Hold Down Release Mechanism
Team Stellar Hold

Final Proposal

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DISCLAIMER

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EXECUTIVE SUMMARY

General Atomics – Electromagnetic Systems (GA-EMS) requested an original design for a fully resettable, non-pyrotechnic hold-down and release mechanism (HDRM) for their 12U CubeSat. This is beneficial for GA-EMS and their customers as it will save money in testing stages and in manufacturing, as they would no longer have to outsource their HDRM's. The device must be able to retain its stowed configuration throughout the launch into space and deploy reliably without releasing any material into space. The resulting design relies heavily on the resettable requirement, and the mechanism that allows resetting is found in shape-memory alloy (SMA). By heating an SMA spring with electrical current, it exerts a force causing it to expand, and then once cooled, it can be re-set back into its loaded, compressed configuration. Combining SMA with a pin puller design supported by a ball-lock-pin inspired locking mechanism, the SMA spring releases the lock, allowing the mechanism to pull the pin into the device. This can be reset by simply manually disengaging the lock and pulling the pin back into its loaded position, and then allowing the lock to re-engage. This report outlines the process taken to define the task and generate the design, then introduces an FMEA analysis and plans to experimentally test and validate the subsystems. The tests will include force analysis, acceleration/turbulence field testing, and fatigue testing. Following this report, refinement of the prototype will be conducted in the form of design iteration, and manufacturing of components. This will lead to the final stages of testing and presenting the fabricated model to GA-EMS in late 2022.

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1 BACKGROUND

1.1 Introduction

Satellites are typically in a folded/stowed away state until they are in their final position, usually orbit, and then they unfold to become operational. The mechanism that allows this operation is called a hold-down release mechanism, or HDRM. These devices need to be relatively small, hold a desired load, and then release the load upon receiving a command. These must be extremely reliable and non-destructive to the satellite, as if the mechanism fails, the entire satellite is likely to be non-functional and cannot be recovered. General Atomics – Electromagnetic Systems (GA-EMS) offers small scale satellites called CubeSats, ranging in size from a loaf of bread to a refrigerator. They typically source their HDRM's from other companies that have a reliable history of manufacturing these devices. Most HDRM's are single use, which eliminates the possibility to perform multiple tests on a single device, eliminating the ability to test for manufacturer defects. GA-EMS has tasked the team at Northern Arizona University to begin a design process for their own HDRM. The goal of this project is to eventually have a device that is as advanced as current, state-of-the-art designs, that GA-EMS can manufacture themselves. Additionally, they need their HDRM to be resettable for multiple uses, to allow each individual device to be tested multiple times for reliability before attaching it to a satellite. This has many benefits for both GA-EMS and the industry.

One main outcome of this project will be GA-EMS saving money on their products. By vertically integrating these satellite components, they will be able to both save money by manufacturing their own product and be allowed to modify it with greater ease to fit their purposes more adequately. Another outcome of this project is potential improvements and advancements in current HDRM technology. As the industry moves away from pyrotechnic (combustible) designs, most HDRM's are still single-use and cannot be reset. By beginning development for a completely resettable HDRM design, it may open or widen a pathway towards safer, more cost-effective resettable HDRM's or lead the industry into an innovation for these mechanisms.

Additional beneficiaries of this project include the clients of GA-EMS satellites. If GA-EMS can provide a mechanism that guarantees greater success of their products, they would receive more business. This would also potentially drive down the costs of the product due to the increase in reliability and decrease in component costs.

1.2 Project Description

The sponsor, GA-EMS, provided a brief introductory project description, reading as follows.

> "Students will develop and work toward a schedule with milestones including a Kickoff Meeting, SRR, PDR, CDR, etc. Performing a Trade Study will inform students of current retention methods of HDRMs and keep GA-EMS abreast of the latest vendor technology. Current GA-EMS CubeSat designs will be used to help students develop requirements of HDRM to bound design. GA-EMS will support this project by supplying technical expertise and assisting with the purchase of COTS mechanical and electrical components, if needed. GA-EMS can support students further by allowing use of 3D printers for custom components. For this first year, the HDRM design should remain simple enough to result in an end of year demo."

This project takes place over the span of two, 16-week semesters, totaling approximately 32 weeks of work. During this 32-week span, the team at Northern Arizona University has goals to generate a functional design that meets all mechanical requirements, fabricate a professional and well-made prototype, and demonstrate it to faculty at GA-EMS. Some requirements for this project are long-term that are beyond the scope of this project timeline, such as materials verification and certification for space use. However, the team at NAU will show that these requirements have reasonable potential to be met with the current design and make suggestions on how to proceed after this 32-week span. This has been decided as a result of meetings and conversations with the engineering team from GA-EMS.

2 REQUIREMENTS

This section will contain information describing what the client requires from the project, and how the team has interpreted and quantified those requirements. As GA-EMS has provided a group of their own engineers to collaborate with us throughout this project, many of the customer requirements they provided are already in the form of engineering requirements. Because of this, some customer requirements have been created based on an engineering requirement provided by GA-EMS. Following the customer and engineering requirements, the requirements are further presented in the form of functional models and a House of Quality (HoQ). These are visual methods of presenting and evaluating the requirements to better understand the end goal of this project.

2.1 Customer Requirements (CRs)

The following list is comprised of the requirements provided by GA-EMS and their weights, with some minor simplifications. These requirements have been assessed and assigned weights for importance and further use in the HoQ. This process was done in collaboration with the team of engineers from GA-EMS, after discussions pertaining to these requirements. The requirement weights are on a scale from 1-5, with five being of the highest importance.

1. No space debris
    a. Weight 5. This is a major requirement, as the industry is leaning away from devices that release material into space.
2. Low outgassing
    a. Weight 3. This is important for a device that is being sent to space, however it is not within the budget or design scope for this portion of the project.
3. No pyrotechnics
    a. Weight 5. The HDRM industry is advancing enough to provide better options than pyrotechnic releases.
4. Deploy solar panels sized 20 by 30cm
    a. Weight 3. This is important for consideration, but the scope of the project considers generating a design that functions, with spatial considerations secondary.
5. Cannot protrude >1cm from external face of CubeSat
    a. Weight 4. This device cannot have any part that protrudes more than one centimeter from the outside of the satellite, as it would not be able to fit in its stowed configuration.
6. Deploy all panels simultaneously
    a. Weight 3. This design is primarily focused on HDRM mechanism itself. The team from GA-EMS allows the connection to the solar panels to be considered a secondary task, if necessary.
7. Easily resettable
    a. Weight 5. This is required for testing purposes, and to remain current with state-

of-the-art designs.

8. Be able to retain stowed config prior to deployment
    a. Weight 5. The HDRM must reliably hold down any load it experiences through the turbulence and forces before deployment.
9. Release on command
    a. Weight 3. The team from GA-EMS considers the release input command a secondary task, as the primary focus is to develop the mechanism. The NAU team may take on this task if time and budget allow it.
10. Have rotational abilities
    a. Weight 2. This requirement would apply to the hinges on the satellite solar panels. This task may be taken on if time and budget allow it.

2.2 Engineering Requirements (ERs)

The following table list of engineering requirements has been developed based on the customer requirements (Table 1). These are the criteria that the designs will be evaluated against when deciding and weighing unique design variants. Target values for each engineering requirement have been assigned, and a broad description of the testing method is noted as well.

Table 1: Engineering Requirements & Target Values

Engineering Requirement	**Target Value**	**Units**	**Testing**
No breakaway parts	0	# Parts	Visual
Low outgassing materials	TBD	%	TBD
No combustion	n/a	n/a	By design
Minimize volume	Max 25	cm^3	By design/ computational
Minimize protruding material	1	cm	By design/ computational
Maximize deployment force	Min 25	N	Force sensor
No deformation	TBD	%	Analysis/ wear testing
Maximize retention reliability	>99	%	NASA acceleration testing standard
Receive input command	n/a	n/a	n/a
Minimize weight	Max 200	Grams	Design/measurement
Minimize reset time	Max 60	Seconds	Trial testing

2.3 Functional Decomposition

The following two sections break down the device into its main functions, presented in the form of a black box model and a functional model. The black box model is intentionally simple to outline the main inputs, outputs, and function of the model. The functional decomposition elaborates on the black box model, by showing the flow of functions including inputs and outputs as the device performs its functions. These models were selected because the functions inside an HDRM are relatively simple, therefore a functional model showing the flows yields a greater understanding of the problem.

