Resettable Hold Down Release Mechanism

Final Report

Nathan Olsen
Valentin Gamez
Maia Warren

Spring – Fall
2022

NORTHERN ARIZONA UNIVERSITY

College of Engineering, Informatics,
and Applied Sciences

Instructor: David Willy

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

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 Nitinol 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 beginning from problem conception to final design with testing and future considerations. The team manufactured a device that demonstrates these concepts, in a 3in^3 (approximately) form factor, which actuates when powered and can be reset by hand once cooled down. Minor setbacks were faced, such as having to use an unideal SMA spring, and some manufacturing problems. Ultimately, the ideal force and size targets were not hit, but the main goal of this project, which is to design a mechanism and demonstrate it works, was achieved without doubt. Looking ahead, future teams may optimize this design for greater force, smaller volume, and higher quality manufacturing.

ACKNOWLEDGEMENTS

We would like to acknowledge General Atomics for creating the project and for the guidance throughout the first semester. Their lists of Engineering and Customer Requirements provided created the basis of the design and lead us towards completing our goals. We would also like to acknowledge Professor Carson Pete for leading us through the first semester and staff meetings, Professor David Willy for being our closest form of contact throughout the second semester and for taking over as our client. Additionally, we would like to thank Perry Wood and the entire staff of the machine shop for their continued help and advice throughout the manufacturing process.

TABLE OF CONTENTS

Contents

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

In the beginning of the project, 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."

Initially, the scope of the project was as described below. However, after the first semester (approximately 16 weeks), GA-EMS withdrew from the project, possibly due to funding issues. Northern Arizona University allowed us to continue with the project, with Dr. Willy as our client and NAU as the sponsor providing funds.

> “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 because of meetings and conversations with the engineering team from GA-EMS.”

While GA-EMS did not have a hand in the project after the half-way point, the scope of this project remains mostly the same. Of course, our team will not be attending a GA-EMS facility, instead the team will be presenting at the capstone symposium along with other engineering capstones. The goals of the project remain the same, with a high-quality proof of concept expected by the end of the project timeline. Communication and mentoring from GA-EMS stopped after the half-way point, therefore our team did not have access to the resources from GA-EMS as described above.

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 had provided a group of their own engineers to collaborate with us, 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 as well as a preferred tolerance for each requirement.

Table 1: Engineering Requirements & Target Values

Engineering Requirement	Target	Units	Tolerance
No breakaway parts	0	-	0
Low outgassing materials	0.1	-	0
No combustion	0	-	0
Minimize volume	1	cu. In	+0.5
Minimize protruding material	1	cm	0.1
Maximize deployment force	25	N	- 5
No deformation	0	%	+2
Maximize retention reliability	100	%	1.5
Receive input command	-	-	-
Minimize weight	200	g	+50 -200
Minimize reset time	30	sec	+30
Maximize SMA Spring life (1N)	50	Cycles	5

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/Work-Process Diagram/Hierarchical Task Analysis

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 that is 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.

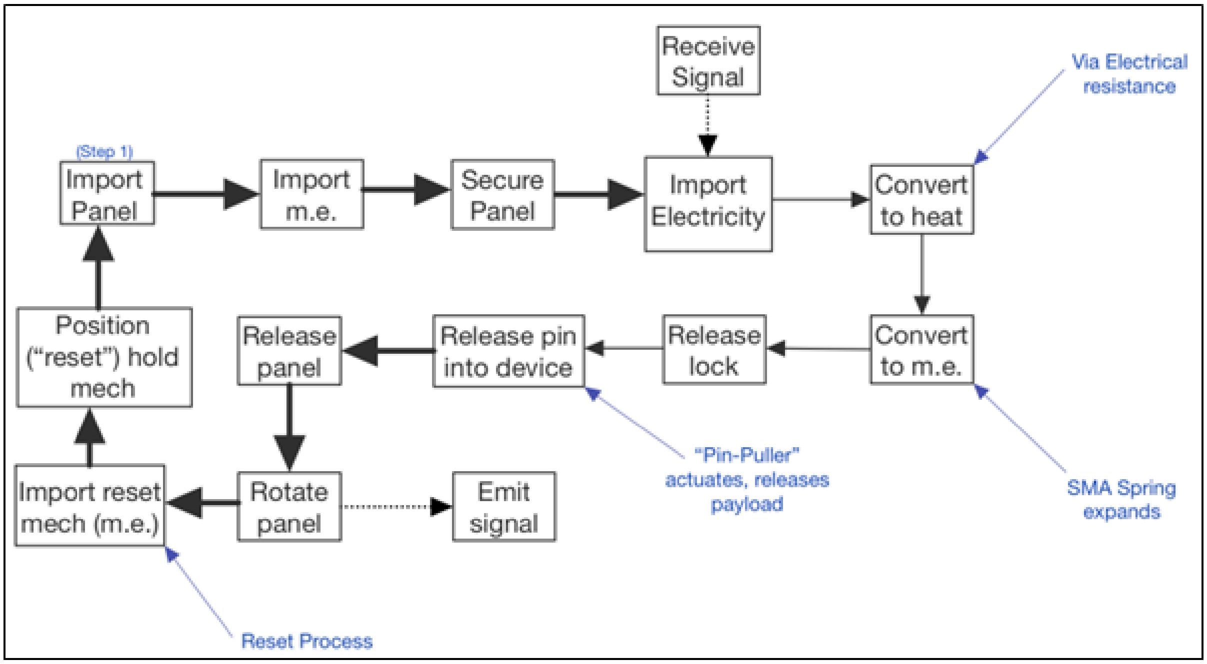


Figure 2: Functional Model for Resettable HDRM (Annotations in Blue)

2.4 House of Quality (HoQ)

This subsection evaluates the customer and engineering requirements using a house of quality (Appendix A) 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 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.

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 DESIGN SPACE RESEARCH

Designing a technical product, like a hold down and release mechanism, requires extensive research into a variety of areas. Important topics to take into consideration include existing HDRM designs and the different approaches to designing an HDRM. An overview of the sources each team member used for design research and benchmarking will be provided in this section.

3.1 Literature Review

Each team member has conducted preliminary research on aspects of the project that are relevant to their role in the team and the success of the project. This research aids in initial design and benchmarking processes. Additionally, this benefits the team in understanding basic limitations for designs, as this research leads into a greater understanding of current state-of-the-art products. As the project progresses further into design iterations and prototyping, further research will be conducted to continually ensure feasibility and guide the team through the project.

Valentin's research mostly consisted of current designs, shape memory alloy research papers and multiple patents, which all help with the design stage for the HDRM [12]–[16]. Maia's research consisted of design variants of current HDRM's, parts vendors, and information provided by GA-EMS and previous capstone teams. [17]–[22]. Nathan's research strictly covered testing procedures, standards and codes for the context of this project [3], [23]. By delegating research topics, the team ensured that knowledge is obtained on design, testing, parts, and current state of the art HDRM's.

3.2 Benchmarking

The benchmarking process for this project has been conducted through internet research and discussions with the representative team of engineers from GA-EMS. Specific areas of focus during this process include non-pyrotechnic designs and resettable designs, as those are design criteria defined by the client. Additional areas of focus during this process are common shapes and sizes for similar devices. After identifying some products to benchmark, the subsystems are benchmarked to compare functions, allowing a thorough analysis and break-down of these products.

3.2.1 System Level Benchmarking

3.2.1.1 Existing Design #1: First Move HDRM

The first existing design that the team found during the benchmarking phase was the First Move HDRM (figure 3). This student designed HDRM worked "flawlessly" during ground testing [22]. It successfully deployed in orbit as well. This design meets a few of our engineering requirements such as no pyrotechnics, low outgassing, and no space debris. However, one requirement the First Move HDRM does not meet is the that the device is not resettable. For the device to release it must melt a dynemma string and can only be reused by replacing this string. This is the designs biggest flaw, and it is the team's most important engineering requirement. The team can take inspiration from this design and what it did successfully, while improving the reset ability of the mechanism.

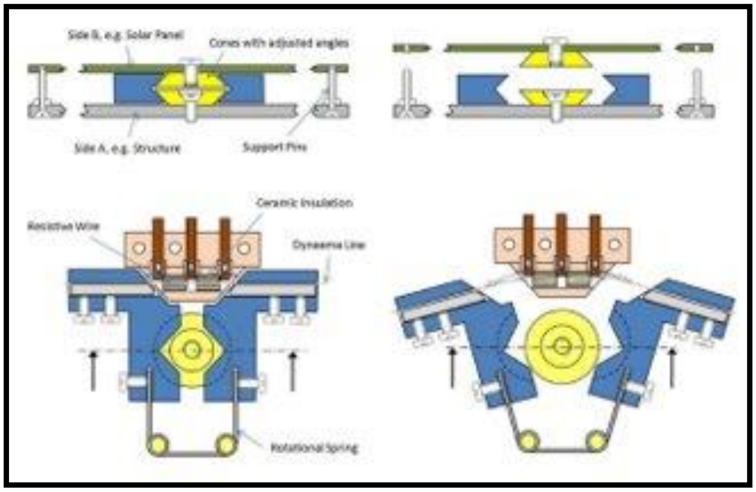


Figure 3: First Move HDRM

3.2.1.2 Existing Design #2: EBAD TiNi Pin Puller

The next design is the EBAD TiNi Pin Puller (figure 4). This is the model that General Atomics previously used and meets all the team's engineering requirements. The TiNi Pin Puller is a fitting example of an HDRM that the team eventually plans to build. The device works by retracting a pin which release the CubeSat panels. It can be reset using an additional device, see figure 5. While this device does have a method for resetting, the team would like to improve this by eliminating the second device and can self-reset. This function can be seen in the next existing design.

Figure 4: Tini Pin Puller

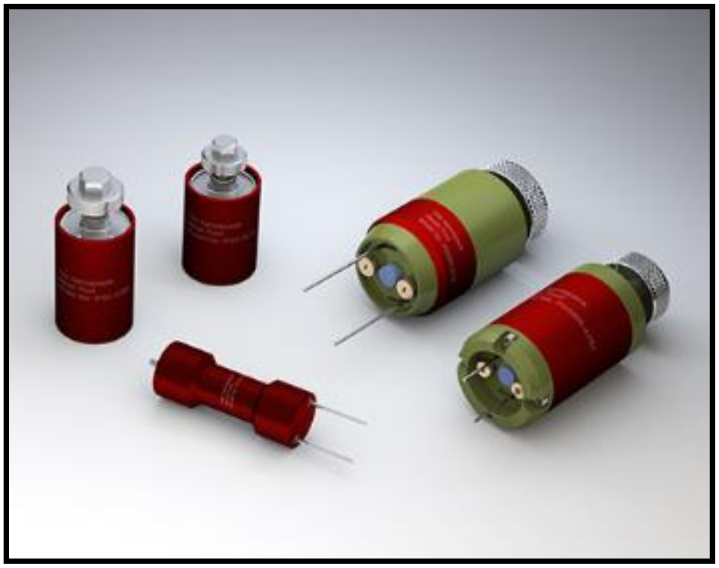


Figure *5:* Tini Pin Puller Reset Device

3.2.1.3 Existing Design #3: React HDRM

The REACT HDRM (figure 6) is a resettable non pyrotechnic device that utilizes a shape memory alloy actuator. This device perfectly meets all the engineering requirements and has the best reset mechanism. The SMA material is the key component that allows for such a great device.

