified materials. Although aluminum 6061-T6 is the space qualified material, we machined the majority of our parts using aluminum 6061-T651, which is a virtually the same alloy, but is more available and less expensive than 6061-T6. Furthermore, AFRL and NASA will always restrict us to purchasing aluminum 6061-T6 from a list of specific suppliers in order to be fully qualified as "space rated".

The rest of the customer requirements are soft, listed in order of importance. The most important is reliability; if the satellites don't separate, the mission will fail. A tether snag is one of the most likely modes of failure once the separation has occurred. These two requirements are closely followed by cost; we are working on a limited budget, and an expensive design does us no good if we cannot afford to build it. Reusability is important in order for the system to be tested. A straight separation will help keep the halves of the satellite aligned and the tether away from any potential snags. The rest of the requirements, such as low mass, low power, and small volume, are typical for space applications.

3.2 Specifications

The engineering specifications derived from these requirements are shown in Table 3.2.1, along with target values. They were again defined for us by the Air Force [6] and in conjunction with the TSATT team.

The targets for mass and power were assigned by the TSATT team based on the limits for the nanosat as a whole. The cost is based on the estimated cost for the flight version of the system. The budget for the alpha prototype is significantly less, at $450. This lower cost is based on borrowing four TiNi Aerospace P-5 pinpullers from another S3FL project for the C-9 tests. The costs in excess of the $400 ME 450 budget will be paid out of the TSATT and C-9 project budgets. The synchronization of actuations is the maximum amount of time between actuations. Since our system of identical mechanisms is symmetrical, the actuations must be as close to simultaneous as possible to achieve a straight release. The spring push-off mounting system will also aid in the guiding of a straight separation. The Center of Gravity (CG) proximity to the longitudinal axis will also be very critical to a straight separation; therefore we must ensure that the CG of the separation system is symmetrical about the longitudinal axis of TSATT to within 0.25 inches.

Table 3.2.1: Engineering Specifications

Specification	Target
Mass	≤ 2 kg
Power	≤ 12 W
Cost	≤$20000
Synchronization of actuations	≤ 500 ms
Tip-off rate	≤ 1°/sec
Push-off velocity	≤ 1 m/s
Vertical height	≤ 2 in
20g axial loading safety factor	≥ 2
Minimum temperature	≤ -20°C
Maximum temperature	≥ 50°C
CG proximity to longitudinal axis	≤ 0.25 in
Actuation cycles	≥ 80

The tip-off rate is the angular velocity imparted to the nanosats during separation. We will be unable to test this directly on the ground, but we can meet this goal by making it as symmetrical as possible, using symmetrical forces, and guiding the two payloads apart. The push-off velocity determines how far they can travel before friction in the tether stops them. The 20g axial loading factor of safety is specified in the Nanosat 4 rules [7]. The weight of the top payload will be resting on the separation mechanism, and it must be able to withstand 20g loading with the given safety factor for yielding of the mechanisms. The minimum and maximum temperature targets are based on the temperature range that component are subjected to from the heat of the sun and cold of space. The pinpullers we plan to use can safely operate between temperature ranges of -60°C to +70°C.

3.3 QFD

The requirements and engineering specifications were used to create a quality function deployment (QFD) diagram, shown in Figure 3.3.1. It shows the relationships between the requirements and specifications, and also between different specifications.

The specifications have been rearranged in order of importance. The QFD indicates that our design will need to focus most on cost, the axial loading safety factor, the number of actuation cycles, and the push-off force. Mass, time span for actuation, and power consumption are also very important.

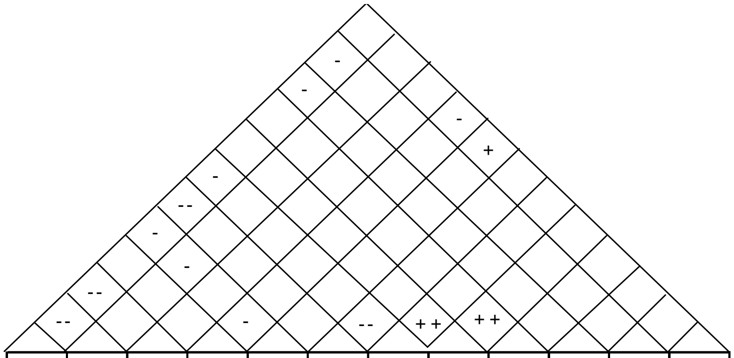
The cross-correlation in the "roof" of the QFD shows that many specifications are negatively correlated, and more than half are negatively correlated to cost. This indicates that we will have to weigh design trade-offs very carefully in order to meet all our target values. The Lightband System, which is our benchmark, meets nearly all specifications, but overshoots both cost and power significantly.

+ medium positive correlation

++ strong positive correlation

- medium negative correlation

-- strong negative correlation



(-) => less is better
(+) => more is better

	Weight	cost (-)	20g axial loading factor of safety (+)	actuation cycles (+)	push-off force (+)	Mass (-)	Power (-)	sychronization of actuations (-)	tip-off rate (-)	CG proximity to axis (-)	minimum temperature (-)	maximum temperature (+)	vertical height(-)
no premature separation	*	3	9			1					1	1	3
space qualified materials	*	9				3					3	3	3
reliable	10	9	9	9							3	3	
minimize potential tether snags	10	3			9	3		3	3	3			
low cost	10	9	3			1	3				1	1	3
reusable	9			9									
low power	9	3	3				9						
large separation distance	8				9								
low mass	7	3	3			9							
straight separation	6							9	9	9			
small volume envelope	5	1	1			3							9
withstand high and low temperatures	4	1									9	9	
Total		267	173	171	162	118	111	84	84	84	76	76	75
Normalized		0.18	0.12	0.12	0.11	0.08	0.07	0.06	0.06	0.06	0.05	0.05	0.05
Importance Rating		1	2	3	4	5	6	7	7	7	10	10	12
Measurement Unit		$	#	#	N	kg	W	ms	°/sec	in	°C	°C	in
Lightband System		110k	5.5	1000	*	2.15	32	0	1	0	-30	105	2.1
Target Values		20k	2	80	15	2	12	500	1	0.25	-20	50	2

Figure 3.3.1: Quality Function Deployment diagram

4.0 CONCEPT GENERATION

Our concepts for a separation system fell into several main categories, organized by which component is load-bearing and how it is actuated. Most of the concepts incorporate pinpullers, since they were specifically recommended to us by engineers from Lockheed Martin. The specific model that would best suit our needs is the P-10 pinpuller from TiNi Aerospace, Inc, due to its small size, low power usage, and high strength [8]. All other pinpullers we found, available from companies such as Starsys and Astro Pioneer, were either too large, not strong enough, or used too much power. More detailed descriptions of each concept are located in Appendix A.

Compression springs will be used in all concepts to apply the force to separate the two payloads. Since exposed springs would not meet the tether snag requirement, we developed the concept of a silo to house the springs on one side, with a cap that would fit inside to compress it. The rod on the inside of the silo serves to guide the spring and prevent buckling. Figure 4.1 shows the spring silo and cap. The number, size, and placement of the springs would vary from concept to concept, but all would incorporate the same basic mechanism for the release force.

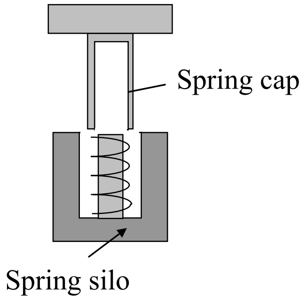


Figure 4.1: Spring Silo and Cap

4.1 Pinpuller

The first concept uses pinpullers to bear the load directly (Figure 4.1.1). Due to the octagonal faceplates and the shear load rating of the pinpullers, we developed the concept around four pinpullers mounted around the edges of the faceplate. The pinpuller would be fixed to a lower mount, with the pin extending through a hole in the upper mount to secure the two payloads. When the pin releases, the upper and lower payloads would separate. An alternative concept with the pinpullers mounted on rings is described in Appendix A.

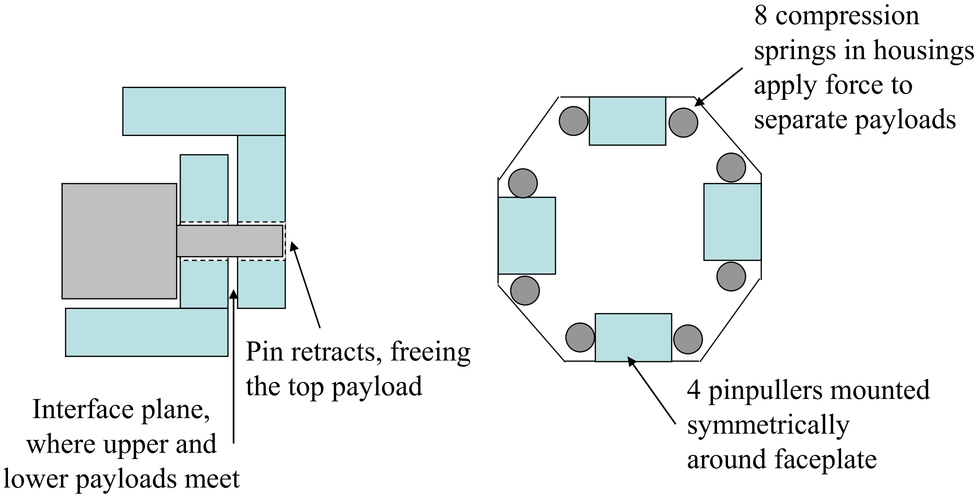


Figure 4.1.1: Four-Mount Pinpuller Concept

This concept has the potential to meet most of the requirements and specifications. It is symmetrical and lightweight, and fits within the volume envelope. It is relatively simple, and the parts are small and easy to machine. However, there are two main drawbacks: the tolerances would have to be very tight, and there is no redundancy. If one pinpuller fails, the whole system fails.

4.2 Pinpuller Toggle

To add redundancy to the system, we considered a toggle concept. The idea is that two pinpullers would be coupled together with a toggle, and both would have to fail for the system to fail. Figure 4.2.1 shows the basic toggle concept.

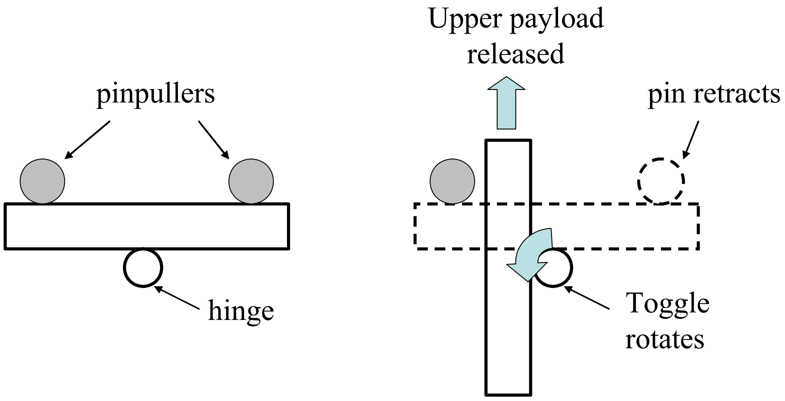


Figure 4.2.1: Toggled pinpullers

The main drawback of this concept is that to have four load-bearing points, we would need eight pinpullers, which is beyond our budget. A design with two sets of toggled pinpullers would be feasible, but would have less stability and strength. The toggle design also transfers the load to the hinge, which, because of its moving parts, geometry, and additional complexity, would be more prone to mechanical failure than a single, precision-made pin.

4.3 Rod

The basic concept is to use rods instead of pinpullers to hold the two payloads together. They could all be actuated simultaneously by a single pinpuller in the center. Figure 4.3.1 shows the basic rod concept.

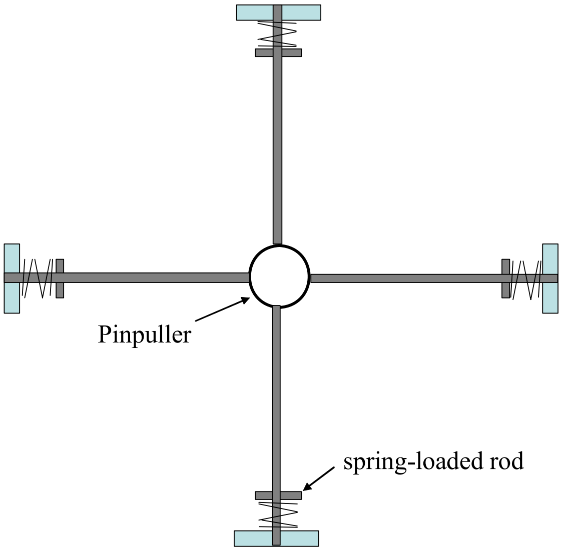


Figure 4.3.1: Basic Rod Concept

This would reduce cost due to fewer pinpullers, and ensure that all four points release at the same time. However, the tether occupies the central axis, so the concept had to be revised to a central ring, actuated by either a motor or pinpuller. The details of all the different variations can be found in Appendix A. While this design uses fewer actuators, the tolerances would need to be even tighter to ensure simultaneous actuation. The springs or gears needed to make the mechanism work would increase the risk of tether snag, as would long exposed rods. The increased complexity of the design also adds to the possible failure modes.

4.4 Clamp

An alternative to pins or rods is to hold the payloads together with clamps. Clamps would provide more surface area for holding, and wouldn't need to overcome the friction that a pin pulling under shear would. We generated several different concepts involving clamps, using different methods of holding them in place. The first uses a wire that can be de-tensioned with a pinpuller toggle. Another possibility is a clampband, which uses a flexible metal band in tension, held in place by a pinpuller. The four rods of previous concepts could be attached to the clamps to actuate them. Finally, two half-rings in the center could be pulled together to actuate clamps, but the design could not be fully symmetrical. Figure 4.4.1 shows the basic clamp concept. More details about each variation can be found in the appendix.

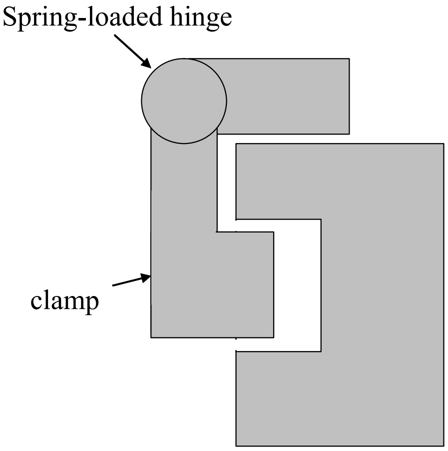


Figure 4.4.1: Clamp Concept

4.5 Double Ring

The final concept, shown in Figure 4.5.1, uses two overlapping rings to secure the payloads. The lower ring is on bearings, pre-loaded with a torsion spring and held in place by a pinpuller. When actuated by the pinpuller, the lower ring turns until the rings no longer overlap. The compression springs then push the two payloads apart. While this design does offer much more surface area to secure the two payloads, there are many more opportunities for the separation to fail. Friction is a large factor, as well as the precise machining that would be required to ensure all four tabs on the lower ring reach the holes on the upper ring simultaneously. The two rings would also be very large, causing mass and machining issues.

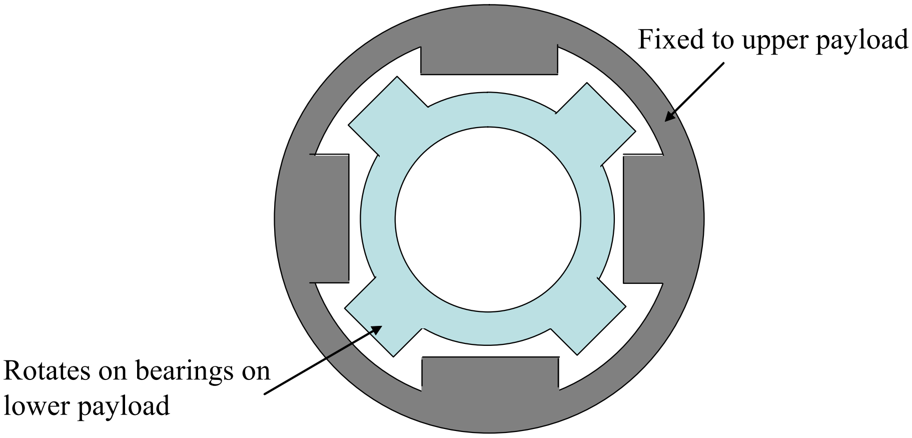


Figure 4.5.1: Double ring concept

5.0 CONCEPT SELECTION

Our concept selection process began by analyzing the strengths and weaknesses of each design. We first eliminated concepts that were deemed infeasible, either because they would not meet key requirements, or because we lack the time, resources, or expertise to complete the design. Once we narrowed the choice down to three concepts, we presented them to senior engineers from Lockheed Martin Space Systems. Based on their expert opinions, we chose the Four-Mount Pinpuller as our final design. The major pros and cons of the top design concepts are listed in Table 5.1.

Table 5.1: Evaluation of the Top Five Concepts

	Pros	Cons
Four-Mount Pinpuller	• Lightweight • Easy to machine • Interchangeable • Small volume	• Tolerances on interface plane • No redundancy
Two Pinpuller Toggles	• Redundancy	• Stability • Failure point at hinge • Added complexity
Spring-loaded Rods, Pinpuller Actuated	• Lower cost • Can increase contact area	• Potential tether snag • Complexity • Tolerances
Lightband Replica	• Tracked from Lightband • Fewer pinpullers • Redundancy	• Complexity • Hard to machine • Large mass • Poor reusability
Double Ring	• More contact area • Redundancy (can use toggle) • Fewer parts • Reusability	• Hard to machine • Large mass • Friction & bearings • Large volume

The P-10 pinpuller and the compression springs, which are common to all designs, are responsible for whether or not the designs will meet many of the specifications. The pinpuller is the only component to use power, the most sensitive to temperature, the limiting factor on actuation cycles, and the only component responsible for synchronization of actuations. The compression springs dictate the push-off velocity. Together the springs and the pinpullers are the key components that dictate the vertical height of the design. Since the concepts all have to potential to meet these specifications due to the shared design aspects, we focused on a few key elements that would differentiate the designs. The primary design concerns were:

- Mass and volume
- Load distribution
- Failure probability of mechanical actuators
- Tether snag
- Tolerances

- Machining time and cost

The load distribution will affect the safety factor on loading, as well as the tip-off rate. The necessary tolerances will affect the tip-off rate and overall feasibility of the concepts, as do the machining time and cost.

Conceptually, the simplest design was the Four-Mount Pinpuller, so all the other designs were compared in relation to this design. This design is lightweight, occupies a small volume, and has easily machined and interchangeable parts. The design suffers from tolerance issues on the interface planes, and the system would fail should any of the pinpullers fail to actuate. However, any design we choose will have tolerance issues, and multiple pieces will be easier to align than all-in-one designs like the Double Ring.

Pinpuller toggles would introduce a layer of redundancy to each pinpuller actuation. A two-toggle design would require the same number of pinpullers, but offers reduced stability and occupies too much space. The addition of a hinge to each mount might also increase the probability of failure, since damage to the hinge could cause it to not actuate smoothly or fail entirely.