2.3.1 Black Box Model

This black box model, shown in figure 1, summarizes the inputs, functions, and outputs of the device. The process begins by securing the load (in this case, a panel), then electrical current is supplied upon receiving a command signal. The device releases the panel, which is moved to its operational location, and a confirmation of release is sent to the operator. When put simply, the device holds a load, and then when energy is supplied, it releases the load. In the case of testing, the device will need to be reset before use. In this case, a reset mechanism must be applied to the device before the load can be secured.

Figure 1: Black Box Model

2.3.2 Functional Model

The functional model demonstrates the flow of functions that the device performs throughout its process cycle, as well as resetting. The derivation of the functional model stems from the inputs and outputs of the black box above. The team chose the functional model to show the functions because this device performs a simple set of functions, and this model effectively demonstrates what is happening within the device. This function flows within this model follow a loop, as to demonstrate that the device is resettable. There may be a tool to aid in the reset function, which is accounted for in these flow models. Figure 2 shows the functional flow model, with annotations noted in blue text and arrows.

This version of the functional model is more explicit in the functions that are happening, to more accurately represent the HDRM being designed. The functions of resetting the mechanism and converting electrical to mechanical energy to release the lock were not understandable based on the previous model, and this version is aimed to refine the understanding of the process.

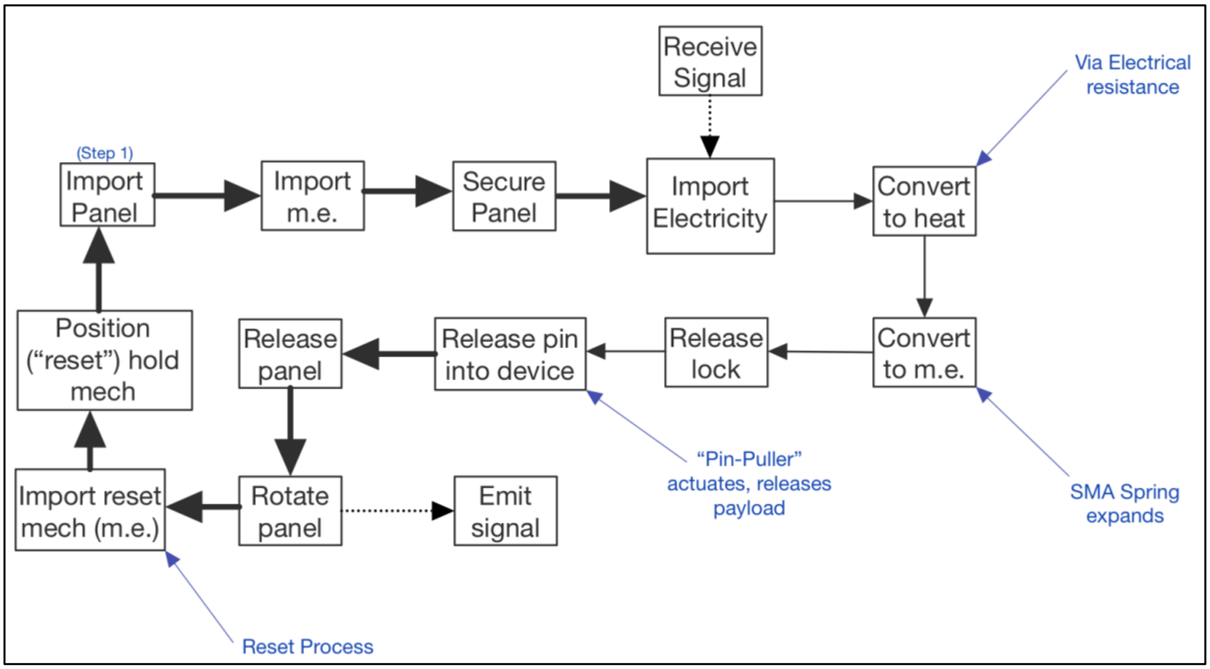

Figure 2: Functional Model for Resettable HDRM (Annotations in Blue)

2.4 House of Quality (HoQ)

This subsection evaluates the customer and engineering requirements using a house of quality (figure 3) and describes its effectiveness, as well as how it has helped in the design process. This HoQ evaluates the weighted customer requirements and engineering requirements. The comparison sections use the values of -1, 0 (blank) or 1 to denote negative, zero, or positive correlation, respectively, between the two requirements being considered. This helped to determine which technical requirements are most important, with respect to the weight of the customer needs.

Based on this HoQ, the correlation matrix between technical requirements and the customer requirements proposes that reliability is the most important requirement. The requirements of no deformation, no combustion, and no breakaway parts (debris) closely follow reliability in importance. However, minimizing the reset time is not one of the most important technical requirements, according to this HoQ. While this is unexpected, the requirements that are previously mentioned (no deformation, combustion, or debris and max reliability) all positively correlate with minimizing the reset time. This verifies the strong importance of this requirement as imposed by the client, GA-EMS. This HoQ has aided in the design process by placing a strong importance and primary focus on generating a non-destructive design that is both reliable and easily resettable, while keeping volume and weight low are less important for the scope of this project.

System QFD

Project: **GA-EMS HDRM**
Date: 04/14/2022
Team Stellar Hold NAU SP22 ME476C

#	Correlations	No Breakaway parts	Low outgassing materials	no combustion	minimize volume	minimize external hardware	maximize deployment force	no deformation	maximize retention reliability	must receive input	minimize weight	minimize reset time
1	No Breakaway parts											
2	Low outgassing materials											
3	no combustion	1	1									
4	minimize volume											
5	minimize external hardware											
6	maximize deployment force					-1						
7	no deformation	1		1								
8	maximize retention reliability	1		1		-1		1				
9	must receive input											
	minimize weight		-1		1		-1					
10	minimize reset time	1		1		-1		1	1			

key
1 = positive correlation
-1 = negative correlation
blank = no correlation

#	Customer Needs	Customer Weights	No Breakaway parts	Low outgassing materials	no combustion	minimize volume	minimize external hardware	maximize deployment force	no deformation	maximize retention reliability	must receive input	minimize weight	minimize reset time
1	No Space Debris	5	1		1		1			1			1
2	low outgassing	3		1					1	1			
3	No pyrotechnics	5	1	1	1				1	1		1	1
4	must deploy solar panels 20x30cm	3				1							
5	cannot protrude more than 1cm from bottom	4					1			-1		1	-1
6	Must deploy panels on all sides simultaneously	3					-1	1		1			
7	Must be able to easily reset	5	1		1	-1			1				1
8	Must be able to retained stowed config prior to launch	5					1	1		1			
9	must release on command	3									1		
10	must have rotational abilities	2											
	Technical Requirement Units		#	%	n/a	cu cm	cm	N	%	%	n/a	g	s
	Technical Requirement Targets		0.00			25.00	1cm	20	TBD	>99		200	<60s
	Absolute Technical Importance		15.0	8.0	15.0	-2.0	11.0	8.0	13.0	17.0	3.0	9.0	11.0
	Relative Technical Importance		3	2	3	0	2	2	3	4	1	2	2

Figure 3: House of Quality

2.5 Standards, Codes, and Regulations

Table 2 provides a list of standards that are relevant in the context of design, validation, analysis, testing and verification, hardware, and materials. Many of these standards are NASA technical standard documents, or other documents generated by NASA. This is due to many of the standards and procedures required for a system interacting with a space environment are modified to fit. The standards beginning with “NASA” in Table 2 are sourced from NASA’s website [1], where there are many more standards than what is listed in this document.

While the scope of this (approximately) 32-week project does not include verification and certification for space applications, many of these standards outline the general requirements for this process, including materials, testing, and verification for environmental conditions. With the current scope of the project, these are used as guidelines for what conditions and goals this project strives for, and, what the requirements are for the end-use product. Other standards listed include information on load analyses and solid mechanics testing, which may be used within this project to perform feasible design verification calculations.