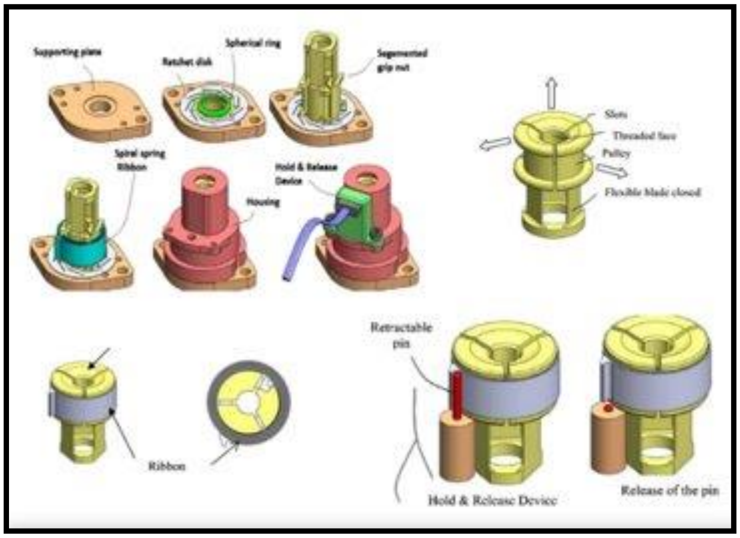


Figure 6: React HDRM

3.2.2 Subsystem Level Benchmarking

3.2.2.1 Subsystem #1: Hold Type

The first subsystem is hold type, which is responsible for holding the CubeSat in the folded position. The hold type is an important subsystem of an HDRM as the device must be able to support enough weight.

3.2.2.1.1 Existing Design #1: First Move HDRM

The First Move HDRM is held together by a dyneema string. A dyneema string is a strong durable material that can support the required weight.

3.2.2.1.2 Existing Design #2: EBAD TiNi Pin-Puller

Design 2 uses a pin to hold together the CubeSat panels. A weight can be hooked around the pin, the panels to stay in place. This is a popular and reliable method for HDRMs.

3.2.2.1.3 Existing Design #3: React HDRM

The React HDRM uses the pin pusher method. A pin is attached to the HDRM and to the CubeSat, holding the two together. This is another effective method that is commonly used.

3.2.2.2 Subsystem #2: Release Type

Once the satellite has been launched into orbit, the HDRM must be able to release the panels. Without a functional release mechanism, the satellite would not be functional, meaning this is an important subsystem.

3.2.2.2.1 Existing Design #1: First Move HDRM

First Move’s release mechanism involves melting the dyneema string that holds everything together. Once the string has been melted it opens the contraption, see figure 3.

3.2.2.2.2 Existing Design #2: EBAD TiNi Pin-Puller

The Pin-Puller releases the payload by pulling in the pin that is supporting the weight. Once the pin is pulled in the panels will spring out due to the hinges that are attached to them.

3.2.2.2.3 Existing Design #3: React HDRM

The React HDRM does the opposite of the pin-puller. Rather than pulling in the pin it pushes out the pin attached to the satellite. This will allow the panels to open freely.

3.2.2.3 Subsystem #3: Reset Mechanism

The reset mechanism is key to saving time, money, and assessing the reliability of the device. It allows for the device to be tested repeatedly and get an understanding of how reliable the device is.

3.2.2.3.1 Existing Design #1: First Move HDRM

This design’s biggest weakness is its reset mechanism. The First Move HDRM can be used again after soldering a new dyneema wire. This current method is not reliable since putting together new parts creates a new untested device, making it difficult to determine how reliable the device is.

3.2.2.3.2 Existing Design #2: EBAD TiNi Pin-Puller

The Pin-Puller uses a secondary device to reset the HDRM, see figure 5. By inserting the device into the HDRM, one can quickly reset the pin position and allow it to run again.

3.2.2.3.3 Existing Design #3: React HDRM

React HDRM uses an SMA actuator to automatically reset the device. Since SMA’s shape can be manipulated using temperature, this allows for many innovative solutions to making the device resettable.

4 CONCEPT GENERATION

Upon understanding of current state-of-the-art mechanisms and designs, each of the three team members brainstormed and sketched a potential HDRM design. Then, these ideas were analyzed as a group, from which the sub-functions were defined, and design concepts generated. The team then generated multiple feasible design alternatives for each sub-function in a morphological matrix. This matrix can be seen in figure 7. Six different full-system concepts were generated, and then evaluated using Pugh Charts and a Decision Matrix. The top three concepts are sketched and shown in section 4.1.

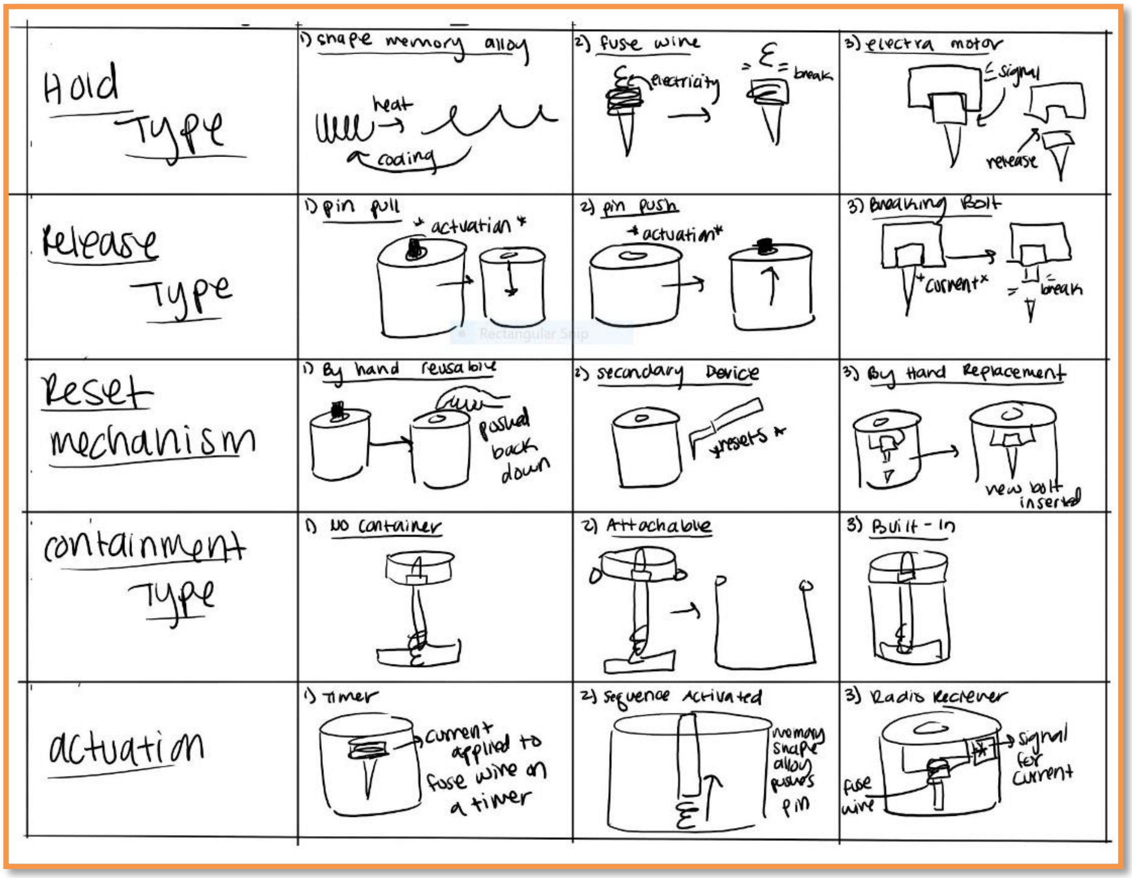


Figure 7: Morphological Matrix

4.1 Full System Concepts

4.1.1 Full System Design #1: Pin Releaser

The following design is a pin-pusher (releaser) design (figures 8 and 9). The illustration in figure 8 shows a cross-section of this concept. The lock parts drawn in green are biased closed, as seen in the left side. A wedge above it is forced down with the expansion of a spring, pushing the lock parts aside and allowing the pin to freely exit the container. The spring is made on nitinol shape memory alloy, to allow it to be actuated using heat generated by electrical current and reset without replacing parts.

Pros

- Reliable locking

- Resettable
- Potential to be a heavy design

Cons

- Mechanically complicated – difficult to manufacture
- Takes up significant "vertical" space (along axis of pin)
- Needs to be contained due to the pin being fully released

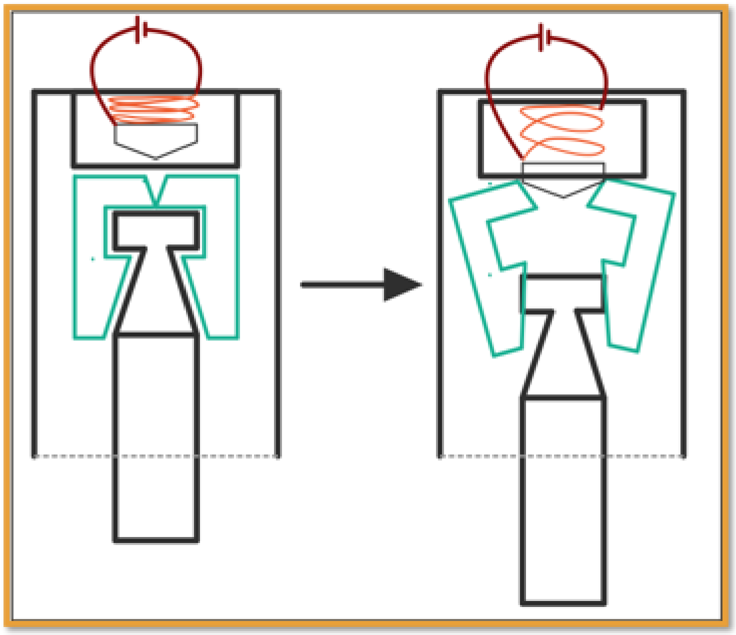


Figure 8: Pin Releaser

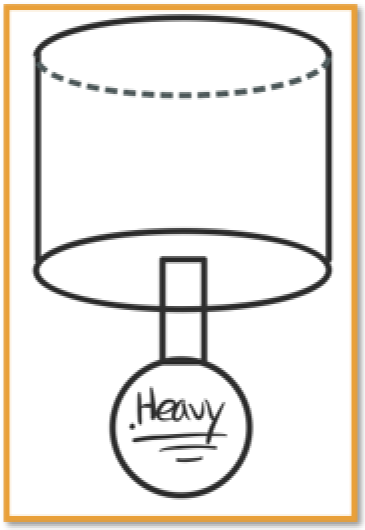


Figure 9: Pin Releaser Pay Load View

4.1.2 Full System Design #2: SMA Actuator

This design uses existing principles of shape memory alloy springs to result in a mechanism that resembles a linear actuator. Figure 10 illustrates this mechanism. There exists two springs, separated by a divider which is connected to the output pin. The leftmost spring is a regular spring to bias the output pin to the right (relative). The rightmost spring is made of shape memory alloy, which when heated up with electrical current, overcomes the bias spring and drives the output pin into the mechanism.