A centrally actuated system of spring-loaded rods would have the advantage of lower cost. The design does present tether snag problems due to the difficulty of shielding the rods from the tether without covering the antennas that will be on the same face of the satellite. The design is also complex and the rods would have to be fabricated within very tight tolerances, in addition to the interface plane.

The Lightband replica would work with only two toggled pinpullers and has the advantage of having the primary load path supported by clamps. However, it would have an extremely large number of small parts that would need to be assembled. Lightband was also reported to have had previous problems with attaining a smooth wire release.

The double ring design distributes the loads experienced by the separation system over the largest area possible and could be actuated with a toggle. However, the design would have very tight tolerances at the point where the cams were released. The design is also extremely large, and may not be able to meet the mass and volume specifications. Due to their large size, the cam rings would be difficult to machine. The Lockheed team also warned about problems with regard to the friction that would have been experienced between the two rotating surfaces.

6.0 FINAL DESIGN CONCEPT

The Four-Mount Pinpuller separation system was chosen as our final design concept. The four-mount concept contains four separate pinpullers mounted symmetrically about the longitudinal axis of the nanosatellite (Figure 6.1).

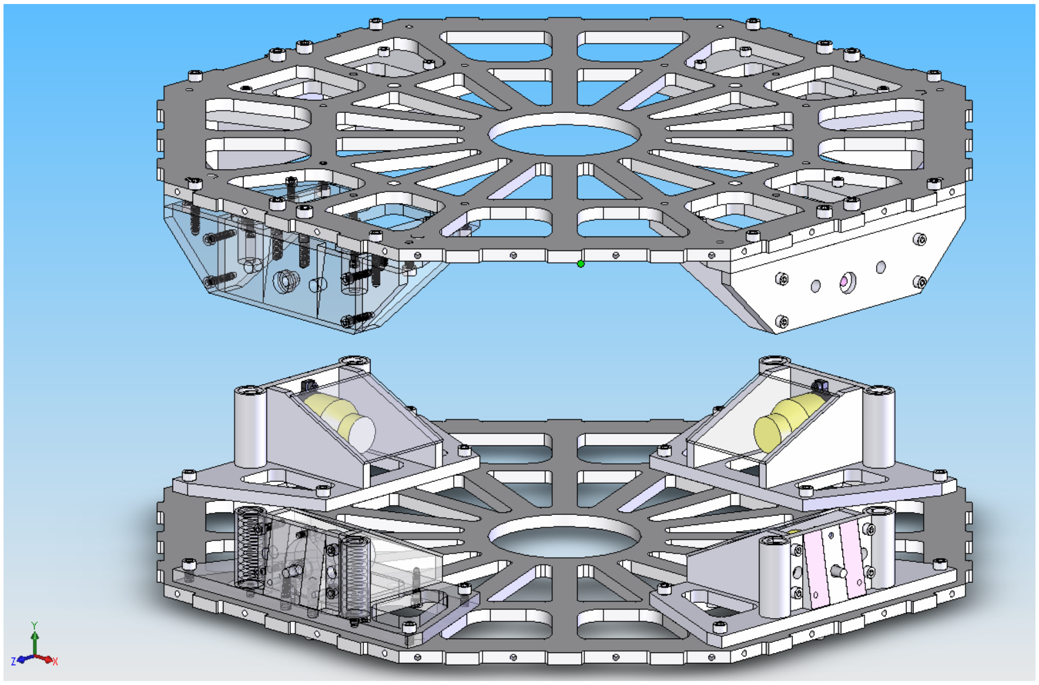


Figure 6.1: Four-Mount Pinpuller arrangement

The mount itself is actually comprised of two separate halves, an upper mount and a lower mount (shown in Figure 6.2), that are each connected to the opposite payload interface plates. Each pair of mounts will interface with each other at the locations of each of the four pinpullers in the system.

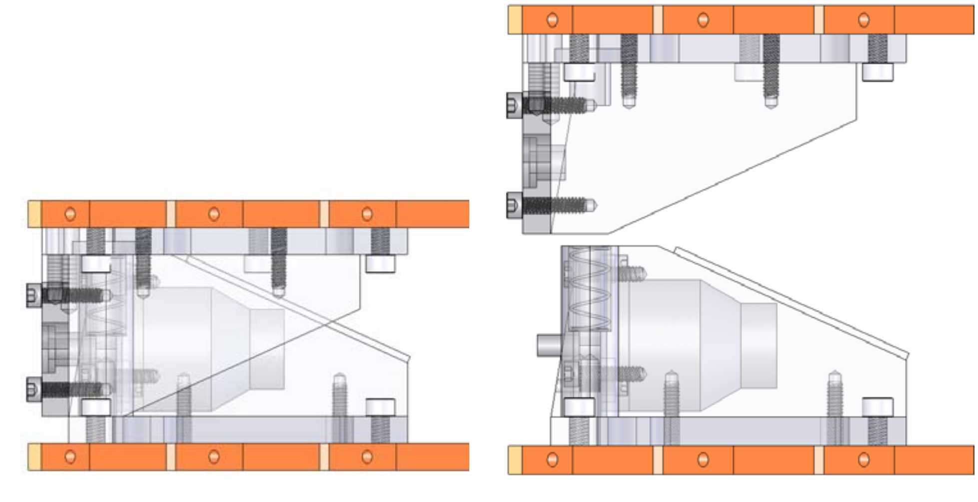


Figure 6.2: Individual mounts attached and separated

The mounts are integrated to securely fasten a pinpuller at the center and house two springs on both sides. Separate parts called spring caps (shown in Figure 6.3) are attached to the upper mount base and will compress the springs in the silo housings. The pin itself will protrude through a slightly inclined plane which matches the incline of the corresponding mount connecting from above. The pin will insert into a Vespel bushing embedded in the inclined plane of the upper mount (shown in Figure 6.3). Vespel is a high performance material that is load-rated and temperature-rated well beyond the mission requirements. It is also an added benefit that the pin and bushing are manufactured to precise tolerances, so we don't have to machine the actual fit for the interface. Structural gussets were also added to the upper and lower mounts to add to the design's structural stiffness.

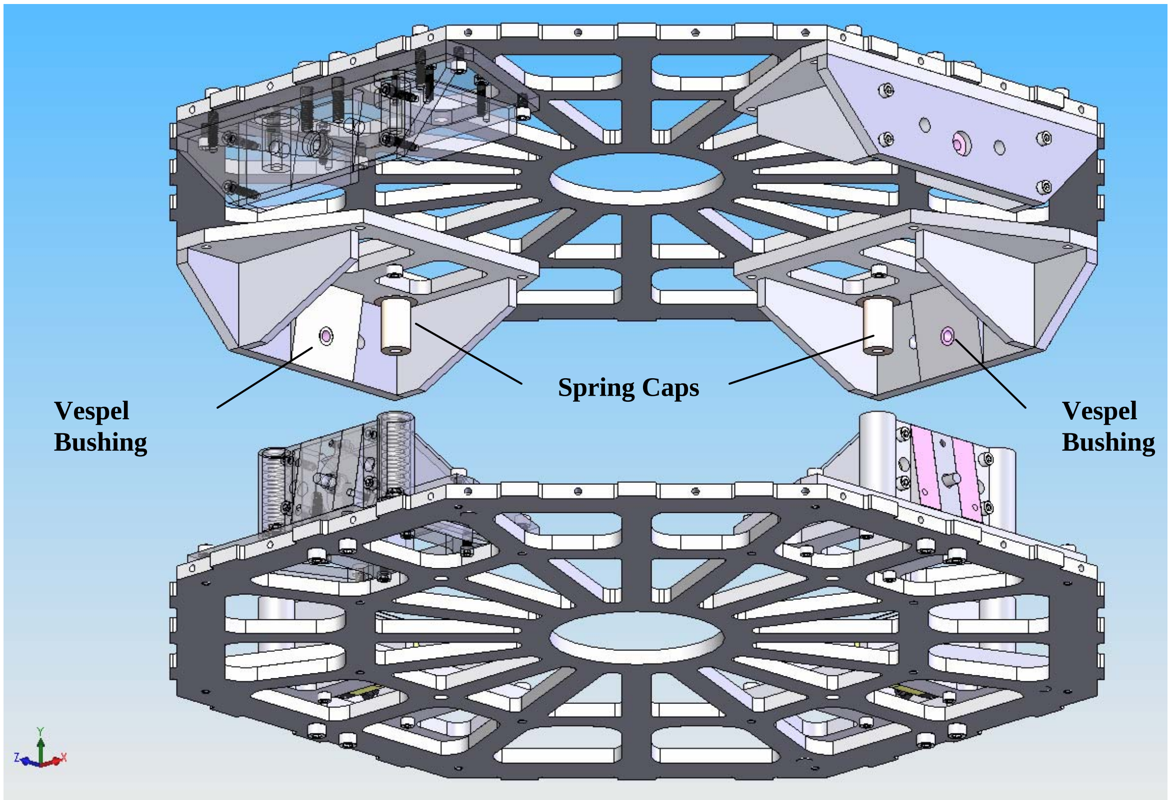


Figure 6.3: View of upper mounts and interface components

Since the most evident shortcoming of this design is acquiring the proper tolerances, we still must ensure that the pin and bushing line up accurately for all four mounts. Furthermore, it is essential that the inclined planes mate precisely with no obtrusive contact points. An irregularity in the contact surface could cause contact stress, which leads to vibrations between the components that would add additional forces to the mechanisms. Professor Pete Washabaugh suggested that we implement a small gap between the inclined interface planes and install Teflon strips on the faces so as to decrease the probability of only single point contact between the faces. The Teflon would also allow the upper mount to slide smoothly across the lower inclined face into launch position (see Figure 6.4).

Based on our engineering analysis the interface mount themselves would not provide enough resistance to the forces that will be exhibited at the interface of the pinpuller. Therefore, each of the upper and lower mounts are fastened to a mounting base in very close proximity to the pinpuller interface in order to withstand the largest magnitude of force through the main load path. In addition to the two main fasteners, the interface mounts are attached with structural gussets to reduce bending in the mount and increase the overall structural stiffness of the system. The gussets are fastened with two fasteners directly to the interface mounts and two fasteners securing the gussets to the mounting bases. The mounting bases are in turn mounted in four critical locations on the TSATT top plates that allow for the most amount of material to encompass the fastener location. Without the mounting bases, the forces would not be distributed consistently across the top plates and would not be in a structurally stable location.

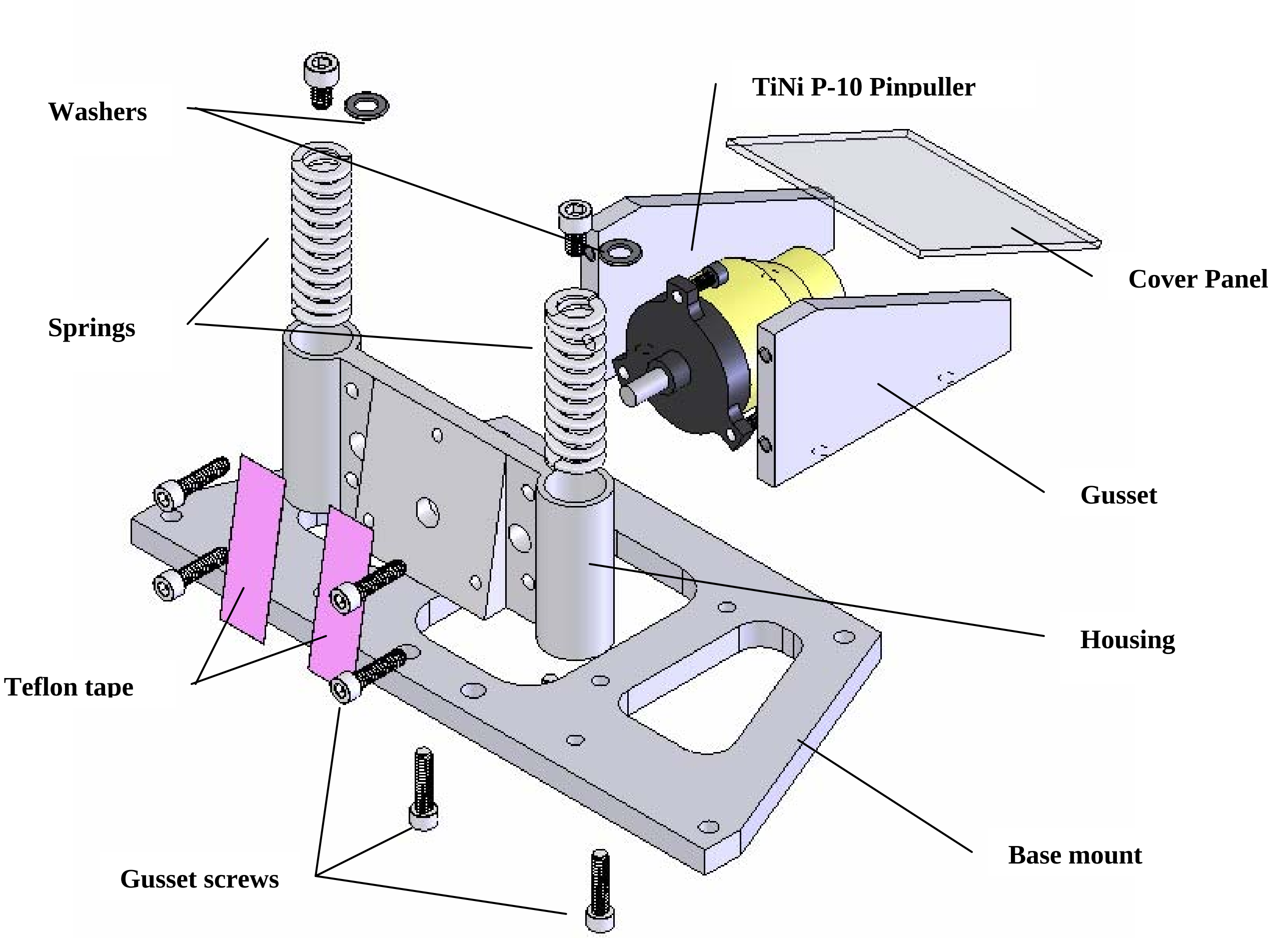


Figure 6.4: Individual components of lower mount exploded

7.0 ENGINEERING ANALYSIS

An overview of the general methods of analysis used and the results of these analyses are described below. The detailed equations, calculations, and part specifications can be found in Appendix C.

7.1 Material Selection

No concrete analysis was done for material selection. Our approach was to use standard space-rated materials. The Vespel bushings were selected for their low coefficient of friction, and the Teflon tape was selected for its nonstick properties. The pinpuller's shaft being inserted into a Vespel bushing was a design tracked from a Lockheed Martin experiment with a similar pinpuller application. Al 6061-T6 is the material of choice for the structure, since it is lightweight and strong, easy to machine, space rated, and readily available.

7.2 Preload

There are two possible limiting factors on the preload supplied by the compression springs. The first is the friction generated as the pins pull out of the bushings, and the second is the maximum side load that can be sustained by the pinpullers during actuation. We first examined the case of friction on the pin. The maximum axial load per pinpuller is 22 N. Since the only axial forces on the pin are from friction, the calculation is simple. The bushings have a coefficient of friction of 0.29, which results in a maximum preload of 75.9 N per pinpuller (303 N total).

Second, we looked at the maximum side load during actuation. Since there are no other forces in the longitudinal direction during actuation, the side load is equal to the preload. The P-10 is rated for a maximum actuation side load of 89 N, which results in a maximum preload of 356 N for the system. Since this result is higher than the previous result, the friction is the limiting factor for preload. Details of the calculations are in Appendix C.

7.3 Launch Loads

The Nanosat-4 guidelines specify that the satellite must withstand 20g of force on all axes with a safety factor of 2 (by analysis) [7]. The most likely failure point is at the pinpullers when subjected to a shear load; therefore, our calculations focus on this failure mode. The P-10 pinpuller from TiNi Aerospace, Inc. can withstand a maximum non-actuation side load of 1469 N, for a total of 5876 N for the system. Assuming a 15 kg upper payload, the 20g load on the separation system is 2940 N. In addition to this load, the pinpullers will also have a preload of 240 N from the compression springs, for a total load of 3180 N. This results in a safety factor of 1.85 on the pinpullers. While this doesn't meet the target safety factor of 2, it is very close, and there are no other suitable pinpullers for our system. Therefore, we will have to verify the final flight hardware by testing rather than by analysis; the Nanosat 4 guidelines only require the safety factor in the absence of testing [7].

Because this is such a critical issue, further analysis will be conducted once the TSATT design is more fully developed. The team will perform FEA to look at loading along other axes, find the fundamental frequency of the entire structure, and investigate the effects of thermal loading.

7.4 Spring Selection

Basic dynamic principles and conservation of energy were applied to calculate the separation velocity and preload for each spring analyzed. The level of detail is appropriate to the problem, since we do not yet have exact masses of the payloads. Should slight adjustments need to be made once TSATT is fully designed, the length of the spring caps can be changed slightly to adjust the initial separation velocity and preload.

7.4.1 TSATT Spring Selection: Initially, the TSATT spring silos were designed to be 1.25" long with a diameter of 0.375". Several springs from Century Spring Corporation were identified for evaluation. These were part numbers 71207, 71148, 71639S and S-1139. Part numbers 71639S and S-1139 do not fit within the initially designed spring silos but provide much better separation velocities at lower preloads. The new silo diameters are 0.54", with a length of 1.5”. The maximum separation velocity of 1 m/s corresponds to a separation distance of 1000 m according to Tethers Unlimited, Inc. Since our target distance is between 100 m and 1000 m, our target velocity is 1 m/s or less. We have selected the 71639S because it provides much lower preload stresses of 163.68 N at a separation speed of 0.7 m/s and is made of stainless steel, which is space qualified.

7.4.2 Prototype C9 Spring Selection: The spring silos in for the prototype are 0.375” in diameter and 1.5” long. We had a choice between two springs. The M-133 spring has a lower spring rate than the 71035S and would therefore have to be compressed more to give a suitable separation velocity. Instead of separation distance, the separation velocity for the prototype is based on safety concerns on the C-9 flight. The tether will be only 1 m long and the separation is in a confined space, so NASA has approved a separation velocity of 0.1 m/s. The M-133 was deemed more suitable as the spring caps would be longer and more similar to the TSATT spring caps. The stiffer 71035S is also more sensitive to an inaccurately manufactured spring cap.

7.5 Fastener Selection

Fasteners were mostly chosen based on availability of surrounding material. As a general rule of thumb set forth by Lockheed Martin, every hole should be its diameter and a half away from the closet edge (shown in Figure 7.5.1).