Table 2: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
SMC-S-016	Test Requirements for Launch, Upper-Stage and Space Vehicles[2]	This provides information on launch conditions and maximum predicted environment (MPE) conditions for different mechanical modes. It also provides extensive information on testing procedures for these MPE's.
GSFC-STD-7000	General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects[3]	This provides information on the environmental verification process and performance testing.
NASA-STD-5002	Load Analyses of Spacecraft and Payloads[4]	This provides the methodologies and practices required for load analyses for payloads.
NASA-STD-5017	Design and Development Requirements for Mechanisms[5]	This provides information such as allowable stresses, factors of safety, and other relevant information for designing a mechanism. Also, some testing information is given in this document.
NASA-STD-5020	Requirements for Threaded Fastening Systems in Spaceflight Hardware[6]	This provides technical information on design and testing requirements for threaded fasteners. This may apply depending on assembly technique.
NASA-HDBK-6025	Guidelines for the Specification and Certification of Titanium Alloys for NASA Flight Applications[7]	This document outlines requirements for proper use of titanium alloys in space hardware. This may apply should the end-use product use titanium.
NASA-STD-6001	Flammability, Off gassing, and Compatibility Requirements and Test Procedures[8]	This standard outlines the procedures and requirements for selecting and testing space materials to meet flammability, off gassing, and other compatibility requirements.
NASA-STD-6012	Corrosion Protection for Space Flight Hardware[9]	This standard describes the surface treatment requirements for corrosion protection for space hardware.
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft[10]	Defines Materials and processes for fabrication, design, and testing. It can be used to define future work on this design in subsequent sections of this project.
ASME V&V 10	Guide for Verification and Validation in Computational Solid Mechanics[11]	This standard from ASME defines the methods for verifying and validating a design using computational solid mechanics. Can be used to validate materials/ geometries before fabrication.

3 Testing Procedures (TPs)

The following section outlines the general procedures and desired outcomes of the testing that will take place between weeks 16-32. The NASA Test Requirements for Launch, Upper Stage and Space Vehicles Standard [2] provides the full guidelines for testing and validating to be accepted for space travel. While this level of testing and verification is not within the scope of this project, the content provides insight as for what typically needs to be tested on a component that is being deployed in space. The following tests are conducted to verify durability, reliability, and ability to withstand some turbulent conditions.

3.1 Testing Procedure 1: Pulling Force

The main function of the HDRM is to retract a pin into itself with enough force to overcome the friction imposed by the payload. The load will be applied in shear on the pin, and as the retraction force is axial, the only resistive force will be that of friction. HDRM's commercially available and used by GA-EMS[12] provide a pulling force of 22.2N, with known maximum forces describing the motion and retention of the device. This test will ensure that the pulling force meets the engineering requirement of 25N and provides data on maximum loads for deployment. The official load analysis procedure defined by NASA [4] cannot be performed at this stage or with the available equipment, but these tests should provide adequate data for the scope of this project.

3.1.1 Testing Procedure 1: Objective

This test will be conducted using a force sensor and different apparatus to simulate the different modes of loading. The device will have a threaded hole within the pin to aid with the reset process – this can also be used to attach a hook or other objects to allow an outward axial load to be applied.

The first set of tests measure the amount of force it takes to drive the pin into the device, or the amount of force with which it retains its axial load. This test will require the force sensor and the pin of the device to be aligned coaxially. Then, slowly, increasing force will be applied to the pin to drive it into the device. The last recorded force before the pin is driven into the device will be the result. This will be repeated for accuracy.

For the shear testing, a side load will be applied to the pin, measured using the force sensor. Varying levels of force will be applied in shear while the device is being actuated, to determine the maximum shear force for the side load applied. A friction factor will be determined to translate the shear force into friction force axially and compared to the forces for the axial load.

Secondly, we will need to know how much force the SMA spring within the device applies axially to pull the pin into the device. This will be conducted by securing both the force sensor and the pin a specific distance apart aligned coaxially. The device will be activated, and the force that is applied to the pin from the SMA spring will be transferred to the force sensor. This will be repeated to verify. Additionally, this process will be used for testing the repeatability of the shape memory spring.

3.1.2 Testing Procedure 1: Resources Required

The load testing will make use of a force sensor with a resolution of 0.1N, to ensure there are minimal resolution errors. Non-elastic wire such as nylon will be used to connect the force sensor to the output pin. The threaded connection to the pin should be accessible using readily available screws. For side loads, components may be manufactured and used for consistency. This may be through 3-d printing or using aluminum components with the machines at NAU's machine shop. This test should be able to be completed without any outside persons helping. Microsoft Excel or MATLAB will be used to record and analyze the results.

3.1.3 Testing Procedure 1: Schedule

This test will take no more than two hours to perform, given there are no issues to resolve. To account for unforeseen issues in testing, a two-week period will allow multiple iterations of the test to ensure the integrity of the process and validity of the results. Additionally in this time frame, the results will be analyzed, and any calculations will be made. This test will be performed twice: once with a prototype and once with a final design. The prototype test will tentatively take place between weeks 20-23, and the final design test will take place after the final hardware review, placing it between weeks 26-30.

3.2 Testing Procedure 2: Retention Reliability

During the launch and flight of the satellite before the CubeSat is deployed into orbit, the launch vehicle experiences significant turbulence of many types. The main component of this turbulence is acceleration, as the vehicle and its components experience acceleration in the form of acoustics, multiple forms of vibrations, shock, and linear acceleration [2], [3], [13], which NASA has specific technical standards for testing. While not enough information is known to be able to qualitatively test all these now, the team plans to introduce the model to an environment like that experience by a launch vehicle.

3.2.1 Testing Procedure 2: Objective

The purpose of this test is to validate that the device can withstand some level of acceleration, including all its components as described above. The results of this should indicate that the device that each subsystem of the device is able to remain in place without breaking or releasing from its loaded configuration. This testing condition has not yet been decided, however there are a few options that present the ability to field test this device.

The team may have an opportunity to mount a device on a scale rocket created by students at NAU. This would introduce some turbulence and substantial amounts of acceleration during take-off and landing. The team may also use a vehicle operating on rough terrain to simulate accelerations such as vibrations and shock, with the HDRM mounted firmly to it. This may come in the form of a bicycle to reduce risks of damaging the device, and to eliminate the energy absorbing features of automotive suspension.

If resources allow, an accelerometer may simultaneously be mounted with the HDRM to record the magnitude of the accelerations that the device is experiencing. This would not bridge the gap to verifying it for space travel but would offer definitive quantitative results that prove that the device can withstand the recorded accelerations.

3.2.2 Testing Procedure 2: Resources Required

Depending on the method chosen for testing the acceleration, the resources required will vary. For a rocket-mounted method, proper restraints to secure the device to a rocket will be required, which will be defined by the operators of the rocket. For a vehicle or bicycle-mounted method, a retention method using common shop material would be sufficient. For data acquisition the required resources would include the Arduino for the program, a power source, the accelerometer, and a storage device for the data. The test would require the rocket team to provide their knowledge, operation and safe flight location, or a team member to provide a bicycle and a safe and suitable test environment. For Arduino troubleshooting, the team can utilize faculty at NAU for assistance setting up the sensors. MATLAB or Microsoft Excel will be used for data analysis.

3.2.3 Testing Procedure 2: Schedule

The team will allow a week to gather the apparatus and required technology. Arrangements will be made for the decided testing method (rocket, bicycle) and requirements for the test will be defined at least two weeks in advance. Upon recording the data, no more than a few hours will be needed, however the team will allow a week to collect data to account for DAQ errors or procedural errors. Total, this test will take place over the maximum span of two weeks once testing arrangements have been made. This test will take place after the final prototype has been created, and before the final design has been manufactured. This will be within weeks 23-36.

3.3 Testing Procedure 3: Fatigue and Wear

Shape memory alloy, although a very impressive material, cannot heat then expanded, and cooled then retracted infinitely. The purpose of this test is to examine the amount of permanent deformation of the SMA spring as a function of number of cycles. The goal of this test is to understand how the SMA fatigues and potential optimizations to the system to minimize critical failure from fatigue. This will allow the team to determine a realistic cycle life for the HDRM being designed.

3.3.1 Testing Procedure 3: Objective

3.3.1.1 TP3 Part 1

This test will be performed under two conditions: loaded and free. The team will first determine the electrical power requirements to adequately heat up the spring to allow it to deform. Once this has been correctly determined, the team will perform repeated cycles of heating and cooling the spring, which allows expansion and retraction. The extended and retraction length after each cycle is recorded. This is to test for permanent deformation while allowing the spring to exercise its full range of motion.

3.3.1.2 TP3 Part 2

The second test will test the fatigue of the spring in terms of the induced expansion force when experiencing a resistive mechanical load. For this experiment, the spring will be bounded axially between a wall and the measurement end of a force sensor. The spring will be repeatedly actuated, and the maximum force for each cycle will be recorded. These results will be compared to those of Testing Procedure 1, as these loads relate and can help determine the maximum number of cycles that can reliably be performed.