Pros

- Simple mechanism
- Can be made relatively small
- Easily resettable

Cons

- No locking mechanism – free moving
- Temperature change much be quick and consistent
- Difficult to ensure the current is reliable enough to actuate while in orbit

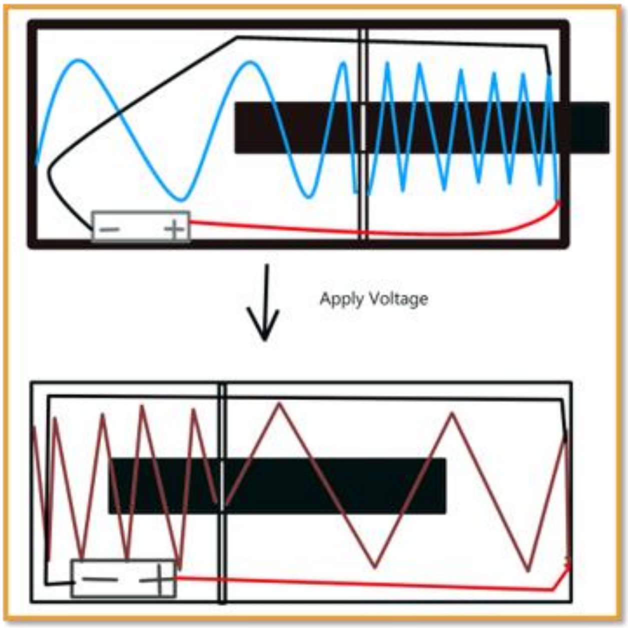


Figure 10: SMA Actuator

4.1.3 Full System Design #3: Locking SMA Actuator

This design functions by pulling the output pin inwards to the mechanism. A bias spring (top) under compression pushes the output pin inwards, stopped by a lock. A release mechanism on the lower portion of the design is engaged to disengage the lock via SMA. Once the lock is released, the compressed bias spring extends, pulling the output pin into the mechanism. This can be seen in figure 11, showing a top view on the left and a cross section side view on the right.

Pros

- Locking

- Easily resettable
- Solar panel lock(s) may be easily attached to the center output pin

Cons

- The bottom spring must be stronger than the weight of the above mechanism
- Temperature change must be consistent
- The locks must move fluidly

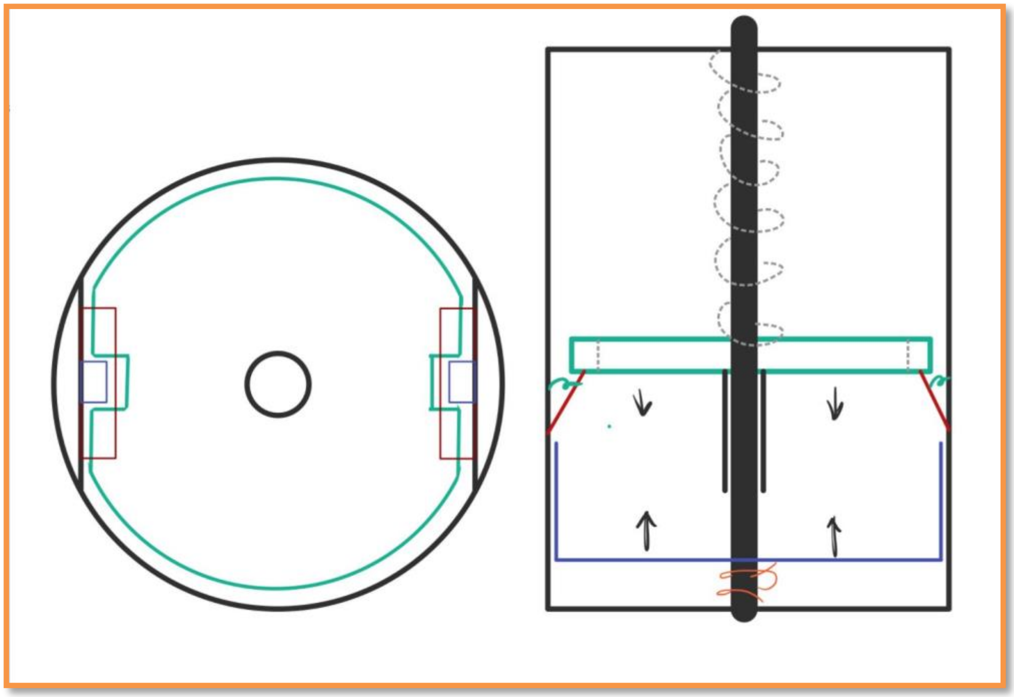


Figure 11: Locking SMA Actuator

4.2 Subsystem Concepts

The following includes the subsystem design concepts for the project.

4.2.1 Subsystem #1: Hold Type

The hold type designs that were created have been used in previous HDRMs and our team is now attempting to improve upon them to create a new holding design. The hold type is the first of two positions the HDRM reaches.

4.2.1.1 Design #1: Shape Memory Alloy

Our team has considered using a shape memory alloy as the hold type for our HDRM because of its ability to be first molded and then change its shape by conducting a change in temperature. The temperature change has to be consistent and reliable, but it is ultimately a simple holding method due to how easily the shape memory alloy can be manipulated.

4.2.1.2 Design #2: Fuse Wire

The fuse wire has also been considered for the innovative design because it is a reliable holding type that can be manipulated around any part by simply wrapping and without any temperature change needed. Once the device is actuated, a current will be applied to break the fuse wire and cause a release. The fuse wire is easily resettable by hand but relies on a consistent current and produces waste from the broken wire.

4.2.1.3 Design #3: Electra Motor

The electronic motor will hold all parts of the HDRM into place and only release once a signal has allowed it to. This method uses electricity to complete its task, so it is not reliant on position, but the design options are limited since it will require an external signal to release the solar panels.

4.2.2 Subsystem #2: Release Type

The release type designs that were created have been used in previous HDRMs and our team is now attempting to improve upon them to create a new releasing design. The release allows the HDRM to reach its second and final position.

4.2.2.1 Design #1: Pin Pull

The pin pull release method works by holding a pin in place and allowing it to be pulled into the device during actuation and move the HDRM into its new position. The pin pull method is reliable since it works from device movement and gravity, but it requires a smooth track for all parts of the device to function properly through multiple tests without ware.

4.2.2.2 Design #2: Pin Push

The pin push release method works by holding a pin in place and pushing it towards to outside of the device during actuation. This step also allows the HDRM to move into its new position. The pin push method also relies on a smooth, ware resistant track and makes the device easily resettable.

4.2.2.3 Design #3: Breaking Bolt

The breaking bolt release method works by holding a pin in place and applying a current to break the bolt, creating room for the HDRM to move into the second position. The breaking bolt method is reliable since it works from pressure and gravity, but it requires a containment device to catch the broken pin and is entirely dependent on current.

4.2.3 Subsystem #3: Reset Mechanism

The reset mechanism designs that were created have been used in previous HDRMs and our team is now attempting to improve upon them to create a new resetting design. Resetting is important while testing because the device must prove to be durable enough for multiple uses.

4.2.3.1 Design #1: By Hand Reusable

The by hand reusable rest mechanism is the most efficient and cost-effective method because it does not require any replacement of parts or extra devices to aid the reset while performing multiple tests. The difficult part of using this method is creating a simple enough design that does not require any new parts or cause ware during testing.

4.2.3.2 Design #2: Secondary Device

A secondary device could cause expenses to rise and require more time during testing, however it could simplify the HDRM design by removing parts that are meant for a reset from within the device itself. There would be a second device to design and test and may create more room for error.

4.2.3.3 *Design #3: By Hand Replacing*

By hand replacement is simpler than using another device and will be easier to manipulate the new parts around the remaining ones. This method will allow for waste of products since the team can remove the waste after each test, but this may also increase the price of the HDRM since more parts are required per test.

4.2.4 Subsystem #4: Containment Type

The containment type designs that were created have been used in previous HDRMs and our team is now attempting to improve upon them to create a new containment design. Containment is important if the design breaks or releases parts.

4.2.4.1 *Design #1: No Container*

The price and the weight of the HDRM design, without including a container, will be lower due to less material being attached; however, it limits the design options because there can be no waste or breaking parts since there will be nothing to catch them and keep them from turning into space debris.

4.2.4.2 *Design #2: Attachable*

The attachable container provides a way to catch any waste from broken or released products and allows for an easy removal of the waste when detached. There is also a higher risk of error since the design is built to be removed and could be weaker when withstanding space conditions.

4.2.4.3 *Design #3: Built-In*

Built in containment will be the simplest design for the HDRM because it will provide freedom for all design ideas that include breaking or released parts. It will also be sturdier than the detachable containment but will make it difficult to remove the waste when resetting.

4.2.5 Subsystem #5: Actuation

The actuation designs that were created have been used in previous HDRMs and our team is now attempting to improve upon them to create a new actuating design. Actuation is the most crucial step for the device because it determines if the HDRM can perform its tasks.

4.2.5.1 *Design #1: Timer*

An internal timer can limit error during actuation because the device will not have to wait for an outside signal and there are fewer steps that need to be completed to begin its tasks. The timer must be tested until deemed reliable and it must allow actuation to occur in the right amount of time to allow the HDRM to unfold perfectly.

4.2.5.2 *Design #2: Sequence Activated*

There is more room for error when using a sequence activated method because if a step in the sequence malfunctions the actuation could never occur, rendering the HDRM useless and wasting the parts and funding. The benefit of using the sequence method is that the actuation happens internally and does not rely on outside signals.

4.2.5.3 Design #3: Radio Receiver

The radio receiver could be a trustworthy form of actuation because if there is no error the HDRM can be told exactly when to unfold by humans remotely, removing device error. The risk of using an outside signal is that the connection could break upon sending the part through the detumble stage and turbulence could disturb the housing of the radio receiver.

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 12 and 13. 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 13 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 12, 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.