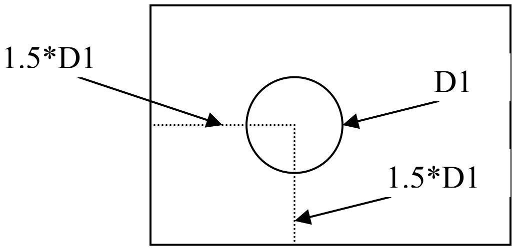


Figure 7.5.1: Hole of diameter D1 is placed 1.5*D1 away from nearest edges

This clearance from neighboring holes or edges will decrease the probability of the part failing at the hole location or the hole shearing the part threads. In some cases, that much clearance is just not feasible so fasteners are chosen to be as small as possible, but generally not going smaller than a #4-40 screw because they don’t provide much holding torque because the threads are very small. However, the P10 pinpullers require three #6-40 screws as a part of the internal design and we must adhere to the specification in our design. To compensate for the small fastener selection, we tried to make the surrounding mounting for the pinpuller as strong and stiff as possible. The most commonly used fastener in our design is a #8-32 because it is small yet still relatively strong in holding torque capabilities. The #8-32 fits almost everywhere because most of the thicknesses of our mounts and plates are ¼” which will allow us to have a minimum of 8 threads per fastener.

All of our fasteners are 18-8 stainless steel, plain coating, socket head cap screws. The 18-8 stainless steel is almost always the material of choice for space flight because it is very strong, corrosion resistant, and has very low-outgassing properties. The reason we use socket head cap screws everywhere in our design is to accommodate the maximum amount of torque in the screws. The hexagonal socket head uses and Alan wrench to fasten the screws which supplies more torque than a standard slotted head or Phillips head. The socket head will also allow for easy access with an Alan wrench when clearance is limited and the tightening angle is very acute. When fastening screws for space flight the standard assembly operation is to use an Alan torque wrench that will exactly torque each fastener without over tightening or under tightening by hand.

7.6 Thermal Contraction and Expansion

We believe that thermal contraction and expansion will play a small role in the tolerance of the holes. Coefficients of Thermal expansion for Stainless Steel, Vespel and Aluminum are sufficiently small such that the differences in expansion experienced in a 50 °C change in temperature is less than 0.2% of the initial dimension. We will experience manufacturing tolerance issues far greater than this figure. These figures are based on free expansion of the material, without taking into account restraining forces that might be exerted by the Aluminum housing around the Vespel sleeve bushing. Therefore, the actual expansion should be less than the values calculated.

Since thermal stresses are very hard to predict in complex geometry, the TSATT team will do FEA analysis of the entire structure to ensure that it can withstand extreme temperatures and maintain a safety margin. The possibility of shear failure of the pinpullers is the top concern for thermal analysis, followed by any unexpected stresses resulting from the draft angle on the interface plane.

7.7 DesignSafe Risk Analysis

Our DesignSafe analysis revealed several minor issues with the TSATT Separation System and the testing of the Separation System. For the full DesignSafe Risk Analysis report, see Appendix D.

One of our primary concerns is the danger of crushing between several of the faces during a reset of the separation system. We believe this concern can be remedied by proper education of the operators. Since either half can be lifted by just one person, only one person should have his/her hands on the satellite during the joining of the two halves.

Our other primary concern was the danger of cutting on the milled edges of the separation system. We thoroughly de-burred the edges of the separation system, and cutting should not be an issue.

The analysis revealed some safety issues with regards to the prototype testing team aboard the C-9 flight. These are mainly concerns with regards to falling, tripping and handling of the prototype in an environment with changing gravity. For these reasons, the team will be supervised by NASA personnel and large handles attached to the prototype for the flight.

There are several electrical concerns as well that pose minimal dangers to personnel. These may prove catastrophic to the operation of the system, since the pinpullers have proven very sensitive to improper voltage and current application. Our electrical team has devised a safety circuit which cuts off power to the pinpullers should the voltage and current exceed specifications.

It would be ideal if our project had no risk associated with it. However, since the pinpullers have a small but finite possibility of failure, we will have to reduce the risk of failure to an acceptable level. Our team has also identified several dangers facing the testing team that are out of our control.

8.0 FINAL DESIGN DESCRIPTION

Our final design concept is based on four pinpullers retaining two halves of a nanosatellite at each of the four pin interfaces. When sufficient current is supplied the pinpullers will separate from one of the retaining payloads and a set of eight springs will eject the payloads apart to a minimum distance of 100 m. The springs also have enough potential energy to preload the pinpullers at 240 N for the system which will allows for the system to stand robustly without the two payloads shifting prior to testing or launch. Furthermore, the preloading will decrease the possibilities of vibration loading occurring at the pin interfaces. If vibration loading is not under control, it has the capabilities to surpass the 20g launch load. The TiNi pinpullers themselves are space qualified to withstand very large loads and operate within a large temperature range. Since the pinpullers are also rated to synchronization to within 500 milliseconds, we can predict that the separation will be as straight as possible. All of our material selections for in-house parts, purchased parts, and fasteners are designed to be space qualified materials i.e. load rated, temperature rated, heritage, low-outgassing, and vacuum rated.

The main separation assembly contains four of these mounting systems total. Each of the four mounts dissolve into an upper mount sub-assembly on the top (Maize) payload and a lower (Blue) mount sub-assembly on the bottom payload. In our design, the lower mount sub-assembly is called the Pinpuller Blue-Mount Assembly while the upper mount sub-assembly is called the Bearing Maize-Mount Assembly. The bill of materials (BOM) is outlined for the main assembly and for the sub-assemblies in Appendix B with quantities and costs. The corresponding dimensioned drawings for the parts and assemblies are also shown in Appendix B. Our team devised a naming convention for organizing our CAD files because our platform of choice, SolidWorks, which involves many parts and assemblies each with different configurations. Each part and assembly has a TSATT configuration and a C-9-prototype configuration which allows us to concurrently view the differences and similarities in the designs. In order to keep track of our designs both for TSATT and for C-9, we used the following hierarchy for our files:

450-SEPARATION SYSTEM ASSEMBLY	(Main assembly)
450-01 PINPULLER-BLUE MOUNT ASSEMBLY	(Sub-assembly)
450-01.01 TiNi P-10 Pin Puller	(Part)
450-01.02 Pin Puller Mount	(Part)
450-01.03 Blue Mounting Base	(Part)
450-01.04 Cover Plate	(Part)
450-01.05 Gusset	(Part)
450-02 BEARING MAIZE-MOUNT ASSEMBLY	(Sub-assembly)

450-02.01 Bearing Mount	(Part)
450-02.02 Maize Mounting Base	(Part)
450-02.03 Spring Push Cap	(Part)
450-03 MLVI-preEDU	(Part)

The parts are the lowest level in the hierarchy beginning with the number of the assembly to which it belongs. The parts are named with lower case text and organized numerically to show the order the parts were inserted into the assembly i.e. in the 450-01 PINPULLER-BLUE MOUNT ASSEMBLY, the first part inserted into the assembly was 450-01 TiNi P-10 Pin Puller since we based our design off of that particular part. The assemblies are named in upper case are numbered in the same fashion as the parts, showing which upper-main assembly it belongs to. This also allows for an easily visible tracking system of the parts and assemblies because typical folders or databases will organize the files in numerical order first which will display the assembly followed by all its parts in order.

Moreover, these preceding parts and assemblies listed with this naming convention represent parts and assemblies that are supplied or manufactured in-house. In fact, all of the parts listed above have been fabricated or are currently being fabricated by our team which the exception of the TiNi Pinpuller, which is supplied by our lab for our prototype. All other parts not listed will have to be purchased by our team or our lab. These items include bearings, springs, washers, nuts, and fasteners. These items are widely available online and almost all the ordered parts can come from McMaster-Carr. The McMaster-Carr website allows for the download of 3-D SolidWorks models of virtually every part they sell. Therefore, for all of our fastener selections we imported directly the part and model number for the intended application of our design. Since we did not have to draw the fasteners ourselves and the fasteners have standard dimensions, we did not supplement their detailed drawings. However, all the parts we intend to order such as fasteners are called out in the assembly bill of materials in the assembly in which they are immediately fastened. The intended purchased parts are have the file name beginning with the manufacturer/supplier name followed by the part number and description of the part i.e. McMaster-Carr #92196A107 Socket Head Cap Screw 4-40 X 5/16".

9.0 PROTOTYPE DESCRIPTION

There are a number of key differences between our final design and our prototype. Most changes were made to simplify the machining process and allow us to complete it within our time frame. Other components were changed to accommodate the needs of the C-9 flights. The detailed drawings and BOM for each prototype part can be found in Appendix B. The final prototype CAD model is shown below in Figure 9.1. Each of the mounts is modular and can be preassembled before being integrated with the entire system (see Figure 9.1.1).

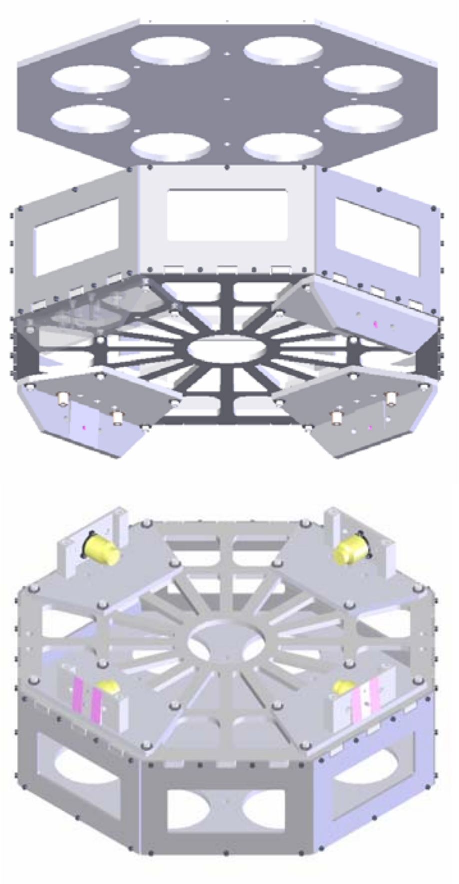


Figure 9.1: Final Prototype Assembly

9.1 Pinpullers

Though the TSATT system is designed around TiNi Aerospace P-10 pinpullers, the prototype will use P-5 pinpullers previously used by another S3FL project. The main differences between the P-5 and P-10 pinpullers include: a smaller shaft diameter, lower side and axial load ratings, and lower power consumption. To this extent the prototype will be adjusted such that the center thru holes for the pinpuller shafts will have a smaller diameter than the TSATT design. Also, since a smaller preload is required for C-9 than TSATT, and with the smaller load ratings of the P-5, the spring silos will not be as deep or as wide on the prototype as on the final design and smaller springs will be implemented. The lower power consumption of the P-5's will also allow for a smaller power supply used for system activation.

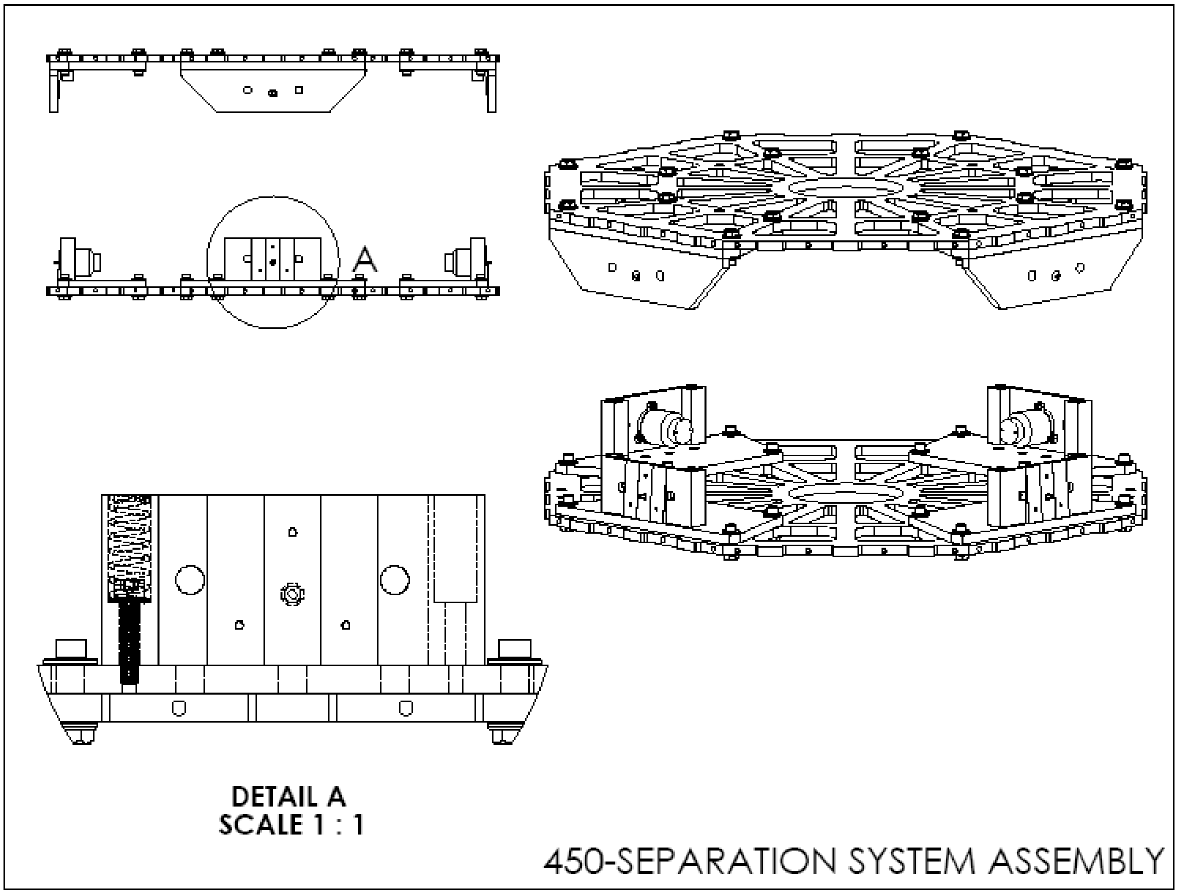


Figure 9.1.1: Prototype Assembly Drawing

9.2 Springs

As mentioned, constraints from C-9 and the P-5 pinpullers necessitate a lower preload on the prototype than on TSATT. To address this, smaller, less stiff springs will be purchased for the prototype than those chosen for TSATT and the spring silos will not be as deep or as wide on the prototype as on TSATT.

9.3 Electrical System

For TSATT, the P-10 pinpullers will be wired so as to draw power from the solar array on the panels of the nanosatellite. For our prototype we will simply connect the P-5's to a power supply for activation requiring a less intricate wiring plan than that of TSATT. Also, as the P-5's require less power for activation than the P-10's, a smaller power supply can be implemented for the prototype.

Though differences between the final design and prototype are present, we will still be able to ascertain pertinent information from the prototype's performance and relate it to that of the final design. Testing with the prototype will allow us to scale and predict TSATT's behavior and verify the concept and practicality of our design. These predictions and verifications will be made through testing that will allow us to analyze the capabilities of pinpullers, possible tip-off rates, and opportunities for tether snag. Through ground testing and tests performed through C-9 analysis can be performed to predict the separation characteristics of TSATT.

10.0 PROTOTYPE MANUFACTURING

Manufacturing of our separation system prototype primarily took place in the Wilson Student Project Center, which is where S3FL's manufacturing tools and office are located. Also, in order to maintain consistency between parts and reduce tolerance errors, the majority of our machining was completed on the same Bridgeport CNC mill located in the Wilson Center. Lathes in Bob Coury's shop were also utilized when necessary for spring cap machining.

To complete fabrication of our prototype, the housings, mounting plates, and spring caps were machined out of T6061 aluminum. The springs were purchased from Century Spring Corporation and inserted following machining completion. The screws, Vespel rod stock, and Teflon tape were purchased from McMaster-Carr and also used for assembly. Finally, we used TiNi Aerospace P-5 pinpullers that were used in a previous S3FL project. For prototype fabrication we proceeded with the following manufacturing plan:

1) Face off jig plate with CNC Bridgeport Mill
2) Drill holes for dowel pins
3) Insert dowel pins
4) Mill lower housings out of T6061 aluminum
5) Drill holes for dowel pins and thru holes for pinpuller shafts
6) Drill and tap holes for mounting screws
7) Mill upper and lower mounting plates out of T6061 aluminum
8) Mill cavities for upper and lower mounting plates
9) Mill depressions for spring caps
10) Drill and tap mounting screw holes in upper and lower mounting plates.
11) Mill Upper housings out of T6061 aluminum
12) Drill and tap screw mounting holes in upper housings
13) Drill press-fit hole for bushings
14) Insert bushings (press-fit)
15) Drill holes in bushings
16) Drill holes for spring silos
17) Insert springs and secure using washer and screw
18) Lathe spring caps(8) out of T6061 aluminum
19) Secure Spring caps to upper housings with screws
20) Secure housings to mounting plates with screws
21) Secure mounts to upper and lower satellite end plates
22) Secure pinpullers to housings with screws
23) Apply Teflon tape to lower housings
24) Secure upper housings to lower housings by compressing springs with spring caps and inserting pins in the through holes

To be more specific, the pieces for the housings were first rough cut out of a large block of T6061 aluminum using a band saw. Small blocks of dimensions 3.875" by 1.050" by 2.000" were cut from the large block and then more precisely machined using the Bridgeport CNC mill with a ½ inch mill bit. In order to secure the work pieces to the jig plate, dowel pin holes were set and drilled. Each piece was then secured to the jig plate and then secured to the mill deck. The center thru holes were the first items to be drilled using a #50, as all other aspects of the housings were dimensioned off of these. Next the mounting holes for the pinpullers were drilled using a #7 drill bit. After this, the cavity between the spring silos was milled using a ½ inch mill bit. Finally, the angled interface was milled with an angled jig plate and a 1 inch two flute carbide facing bit. The total machining time for each housing was approximately 10 hours.

Following the pinpuller housings, the mounting plates were machined out of T6061 aluminum and using a ½ inch mill bit. First dowel pin holes were drilled and then the work piece was secured to the jig plate. Finally the cavities were milled out and the holes for the spring caps were drilled and tapped. The total machining time for each mounting plate was approximately six hours.

The complete manufacturing took just over one month and was finalized the day before the Expo.

10.1 Importance of Tolerances

To reduce large tolerance issues, our team has manufactured a jig plate (Figure X) for manufacturing each component. Tolerance issues had the greatest presence in terms of pinpuller hole alignment and angled face interface. By adjusting for tolerance issues with the prototype, problems encountered with the design were reduced. Also, through tight tolerances we manufactured a prototype that is as close to the actual design as possible and therefore extremely beneficial for relating prototype testing to design estimates.