3.3.2 Testing Procedure 3: Resources Required

The required resources include the device itself, an additional SMA spring, testing hardware and testing software. The testing hardware includes the force sensor, electrical components to power the SMA spring, and apparatus to contain and hold the test. This containment may be 3-d printed or manufactured using resources available at NAU. The data recording for part 1 test will use video analysis techniques to record the lengths of the spring after each cycle. This is done to prevent the spring from overheating and to allow a constant load time for each cycle. The data recording part 2 will simply be visual readings of the force sensor, although video may be taken to avoid mistakes in reading the device. All data will be imported into Microsoft excel to be analyzed.

3.3.3 Testing Procedure 3: Schedule

Once a well-fabricated final prototype has been obtained, the only preparation for this test will be to construct a testing apparatus. The team will allow a week to design and manufacture this, and allow an additional week to conduct tests, troubleshoot errors and perform data analysis. It is likely that this test will be divided into two separate time slots, as part 1 can be performed without a final prototype. This portion of the test will be conducted between week 17-21 and the second test will be conducted between week 26-30 once the final hardware review is complete.

4 Risk Analysis and Mitigation

Before finalizing the design, the team must analyze potential failures and mitigation plans through the FMEA. The team carefully selected 4 important subsystems to analyze for any potential failures. Ten potential failure modes were found for each critical subsystem, for a total of forty potential failure modes. The shortened FMEA is shown in table 3 while the full FMEA can be found in Appendix C.

4.1 Critical Failures

Table 3: Shortened FMEA

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanism s of Failure	RPN	Recommend ed Action
SMA	Permanent deformation	Change pin position	Over voltage/ temperature	48	Test environment conditions
SMA	Fatigue life	Change pin position	High and low cycles	80	Test SMA Fatigue life
SMA	Temperature /Electrical	Unable to change pin	Below required voltage	343	Test wires
SMA	Fatigue-crack growth	Change pin position	cyclic stresses below Ultimate tensile stress	120	Test for Fatigue crack growth
SMA	Overload fracture	Change pin position	Excessive stress or strain	80	Verify SMA can handle load
Spring	Stress relaxation	Unable to keep pin in place	Held at a certain stress for prolonged period of time	36	Keep spring in rested position
Spring	fracture due to fatigue	Unable to keep pin in place	repetitive cyclic brief time stress	72	Test for cycle life
Pin	Deformation wear	Unable to hold load	Overstressi ng	48	Pick the best material for load
Pin	Impact fatigue	exposed space debris	Impact loading	90	Control impact loading
Pin	Impact wear	Unable to hold load	Wrong material	56	Pick the best material for load
Lock Mechanis m	Wrong Configuratio n	Pin will not retract	Human Error	140	Verify lock configuration

Pin	Deformation wear	Unable to hold load	Overstressi ng	9	Pick the best material for load
Spring	fracture due to fatigue	Unable to keep pin in place	repetitive cyclic brief time stress	72	Test for cycle life
SMA	Deformation wear	Pin will not retract	Overstressi ng	84	Test for deformation
SMA	Fatigue Fracture	Pin will not retract	cyclic stresses below Ultimate tensile stress	84	test fatigue life
Wires	Degradation	SMA actuator will not work	Using overtime	45	Check wire life
Wires	Heating of cable	SMA actuator will not work	Generated by the resistance to current flow	108	Verify resistance
Wires	Electrical Overloading	SMA actuator will not work	Applying too much load	210	Verify electrical output
Battery	Defective connection	SMA actuator will not work	Human Error	21	Check connections
Battery	Loose connector	SMA actuator will not work	Human Error	24	Check connections
Lock Mechanis m	Wrong Configuratio n	Unable to reset pin	Human Error	224	Change lock configuration
SMA	Fatigue life	Change pin position	High and low cycles	80	Test SMA Fatigue life
SMA	Temperature /Electrical	Unable to change pin	Below required voltage	343	Test wires
SMA	Fatigue-crack growth	Change pin position	cyclic stresses below Ultimate tensile stress	120	Test for Fatigue crack growth
SMA	Overload fracture	Change pin position	Excessive stress or strain	80	Verify SMA can handle load
Spring	Stress	Unable to	Held at a	168	Keep spring

	relaxation	keep pin in place	certain stress for prolonged period of time		in rested position
Pin Platform	Slips	Unable to reset pin	Applying force in wrong direction	147	Test reliability of lock mechanism
Pin Platform	Flaking	Rough resets	Repeating trial runs, rubbing on ball bearings	32	See lubricant option
Ball Bearings	Flaking	Rough resets	Rubbing on Pin Platform	32	See lubricant option
Ball Bearings	Spalling	slower/ no reset	surface fatigue	24	See lubricant option
Ball Bearings	Flaking	Unable to lock	Rubbing on Pin Platform	48	See lubricant option
Ball Bearings	Spalling	Unable to lock	surface fatigue	24	See lubricant option
Lock Platform	Slips	unlocks	Force in wrong direction	84	Test reliability of lock mechanism
Lock Platform	Flaking	Rough surface/ locking	Repeating trial runs, rubbing on ball bearings	32	See lubricant option
Lock Platform	Wrong Configuration	Locks in wrong position	Human Error	224	Change lock configuration
Spring	Stress relaxation	insufficient force output	Held at a certain stress for prolonged period of time	54	Keep spring in rested position
SMA	Fatigue life	Change pin position	High and low cycles	80	Test SMA Fatigue life
Switch	Unexpected current flow	actuates SMA, unlocks	faulty switch/ battery	24	Test components before
Lock Platform	Poor tolerance fits	Will not lock	Manufacturing	18	Outsource materials for

					lock
Pin	Axial force in wrong direction	Unlocks	Force in the wrong direction	120	Test various applied forces

4.1.1 Potential Critical Failure 1: SMA – Temperature/Electrical (Release)

The shape memory alloy springs will be triggered by heating them with a current. If the voltage is not high enough the springs will not be heated enough to change their shape, resulting in the pin not retracting. This can be caused by a faulty battery source, wires, or human error of improper electrical connections. This failure can be mitigated by testing and purchasing high quality electrical components. Also, by conducting frequent wiring inspections.

4.1.2 Potential Critical Failure 2: Lock Mechanism – Wrong Configuration (Reset)

Having the lock mechanism in the wrong configuration could result in the device being stuck and not able to reset. This could be caused by applying force on the pin in the wrong direction or by some other force that could move the lock configuration. Mitigating this failure can be done through prototyping and testing various lock designs and preventing accidental and unexpected forces.

4.1.3 Potential Critical Failure 3: Wires – Electrical Overloading (Release)

An unexpected electrical surge can lead to the wires electrically overloading. This will damage the wires leading to no current flow in the SMA springs for actuation. This can be prevented by not connecting multiple power-consuming items to one source and by regularly inspecting the wires.

4.1.4 Potential Critical Failure 4: Pin Platform – Slip (Locking Mechanism)

The pin platform slipping is a potential failure that will result in unwanted retraction of the pin. This failure can be caused by unexpected forces and possibly during an environment where the device is exposed to an extended amount of vibration. To prevent this failure, the team must utilize their prototypes and use a testing environment with similar vibration conditions to see the reliability of the device.

4.1.5 Potential Critical Failure 5: Pin – Axial force (Locking Mechanism)

An axial force applied on the pin in the opposite direction could result in an undesired retraction of the pin. This can be caused by some object hitting the pin and applying the right amount of force. This can be prevented through a force analysis/ testing to ensure that the ball bearing mechanism can resist a substantial amount of force.

4.1.6 Potential Critical Failure 6: Spring – Stress Relaxation (Reset)

Springs may undergo stress relaxation when they are put under a specific amount of stress for a prolonged period of time. This will result in a weaker spring that will not provide the necessary amount of force output for reset. This can be prevented through the proper spring analysis and choosing the right material for this application.

4.1.7 Potential Critical Failure 7: Wires – Overheating (Reset)

Overheating wires will result in the SMA springs not being able to actuate. This failure is a result of loose connections that can wear and tear the link and hinder the current flow. This can be prevented through regular inspection of the wires and ensure that all connections are connected properly.