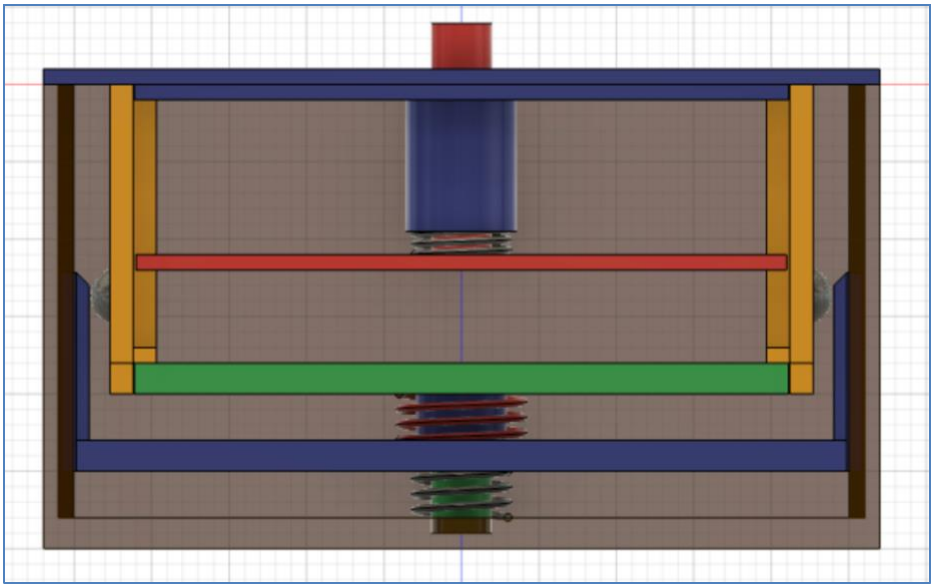


Figure 12: Front-View of the Device Prototype

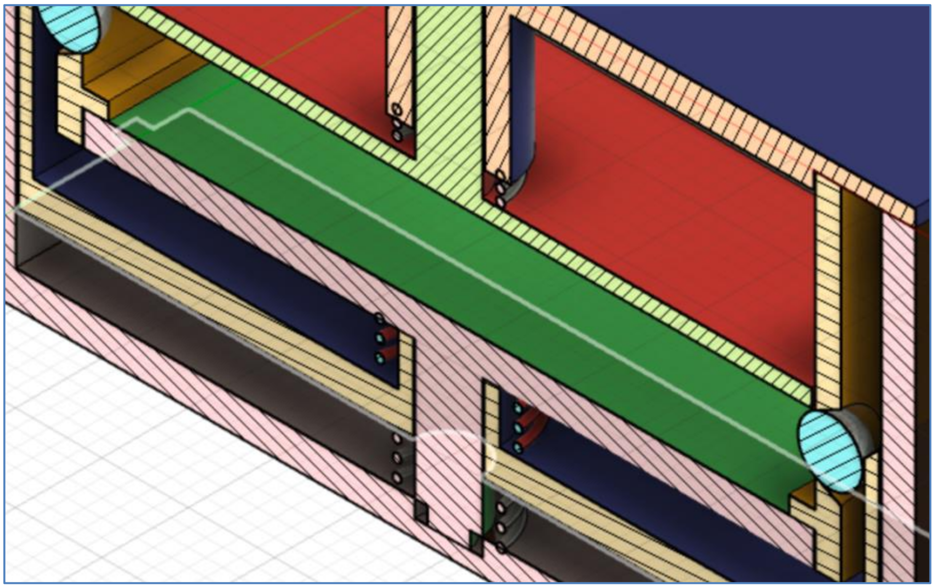


Figure 13: Isometric, Cross-Section View of the Device

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 must 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

5.1.2.1 First Prototype

The first 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 14 and 15 are photos of the first design prototype. As the team works towards the final model, the team will stray away from 3-D printing and work towards downscaling, integrating the SMA spring, and manufacturing out of stronger materials.

Figure 14: First Angle of First Prototype

Figure 15: Second Angle of First Prototype

Preceding the first prototype, the team had 3D printed a non-functional model to serve as a visual aid in the first presentation to the client. This model can be seen in figure 16, it is not considered as an official prototype as it was generated purely for a visual.

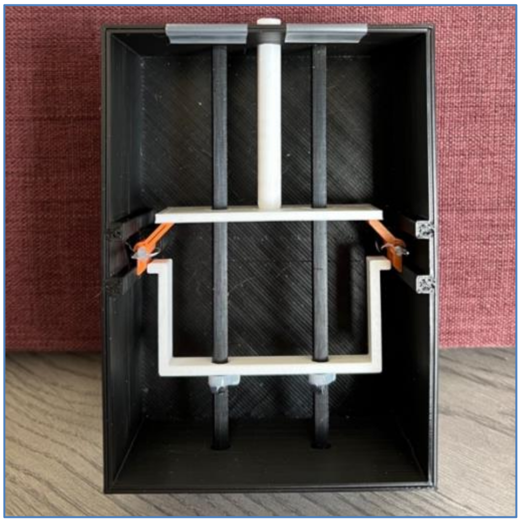


Figure 16: 3D Printed visual for presentation

5.1.2.2 Second Prototype

The second prototype generated is the same in function as the first one, but slightly optimized in shape, therefore it is significantly smaller. Figure 17 shows the second prototype, which is only slightly larger than the final model will be, at $4in^3$.

*Figure 17: Second Prot*otype optimized for size.

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 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.

Most 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. 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 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 are added in with the implementation costs for testing and repairs. The total of implementation resulted in about $500, leaving us with a $1,500 cushion out of our $2,000 total budget.

In Appendix B, the team's schedule for the project can be found. 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 and exploded view can be seen of the final design selected (figure 18 and 19). This is not the optimized and final model of the design, but just the selected design generated on a large scale.

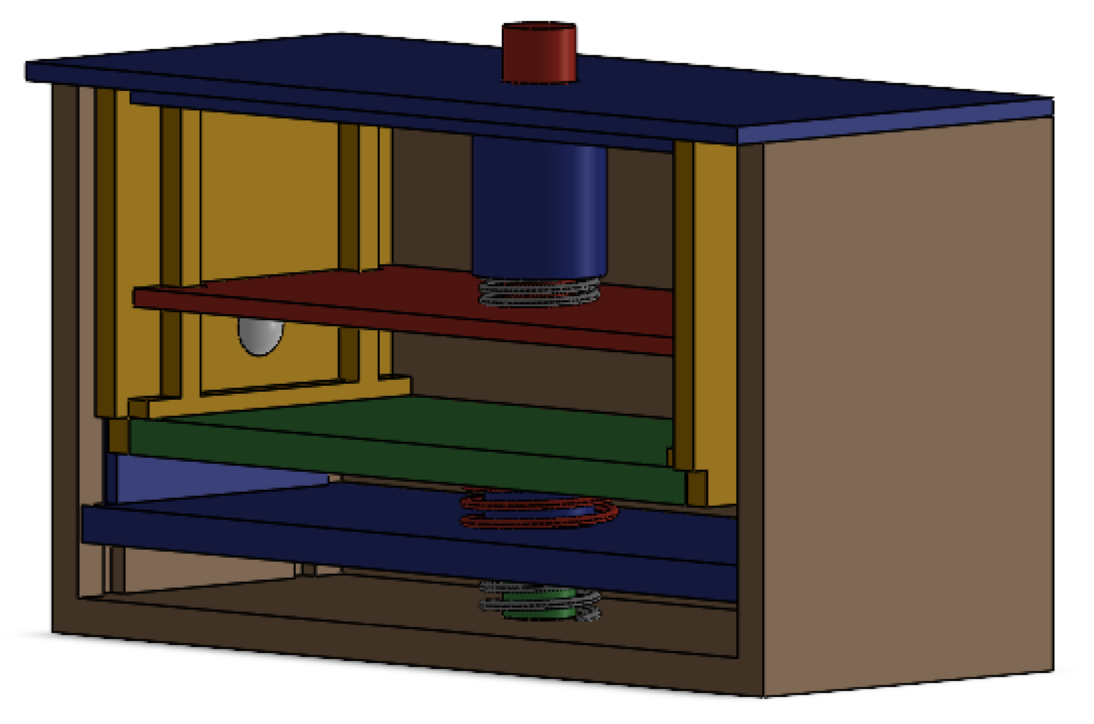


Figure 18: Assembly View of the CAD Model

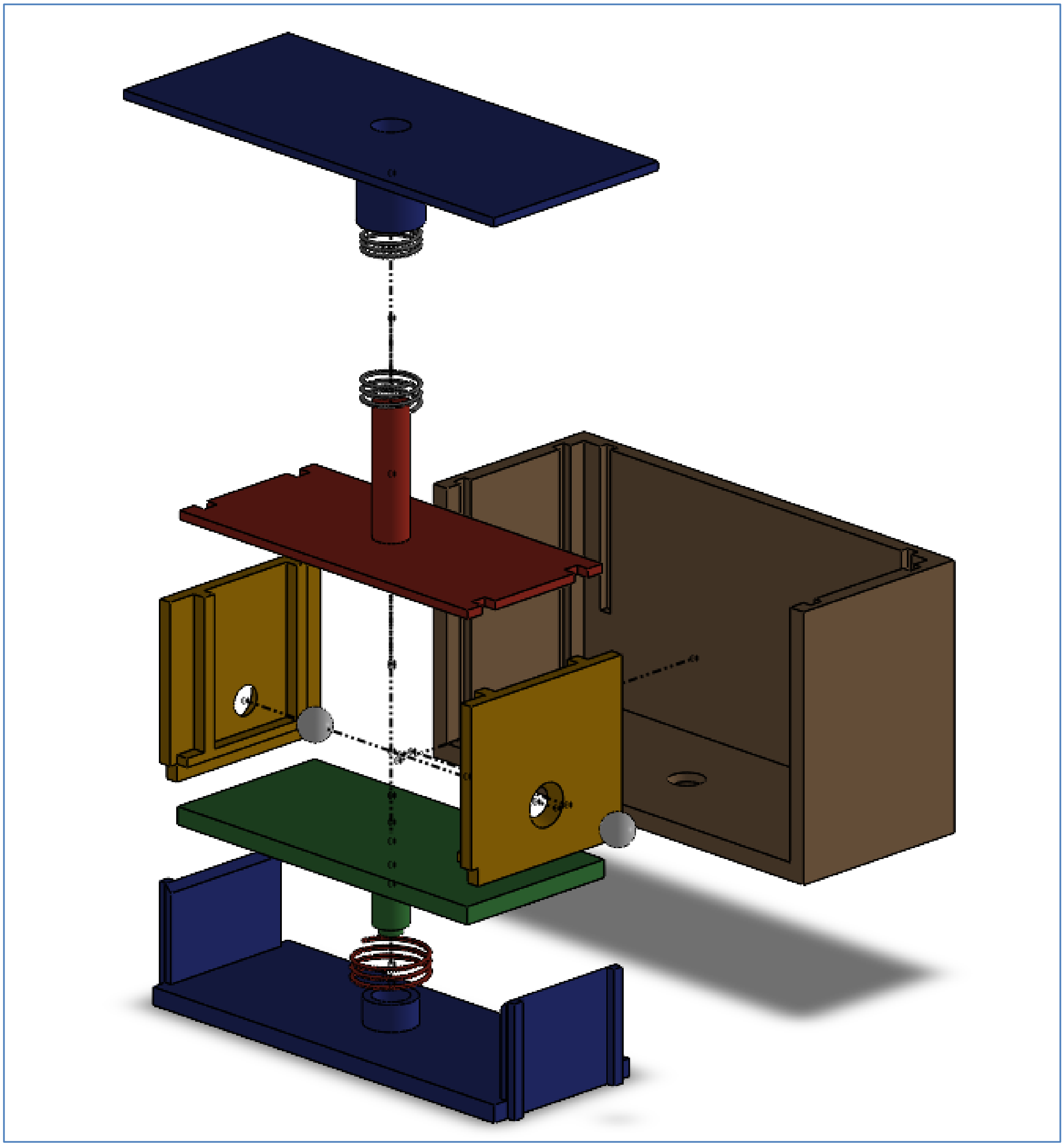
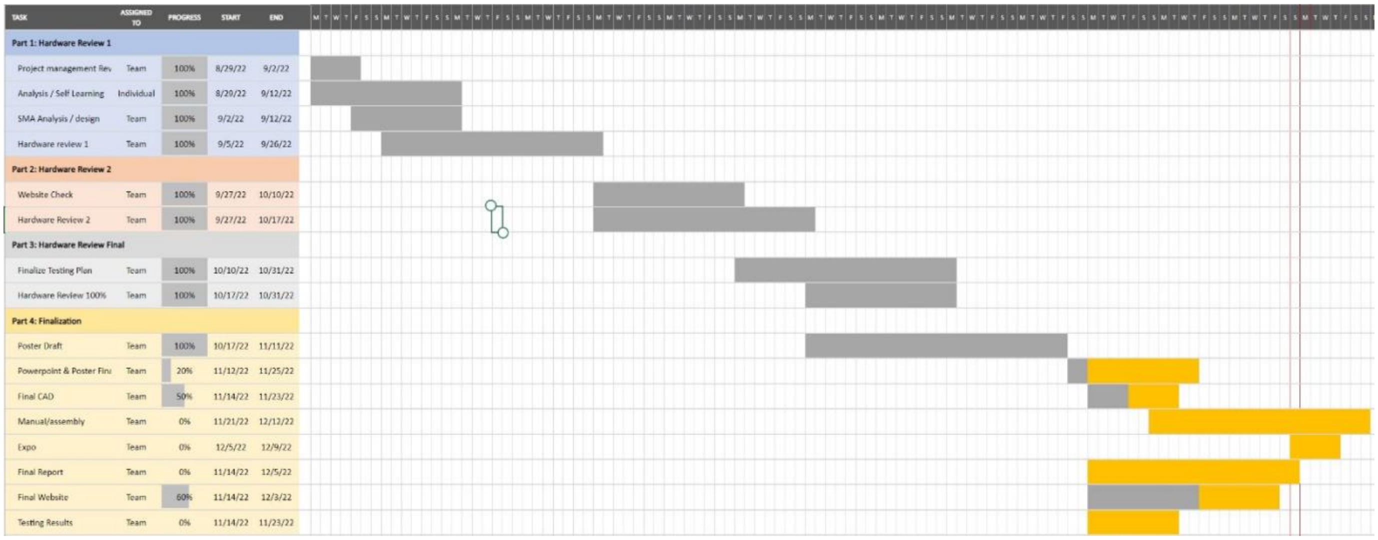