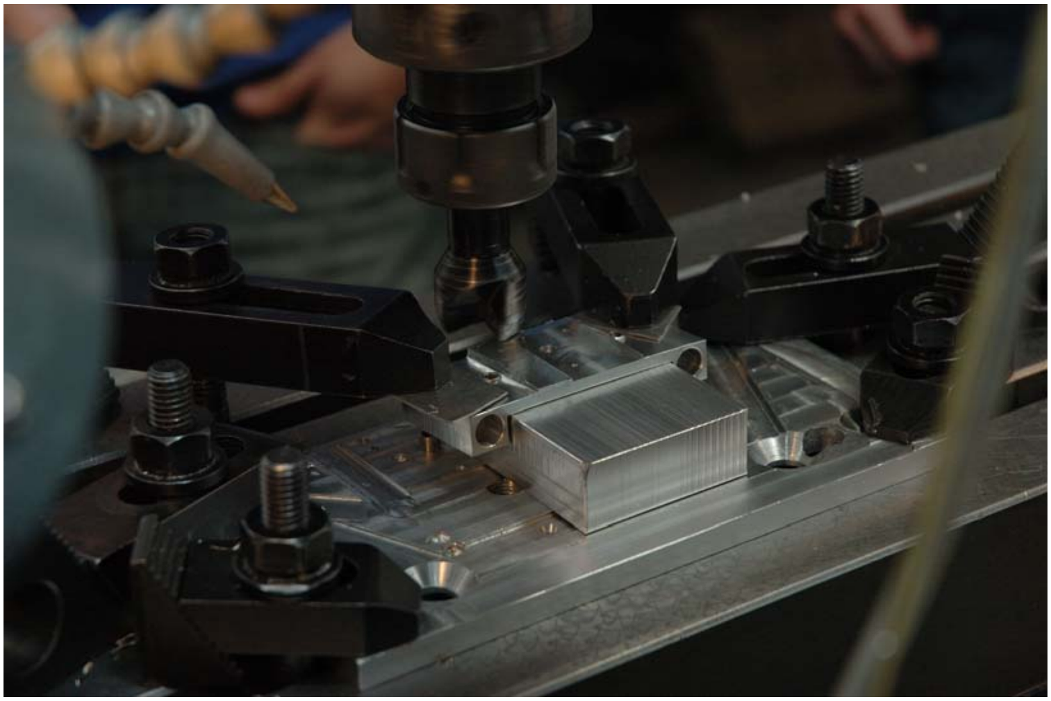


Figure 10.1.1 Angle Jig fastened to flat jig plate

10.2 Differences Between Prototype and Final Design

Mounting holes for housings on the prototype are clearance holes to allow for adjustability due to tolerances. For the prototype we used TiNi Aerospace, Inc. P-5 pinpullers whereas P-10 pinpullers will be used for the final design. We also fabricated our own bushings out of Vespel because the P5 pinpuller shafts are too small for standard dimension bushings. In the TSATT design, standard-dimension flanged Vespel bushings will be implemented.

10.3 Assembly of Key Components

Following machining completion, the most problematic assembly step was aligning all four pinpullers such that the system was secured correctly. Since tolerance issues accumulated throughout the machining process could have led to problems when trying to mount and align the pinpullers to their respective housings and end plates, we used clearance holes and nuts and bolts for most of the prototype assembly. This allowed for adjustability in assembly so as to have all pinpullers as tightly aligned as possible with the tools and time at our disposal.

11.0 VALIDATION

The prototype will undergo a series of tests and measurements to validate that the targets for the engineering specifications have been met. A number of these can be performed on the ground, while others will be validated during the C-9 microgravity flights in August.

11.1 Completed Testing

Several of the required ground tests have been completed successfully. The P-5 pinpuller testing verifies the design of the TiNi pipullers, including power, actuation time and synchronization, and allowable axial loading. The pinpuller tests performed were:

1. Single pinpuller actuation
   - Actuation of a single P-5 pinpuller while mounted to a pinpuller mount.
2. Single mounted pinpuller actuation
   - Actuation of a single P-5 pinpuller with full maize and blue mount assemblies.
3. Dual pinpuller synchronized actuation
   - Simultaneous actuation of two P-5 pinpullers on pinpuller mounts.
4. Integrated system dual pinpuller drop test
   - Simultaneous actuation of two P-5 pinpullers while integrated into full separation system.

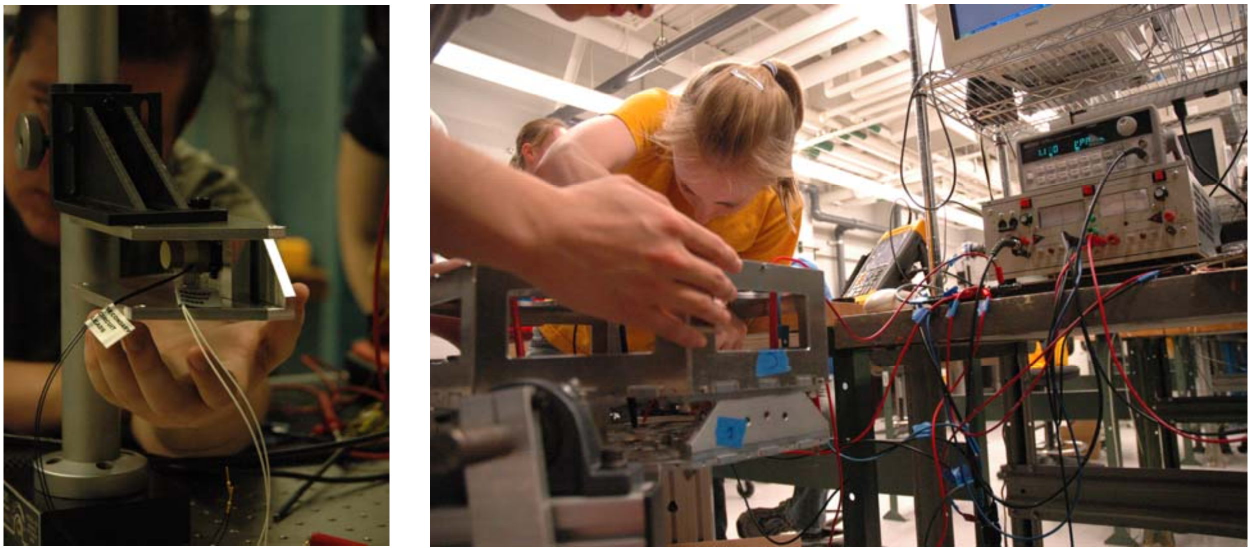


Figure 11.1.1: left) Setup for single mounted pinpuller actuation test. **right)** Setup for integrated system dual pinpuller drop test.

The current and voltage profiles were captured for each test, allowing us to verify the power and actuation time. The synchronization of the pinpullers was within 6 ms, with an overall actuation time of 100 ms. This is well within our specification. The resistance of each pinpuller is 6.3 ± 0.1 **Ω**, and they each require 0.55 amps to actuate. This translates to 1.9 W per pinpuller, for a system total of 7.6 W. To achieve the same actuation time with the P-10 pinpullers, which have a resistance of 5.8 ± 0.5 **Ω**, each pinpuller would require 0.8 amps for a total of 14.8 ± 0.3 W [8]. Therefore, the system currently does not meet our specification of 12 W. However, the TSATT power and electrical team is attempting to accommodate more power. Through the drop test, we also verified the alignment and clearances of the prototype. Similar testing will be done on the P-10 pinpullers for the TSATT mission, verifying the synchronization, actuation time, power, and loading capabilities.

11.2 Validation By Inspection

We verified the vertical height and Center of Gravity by simple inspection. The vertical height was measured to be 2.00 ± 0.01”, which meets the specification. The system was designed to be perfectly symmetrical, so if the tolerances are small, the Center of Gravity should meet the specification. We measured the parts and holes to be within 0.01” of the specified dimensions, so we are confident that the Center of Gravity is within 0.25” of the center.

Since the prototype does not match the final design exactly, we could not find the mass by measurement. However, we do know the material properties and dimensions, and we found the projected system mass to be 2.2 kg using our SolidWorks model. This is slightly over our specification of 2 kg, but close enough for the TSATT team at this stage of the project.

11.3 Future Ground Testing

The basic operation of the system will be tested on the ground prior to the C-9 flights, as well as maximum and minimum temperature. An air table or ball bearings will be used to test the basic operation of the prototype. While the separation velocity cannot be measured, the friction will be reduced as much as possible to allow the two payloads to separate. A thermal chamber will be used to verify continued operation under the maximum and minimum temperature conditions. The 20g axial loading safety factor cannot be directly tested, but we can verify that it is greater than one by showing survivability during the tests prescribed by the Nanosat-4 guidelines: sine burst, random vibration, and shock tests [7]. Since the prototype is not designed to withstand the same loads as the final design, load-rated rods will be substituted for the P-5 pinpullers. The full battery of tests would be performed on the flight hardware, including the pinpullers, to qualify it.

11.3 C-9 Microgravity Flights

The C-9 microgravity flights will serve to verify the tip-off rate and push-off velocity of the prototype. Each separation will be recorded by a number of video cameras, and colored markers will be placed at key points on the prototype to enable analysis of the velocity and rotation of the two payloads. The synchronization of actuations will be measured by the current profile through each pipuller. While the number of cycles for the final flight hardware cannot be verified in advance, the number of actuations each prototype pinpuller undergoes will be documented. If the P-5 pinpullers survive the 100 cycles they are rated for, we can reasonably assume that the P-10 pinpullers will as well, since the same engineering and testing methods are used for both.

12.0 DESIGN CRITIQUE

We believe that the design meets all the design specifications and requirements set forth by our sponsor.

The design is compact and fits within the space constraints put forth by our sponsor. The design also allows for a great deal of stiffness in the structure in the unfired position, this would prevent vibration stresses during launch. The pinpullers have also demonstrated the ability to fire simultaneously on tests. The pinpullers do not require high current for actuation compared to the other mechanisms that we considered. There are also minimal corners for the tether to be snagged on.

The most notable design change caused by the validation of the prototype is the change to the spring caps. The spring caps were designed to be secured to the mounting plate; however, this caused issues with fitting the two halves of the separation system together. The spring caps were loosened such that they could move in the plane of the mounting plate while still secured in the normal direction. Thus, in the unfired position, only the inclined faces would prevent movement in the plane of the mounting plates. This design change reduces the guiding effect that the spring caps would have during the firing sequence.

Another weakness in the design is the lack of redundancy in the individual pinpuller mounts. The entire system would fail should any of the four pinpullers fail to function. Incorporating a toggle would help reduce our dependence on four components functioning perfectly, but would also increase the power drawn by the system.

We have also identified that having the primary load path going through the actuators is another weakness of the design. This might cause the actuators to be more likely to fail because they experience loads that are closer to their rated limits.

There are also strict manufacturing and assembly tolerances to meet for the design to be successful. The design requires that the parts be machined to very close tolerances for successful operation. Due to the limitations of the Wilson Student Project Center machines, the TSATT flight hardware will most likely have to be manufactured out-of-house.

13.0 RECOMMENDATIONS

Based on our experiences throughout the semester, particularly in the week leading up to the completion of our prototype, there are several recommendations we would like to provide to our sponsor and those continuing with the project.

13.1 Fabrication

Upon assembly of the separation system prototype, it was discovered that once the spring caps were secured to the mounting plates, it was difficult to line them up with their respective spring silos, and therefore difficult for the two halves to properly sit together. In response to this, all the caps were left slightly loose so as to allow for adjustment upon insertion in the silos. The cause of this is most likely due to tolerance errors from manufacturing. Not all caps were made on the same lathe, and therefore minor inconsistencies arose. Also, the spring caps were the first components completed but were not implemented until final assembly of the prototype. To rectify this situation, we suggest re-fabrication of the eight spring caps, with particular attention paid to ensuring proper dimensions and tolerances. Dimensioned drawings are included in Appendix B and will be supplied to S3FL.

Another area of concern is the spring cap/spring interface. During assembly, the springs were wrapping around the caps thus getting stuck in the silo and ruining the springs. This is partially due to the size of the spring caps, and largely due to the size of the springs. When calculating the spring constant and also the size of the springs required to meet the requirements of both C-9 and TSATT, analysis was performed under the assumption of zero gravity. Therefore the appropriate spring dimensions were quite small, especially the thickness of the wire. In response to this, we recommend that further spring analysis be carried out, particularly in regards to finding a thicker spring (wire thickness). Additionally, further efforts might be made to fashion some sort of cover for the spring, such as a washer, so that the spring cap does not contact the spring, thereby reducing the likelihood that the spring would wrap around the cap. Because the springs for C-9 are much thinner and smaller than those for TSATT, we do not anticipate a problem with the final design, but for testing purposes, the problem must be addressed for C-9.

Finally, to ensure proper tolerances for the final system, members of S3FL might find it helpful to measure the dimensions of the components with the aid of a CMM device. Though components of the prototype were machined with special attention paid to precision, further assistance should prove beneficial. There was insufficient time to utilize CMM measurements during the project timeline of ME 450; however, we recommend that members of S3FL utilize the instruments at their disposal to ensure proper dimensions and tolerances.

13.2 Further Testing

To further investigate the validity of our design, we recommend that members of S3FL perform further testing. In addition to testing already completed, we recommend use of a shock test, vibe test (both sine wave and random noise), and possibly a linear separation with the assistance of linear rails or an air table. Of particular concern is the effect of vibrations on the prototype, and whether larger preloads will be necessary. Since the P-5 pinpullers cannot withstand the necessary loading conditions, load-rated rods of the proper diameter should be used in place of the pinpullers during strenuous testing.

14.0 CONCLUSIONS

The TSATT mission required a novel in-house design for a separation system as an alternative to pyrotechnics and commercial separation systems costing well over $110,000. We have finalized our separation system design and completed fabrication of a prototype with full-scale interface and 1/10th scale separation velocity, integrated into a half-mass satellite prototype. Furthermore, we validated the concept of the Four-Mount Pinpuller System by successfully completing a drop test as a result of the synchronization of two pinpullers integrated into the prototype. The drop test proved that the system could sustain a successful retraction of two pinpullers against frictional forces in the bearings, sufficient clearance and friction in separation system mounts under 1g, and an independent separation system capability.

We chose the Four-Mount Pinpuller concept for our final design, and have refined it with analysis. Component sizing and critical safety factors have been verified with calculations. Our prototype has been simplified for machining purposes, and slight modifications have been made to accommodate the C-9 flight. The springs supply a lower preload and separation velocity, and P-5 pinpullers are substituted for the P-10's since they are available immediately. Since the basic structure and operation remains the same, we can validate our design with the prototype, and scale the test results for TSATT.

Our completed prototype consists of 24 separate machined components (housings and spring caps), plus eight springs, four P-5 pinpullers, four sleeve bushings, eight strips of Teflon tape, and assorted nuts, bolts, and screws. For the prototype, springs were purchased from Century Spring Corporation, Vespel rod from McMaster-Carr, and P5 pinpullers were implemented from TiNi Aerospace. Complete prototype manufacturing took just over a month and was operational just before the Design Expo on April 13th.

More validation of our prototype taking place this summer will include developing a circuitry system for safely delivering required power to actuate the four P-5 pinpullers simultaneously, evaluating the entire system's functional capabilities in a thermal chamber, and verifying the load capabilities of the pinpullers. We cannot accurately measure the separation velocity from the spring force prior to the microgravity flights, but we can test basic functionality with an air table and predict that the system can separate independently. Aboard the actual C-9 microgravity flights this summer, S3FL students will be able to measure the tip-off rate and separation velocity. Finally, after all aspects of our separation system design have been proven and all failure points have been corrected, the Four Mount design will be ready for conversion into a flight ready module for the TSATT mission bound for experimentation in outer space.

15.0 ACKNOWLEDGEMENTS

We would like to thank the following people and groups for their invaluable help on this project:

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Tom Liu, Graduate Student, Department of Aerospace Engineering
Yang Li, Undergraduate Student, Department of Aerospace Engineering
Ashley Smetana, Undergraduate Student, Department of Aerospace Engineering
Bogdan Oaida, Undergraduate Student, Department of Aerospace Engineering
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S3FL Machining Team
Abe, Bob, Charlie and Devin – the P-5 pinpullers

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Bob Coury, Department of Mechanical Engineering
Marv Cressey, Department of Mechanical Engineering
Steve Vice, Department of Mechanical Engineering
John Mears, Department of Mechanical Engineering
Wilson Student Team Project Center Staff

Lockheed Martin:
Ed Boesinger, Senior Manager, Lockheed Martin Space Systems Company

16.0 REFERENCES

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http://www.hstc.com/sepbolts.html

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[5] Saab Technical Brochure
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[6] Starsys Webpage
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[8] TiNi Aerospace Webpage http://www.tiniaerospace.com

APPENDIX A- DESIGN CONCEPT CATALOG

A.1 Pinpuller

The pinpullers bear the load directly in the basic four-pinpuller concept. In the first variation, the pinpullers are mounted on four separate housings around the faceplate of the lower payload (Figure A.1.1). The pins protrude through holes in the upper payload to hold it securely. When the pins retract, the upper payload is ejected by the eight compression springs located in housings by the pinpuller mounts.

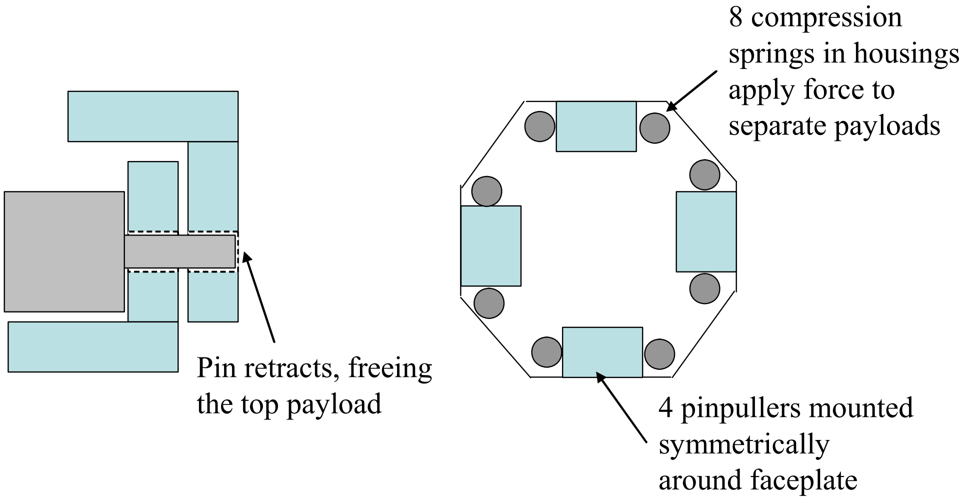


Figure A.1.1: Four-Mount Pinpuller Concept

In the second variation, the pinpullers are mounted to the inner of two concentric rings (Figure A.1.2). The pins protrude through holes in the outer ring to hold the payloads together. Instead of separate spring caps and silos, the springs are compressed directly by the upper ring.

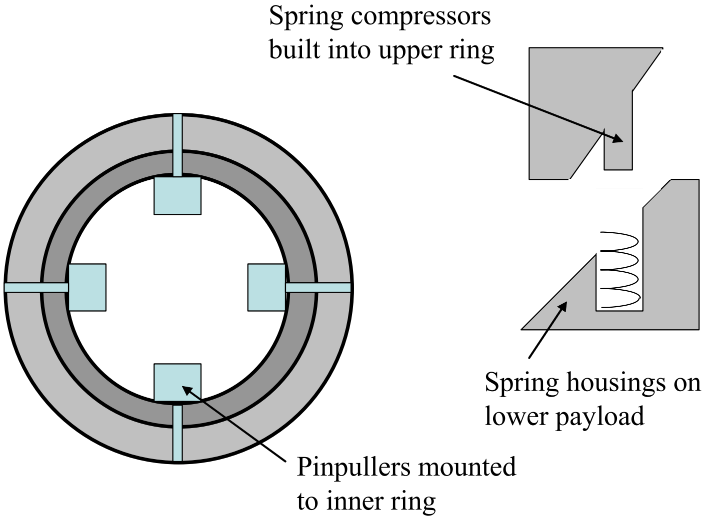


Figure A.1.2: Ring-mounted Pinpuller Concept

A.2 Pinpuller Toggle

The idea behind the pinpuller toggle is to introduce redundancy into the system. The pinpullers are paired, and if either of the two pinpullers actuates, the toggle will release the upper payload. The basic concept is shown in Figure A.2.1. The system could be made with either two or four pairs of toggled pinpullers.