4.1.8 Potential Critical Failure 8: SMA – Fatigue Crack Growth (Reset)

The SMA spring is the most critical component of the reset subsystem. Fatigue crack growth can result in a faulty SMA spring, meaning that the device will no longer have the reset capability. Cyclic stresses below the ultimate tensile strength cause this failure. Mitigating this failure will involve testing the springs limit and ensuring that the device's SMA springs are replaced before reaching that point.

4.1.9 Potential Critical Failure 9: Pin – Impact Fatigue (Hold Down)

Since the pin will be in an environment where it will be under a constant load and vibration it may undergo impact fatigue. This could result in a failure of the pin where it can no longer be used effectively. Methods for mitigating this issue involve selecting the appropriate material and softening stress concentrations wherever possible.

4.1.10 Potential Critical Failure 10: Pin – Deformation Wear (Hold Down)

The pin of the device will be required to hold a load for an extended period. This could result in deformation wear, creating a pin that can no longer be used reliably. Preventing this failure will require material force analysis and choosing that appropriate material for this design.

4.2 Risks and Trade-offs Analysis

Many of the critical failures listed above played roles in the design and what pieces we chose to include or stray from. For example, potential failure 1 focuses on temperature and electrical aspects of the device. In the previous design we attempted to use two shape memory alloy springs that relied on a current to change the heat in the device. Including two of these springs left us with twice the risk of potential failure. In the chosen design we have decided to switch to using two normal springs and only one shape memory alloy spring so we can focus on only activating one. By choosing to focus on this potential failure, we were brought to our new and current design which in turn forced us to focus less on potential failure 2, the lock mechanism. This was because our design now is held in place by detent rather than a lock. We believe that making this decision will not hurt the design because although it has the potential to fail during turbulence, the device has been simplified significantly which allows us to focus on testing enough times to make sure the detent can withstand any space conditions.

Another example can be found in potential failure 6, stress relaxation, after mitigating potential failure 7, overheating. The main relation with these two failures comes from the heat being applied to the spring without overheating it and causing too much stress so that the shape memory alloy spring cannot continue to reset. The team will need to run many tests on how much heat the spring can handle (maximum and minimum heat to actuate), and how to perfect sending only the necessary amount of current through the wires to ensure there are no malfunctions. This will be done by testing, not only how much heat the wires can transport safely, and how little heat the spring needs to actuate, but also by testing to find what the failure points are. If the team is able to test and find the exact failure points on extra materials, we will be able to find the perfect balance to ensure there is never too little or too much current and create a range to stay within. This will become especially important in the final model sent into orbit because the testing will need to be thorough enough to never wear out materials. If the materials can continue to be reset and reused, GA-EMS will be able to save a great deal of money without needing to replace parts made from space grade materials.

Each risk was weighed against the others and against the designs we were working with so that we knew which would be the most important to focus on and how the potential failures could be minimized/contained within their individual parts. Ultimately, weighing these top 10 risks is what led the team to the new design and allowed us to feel confident that it is the best suited design to limit potential failures during testing and when in use.

5 DESIGN SELECTED – First Semester

The purpose of this section is to introduce the design that the team has selected to move into the prototyping and further developing stages. The team has iterated the design, and generated a prototype based on that. The following sections break down and explain the mechanism inside our device and describe the future plans to manufacture and finalize this design.

5.1 Design Description

The current state of the design has varied since the preliminary design report. The previous design utilized a lever, or gate style lock, which has been removed and replaced with a new lock inspired by ball-lock pins, shown in figures 4 and 5. The upwards protruding pin connected to the horizontal plate, is loaded with a steel spring intended to force it down, into the device. However, figure 5 shows two ball bearings, one on either side, providing a physical barrier resisting the pin's downward motion. To allow the ball bearings to move aside and allow the pin to be driven into the device, the component placed between the two lower springs needs to move downwards. The middle spring, seen best in Figure 4, is made of SMA, and will expand, forcing the lower component downwards, allowing the mechanism to drive the pin into the device. The rest of the components are simply structured to contain and guide the dynamic parts with the device. Note that the figures below and the CAD are intended for ease of prototyping and design review purposes; future iterations of this will take on a different form, but the relevant mechanisms and subsystems will remain the same.

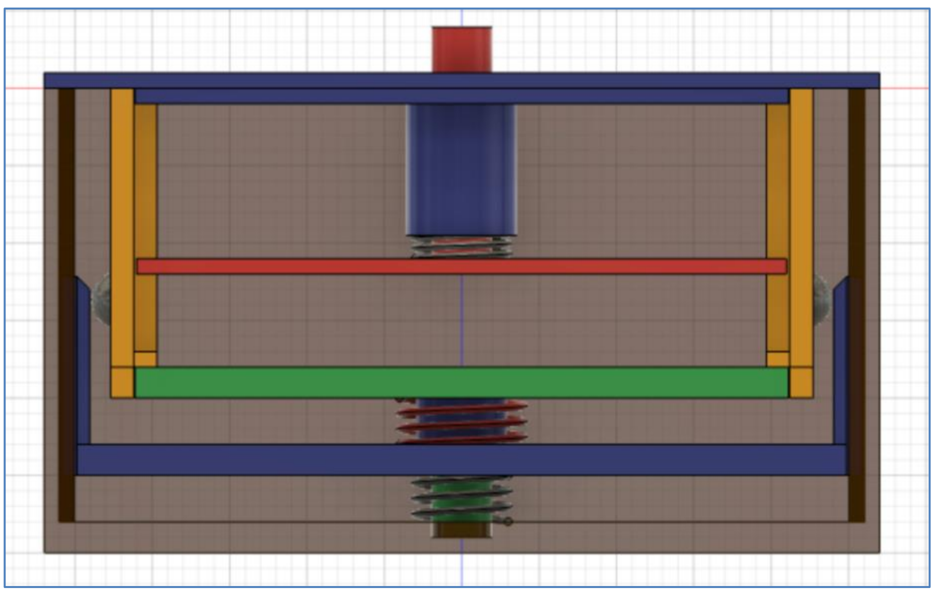

Figure 4: Front-View of the Device Prototype

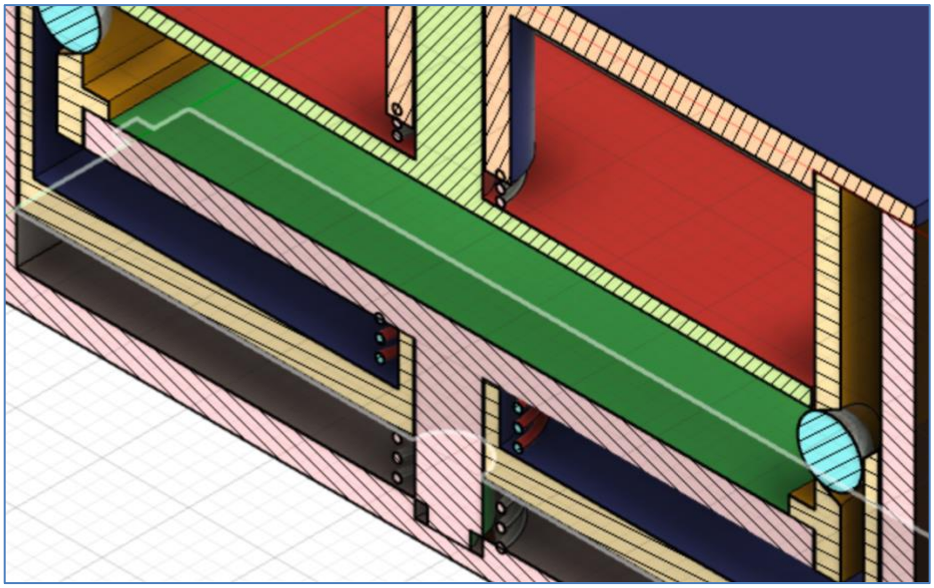

Figure 5: Isometric, Cross-Section View of the Device

5.1.1 Subsystems

5.1.1.1 Hold/reset type – SMA Spring

The shape memory spring is the only controllable component in this device – everything else is activated as a result of the SMA's movement. This was chosen as it is resettable by nature and eliminates the requirement for a more complicated mechanism or the integration of complex electrical components such as computers and motors.

5.1.1.2 Release type – Pin Puller

A pin-puller design was chosen as it allows the load to be directed in shear on the pin extending out of the device. With a pin-pusher, the pin is released to exit the device with the load and has to be loaded in tension. A pin-puller allows lower-force internal components as there is minimal axial force to account for.