Figure 19: Exploded View of the CAD Model

6 Project Management – Second Semester

6.1 Gantt Chart

The actual second semester Gantt Chart can be seen below. The chart shows the second semester broken into four parts to help assign project goals to each section. Part one, in blue, focused on the group's first presentation, Hardware Review 1. This section was comprised of four team assignments. Each of these assignments had a due date given by the professor and were completed fully on time. The manufacturing portion of this section was rearranged and squished into the later weeks due to the team having to wait for available machine shop trainings. The schedule could have been improved by receiving training earlier in the semester or in previous semesters. The second section, in pink, was focused on the group's second presentation, Hardware Review 2. This section was comprised of two team assignments that were each given due dates and that the team completed on time. The bulk of the device manufacturing was completed during this section. This was when the team ran into the most design setbacks and had to problem solve on the spot. While each problem had a solution, the manufacturing schedule was stretched out in the chart because of the extra time it took to remake a part to match the solution. The third section, in gray, was designated to manufacturing completion and the third presentation, Final Hardware Review. This section also had two sub sections within it which were assigned due dates from both the professor and from the team in order to stay on track. Each of these assignments were completed on time or stretched out within the schedule to be completed by the end of the section. The final section held the largest portion of work with eight subsections. This was because all project finalization was completed in this portion. Each of the assignments had strict due dates due to the semester coming to a close which helped the team manage to complete each part without rearranging the schedule.



TASK	ASSIGNED TO	PROGRESS	START	END
Part 1: Hardware Review 1				
Project management Rev	Team	100%	8/29/22	9/2/22
Analysis / Self Learning	Individual	100%	8/29/22	9/12/22
SMA Analysis / design	Team	100%	9/2/22	9/12/22
Hardware review 1	Team	100%	9/5/22	9/26/22
Part 2: Hardware Review 2				
Website Check	Team	100%	9/27/22	10/10/22
Hardware Review 2	Team	100%	9/27/22	10/17/22
Part 3: Hardware Review Final				
Finalize Testing Plan	Team	100%	10/10/22	10/31/22
Hardware Review 100%	Team	100%	10/17/22	10/31/22
Part 4: Finalization				
Poster Draft	Team	100%	10/17/22	11/11/22
Powerpoint & Poster Fin	Team	20%	11/12/22	11/25/22
Final CAD	Team	50%	11/14/22	11/23/22
Manual/assembly	Team	0%	11/21/22	12/12/22
Expo	Team	0%	12/5/22	12/9/22
Final Report	Team	0%	11/14/22	12/5/22
Final Website	Team	60%	11/14/22	12/3/22
Testing Results	Team	0%	11/14/22	11/23/22

6.2 Purchasing Plan

The actual purchasing plan or Bill of Materials (BOM) can be seen in Appendix B. This table includes the part description, cost, quantity, date purchased, whether it was bought or made, the primary vendor, and the manufacturer. The BOM is different than the one made at the beginning of the semester because the group continued to add or remove purchases from the list as manufacturing speedbumps came. All purchases are included from both semesters even if the parts are not being used in the final design. This is so the team knew the budget was not exceeded. The total can be seen at the bottom of the table, showing that all purchased parts remained significantly under the budget given. The budget allotted $2,000 to be spent, and the team used only $457.38. The team chose very cheap materials that came in bulk so that if an error was made, no extra orders had to be made. The cost of the future design is expected to increase due to use of higher-grade materials being utilized, future testing conditions being modeled, more accurately weighted solar panels incorporated into the design, cost of manufacturing on a more precise scale and a customized SMA spring being designed.

6.3 Manufacturing Plan

The actual manufacturing plan from the second semester can be seen in Appendix D. The plan includes the name of the part, the process/material, the source, the weight, the time, the weighted time, the percent build per part, and whether or not the build had been finished (green) or if it was implemented into the device if it was not being manufactured (white). The weights and percentages were changed throughout the manufacturing process if the team realized a portion took more or less time than expected and based on how reliant a successful device actuation was on the part's dimesons being nearly perfect. The team could have expected much more time for each part because several hours were added to the breakdown the further into manufacturing we went. All parts were completed effectively in the end and extra time was put in by all members to create a functional device. Pictures of all 16 parts can be seen in the plan.

7 Final Hardware

7.1 Final Hardware Images and Descriptions

Figure 20: Final assembled HDRM

Figure 20 above shows the final model after manufacturing and assembling. The final fabricated model is made from aluminum, with some parts 3D printed in a Stratasys PolyJet printer, and some low-friction plastics such as PTFE and HDPE. Most of the aluminum parts were manually machined at the fabrication shop at NAU, and one part was automated in the CNC machine. Encasing the model is a 3-d printed sleeve; this is because the original method of assembly was unable to be fabricated. Figures 21 and 22 show the final HDRM fully assembled with the circuit and power supply.

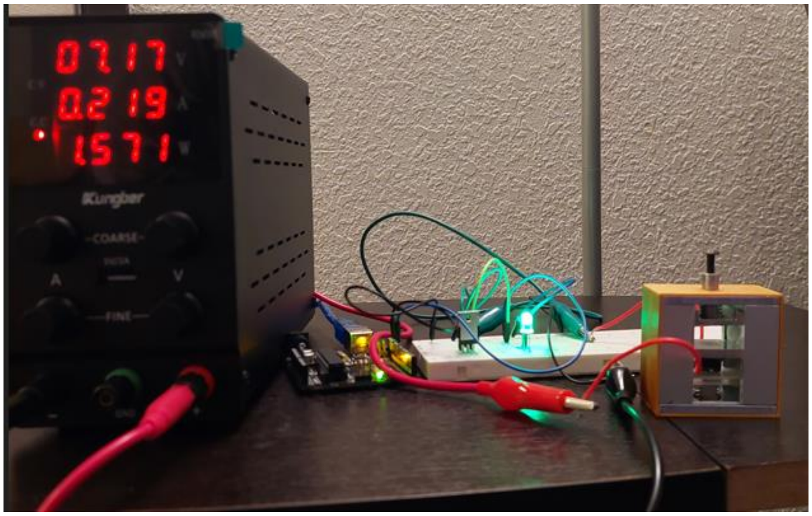


Figure 21: Fully Assembled Design (Front View)

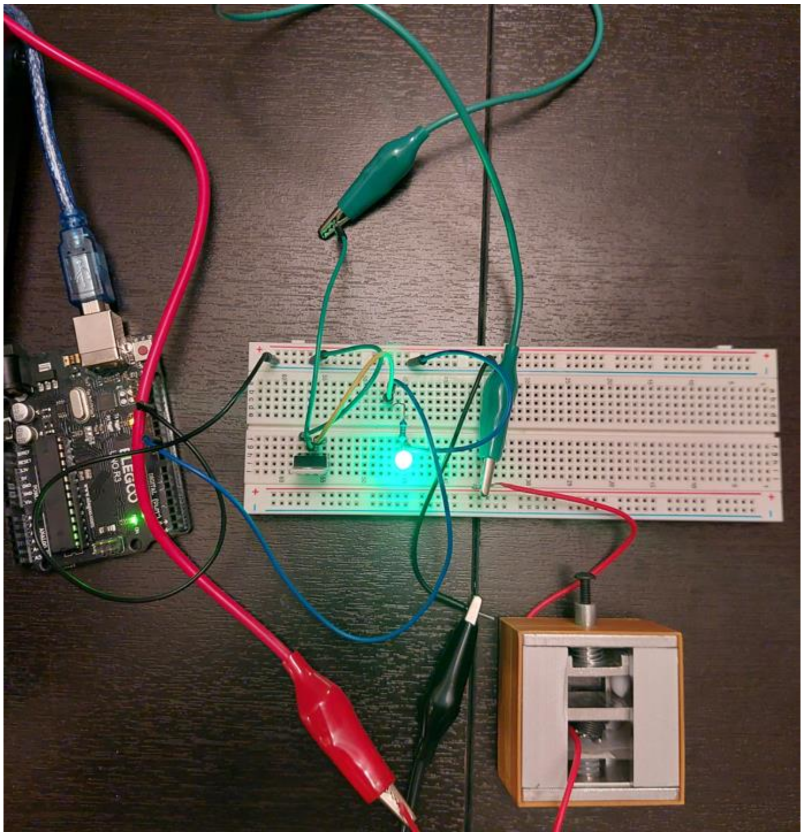


Figure 22: Fully Assembled Design (Top View)

7.2 Design Changes in Second Semester

A couple minor design changes were introduced in the second half of this project timeline. Ultimately the original design remained implemented and proved functional, however due to problems with sourcing parts, manufacturing limitations and electrical hurdles, some small design changes were needed.

7.2.1 Design Iteration 1: SMA Spring

The original design called for a custom nitinol shape memory spring that incorporates the forces, dimensions, and range of motion the team desired. Due to communication issues and lack of willing vendors, this custom spring could not be sourced, and the team was forced to use one that is commercially available off-the-shelf. This introduced a problem of the spring not being strong enough for the design we had at the time.

7.2.2 Design iteration 2: Assembly

Initially, the design called for the top and bottom of the design to screw into the body, holding the entire assembly together. However, as this is a small model, the taps and drill bits broke in attempt to create the holes. The team decided that it is too great a risk to try again and opted for a friction-fit sleeve to hold the assembly together. Figure 23 shows the original design for assembly, and figure 20 above shows the iterated design for assembly, the orange/gold band around the edges is the sleeve.

Figure 23: Original CAD for assembly

7.2.3 Design iteration 3: Power Supply Circuit

Initially, the team planned to simply run a voltage controlled direct current through the SMA spring to actuate it. However, in the testing processes, we realized that a DC power supply significantly increases the risk of breaking the spring and reduces its life cycle. The team then assembled a PWM circuit using a transistor to provide alternating current in a more controllable environment. Figure 24 below shows the new circuit with the PWM implemented.