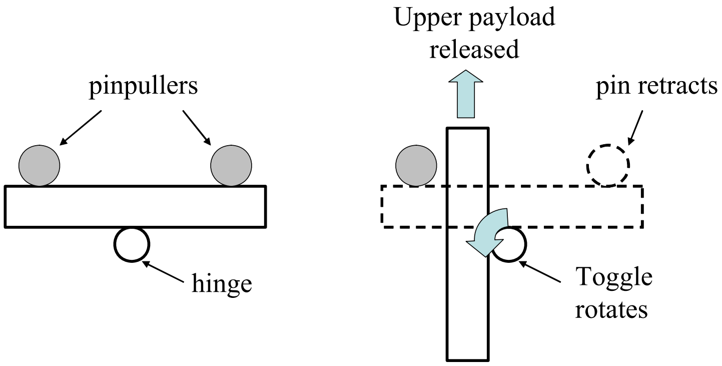


Figure A.2.1: Toggled Pinpuller Concept

A.3 Rods

The basic rod concept is to use a mechanical setup with rods that can be actuated simultaneously by a single actuator (or toggled actuator) in the center. There are five different variations.

1. The first concept has four spring-loaded rods pressed up against a ring (Figure A.3.1). The ring is preloaded by a torsion spring, and held in place by a pinpuller. When the pinpuller releases the ring, it rotates until the rods line up with holes in the ring. The compression springs will then push the rods into the holes in the ring, and out of the holes in the other half of the satellite, separating the two payloads.

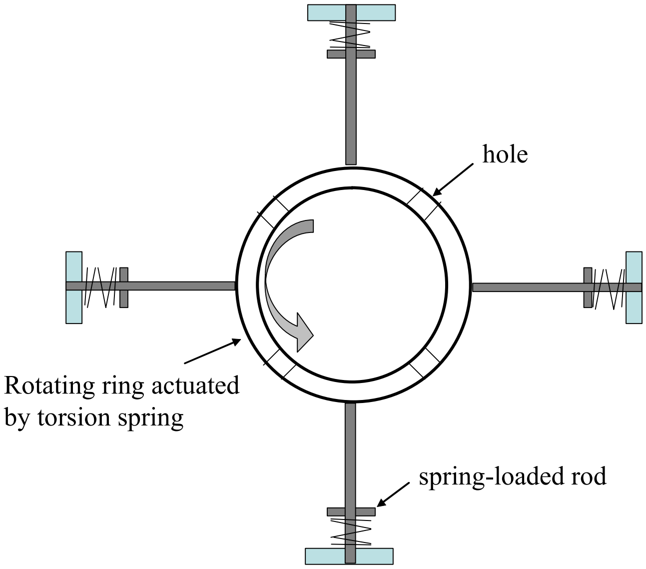


Figure A.3.1: Ring with Holes Concept

2. An alternative to holes in the ring is to make it a cam, shaped so the rods will retract quickly as the ring turns (Figure A.3.2). The rods could either be spring-loaded, or held in tracks on the cam. This would reduce the stress concentrations in the ring, and a track would reduce the possibility of failure introduced by the compression springs. However, for simultaneous actuation, the cam would need to be precisely machined, and alignment would be essential. Friction would also become an issue with the track option, and bearings or lubricant would need to be employed.

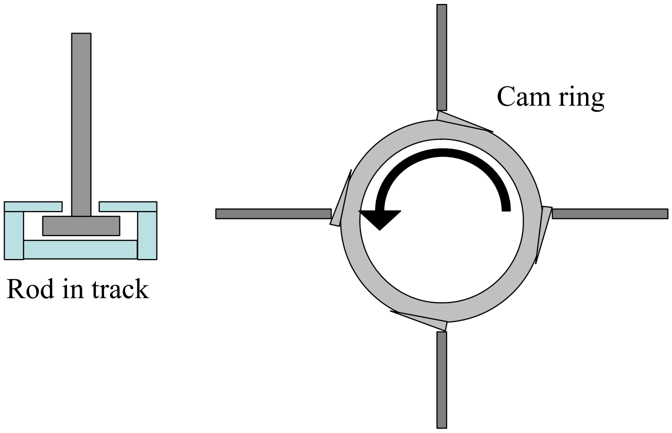


Figure A.3.2: Cam Ring Concept

3. A third option is to actuate the ring vertically, eliminating the need for a torsion spring (Figure A.3.3). However, it would introduce more compression springs, and more complex geometry to keep everything symmetrical. This design might not be able to meet the vertical height requirement, and the extra spring housings would add extra mass.

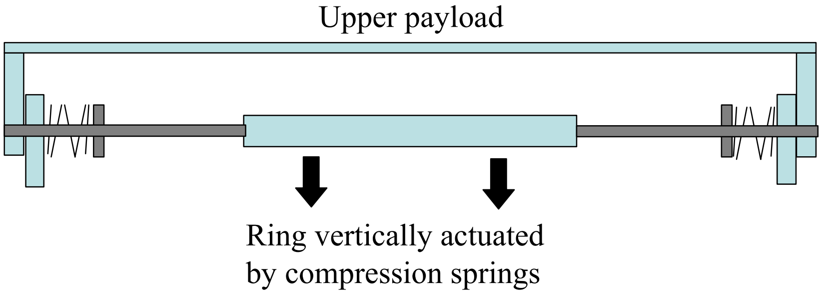


Figure A.3.3: Vertically Actuated Ring Concept

4. Another concept is to put gear teeth on the ring and rods, and offsetting the rods in a symmetrical pattern to allow the ring to move them (Figure A.3.4). This eliminates the need for spring actuation, but introduces more opportunity for tether snag. It may also be more difficult to attach the off center design due to the geometry of the faceplates.

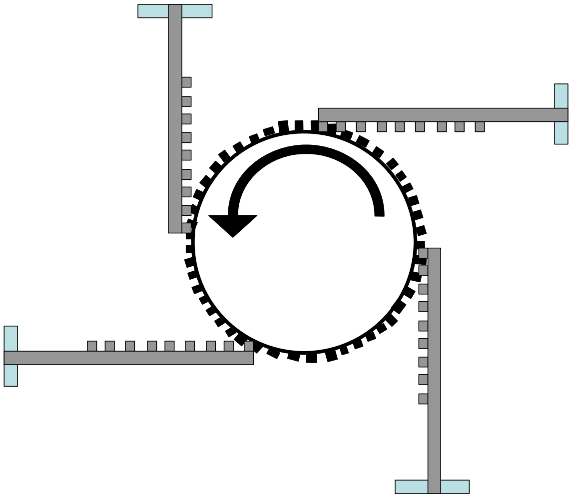


Figure A.3.4: Gear Concept

5. A fifth variation is to use a motor to actuate the ring. This would work for any of the previous options with the exception of the vertical actuation, when a pinpuller would make more sense. The motor would eliminate the need for spring actuation on the ring, but would be larger than a pinpuller.

A.4 Clamps

The basic clamp concept uses a spring-loaded clamp to hold the two payloads together. This increases the surface contact area, and eliminates the possibility of failure by friction as the pins or rods pull out of holes. There are four different variations of the clamp concept.

1. The first concept is tracked from the Standard Lightband described in the Benchmarking section. The basic concept is shown in Figure A.4.1, including the layout, the wire release housing, and the clamp. It uses a wire in tension to hold four clamps in place. The clamps are spring-loaded, so when the wire becomes de-tensioned, the clamps will rotate about their hinges and free the upper payload. The wire release mechanism is operated by toggled pinpullers. The wire is wrapped around two pins so that if either or both retract, the wire will become loose. While this toggle makes the system redundant in a very simple way, it would be difficult to reset for the C9 mission. The spring-loaded clamps would be more complex than simple pinpuller housings, and the wire would need to be completely covered to avoid tether snag. This would add mass and complexity to the system.

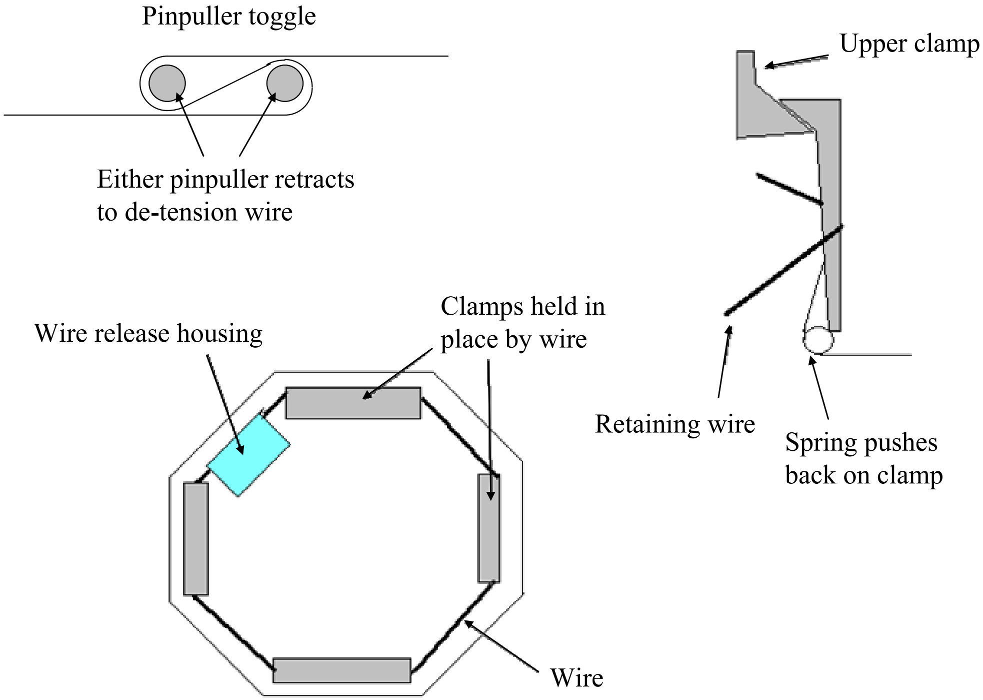


Figure A.4.1: Lightband Replica Concept

2. The second variation is the clampband concept (Figure A.4.2). A flexible ring would wrap around the four spring-loaded clamps the keep them in place. It would be in tension, with overlapping ends held together by a pinpuller. When the pinpuller retracts, the clampband will spring open, releasing the clamps and the upper payload. However, a flexible band would be very difficult to design, and the shear load on the pinpuller might be too great.

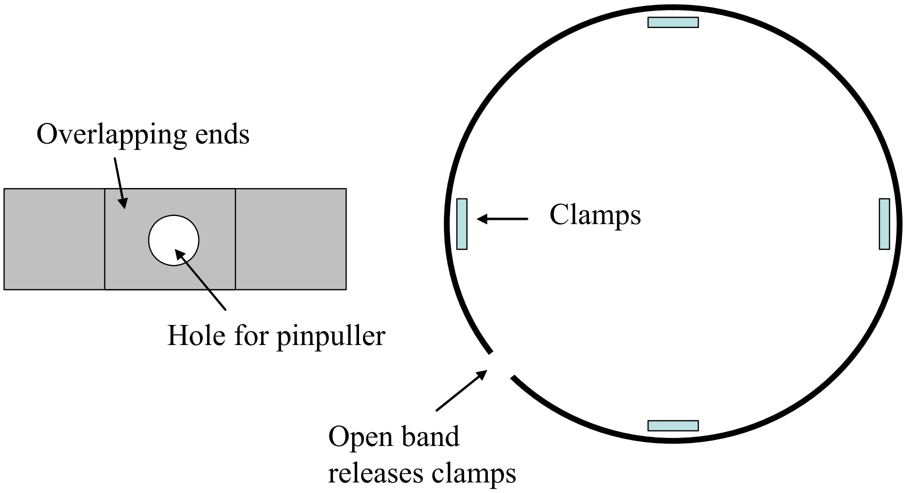


Figure A.4.2: Clampband Concept

3. The third variation is derived from the Motorized Clampband, which uses a series of linkages to make an inner ring "shrink". While a linkage system would be beyond the scope of this project, a simpler alternative is to use to half-rings that can be brought together to effectively "shrink" the circle. The basic concept is shown in Figure A.4.3. The half-rings would be connected to spring-loaded clamps, which would release the upper payload when the rings are brought together. This design could not be made completely symmetrical, however, which might affect the stability of the system or the tip-off rate at separation.

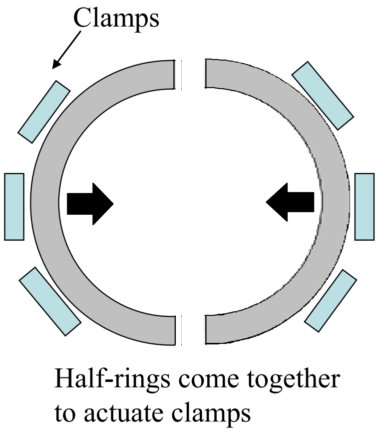


Figure A.4.3: Half-ring Clamps Concept

4. The fourth variation is also related to the earlier rod concepts (Figure A.4.4). Instead of the rods fitting into holes in the upper payload, they would attach to spring-loaded clamps. While slightly more complicated, this concept adds greater contact area and reduces friction.

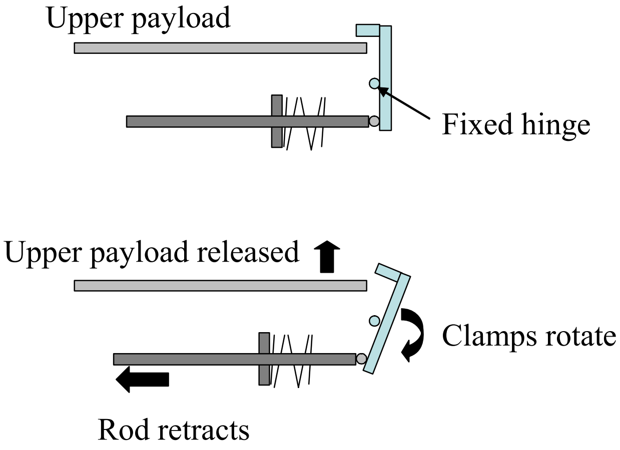


Figure A.4.4: Rod-actuated Clamp Concept

A.5 Ring

The double ring concept uses the idea of concentric rings shown in previous concepts (Figure A.5.1). The two rings would have slots and tabs, restricting or allowing vertical travel depending on the relative orientation of the rings. The upper ring would remain fixed, while the lower would be torsion spring-loaded and rotate on bearings. A pinpuller would be used to hold the lower ring in place until separation. This concept would be very secure because of the large contact area, but the rings would be large and heavy, and difficult to machine. The bearings would also take up a lot of space, and make the design more complex. The twisting of the lower ring might also make the payloads spin relative to each other as they come apart.

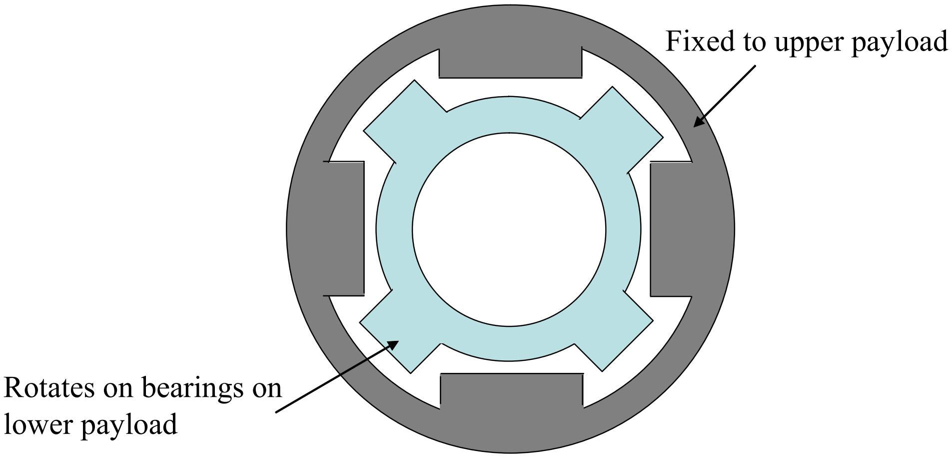


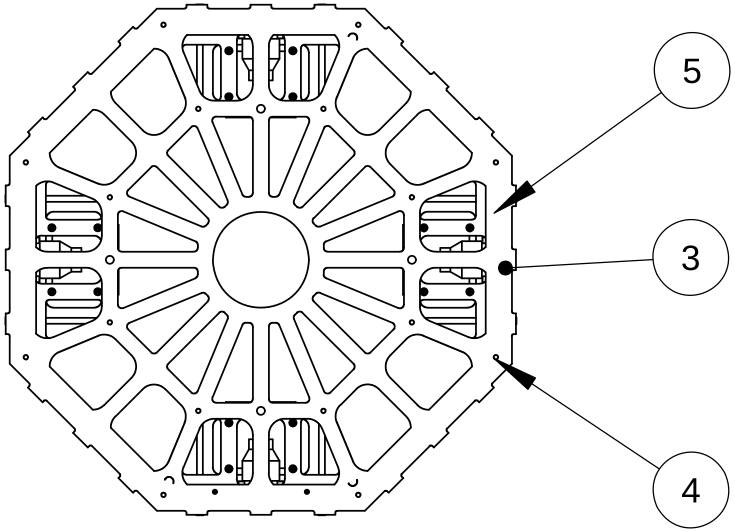
Figure 5.1: Double Ring Concept

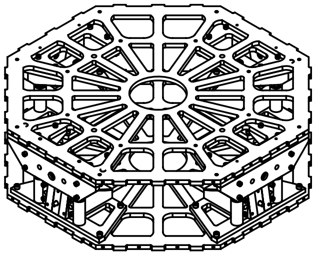
APPENDIX B- BILL OF MATERIALS AND DETAILED DRAWINGS

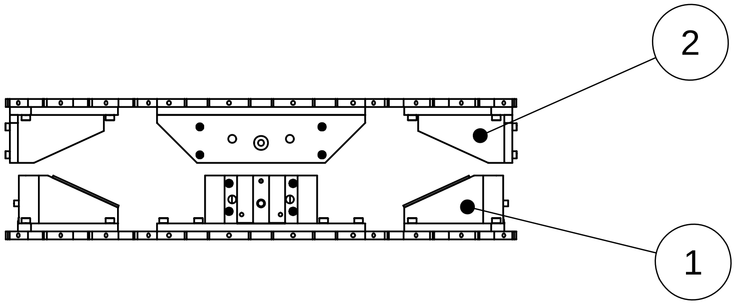
These drawings can be found on the following pages:

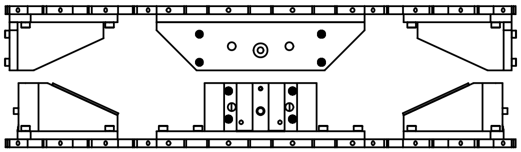
450-SEPARATION SYSTEM ASSEMBLY
450-01 PINPULLER-BLUE MOUNT ASSEMBLY
450-01.01 TiNi P-10 Pin Puller
450-01.02 Pin Puller Mount (prototype)
450-01.03 Blue Mounting Base (prototype)
450-01.04 Cover Plate
450-01.05 Gusset
450-02 BEARING MAIZE-MOUNT ASSEMBLY
450-02.01 Bearing Mount (prototype)
450-02.02 Maize Mounting Base (prototype)
450-02.03 Spring Push Cap
450-03 MLVI-preEDU

ITEM NO.	PART NUMBER	COST	QTY
1	450-01 TSATT PINPULLER-BLUE MOUNT ASSEMBLY	$5230.48 (ea.)	4
2	450-02 TSATT BEARING-MOUNT ASSEMBLY	$66.34 (ea.)	4
3	450-03 TSATT MLVI	$150.00 (plate)	2
4	McMaster-Carr #92196A194 Socket Head Cap Screw 8-32 X 1/2"	$5.35 (100 pk.)	32
5	McMaster-Carr #92196A110 Socket Head Cap Screw 4-40 X 1/2"	$3.97 (100 pk.)	8
	Total Cost of TSATT Separation System	$21,496.60	



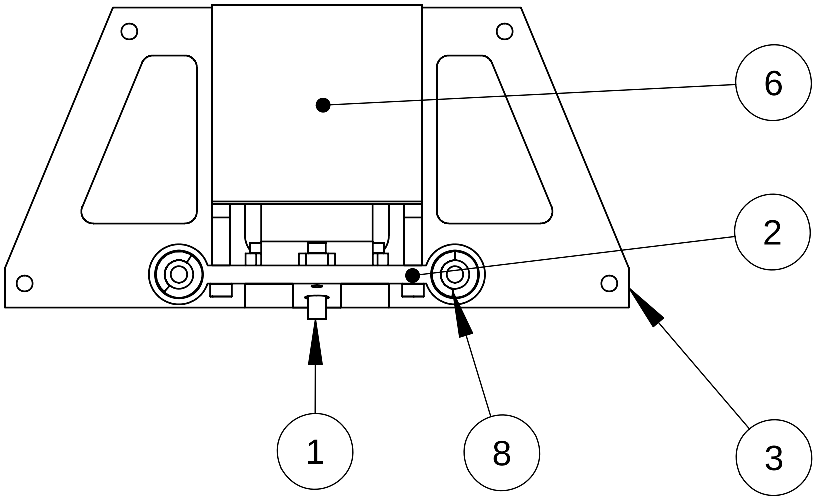


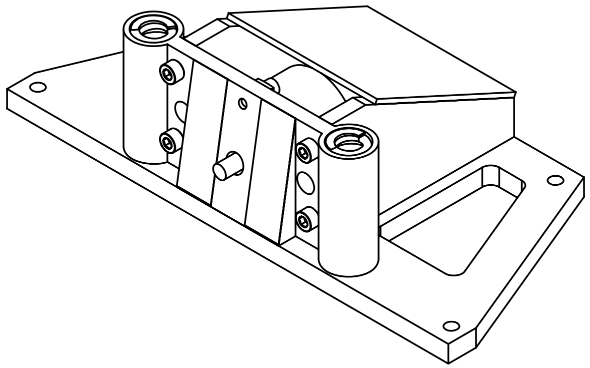


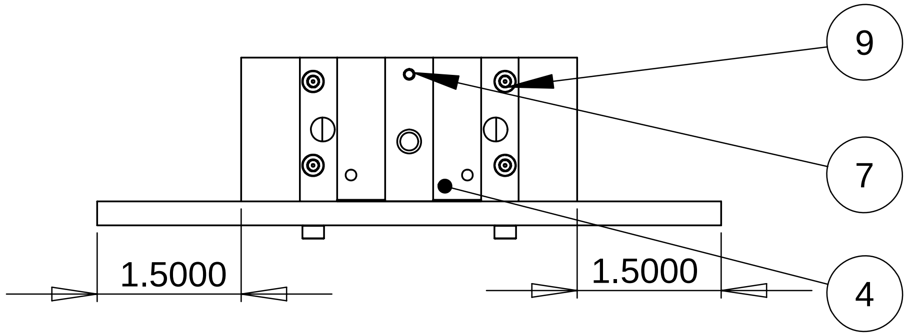


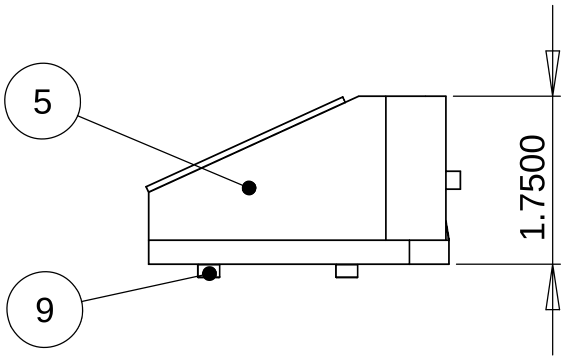
450-SEPARATION SYSTEM ASSEMBLY

ITEM NO.	PART NUMBER	COST	QTY
1	450-01.01 TiNi P10 Pinpuller	$5,200 (ea.)	1
2	450-01.02 TSATT Pin Puller Mount	$8.00 (plate)	1
3	450-01.03 TSATT Blue Mounting Base	$5.00 (plate)	1
4	450-01.04 Cover Plate	$1.00 (sheet)	1
5	450-01.05 Structural Gusset	$5.00 (plate)	2
6	Century Spring #71639S Stainless Steel 0.54" OD, 1.5" Length	$30.00 (24 pk.)	2
7	McMaster-Carr #76495A52 Tape Coated with Teflon PTFE .003" Thick, 0.5" Width	$5.03 (5-yd roll)	2
8	McMaster-Carr #92196A107 Socket Head Cap Screw 4-40 X 5/16"	$3.40 (100 pk.)	3
9	McMaster-Carr #92196A149 18-8 Socket Head Cap Screw 6-32 X 9/16"	$7.49 (50 pk.)	8