5.1.1.3 Lock type – Ball-lock

The ball-lock was chosen as it can be manufactured from simpler shapes and ball bearings are COTS parts. Compared to its previous option, the lever/gate lock, the lever would need to be on a hinge, and manufactured accurately on a scale that would be extremely difficult.

5.1.2 Prototyping

The prototype is significantly larger than the final product will be, as it is easier to verify the mechanism. It is approximately five inches in width, and the pin protrudes approximately one quarter inch from the outer surface. It is mostly 3-D printed and serves mainly as a proof of concept for the locking and pin-pulling sub-systems. At the time of this report, the SMA spring is still on order, therefore the team could not integrate it into the prototype. Instead of fasteners, elastic bands are used to hold the device together for easy and quick disassembly. Figures 6 and 7 are photos of the current design prototype. Moving forward, the team will stray away from 3-D printing and work towards downscaling, integrating the SMA spring, and manufacturing out of more professional materials.

Figure 6: First Angle of Prototype

Figure 7: Second Angle of Prototype

5.2 Implementation Plan

Team Stellar Hold plans to begin implementation by building a prototype of the HDRM. The prototype will be made on a larger scale than the final device so that errors and weak points are easier to spot. This is also because the team has decided to use less expensive materials when testing so that the design flaws can be seen, and the prototype can be rebuilt without repurchasing expensive material that may cause the team to exceed the budget allotted for testing. The device will require 50-100 test runs to determine how soon/what parts of the HDRM will wear and how reliable the design is. The device is designed to be resettable by hand for as many tests as needed; this allows the team to make any physical/operational changes to the system as deemed necessary.

The majority of the resources needed to implement the chosen design come from the General Atomics team for testing information and ordered materials for building/updating the prototype. The team has researched/ordered materials from multiple websites, but most have come from McMaster Carr or Amazon, like Nitinol springs or ball-nose plungers. Some materials the team plans to use during prototyping are supplied by Northern Arizona University in the machine shop, like aluminum blocks that will be used to shape the container from. Our General Atomics team has supplied testing information in the form of space conditions that the HDRM will need to operate during, and dimensions of the CubeSat that the HDRM will need to fit inside of, so that the team can ensure it is designed at the right size and can perform correctly with the weight of the panels. Lastly, the team plans to use the facilities on campus such as the wind tunnel when testing against space conditions, the machine shop to shape the HDRM, and the electrical engineering lab to apply current to change the temperature and actuate the Nitinol spring.

The Bill of Materials for the prototype is included in the budget breakdown which can be found in Appendix A below. The budget breakdown includes the BOM as well as the breakdown for travel and the testing/repairs budget. The table includes sources of the materials, price, and quantity. The raw prices of the parts ($200) are added in with the implementation costs for testing ($100) and repairs ($100). The total of implementation resulted in $400, added to $3,000 for travel, leaving us with a $1,600 cushion out of our $5,000 total budget.

In Appendix B, the team's schedule for second semester can be seen. The tentative schedule was created as a Gantt Chart with a mix of the capstone course's plan and the General Atomics team's plan without definitive dates. It shows the plan for implementation activities throughout the weeks with testing, repairs, prototyping and creating a final model.

Below the CAD model assembly view can be seen of the final design selected.

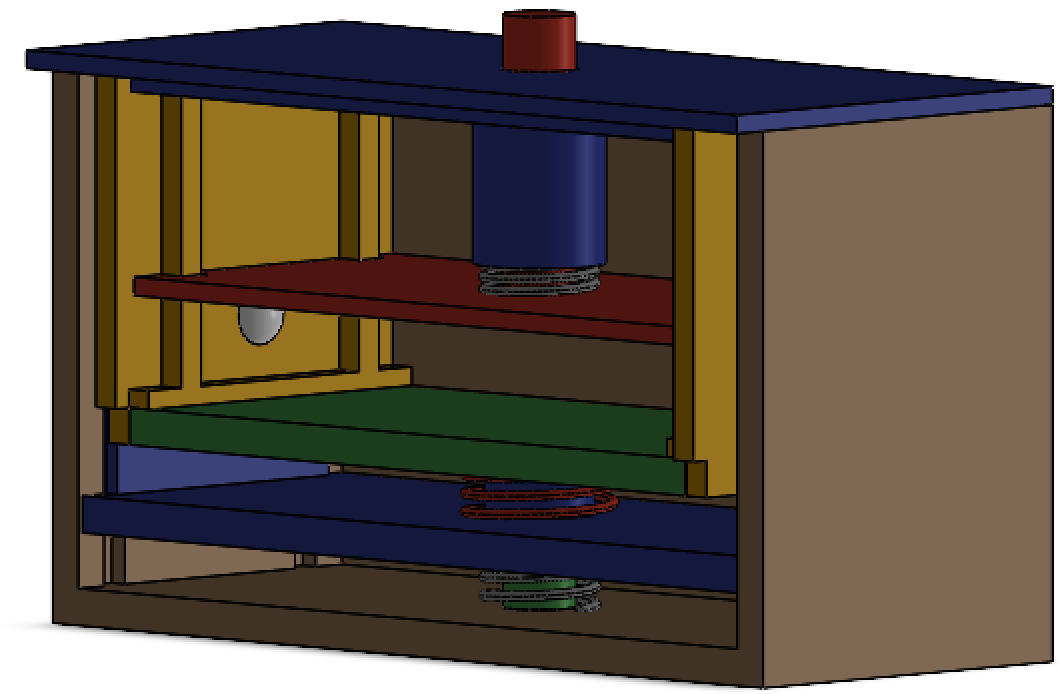

Figure 8: Assembly View of the CAD Model

Below the CAD model exploded view can be seen of the final design selected.