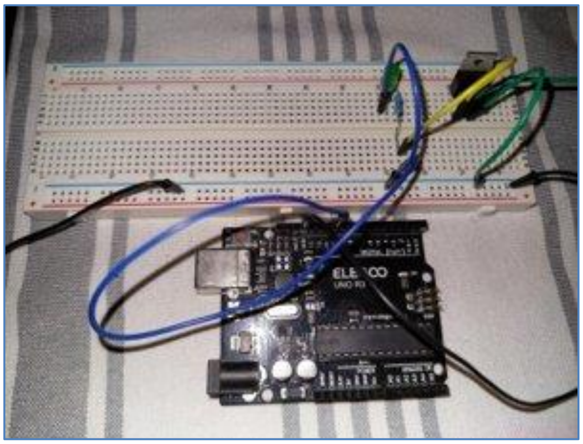


Figure 24: PWM power supply circuit

7.3 Challenges Bested

The biggest challenge that the team faced and did not expect is the amount of time it takes to manufacture. The team spent a collective 40 hours in the machine shop creating the parts for the final model with the right tolerances (desired ±0.001”). Additionally, implementing the off-the-shelf spring posed a problem that the team faced around the 2/3 build milestone.

8 Testing

8.1 Testing Plan

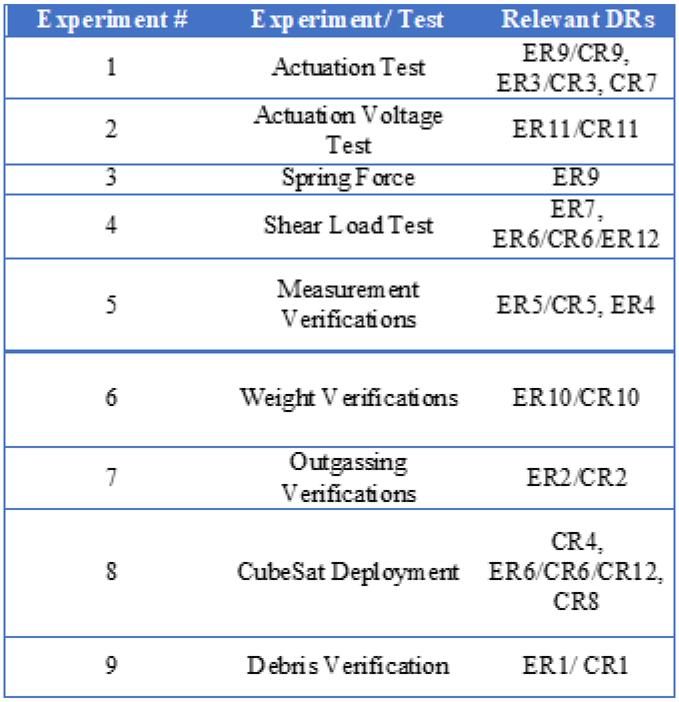
The QFD (Appendix A), table 1, and 3 highlight the engineering and customer requirements the team had to meet. Table 4 shows a summary of the experiments the team had to perform in order to evaluate whether the final design meets the proper design requirements. Tests 5 through 9 are primarily measurement and calculation related experiments that do not require any formal experimental procedures. Tests 1 through 4 require formal experimental procedures that were outlined in the finalized testing plan document. Some of these details and procedures are outlined below.

Table 3: Labeled CRs and ERs

#	CR	ER
1	No Space Debris	No breakaway parts
2	Low Outgassing	Low outgassing materials
3	No Combustion	No combustion
4	20x30 cm Deploy Solar Panels	Minimize volume
5	Minimize Protruding Material	Minimize protruding material
6	Maximize Deployment Load/ Simultaneously	Maximize deployment force
7	Easily Resettable	No deformation
8	Retain Stowed Configuration prior to deployment	Maximize retention reliability
9	Receive Input Command	Receive input command
10	Minimize Weight	Minimize weight
11	Minimize Reset Time	Minimize actuation time

12		Max. SMA spring life @ 1N

Table 4: Top Level Testing Summary



Experiment #	Experiment/ Test	Relevant DRs
1	Actuation Test	ER9/CR9, ER3/CR3, CR7
2	Actuation Voltage Test	ER11/CR11
3	Spring Force	ER9
4	Shear Load Test	ER7, ER6/CR6/ER12
5	Measurement Verifications	ER5/CR5, ER4
6	Weight Verifications	ER10/CR10
7	Outgassing Verifications	ER2/CR2
8	CubeSat Deployment	CR4, ER6/CR6/CR12, CR8
9	Debris Verification	ER1/ CR1

8.1.1 Experiment 1: Actuation

For experiment 1, ER9/CR9, ER3/CR3, and CR7 will be tested through actuation tests. This experiment is designed to test how well the device can actuate by sending a current through the nitinol spring a set number of times. The equipment needed will be a power supply with adjustable voltage output and a phone/ timer. Both the voltage and time to actuate will be isolated to properly assess the performance of the nitinol actuator. No variables need to be calculated, however, the results of experiment 2 will output the optimal voltage and time variables. The results of the experiment demonstrate how the performance of the actuation is affected after 100 actuations. To define performance, the team is specifically focusing on how actuation time is impacted and if the force output of the nitinol spring is affected. Equation 1 will be used to compare the force outputs of the nitinol spring.

$$F_N = \frac{G_{max} * d^4}{8 * D^3 * N} * \delta_L \tag{1}$$

8.1.2 Experiment 2: Actuation Voltage

Experiment 2 will focus on verifying ER11 and CR11, which deals with actuation time. A power supply with adjustable voltage output and a timer will be needed for this experiment. The procedure for this experiment will start with actuating the nitinol spring at 5 different voltages that range from 5v to 10v to determine which is the most optimal voltage setting. Once the voltage begins to have little effect on the time, the lower voltage will be selected. This will ensure that the device has the quickest actuation time possible. Equation 2 will be used to calculate the predicted time value for the corresponding current. This value will be used to compare to the experimental one for verification.

$$I = \sqrt{\frac{m * c * (T_2 - T_1)}{R * t}} \tag{2}$$

8.1.3 Experiment 3: Spring Force

For the spring force test the following design requirement will be tested: ER9. This will verify whether the nitinol spring can overcome the opposing normal spring to actuate the device. The procedure will involve using a load sensor to check the springs force output, along with the nitinol spring. If the nitinol spring force is not greater then the team will need to find a spring that it can overcome. The expected nitinol spring force will be calculated using equation 1. This answer will be compared to the results of the test to verify the solution.

8.1.4 Experiment 4: Shear Load Test

The load test will be used to verify that the device meets ER7, ER/CR6, which revolve around meeting load requirements. The device must be able to hold a load perpendicular to the device of at least 25 N. The procedure will start with adding a load to the pin starting at 5 N and increasing in increments of 5 until 25 N is reached. If the pin can handle a load of 25 N without deforming, then it has met the requirements.

8.2 Testing Results

Table 5 and 6 show the finalized specification sheet for ERs and CRs. These tables specify which design requirements were met through the testing results. The main requirement that the team’s client required was the ability to easily reset the device, which the final design does meet. The requirements that aren’t met are the low outgassing materials, minimize volume, maximize deployment force, and maximize nitinol actuator life. With initial discussions with General atomics, not meeting these requirements was considered to be acceptable as they were not the main priority or focus but should be met in future iterations of the project and before commercial use.

Table 5: Specification Sheet for ERs

Engineering Requirement	Target	Units	Tolerance	Measured/ Calculated Value	ER Met? Y/N	Client Acceptable? Y/N
No breakaway parts	0	-	0	0	Y	Y
Low outgassing materials	0	-	0	-	N	Y
No combustion	0	-	0	0	Y	Y
Minimize volume	1	cu. In	+0.5	3.4 in^3	N	Y
Minimize protruding material	1	cm	0.1	0.1 mm	Y	Y
Maximize deployment force	25	N	- 5	14.5	N	Y
No deformation	0	%	+2	0	Y	Y
Maximize retention reliability	100	%	1.5	100	Y	Y
Receive input command	-	-	-	-	Y	Y
Minimize weight	200	g	+50 -200	75	Y	Y
Minimize reset time	30	sec	+30	15	Y	Y
Maximize SMA Spring life (1N)	50	Cycles	5	20	N	Y

Due to current budget, time, and manufacturing capabilities, these requirements were expected to not be met. For low outgassing, a 3D printed resin had to be used in place of an aluminum part since the team did not have the manufacturing capabilities needed to make it. Resins are known to fail outgassing requirements and as a result, the team did not meet this requirement. The team also did not have the manufacturing capabilities to minimize the volume to the specified requirement and therefore did not meet this requirement. Maximizing the deployment force and the nitinol actuator life failed due to the team not being able to find a vendor that could supply a custom nitinol spring with the desired dimensions. This resulted in the team having to design around the nitinol spring they could purchase from amazon. While this spring does work, it has *a much lower force output requiring design changes that impacted these requirements.*

Table 6: Specification Sheet for CRs

Customer Requirements	CR Met? Y/N	Client Acceptable? Y/N
No Space Debris	Y	Y
Low Outgassing	N	Y
No Combustion	Y	Y
Can deploy 20x30cm panels	N	Y
Minimize protruding material	Y	Y
max deployment load / simultaneously	N	Y
Easily resettable	Y	Y
Retain stowed config prior to deployment	Y	Y
Receive input command	Y	Y
Minimize Weight	Y	Y
minimize reset time	Y	Y

9 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 6 while the full FMEA can be found in Appendix C.

9.1 Potential Failures Identified First Semester

The shortened FMEA is shown in table 6. It shows all of the potential failure modes the team identified in the first semester. The table goes into detail about how critical each failure mode is, represented by the RPN, and the recommended action. The top ten failure modes with the highest RPN values will be analyzed further in the Risk Mitigation section.

Table 7: Shortened FMEA

Part and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended 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	Overstressing	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 Mechanism	Wrong Configuration	Pin will not retract	Human Error	140	Verify lock configuration
Pin	Deformation	Unable to	Overstressi	9	Pick the best

	wear	hold load	ng		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	Overstressing	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 Mechanism	Wrong Configuration	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 relaxation	Unable to keep pin in	Held at a certain	168	Keep spring in rested

		place	stress for prolonged period of time		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

9.1.1 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.

9.1.2 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.

9.1.3 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.

9.1.4 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.

9.1.5 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.

9.1.6 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.

9.1.7 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.

9.1.8 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.

9.1.9 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.

9.1.10 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.

9.2 Potential Failures Identified This Semester

After the team began to manufacture and test the final HDRM design, new potential failure modes were identified. There were three main failure modes that were identified in the second semester. These failures have been highlighted in yellow in the full FMEA in appendix C as well as below.

9.2.1 New Potential Critical Failure 8: SMA Actuator – Transistor heating

The team changed the original DC circuit that was used to power the NiTinol spring to a PWM circuit. While this greatly improved the life cycle of the actuator (by a factor of 10) a potential failure was found where the Mosfet transistor that is in the circuit can heat up instead of the NiTinol spring. This can be mitigated by using a Mosfet transistor that has very low internal resistance, below 5 milli ohms.

9.2.2 New Potential Critical Failure 9: SMA Actuator – Nitinol Fatigue

While replacing the DC circuit with a PWM circuit greatly improved the life cycle of the spring, it still fatigues quickly. Through testing, the team noticed that after 30 cycles the nitinol's force output reduced by almost 50%. Meaning that after 30 cycles it will no longer produce enough force output to actuate. To mitigate this, the team must purchase a custom made Nitinol spring with ideal dimensions for a higher force output. This will expand the life cycles as it will produce greater initial force output.