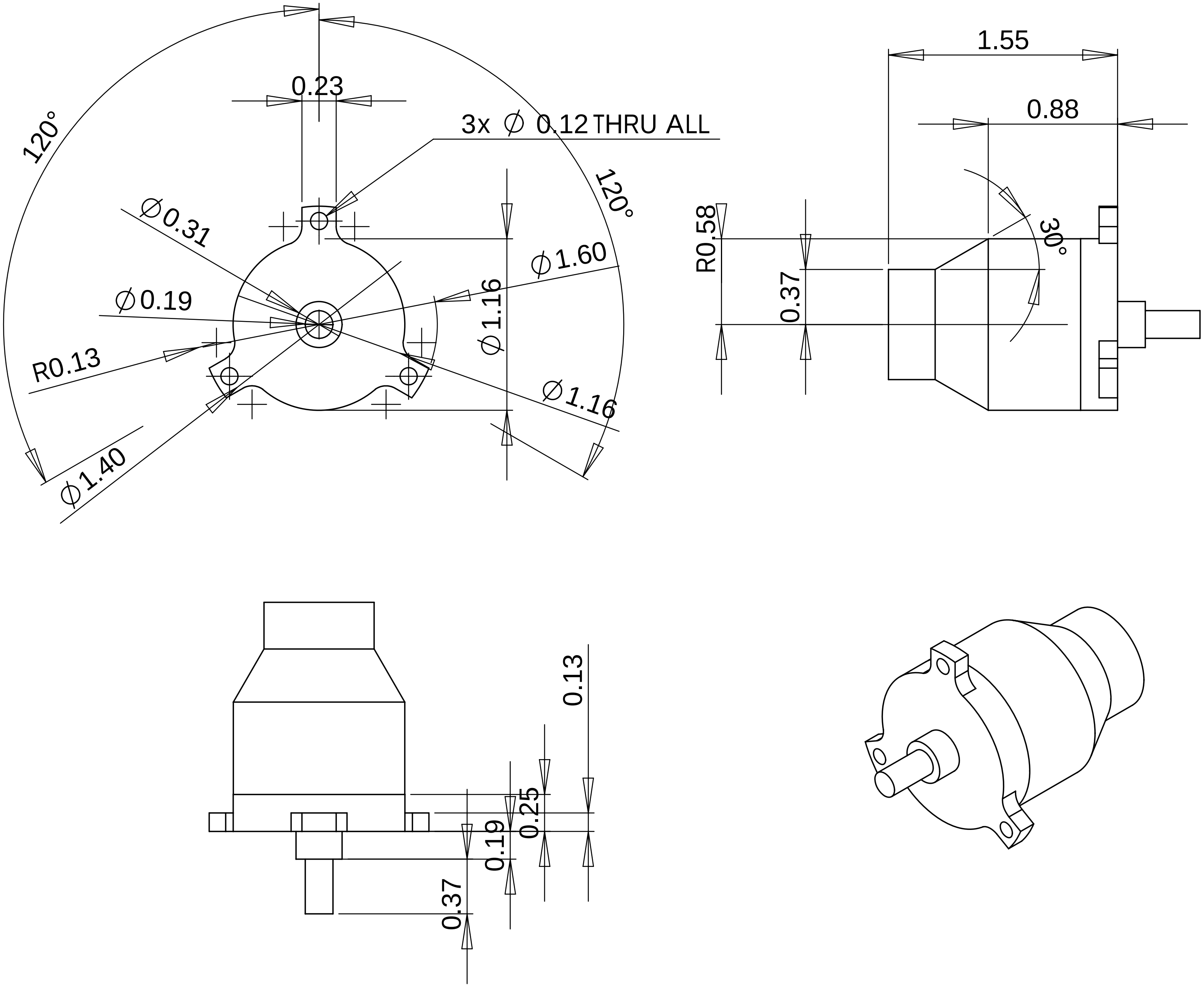




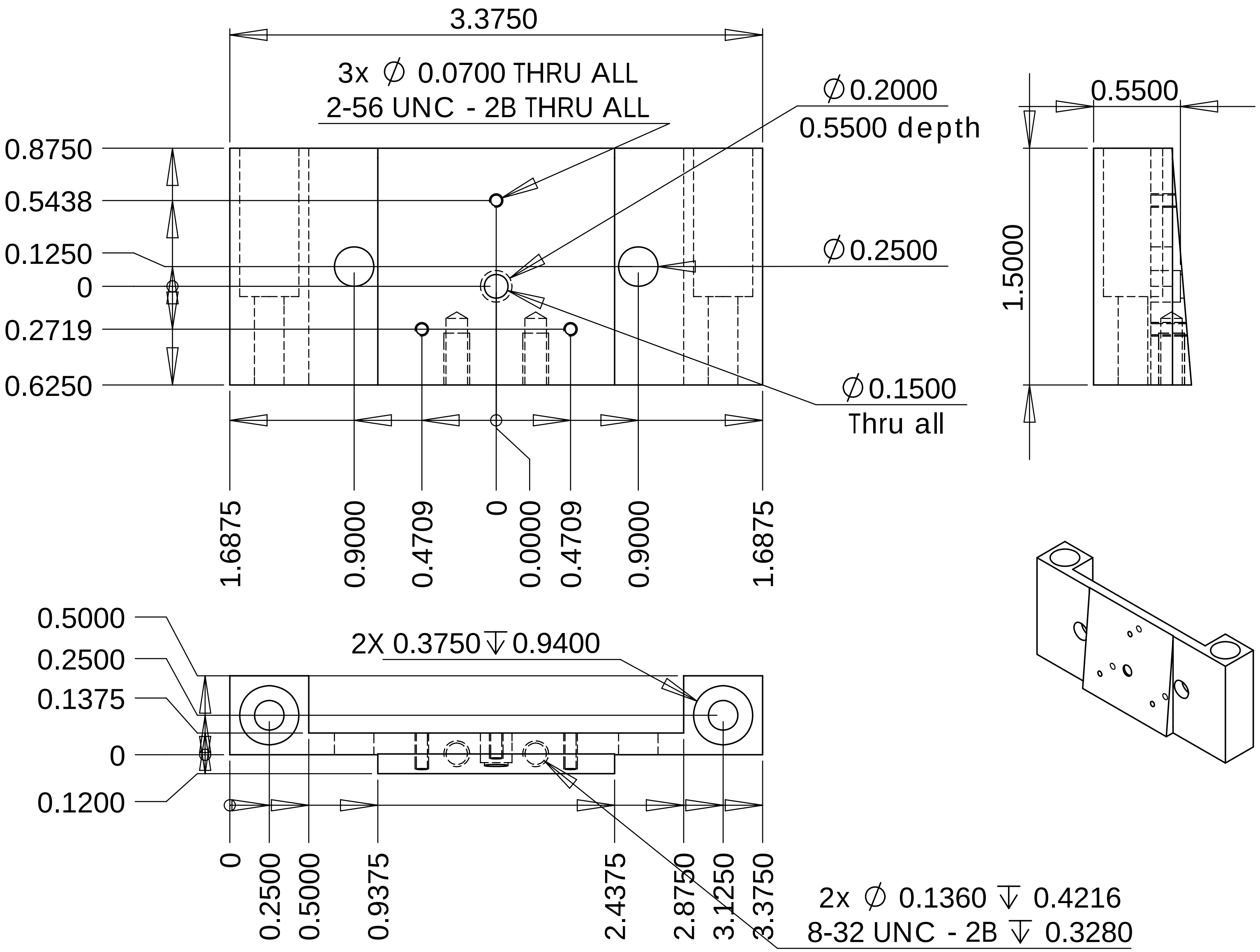




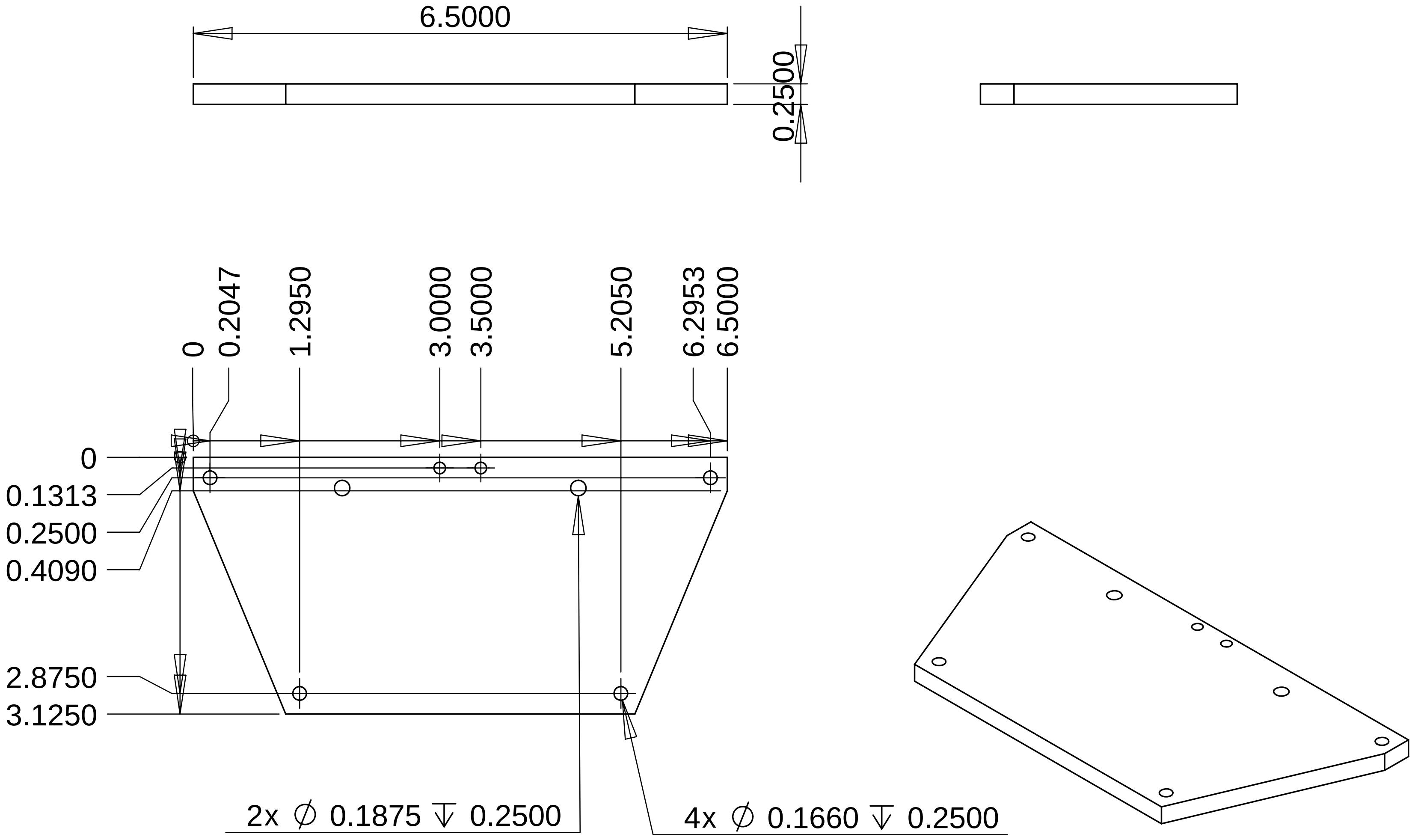
450-01 PINPULLER BLUE-MOUNT ASSEMBLY



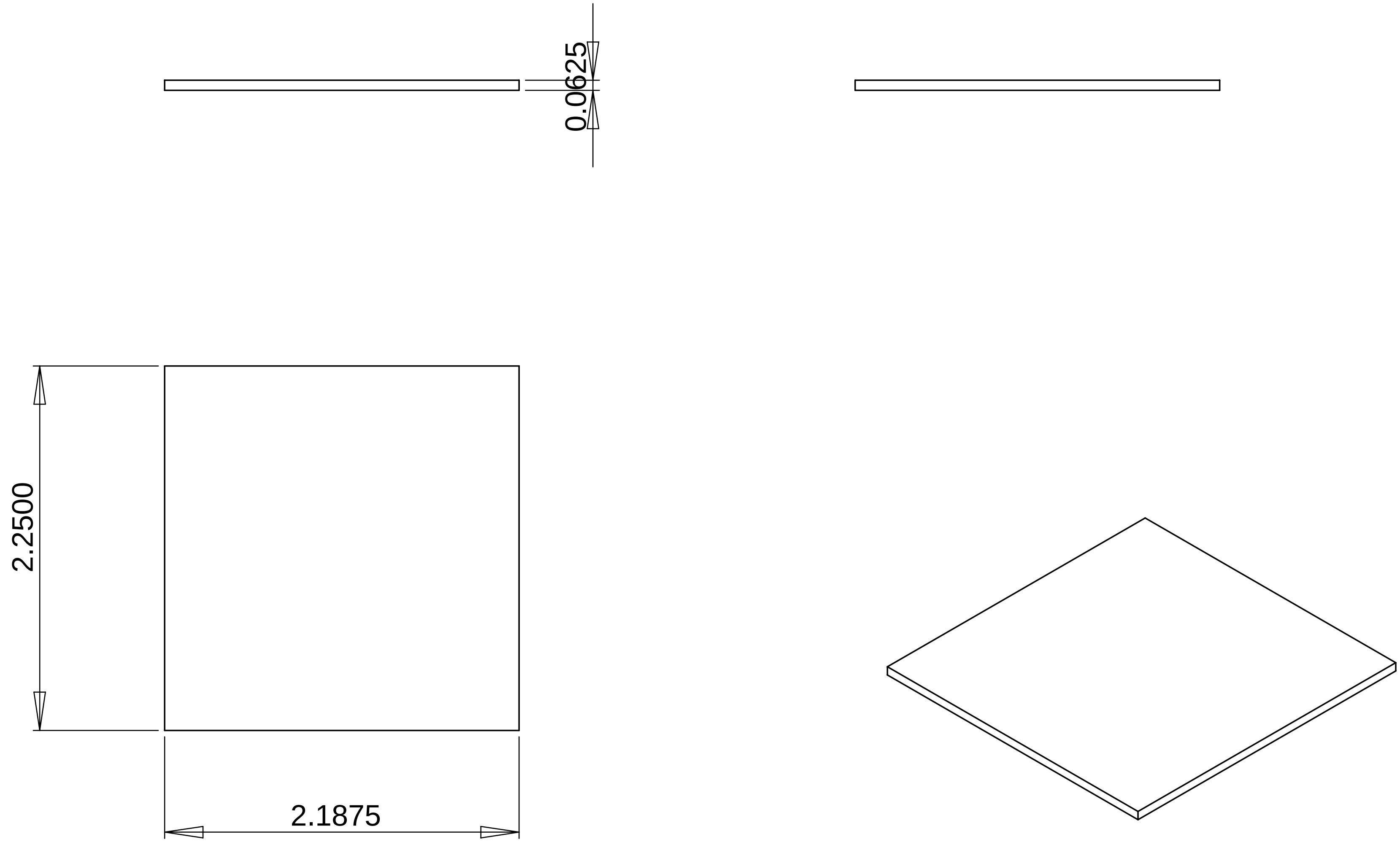
450-01.01 TiNi Pin Puller



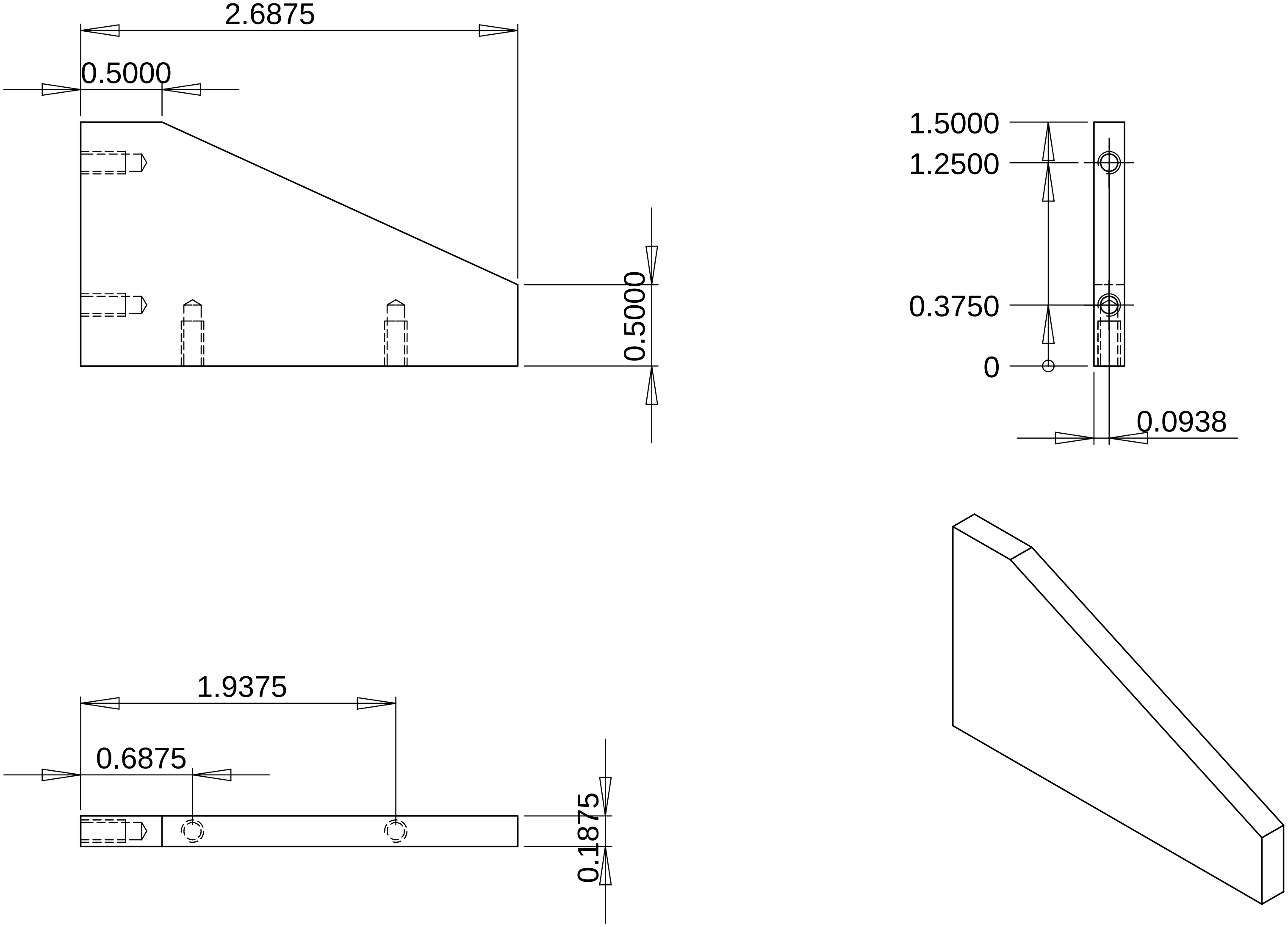
450-01.02 Pin Puller Mount



450-01.03 Blue Mounting Base



450-01.04 Cover Plate



450-01.05 Gusset

ITEM NO.	PART NUMBER	COST	QTY
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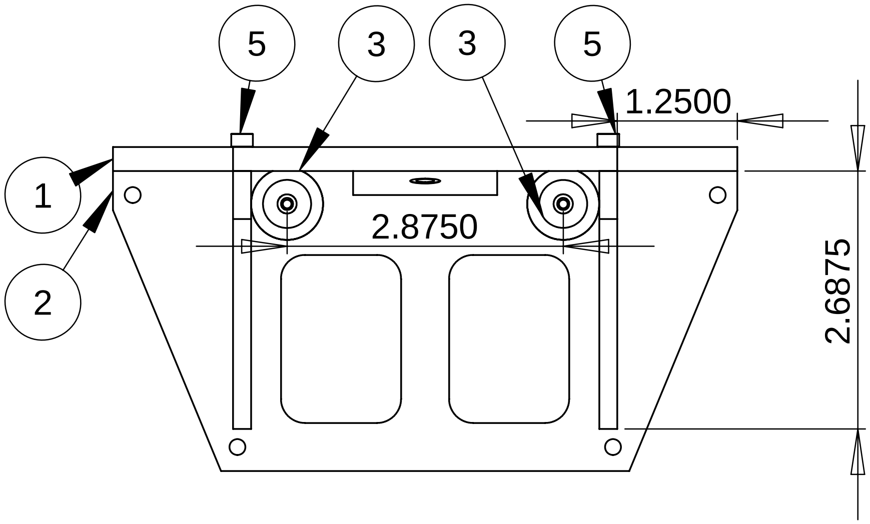
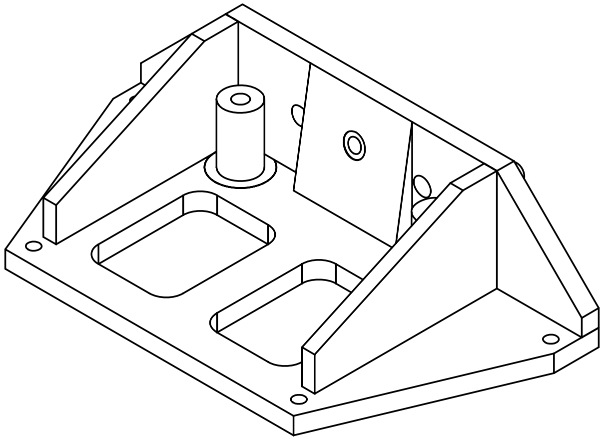
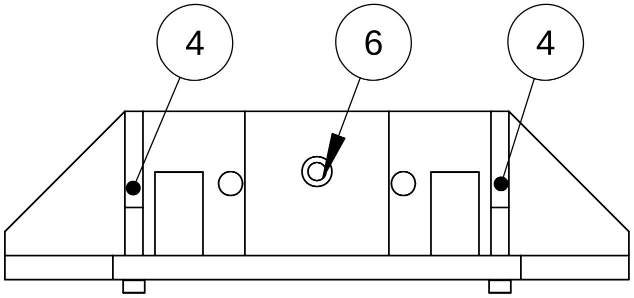
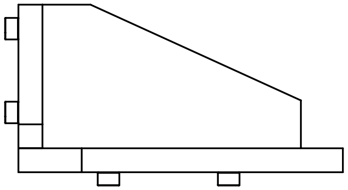
2	450-02.02 TSATT Maize Mounting Base	$5.00 (plate)	1
3	450-02.03 TSATT Spring Push Cap	$15.00 (rod)	2
4	450-01.05 Structural Gusset	$5.00 (plate)	2
5	McMaster-Carr #92196A149 18-8 Socket Head Cap Screw 6-32 X 9/16"	$7.84 (50 pk.)	8
6	McMaster-Carr #58315K51 3/16" Vespel Bearing, 5/16" Od, 1/4" L, 7/16" Flange	$29.38 (ea.)	1