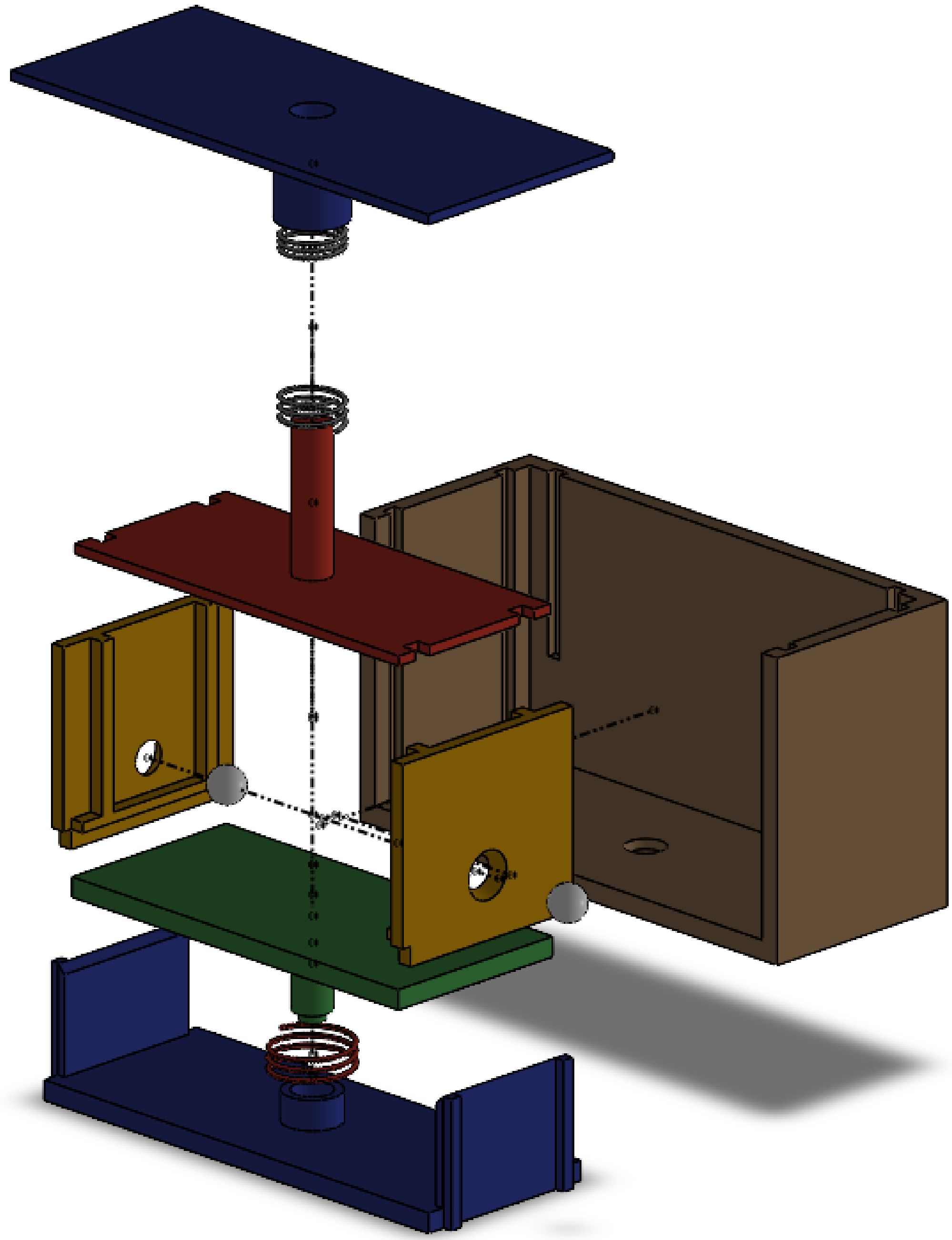

Figure 9: Exploded View of the CAD Model

6 CONCLUSIONS

Our team began the project with a very open-ended prompt: to build an originally designed HDRM that will operate a CubeSat. After some deliberation amongst ourselves and the GA-EMS team, our three-member group took off and allowed the design process to start. We were given some requirements such as no space debris, low emission, size requirements, fully resettable, and a two-part (hold then release) function. Moving through the design process, beginning with customer needs/engineering requirements, leading to a Pugh Chart and Decision Matrix, then to a Black Box Model and House of Quality, narrowing down the final three designs to the final one. This design was selected as it performs the functions as well or better than its competitors and seems to be simpler in design and manufacturing. The team constructed a low-fidelity prototype which aided in the risk and trade-off analysis and will lead into testing of how well the design meets the requirements. The beginning of prototyping has already taught us how differently the device actually operates, compared to our plans on paper. One thing we now know for sure is that we still have so much learning to do throughout the next semester as we dig deeper into testing. We are very hopeful that the more we spend on testing, the more we will know about how to perfect this device and make it ready to be scaled to size, certified, and sent into orbit in a CubeSat.

7 REFERENCES

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8 APPENDICES

8.1 Appendix A: Budget Breakdown

Budget Breakdown		
Device Manufacturing Budget:	Travel Budget:	**Leftover:**
$450	$3,000	**$1,550**
Total =	**$3,450**	

Travel Budget			
Description:	**Price ($):**	**Quantity:**	**Source:**
Gas (To and from Phoenix)	$50	1	Gas Station
Parking (Airport)	$14	5	Airport Lot
Flight (Round Trip)	$580	3	American Airlines
Uber (Airport – Hotel)	$70	2	Uber
Hotel (Two Rooms)	$200	4	Average online
Uber (To and from GA)	$200	N/A	Uber
Total Cost =	**$3,000**		
Device Manufacturing Budget			
Part Description:	**Part Price ($):**	**Quantity:**	**Source:**
Electrical Components	$50 (estimated)	1	McMaster Carr
Gate Latch	$6.88	4	Amazon
Nitinol Spring(2.4mm)	$21.25	1	Amazon
Aluminum Block	$36.99	1	Amazon
Spring	$3.99	2	Amazon
Ball-Nose Spring Plunger	$8.38	2	McMaster Carr
Arduino	$39.50	1	Amazon
Total Cost =	**$200**	**($250 allotted to account for tax/shipping)**	
Manufacturing Total: $250	**Testing Total: $100**	**Repairs Total: $100**	**Final Total: $450**

8.2 Appendix B: Semester 2 Gantt Chart

8.2.1 Appendix B-1: Weeks 17-24

GA-EMS HDRM

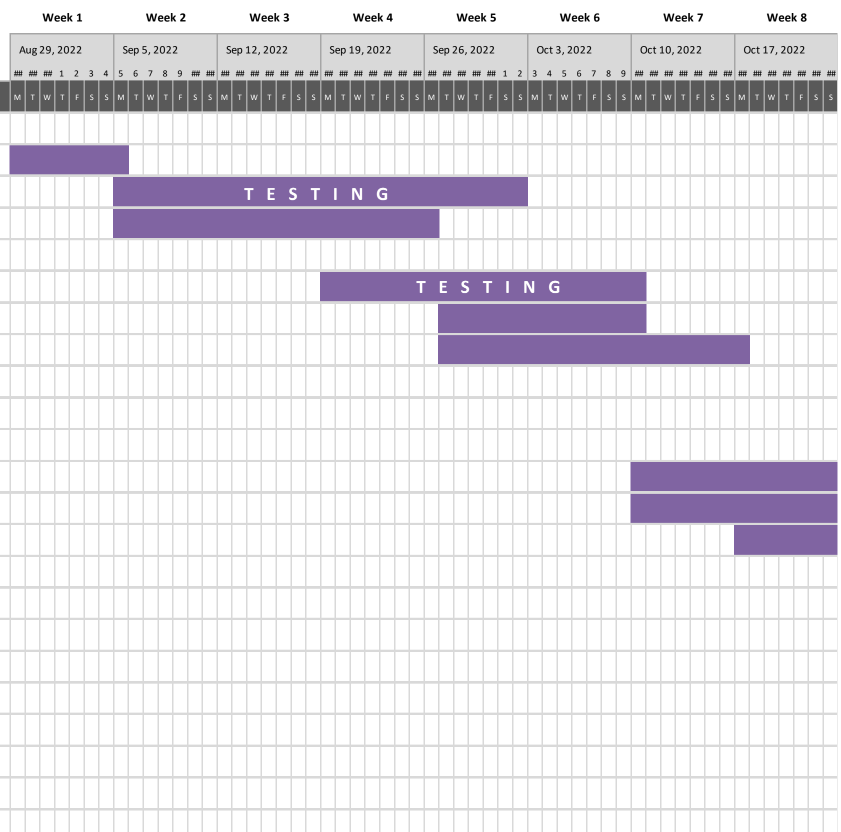
Northern Arizona University
Team 4: Stellar Hold

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Project Start: Mon, 8/29/2022

Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Part 1: Hardware Review 1				
Project management Re	Team	0%	8/29/22	9/5/22
TP3 Part 1	Team	0%	9/5/22	10/2/22
Hardware review 1	Team	0%	9/5/22	9/26/22
Part 2: Hardware Review 2				
TP1 round 1		0%	9/19/22	10/10/22
Website Check	Team	0%	9/27/22	10/10/22
Hardware Review 2	Team	0%	9/27/22	10/17/22
Part 3: Hardware Review Final				
TP1 round 2		0%	10/31/22	11/21/22
TP3 part 2		0%	10/31/22	11/21/22
TP2		0%	10/10/22	10/31/22
Finalize Testing Plan		0%	10/10/22	10/31/22
Hardware Review 100%		0%	10/17/22	10/31/22
Part 4: Finalization				
Poster		0%	10/31/22	11/14/22
Powerpoint		0%	11/7/22	11/14/22
Final CAD		0%	11/1/22	11/21/22
Manual/assembly		0%	11/8/22	11/21/22
Expo		0%	11/28/22	12/4/22
Final Report		0%	11/14/22	12/5/22
Final Website		0%	11/14/22	12/5/22
Testing Results		0%	11/14/22	12/10/22