9.2.3 New Potential Critical Failure 10:Bearing Lock – Excessive Heating

With the final design, the team noticed that the materials surrounding the Nitinol will experience heating through conduction. The Nitinol spring will continue to heat up until the system is shut down, if it is overheated the heat will transfer to the surrounding materials and may damage them. This was noted during a demonstration where the actuator was heated for too long and it exceeded the 3D printed lower platform's max operating temperature, damaging it as a result. To mitigate this issue, the team has placed an insulative film with a higher operating temperature to reduce the heat transfer due to convection to the surrounding materials.

9.3 Risk Mitigation

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.

10 LOOKING FORWARD

This project was initially planned to be the kickstarter for a multi-year, milti-capstone project, taken on by many undergraduate teams and building upon the previous design. At the time that GA-EMS was the sponsor, their plan was that by the end of these two semesters, our team would have proven a functional design to begin the process. Designing and building a device to be sent into space requires more work than a group of undergraduate students can complete in a two-semester timeline; and so there is much work left to do before a device using our design might be sent to space.

10.1 Future Testing Procedures

10.1.1 Acceleration and acoustics testing

An HDRM will have to withstand accelerations, turbulence, and acoustics (vibrations) when it is in travel to space on the spacecraft. NASA has outlined standards and testing procedures for these, whose requirements will need to be met (if applicable) before it is able to be loaded onto an actual satellite.

10.1.2 Custom SMA spring manufacturing (optional)

One challenge that was not overcome during this project was sourcing the desired SMA spring for the device. As nitinol SMA helical springs are not easily custom ordered, it may be in the interest of a future group to dedicate a sub-group to the design and manufacturing of a nitinol SMA spring. This would decrease the cost of ordering from a third-party and be a great accomplishment for a group.

10.1.3 NASA certification

Section 2.5 outlines some important standards and codes for devices, materials and objects in general that intend to be sent into space. For our design to hypothetically ever be sent into space, it must first comply with NASA's codes and standards. This process is lengthy and can only be completed after future iterations bring this device down to a competitive form and functionality.

10.2 Future Iterations

10.2.1 Scale Down

Commercially available HDRM's with similar force ratings have a total volume of approximately $1in^3$ [24]. With the level of manufacturing ability, available manufacturing techniques and budget, complex geometries and extremely tight tolerances are unachievable for this project currently. A future team may be able to modify the CAD and manufacture a model that takes up less volume.

10.2.2 Materials

Another aspect of scaling down the design is consideration for material strength for small parts. Aluminum is likely to bend or deform if manufactured on a small scale, however titanium is much more rigid and stronger than aluminum and may be a better decision for the components in the device. Additionally, the resin part 3D printed would not qualify as low-outgassing and would not be allowed into space. This could be replaced by a precision machined piece from a low-friction, low-outgassing thermoplastic, such as PEEK or Ultem.

10.2.3 Custom Spring

As previously stated, the initial design called for a custom SMA spring, to maximize force output for a given set of dimensions and range of motion. This was unable to be sourced and would likely be very expensive if obtainable. A future team could and attempt to obtain this custom spring, or possibly explore the process of manufacturing and training the SMA in-house.

11 CONCLUSIONS

Our team began the project with a very open-ended prompt: to design a new, resettable HDRM that will operate a CubeSat. After multiple discussions and meetings amongst ourselves and the GA-EMS team, our group was given some requirements such as no space debris, low emission, size requirements, fully resettable, and a two-part (hold then release) function. The design process began with generating some technical engineering requirements, weighing those requirements using a Pugh chart, decision matrix, and a QFD or house of quality. This design was selected as it performs functions like that of its competitors and seems to be simple in design and manufacturing. The team constructed multiple low-fidelity 3D printed prototypes which aided in the risk and trade-off analysis and provided insight into testing of how well the design meets the requirements. The prototyping stage showed helpful when iterating for manufacturing out of higher quality materials. The manufacturing process proved challenging in reaching tolerances and general fabrication of small-scale parts. This two-semester project resulted in what may be considered as a fully functional high-fidelity prototype demonstrating a new mechanism for a resettable HDRM. This, however, is acceptable as it fully demonstrates the goal of the project and leaves significant room for future iterations and modifications by a team with more time and a greater budget.

11.1 Reflection

The main motivation for this project was that GA-EMS needs a more economical way of testing HDRMs and satellites without paying a large markup on other companies' products. If GA-EMS can generate a competitive and acceptable substitution for the other options, but manufacture it themselves, it would save a significant amount of money on their satellites. Additionally, by using more resettable HDRM's, there is less waste from disposing of single-use HDRM's, providing some aid to conservation of materials and energy.

11.2 Resource Wishlist

One of the challenges that our team faced throughout the project was the originally intended sponsor, GA-EMS withdrawing from the project halfway through. The biggest consequence of this was that we lost the resource of having multiple engineers from the company available to mentor and advise us throughout the project.

Another resource that would have been helpful to have in the design process is someone with expertise in thermal SMA materials. They may have been able to advise us in a way that could have eliminated the need for a custom SMA spring.

A knowledge in manufacturing is also greatly desired; none of the team members had any previous knowledge in using machines for manufacturing, and therefore designing for manufacturing and the actual fabrication process was not as smooth as it could have been. It would be useful if there was a dedicated course and lab for manufacturing processes and DFMA.

11.3 Project Applicability

This project was introduced as a close collaboration between us undergraduate students and a group of professional engineers at a very large engineering company. We were all very excited to work with engineers from General Atomics and the possibility of having that valuable connection to the company, which is extremely desirable for anyone trying to build a good resumé. Although this collaboration did not work out, the team still gained valuable information from this interaction: economics are something that will never go away and cannot be forgotten about. Project feasibility, budgeting, and accounting, although not the primary concern of an engineering, determines what an engineer does and does not work on, and the budget for those projects. Being smart and mindful with money and economics is more vital than a good design when it comes to engineering.

This entire process was the ultimate demonstration that time management is key, and a good design is only good if you can actually make it a real product. As clear as hindsight may be, it only shows that the design process is the source of a good product, and a successful design process only comes with proper and thorough research.

12 REFERENCES

[1] "NASA Technical Standards | Standards." https://standards.nasa.gov/nasa-technical-standards (accessed Apr. 12, 2022).

[2] "Test Requirements for Launch, Upper-Stage and Space Vehicles," Air Force Space Command, SMC Standard SMC-C-016, Sep. 2014.

[3] "GENERAL ENVIRONMENTAL VERIFICATION STANDARD (GEVS) For GSFC Flight Programs and Projects." IHS, Apr. 22, 2013. Accessed: Mar. 20, 2022. [Online]. Available: https://mechanical-engineering.gsfc.nasa.gov/GSFC-STD-7000%20Rev%20A%20GEVS.pdf

[4] "Load Analysis of Spacecraft and Payloads," Office of the NASA Chief Engineer, NASA Technical Standard NASA-STD-5002A, Sep. 2019.

[5] "Design and Development Requirements for Mechanisms," Office of the NASA Chief Engineer, NASA Technical Standard NASA-STD-5017A, Jul. 2015.

[6] "Requirements for Threaded Fastening Systems in Spaceflight Hardware," Office of the NASA Chief Engineer, NASA Technical Standard NASA-STD-5020B, Aug. 2021.

[7] "Guidelines for the Specification and Certification of Titanium Alloys for NASA Flight Applications," Office of the NASA Chief Engineer, NASA Technical Standard NASA-HDBK-6025, Apr. 2017.

[8] "Flammability, Offgassing, and Compatibility Requirements and Test Procedures," Office of the NASA Chief Engineer, NASA Technical Standard NASA-STD-6001B, Apr. 2016.

[9] "Corrosion Protection for Space Flight Hardware," Office of the NASA Chief Engineer, NASA Technical Standard NASA-STD-6012A, Mar. 2022.

[10] "Standard Materials and Processes Requirements for Spacecraft," Office of the NASA Chief Engineer, NASA Technical Standard NASA-STD-6016C, Sep. 2021.

[11] American Society of Mechanical Engineers, *Standard for verification and validation in computational solid mechanics: an international standard.* 2020.

[12] "TiNi^{TM} Pin Puller," *Ensign-Bickford Aerospace & Defense*, Oct. 25, 2019. https://www.ebad.com/tini-pin-puller/ (accessed Mar. 20, 2022).

[13] P. S. Lobo, J. Almeida, and L. Guerreiro, "Shape Memory Alloys Behaviour: A Review," *Procedia Eng.*, vol. 114, pp. 776–783, Jan. 2015, doi: 10.1016/j.proeng.2015.08.025.

[14] "Mechanical Engineering Branch." https://mechanical-engineering.gsfc.nasa.gov/designref.html#a101 (accessed Mar. 20, 2022).

[15] D. Novotney, G. KACZYNSKI, and C. Boucher, "Hold down release mechanism with integral sensing," EP3351477A1, Jul. 25, 2018 Accessed: Mar. 20, 2022. [Online]. Available: https://patents.google.com/patent/EP3351477A1/en?q=HDRM+spacecrafts&oq=HDRM+for+spacecrafts

[16] W. J. SPARK, "Hold down and release mechanism for a deployable satellite solar panel," US10926891B2, Feb. 23, 2021 Accessed: Mar. 20, 2022. [Online]. Available: https://patents.google.com/patent/US10926891B2/en?q=HDRM+spacecrafts&oq=HDRM+for+spacecrafts

[17] "GA CubeSat Capstone." https://www.ceias.nau.edu/capstone/projects/ME/2020/20Spr2_GACubesat/ (accessed Mar. 20, 2022).

[18] *Hold-Down and Release Mechanisms for Non-Pyrotechnic Release of Satellites and Appendages*, (Jan. 27, 2021). Accessed: Mar. 20, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=Wvho5dZkynA

[19] "V. Gamez, N. Olson, M. Warren, 'Meeting with GA-EMS Team,' in Design Advice and Requirements, 3/4/2022."

[20] "McMaster-Carr." https://www.mcmaster.com/ (accessed Mar. 20, 2022).

[21] S. Dahake, N. Awate, and R. Shelke, “Design and Analysis of Release Mechanism using Shape Memory Alloy for Spacecraft,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1206, no. 1, p. 012012, Nov. 2021, doi: 10.1088/1757-899X/1206/1/012012.