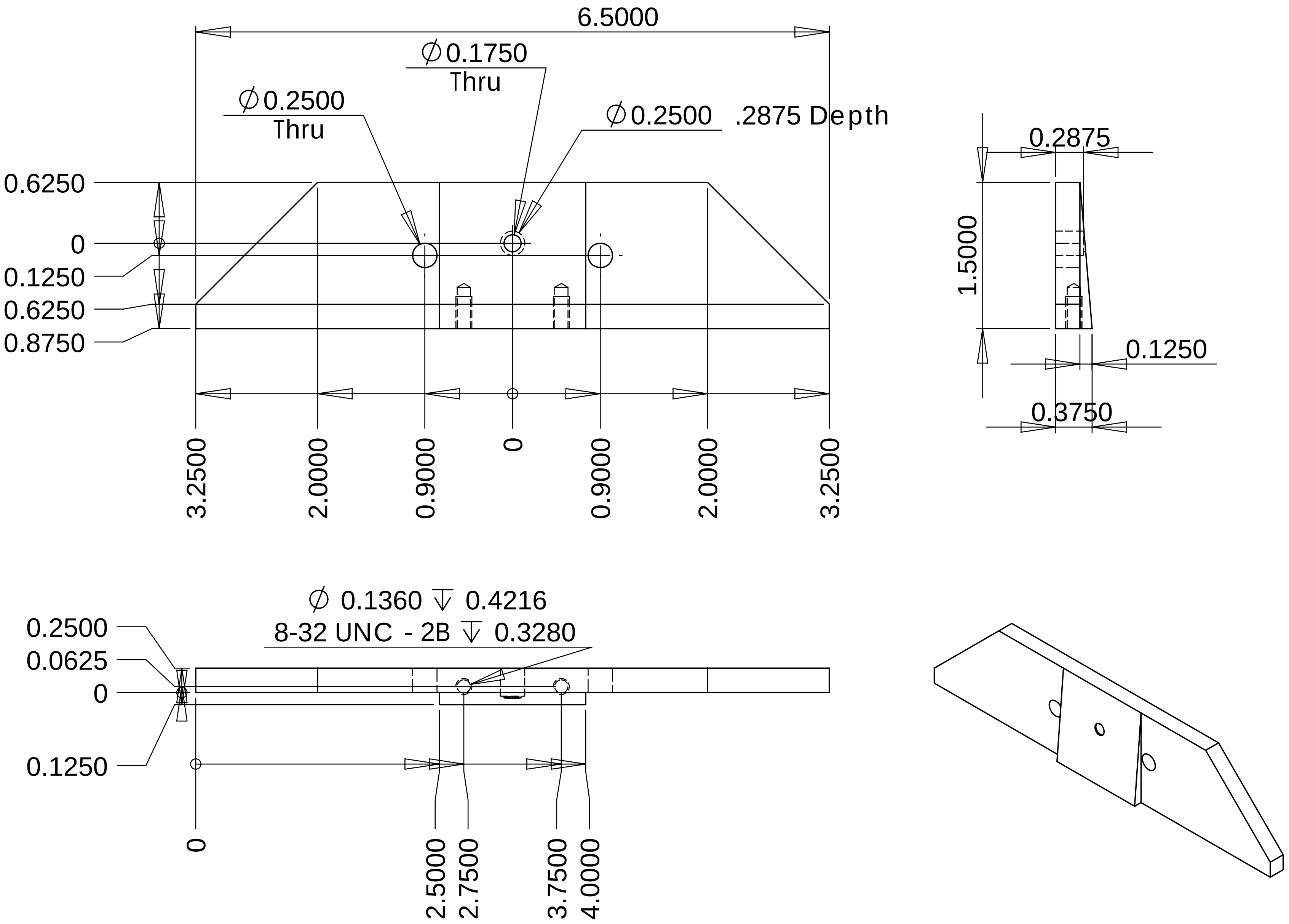




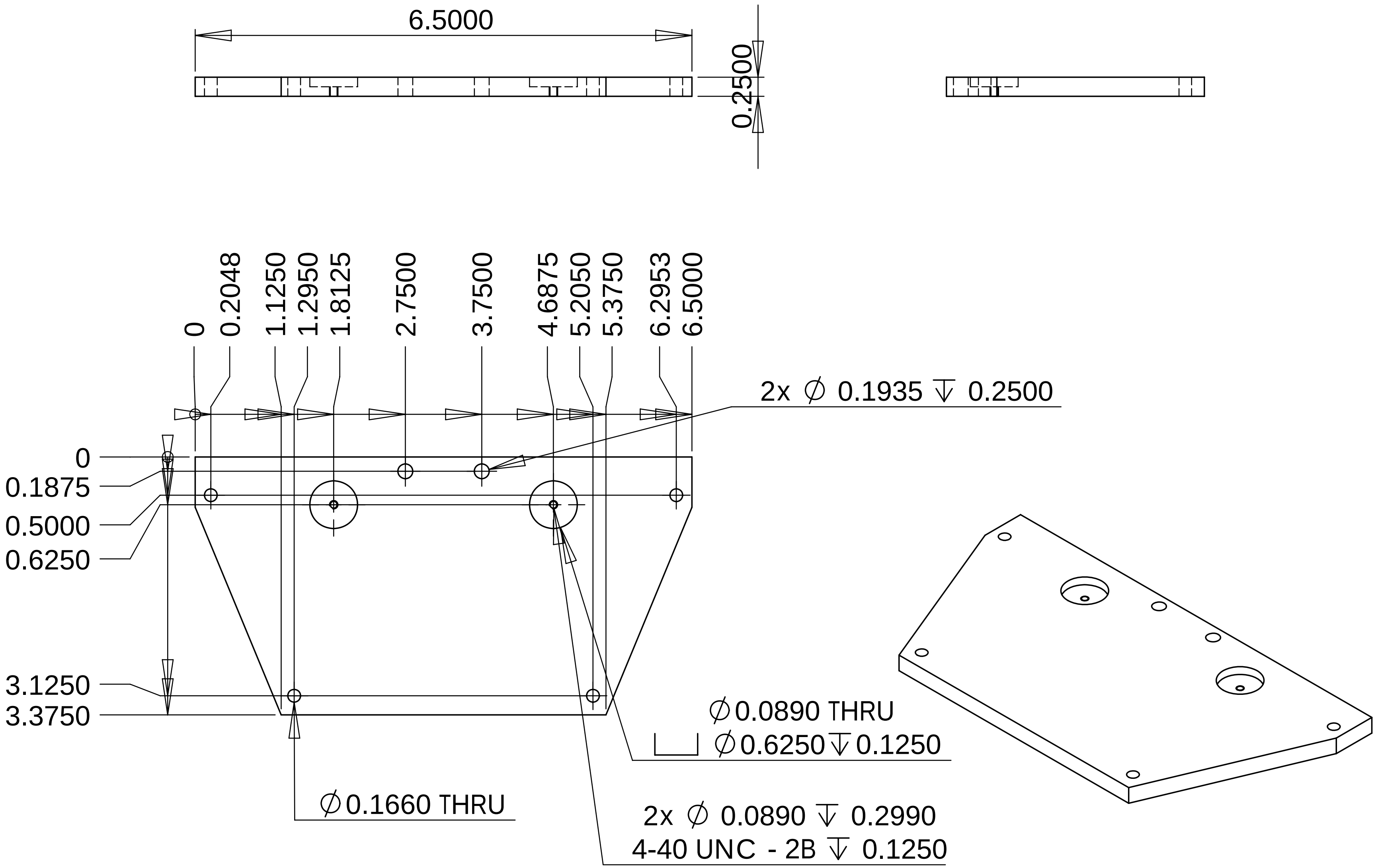




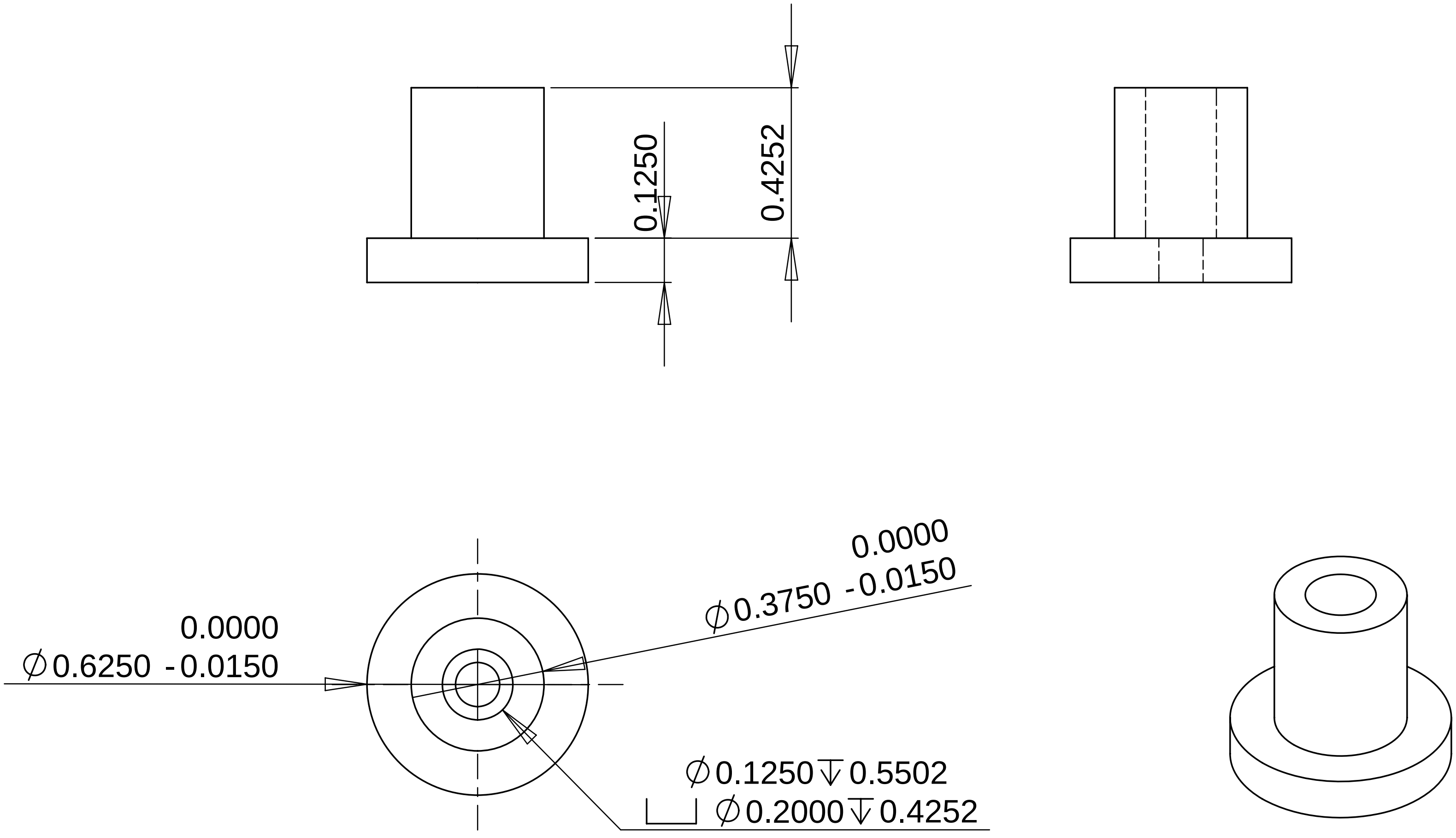
450-02 BEARING-MAIZE MOUNT ASSEMBLY



450-02.01 Bearing Mount



450-02.02 Maize Mounting Base



450-02.03 Spring Push Cap

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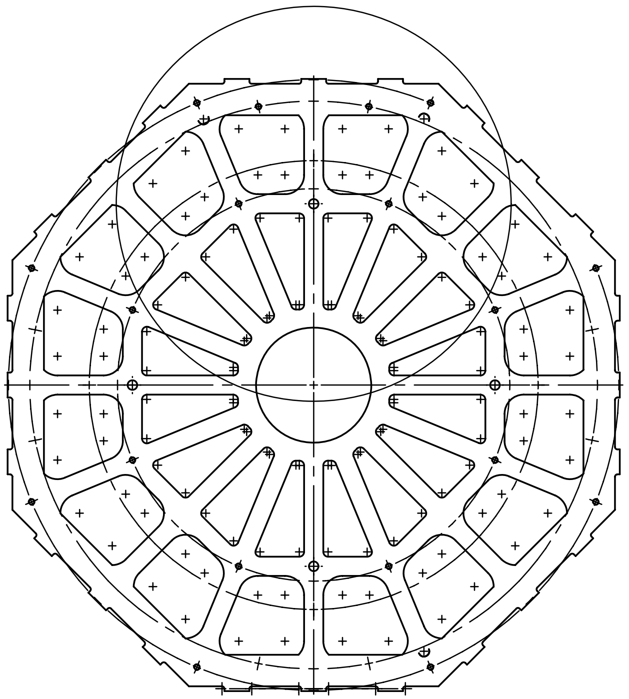

DETAIL A
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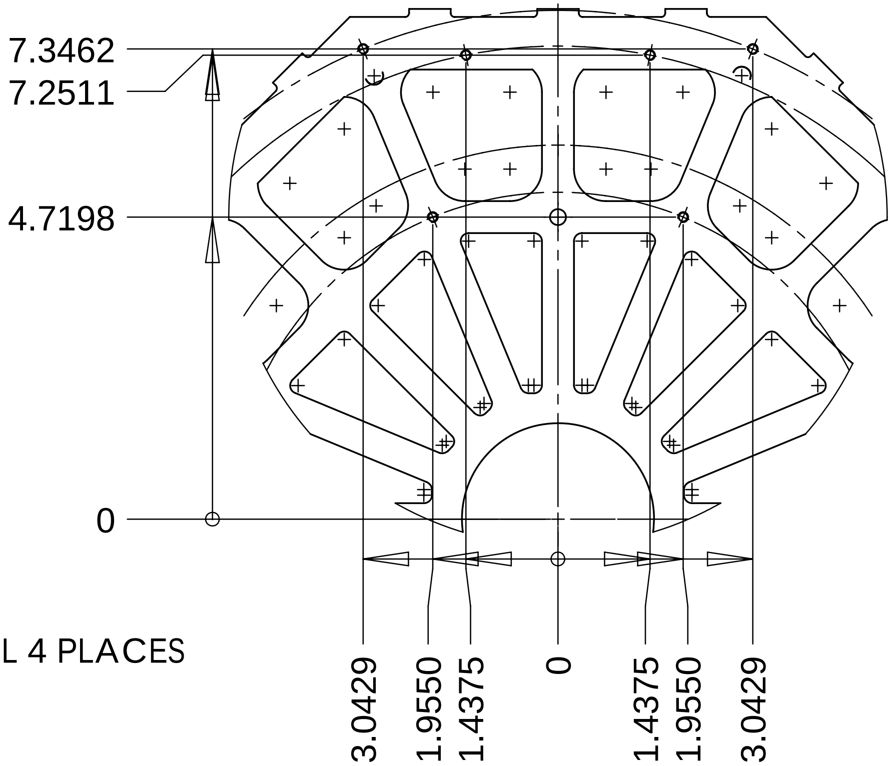
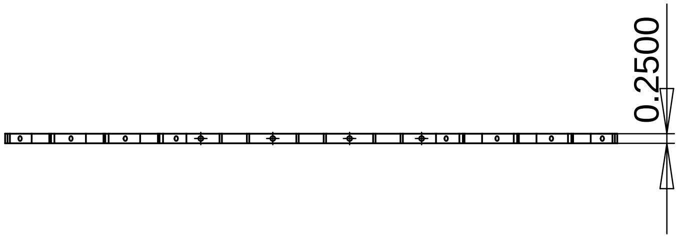
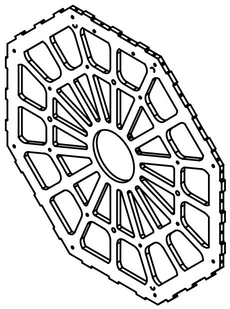


TYPICAL 4 PLACES





450-03 TSATT MLVI Interface Plate

APPENDIX C- CALCULATIONS

Both the preload and launch load calculations were based on the strength ratings of the P-10 pinpullers. Since TiNi Aerospace, Inc. does extensive testing on their products, there is no need to do an in-depth stress analysis of our own. The published pinpuller specifications for strength are shown in Table C.1, along with the values for a four-pinpuller system. The same specifications are listed in Table C.2 for the P-5 pinpuller, which will be used in the prototype.

Table C.1: P-10 pinpuller strength characteristics

	Per P-10 pinpuller	4-Pinpuller System
Max axial load	22 N	N/A
Max side load (non actuation)	1468 N	5872 N
Max side load (actuation)	89 N	356 N

Table C.2: P-5 prototype pinpuller strength characteristics

	Per P-5 pinpuller	4-Pinpuller System
Max axial load	9 N	N/A
Max side load (non actuation)	222 N	888 N
Max side load (actuation)	44 N	176 N

C.1 Preload

The maximum allowable preload is dictated by either the friction force on the retracting pins, or the max side load of the pins, whichever is less. The maximum side load of the system is 356 N, as shown in Table C.1. The friction force is found by (1), where F_{fr} is the friction force, μ is the coefficient of friction between the bushings and pins, and N is the normal force (side load) on each pin.

$$F_{fr} = \mu N \tag{1}$$

The friction force cannot exceed the maximum axial load specified in Table 1, so we solve (1) for N given the coefficient of friction of Vespel, which is 0.29 for the worst grade. We use this grade as a worst-case scenario, since our supplier does not publish a value for coefficient of friction. Thus, the maximum preload per pinpuller, N, is 75.86 N.

$$F_{fr} = 22 = (.29)N$$
$$N = \frac{22}{.29} = 75.86$$

The maximum 4-pinpuller system preload is then 303.4 N. This is less than the 356 N maximum dictated by the max side load, so we must design to the smaller preload. The springs will be chosen so as to give as large a factor of safety as possible on this preload, while still meeting the geometric constraints and the desired separation velocity.

A similar calculation for the prototype shows that the maximum preload for the 4-pinpullers system is 124 N.

C.2 Launch Loads

The Nanosat-4 guidelines specify that the separation system must hold during launch loads of 20g with a safety factor of 2.0 by analysis, or 1.0 by testing. The P-10 pinpuller is the strongest pinpuller that will fit within our volume envelope and meet our power specifications. Our analysis then consists of checking the safety factor on the side loading of the pins under 20g loading with the additional preload. The launch loads are found by (2), where *F* is the maximum launch load, *m* is the mass of the upper payload (15 kg), and *g* is the gravitational constant.

$$F = 20mg \tag{2}$$

Solving (y) for *F*, we find that the maximum launch load is 2940 N. From our spring selection, we know that the preload is 164 N. Thus, the maximum side load on the 4-pinpuller system is 3104 N. We calculate the factor of safety:

$$F.S. = \frac{\max allowableload}{\max load} = \frac{5872}{3104} = 1.89$$

We find that the factor of safety is less than 2.0, so we will have to qualify the spacecraft by testing.

The prototype will be subjected to 2g loads on the C-9 flight, which by (2) is 294 N. The preload from the springs is 4.9 N, for a total load of 299 N on the prototype. We then calculate the factor of safety to be 2.97.

C.3 Spring Selection

We used the momentum conservation equations and energy conservation equations to derive the separation speed for a particular set of springs. We assumed that no friction exists between the two halves of the satellite during separation. We expect that there would be some friction in the spring silos should the caps be in contact with the well, but these should be negligible. Simplifying the following two equations:

$$M_1V_1 + M_2V_2 = M_1U_1 + M_2U_2 = 0 \tag{3}$$

$$\frac{1}{2}M_1V_1^{\,2} + \frac{1}{2}M_2V_2^{\,2} = \#springs \cdot \frac{1}{2}kx^2 \tag{4}$$

V_1 and V_2 refer to the final velocities of the two halves of the satellites in the frame of reference of the satellite before separation. U_1 and U_2 are the initial velocities of the two halves. M_1 and M_2 refer to the masses of each half of the satellite. The springs have a spring constant *k* and a maximum deflection *x*. For TSATT, we calculated all final velocities with respect to the maximum deflection of the spring because those figures would provide the maximum velocities for a particular preload.

From the momentum conservation equation, we have:

$$|V_1| = |V_2| = V \tag{5}$$

Thus, we obtain

$$MV^2 = \# springs \cdot \frac{1}{2} kx^2 \tag{6}$$

The preload experienced by each pinpuller is then:

$$F = \frac{\# springs}{\# pinpullers} kx \tag{7}$$

Solving these equations for specific springs, we obtain the results shown in Tables X1 and X2. The selected springs achieved the velocity nearest to (but not above) the specification, while complying with the geometric constraints and maintaining a safety factor of at least 1.5. In the case of the prototype springs, we chose the springs with a longer deflection for better accuracy.

Table C3: TSATT Spring Selection

Part Number	71207	71148	71639s	S-1139
Spring Rate (N/m)	5600	3000	930	1600
Max Deflection (m)	0.013	0.012	0.022	0.021
Length (in)	1.25	1.25	1.5	1.5
Outer Diameter (in)	0.36	0.36	0.54	0.515
Deflection for 1m/s separation (m)	0.0129	0.0177	0.0318	0.0242
Maximum Separation Speed (m/s)	1.0047	0.6788	0.6929	0.8675
Preload (N)	579.66	288.00	163.68	268.80
Preload Per Pin Puller (N)	144.91	72.00	40.92	67.20
Preload Factor of Safety	0.52	1.05	1.85	1.13

Table C.4: Prototype C9 Spring Selection

Part Number	M-133	71035S
Spring Rate (N/m)	40	680
Max Deflection (m)	0.02	0.012
Deflection for 1m/s separation (m)	0.0108	0.0026
Preload (N)	4.90	20.20
Preload Per Pin Puller (N)	1.22	5.05
Preload Factor of Safety	35.9	8.71

C.4 Thermal Contraction and Expansion

The Coefficients of Linear Thermal Expansion for the various materials used in the housings are:

Aluminum: 23E-6 °C^{-1}
Vespel: 37.8E-6 to 54E-6 °C^{-1}
Stainless Steel: 17.3E-6 °C^{-1}

Expressed as a ratio, The Coefficient of Thermal Expansions relative to stainless steel are:

Aluminum: 1.33
Vespel: 2.18 to 3.12
Stainless Steel: 1

The diameter of the Vespel bushing is 0.635 cm and the diameter of the pinpuller pin is 0.478 cm. Assuming that the Vespel is isotropic and free expansion occurs between the layers, the following increases in diameters can be expected from a 50 °C rise in temperature:

Aluminium Hole: 0.000730 cm
Vespel Bushing Outer Diameter: 0.00120 to 0.00171 cm
Vespel Bushing Inner Diameter: 0.000903 to 0.00129 cm
Stainless Steel Pin: 0.000414 cm

The greatest difference is between the Vespel bushing and stainless steel pin. The difference is 0.000877 cm, which is 0.183% of the initial dimension of the hole. Because this calculation is based on free expansion, the actual change in dimension should be less.

designsafe Report

Application:	TSATT Separation System	Analyst Name(s):	Emily Marks, Michael Eller, Matthew Carnaghi, Eugene Kheng
Description:		Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
electrician / controls technician troubleshooting	electrical / electronic : improper wiring Current Leaks might cause the system to fail to fire properly	Slight Frequent Unlikely	Moderate				
electrician / controls technician troubleshooting	electrical / electronic : overloading Overloading the pinpuller circuitry might cause the actuating element to burn out	Serious Remote Unlikely	Moderate	Safety cutoff circuit implemented	Serious Remote Negligible	Low	
electrician / controls technician connect lines / wires	mechanical : cutting / severing Wires have to be run through small spaces	Slight Occasional Unlikely	Moderate				
electrician / controls technician test circuits	electrical / electronic : overloading Overloading the pinpuller circuitry might cause the actuating element to burn out	Serious Remote Unlikely	Moderate	Safety cutoff circuit implemented	Serious Remote Negligible	Low	
leader / supervisor inspect parts	<None>						
leader / supervisor walking along / by equipment	<None>						
manager trouble-shooting / problem solving	<None>						
manager supervisory task(s)	ergonomics / human factors : interactions between persons Disagreements	Minimal Frequent Negligible	Low				

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
manager demonstration	<None>						
engineer modify parts / components	mechanical : cutting / severing Cutting on mating edges between the upper and lower mounts	Slight Remote Unlikely	Low	Edges are deburred to reduce number of sharp edges	Minimal Remote Unlikely	Low	
engineer conduct tests	mechanical : cutting / severing Cutting on mating edges between the upper and lower mounts	Slight Occasional Negligible	Low	Edges are deburred to reduce number of sharp edges	Minimal Occasional Negligible	Low	
engineer conduct tests	mechanical : pinch point Small gaps between several faces	Slight Occasional Unlikely	Moderate	Operator training: hands should not be inside the mechanism	Slight Occasional Negligible	Low	
engineer conduct tests	mechanical : unexpected start Surges in the electrical system	Slight Frequent Negligible	Low				
engineer conduct tests	slips / trips / falls : slip Tests are conducted in low gravity environment	Serious Occasional Unlikely	Moderate				
engineer conduct tests	slips / trips / falls : trip Tests are conducted in low gravity environment	Slight Occasional Unlikely	Moderate				
engineer conduct tests	slips / trips / falls : impact to / with The prototype separates very slowly, but moves freely in the weightless environment	Slight Occasional Negligible	Low	Separation speed is reduced to 0.1m/s	Minimal Occasional Negligible	Low	
engineer conduct tests	slips / trips / falls : object falling onto Tests are conducted in low gravity environment; the prototype might fall unexpectedly when the aircraft moves into the high gravity portion of its flight path	Serious Occasional Negligible	Moderate	Large Handles are attached to the prototype to assist catching the separated halves	Serious Remote Negligible	Low	
engineer conduct tests	ergonomics / human factors : repetition Tests are conducted multiple times on the same flight	Minimal Remote Unlikely	Low	Assist tool is provided to reduce difficulty in reseting the pinpullers	Minimal Remote Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
engineer conduct tests	ergonomics / human factors : lifting / bending / twisting The prototype will have to be lifted to a suitable height before tests are conducted	Slight Remote Negligible	Low				
engineer conduct tests	confined spaces : confined spaces Tests are conducted within the confines of a passenger aircraft	Minimal Remote Negligible	Low				
engineer design components / systems	ergonomics / human factors : interactions between persons Disagreements	Minimal Frequent Negligible	Low				
engineer trouble shooting	mechanical : pinch point Small gaps between several faces	Slight Occasional Unlikely	Moderate	Operator training: hands should not be inside the mechanism	Slight Occasional Negligible	Low	
engineer communicate with / supervise others	ergonomics / human factors : interactions between persons Disagreements	Minimal Frequent Negligible	Low				
engineer inspect machinery	mechanical : pinch point Small gaps between several faces	Slight Remote Negligible	Low	Operator training: hands should not be inside the mechanism	Slight Remote Negligible	Low	
engineer assemble components	mechanical : cutting / severing Cutting on mating edges between the upper and lower mounts	Slight Remote Unlikely	Low	Edges are deburred to reduce number of sharp edges	Minimal Remote Unlikely	Low	
engineer assemble components	mechanical : pinch point Small gaps between several faces	Slight Remote Unlikely	Low	Operator training: hands should not be inside the mechanism	Slight Remote Negligible	Low	
engineer set-up	mechanical : cutting / severing Cutting on mating edges between the upper and lower mounts	Slight Remote Unlikely	Low	Edges are deburred to reduce number of sharp edges	Minimal Remote Unlikely	Low	
engineer set-up	mechanical : pinch point Small gaps between several faces	Slight Remote Unlikely	Low	Operator training: hands should not be inside the mechanism	Slight None Negligible	Low	
engineer set-up	material handling : movement to / from storage The prototype is heavy	Minimal Remote Negligible	Low	The prototype is mounted on a moveable stand with wheel locks	Minimal None Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
engineer set-up	material handling : excessive weight The prototype is heavy	Minimal Remote Negligible	Low	The prototype is mounted on a moveable stand with wheel locks	Minimal None Negligible	Low	