8.2.2 Appendix B-2: Weeks 18-32

GA-EMS HDRM

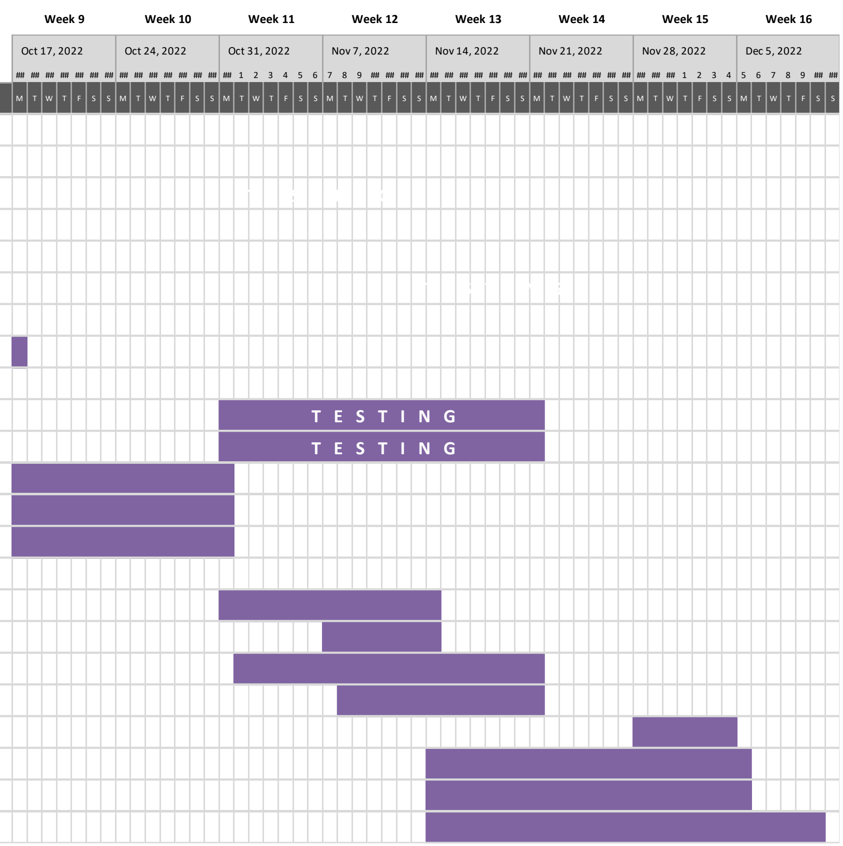
Northern Arizona University
Team 4: Stellar Hold

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Project Start: Mon, 8/29/2022

Display Week: 8

TASK	ASSIGNED TO	PROGRESS	START	END
Part 1: Hardware Review 1				
Project management Re	Team	0%	8/29/22	9/5/22
TP3 Part 1	Team	0%	9/5/22	10/2/22
Hardware review 1	Team	0%	9/5/22	9/26/22
Part 2: Hardware Review 2				
TP1 round 1		0%	9/19/22	10/10/22
Website Check	Team	0%	9/27/22	10/10/22
Hardware Review 2	Team	0%	9/27/22	10/17/22
Part 3: Hardware Review Final				
TP1 round 2		0%	10/31/22	11/21/22
TP3 part 2		0%	10/31/22	11/21/22
TP2		0%	10/10/22	10/31/22
Finalize Testing Plan		0%	10/10/22	10/31/22
Hardware Review 100%		0%	10/17/22	10/31/22
Part 4: Finalization				
Poster		0%	10/31/22	11/14/22
Powerpoint		0%	11/7/22	11/14/22
Final CAD		0%	11/1/22	11/21/22
Manual/assembly		0%	11/8/22	11/21/22
Expo		0%	11/28/22	12/4/22
Final Report		0%	11/14/22	12/5/22
Final Website		0%	11/14/22	12/5/22
Testing Results		0%	11/14/22	12/10/22



8.3 *Appendix C: FMEA*

Product Name: Resettable HDRM		Development Team: Stellar Hold				Page No of			
System Name: Hold Down and Release Mech						FMEA Number			
Subsystem Name						Date: 4/15/2022			
Component Name									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Hold Type									
SMA	Permanent deformation	Change pin position	8	Over voltage/ temperature	2	Heat SMA	3	48	Test environment conditions
SMA	Fatigue life	Change pin position	8	High and low cycles	5	Force inspection	2	80	Test SMA Fatigue life
SMA	Temperature/Electrical	Unable to change pin	7	Below required voltage	7	Use Multimeter	7	343	Test wires
SMA	Fatigue-crack growth	Change pin position	8	cyclic stresses below Ultimate tensile stress	5	Force inspection	3	120	Test for Fatigue crack growth
SMA	Overload fracture	Change pin position	8	Excessive stress or strain	5	Force inspection	2	80	Verify SMA can handle load
Spring	Stress relaxation	Unable to keep	6	Held at a certain stress for	6	Force inspe	1	36	Keep spring in rested

		pin in place		extended period of time		ction			position
Spring	fracture due to fatigue	Unable to keep pin in place	6	repetitive cyclic brief time stress	6	Force inspection	2	72	Test for cycle life
Pin	Deformation wear	Unable to hold load	8	Overstressing	3	Visual inspection	2	48	Pick best material for load
Pin	Impact fatigue	exposed space debris	9	Impact loading	5	Visual inspection	2	90	Control impact loading
Pin	Impact wear	Unable to hold load	7	Wrong material	4	Visual inspection	2	56	Pick best material for load
Release Type									
Lock Mechanism	Wrong Configuration	Pin will not retract	5	Human Error	7	Visual inspection	4	140	Verify lock configuration
Pin	Deformation wear	Unable to hold load	3	Overstressing	3	Visual inspection	1	9	Pick best material for load
Spring	fracture due to fatigue	Unable to keep pin in place	6	repetitive cyclic brief time stress	6	Force inspection	2	72	Test for cycle life
SMA	Deformation wear	Pin will not retract	7	Overstressing	4	Visual inspection	3	84	Test for deformation
SMA	Fatigue Fracture	Pin will not retract	7	cyclic stresses below Ultimate tensile stress	4	Visual inspection	3	84	test fatigue life
Wires	Degradation	SMA actuator will not work	3	Using over time	3	Visual inspection	5	45	Check wire life
Wires	Heating of cable	SMA actuator will not work	3	Generated by the resistance to current flow	6	Temperature check	6	108	Verify resistance
Wires	Electrical Overloading	SMA actuator will not work	5	Applying too much load	7	Multimeter	6	210	Verify electrical output

Battery	Defective connection	SMA actuator will not work	3	Human Error	7	Multi meter	1	21	Check connections
Battery	Loose connector	SMA actuator will not work	3	Human Error	8	Multi meter	1	24	Check connections
				Reset					
Lock Mechanism	Wrong Configuration	Unable to reset pin	8	Human Error	7	Visual inspection	4	224	Change lock configuration
SMA	Fatigue life	Change pin position	8	High and low cycles	5	Force inspection	2	80	Test SMA Fatigue life
SMA	Temperature/Electrical	Unable to change pin	7	Below required voltage	7	Use Multi meter	7	343	Test wires
SMA	Fatigue-crack growth	Change pin position	8	cyclic stresses below Ultimate tensile stress	5	Force inspection	3	120	Test for Fatigue crack growth
SMA	Overload fracture	Change pin position	8	Excessive stress or strain	5	Force inspection	2	80	Verify SMA can handle load
Spring	Stress relaxation	Unable to keep pin in place	8	Held at a certain stress for extended period of time	7	Force inspection	3	168	Keep spring in rested position
Pin Platform	Slips	Unable to reset pin	7	Applying force in wrong direction	7	Visual inspection	3	147	Test reliability of lock mechanism
Pin Platform	Flaking	Rough resets	4	Repeating trial runs, rubbing on ball bearings	4	Force inspection	2	32	See lubricant option
Ball Bearings	Flaking	Rough resets	4	Rubbing on Pin Platform	4	Force inspection	2	32	See lubricant option
Ball Bearings	Spalling	slower/ no reset	4	surface fatigue	3	Visual inspection	2	24	See lubricant option

Lock Mechanism									
Ball Bearings	Flaking	Unable to lock	4	Rubbing on Pin Platform	4	Force inspection	3	48	See lubricant option
Ball Bearings	Spalling	Unable to lock	4	surface fatigue	3	Visual inspection	2	24	See lubricant option
Lock Platform	Slips	unlocks	7	Force in wrong direction	6	Force inspection	2	84	
Lock Platform	Flaking	Rough surface/ locking	4	Repeating trial runs, rubbing on ball bearings	4	Force inspection	2	32	See lubricant option
Lock Platform	Wrong Configuration	Locks in wrong position	8	Human Error	7	Visual inspection	4	224	Change lock configuration
Spring	Stress relaxation	insufficient force output	9	Held at a certain stress for extended period of time	6	Force inspection	1	54	Keep spring in rested position
SMA	Fatigue life	Change pin position	8	High and low cycles	5	Force inspection	2	80	Test SMA Fatigue life
Switch	Unexpected current flow	actuates SMA, unlocks	8	faulty switch/ battery	3	Visual inspection	1	24	Test components before
Lock Platform	Poor tolerance fits	Will not lock	6	Manufacturing	3	Measure	1	18	Outsource materials for lock
Pin	Axial force in wrong direction	Unlocks	10	Force in the wrong direction	6	Force inspection	2	120	Test various applied forces