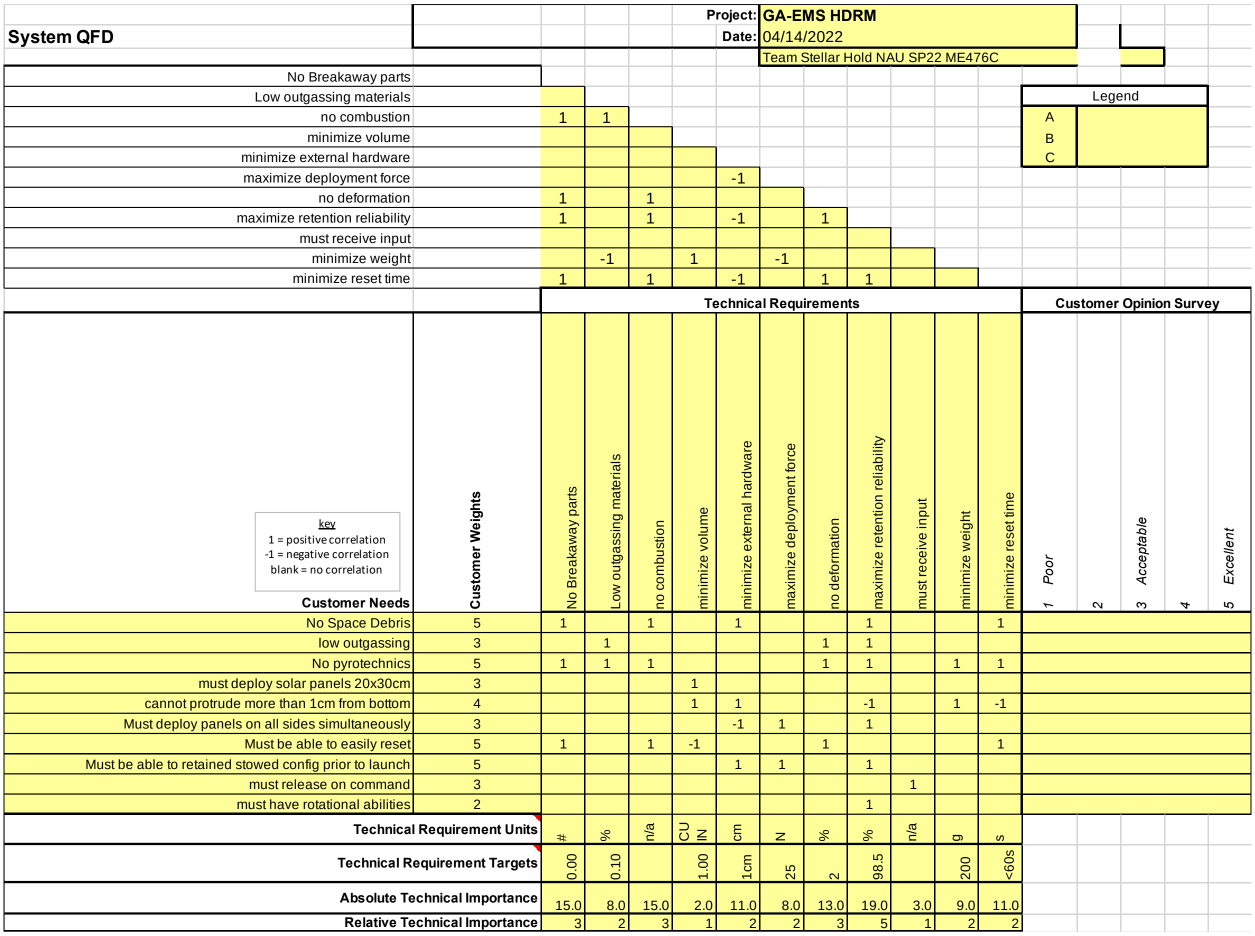
[22] M. Langer *et al.*, “Results and lessons learned from the CubeSat mission First-MOVE,” Apr. 2015.

[23] “PAYLOAD SPECIFICATION FOR 3U, 6U AND 12U,” Aug. 06, 2018. https://planetarysystemscorp.com/wp-content/uploads/2002367F-Payload-Spec-for-3U-6U-12U.pdf

[24] “TiNi^{TM} Pin Puller,” *Ensign-Bickford Aerospace & Defense*, Oct. 25, 2019. https://www.ebad.com/tini-pin-puller/ (accessed Apr. 14, 2022).

13 APPENDICES

13.1 Appendix A: QFD; House of Quality



System QFD

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

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

Legend	
A	
B	
C	

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

		Technical Requirements											**Customer Opinion Survey**				
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 Poor*	*2*	*3 Acceptable*	*4*	*5 Excellent*
No Space Debris	5	1		1		1			1			1					
low outgassing	3		1					1	1								
No pyrotechnics	5	1	1	1				1	1		1	1					
must deploy solar panels 20x30cm	3				1												
cannot protrude more than 1cm from bottom	4				1	1			-1		1	-1					
Must deploy panels on all sides simultaneously	3					-1	1		1								
Must be able to easily reset	5	1		1	-1			1				1					
Must be able to retained stowed config prior to launch	5					1	1		1								
must release on command	3									1							
must have rotational abilities	2								1								
Technical Requirement Units		#	%	n/a	CU IN	cm	N	%	%	n/a	g	s					
Technical Requirement Targets		0.00	0.10		1.00	1cm	25	2	98.5		200	<60s					
Absolute Technical Importance		15.0	8.0	15.0	2.0	11.0	8.0	13.0	19.0	3.0	9.0	11.0					
Relative Technical Importance		3	2	3	1	2	2	3	5	1	2	2					

13.2 Appendix B: Purchasing Plan

Part Description:	Cost:	Quantity:	Date:	Make/ Buy:	Primary Vendor:	Manufacturer:
Acrylic Sheets	21.83	2	09/06/22	Buy	Amazon	Acrylic Mega Store
Nitinol Spring (2.4 mm)	19.58	1	02/23/22	Buy	Amazon	Kellogg's Research Lab
Aluminum Block	$40.39	2	09/06/22	Buy	Amazon	VERNUOS
Generic Springs	$14.18	1	09/06/22	Buy	Amazon	Ninoge
Ball-Nose Plunger	$8.38	2	04/05/22	Buy	McMaster-Carr	McMaster-Carr
Arduino	$49.12	1	09/06/22	Buy	Amazon	Arduino
Aluminum Rod	$30.43	1	09/06/22	Buy	McMaster-Carr	McMaster-Carr
U-Channel	$29.55	2	10/5/22	Buy	McMaster-Carr	McMaster-Carr
PTFE Balls	$12.28	1	10/5/22	Buy	McMaster-Carr	McMaster-Carr
Polyethylene Rod	$5.01	1	10/5/22	Buy	McMaster-Carr	McMaster-Carr
Socket Head Screw	$19.81	1	10/5/22	Buy	McMaster-Carr	McMaster-Carr
PTFE Film	$24.45	1	10/5/22	Buy	McMaster-Carr	McMaster-Carr
Drill Bit	$6.84	1	10/5/22	Buy	McMaster-Carr	McMaster-Carr
Compression Spring	$7.24	1	10/5/22	Buy	McMaster-Carr	McMaster-Carr
Compression Spring (Short)	$29.28	1	10/5/22	Buy	McMaster-Carr	McMaster-Carr
Flat Head Screw	$9.27	1	10/5/22	Buy	McMaster-Carr	McMaster-Carr
Load Cell	$10.42	2	10/5/22	Buy	Amazon	ALAMSCN
SMA Spring	$20.93	2	10/5/22	Buy	Amazon	NexMetal
Standoff "Kit"	$21.83	1	10/5/22	Buy	Amazon	VIGRUE
MOSFET Transistor	$10.50	1	10/31/22	Buy	Amazon	Bridgold
M1 Bit/Tap	$8.50	2	10/18/22	Buy	Amazon	Drill America Store
Power Supply	$62.91	1	10/18/22	Buy	Amazon	Kungber
3D Printed Part	$20.02	1	10/10/22	Make	NAU	NAU Idea Lab
3D Printed Part	$16.04	1	10/26/22	Make	NAU	NAU Idea Lab
Part Total:	**$457.38**					
Total Budget:	**$2,000.00**					
Remaining Budget:	**$1,542.62**					

13.3 *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					
Actuator	Transistor Heating	No Actuation	9	No expanding Nitinol (No pin retraction)	6	Test actuation with differed tranistors	2	108	Select Mosfet transistor with low internal resistance (<5 milli ohms)
Actuator	Nitinol Fatigue	No Actuation	9	No expanding Nitinol (No pin retraction)	6	Nitinol Fatigue tests	2	108	Select Nitinol spring with optimal dimensions to increase force output
Bearing Lock	Excessive Heating	Material Deformation	9	Exceeding Operation Temperatures	5	Heat transfer analysis	3	135	Add multiple layers of insulative material between

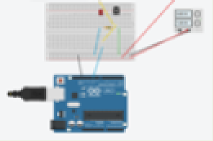
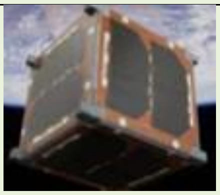
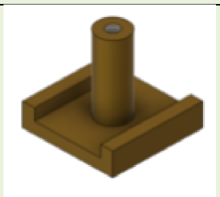
									nitinol and surrounding materials
SMA	Permanent deformation	Change pin position	8	Over voltage/ temperature	2	Heat SMA	3	48	Test environment conditions
SMA	Fatigue life	Change pin position	8	High and low cycles	5	Force inspection	2	80	Test SMA Fatigue life
SMA	Temperature/Electrical	Unable to change pin	7	Below required voltage	7	Use 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	6	Held at a certain stress for extended period of time	6	Force inspection	1	36	Keep spring in rested 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

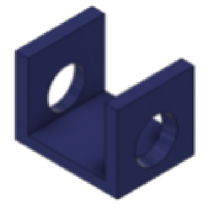
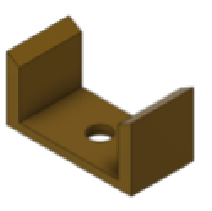
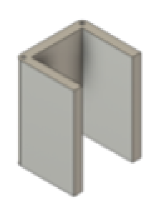
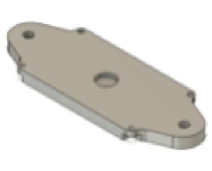
Spring	fracture due to fatigue	Unable to keep pin in place	6	repetitive cyclic brief time stress	6	Force inspection	2	72	Test for cycle life
SMA	Deformation wear	Pin will not retract	7	Overstressing	4	Visual inspection	3	84	Test for deformation
SMA	Fatigue Fracture	Pin will not retract	7	cyclic stresses 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	Multimeter	1	21	Check connections
Battery	Loose connector	SMA actuator will not work	3	Human Error	8	Multimeter	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 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 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

13.4 Appendix D: Manufacturing Plan

#	**Photo**	**Name**	**Process / Material**	**Source**	**Weight**	**Time (h)**	**Weighted Time**	**Build %**	**Finished (Y,P)**
1		Circuit	Arduino, SMA, Electrical Components		0.2	12	2.4	49%	Y
2		Cube Sat Demo	Acrylic, w/ hinges		0.15	3.5	0.525	11%	Y
3		Output Pin	Mill & COTS shaft ¼” AL	McMaster	0.1	5	0.5	10%	Y

4		Bearing Support	CNC AL	McMaster U-Channel	0.1	5	0.5	10%	Y
5		Bearings	PTFE 3/8” Ball	McMaster	0.05		0	0%	y
6		Lower Lock Slide	Mill / sander / file AL	Purchased	0.1	3	0.3	6%	Y
7		Main Enclosure	Mill/drill	McMaster U-Channel	0.05	3	0.15	3%	y
8		Bottom Cap	Mill - AL	Purchased	0.05	3	0.15	3%	Y

9		Top Cap	Mill- AL	Purchased	0.1	3	0.3	6%	Y
10		Lower Shaft	HDPE or UHMW Polyethylene	McMaster	0.05	1	0.05	1%	y
11		Body Screws	Source	91292A264			0	0%	
12		Top Spring	Source	1986K78 – 2.09 lb spring	0.02		0	0%	
13		Bottom Spring	TBD	TBD	0.02		0	0%	

14		PTFE Film	Source & Cut to size. (Maybe laser Cutter)	McMaster - https://www.mcmaster.com/2208T61	0.01	1	0.01	0%	
15		Conical Drill Bit	Source	McMaster - 8910A11			0	0%	
16		Flat Head Screw	Source	McMaster - 91294A128			0	0%	
					1	39.5	4.885	100%	