Electromechanical Recovery System (ERS)

Portland State Aerospace Society (PSAS)

ME 493 Final Report - Spring 2019

Grady Goodenough
Annaliese Hernandez
Marie House
Alan Hurley
Nate Stickrod
Gabe Watson

Academic Advisor: Lemmy Meekisho

Industry Advisor: William Winters

Executive Summary

This document details the motivation, background, product design specifications, conceptual design analysis, details on the final design, and verification through prototype testing. The Portland State Aerospace Society (PSAS) will use the resulting design built by the Electromechanical Recovery System (ERS) capstone in their rocket during the 2019 Summer launch. The ERS is comprised of two systems, the nose cone separation and the drogue parachute release. The nose cone release utilizes a DC motor, lost motion, and an open body design to meet each of our design specifications while being a robust and reliable system. The drogue parachute release uses a system employed by skydivers, taking a simple, mechanical design that can withstand the shock of parachute deployment while requiring very little force to actuate. Prototype testing for both of these systems verified that the systems are able to withstand the environments experienced during launch. This report will act as verification that the design specifications set at the beginning of the project were met, and the system is ready to use during the next PSAS launch.

Table of Contents

Introduction

Overview

Our customer, the Portland State Aerospace Society (PSAS), is a university group at Portland State University (PSU) that builds and flies high powered amateur rockets and nanosatellites. The group has a legacy of innovative student led projects - including our capstone, the Electromechanical Recovery System (ERS). Previous PSAS rocket recovery systems used explosive powder to separate the nose cone from the body of the rocket and to sever the line that connects the body to the drogue parachute. Our Electromechanical Recovery System improves on previous systems by eliminating the use of consumable components (i.e. the explosives) and allows both parachutes to be stored within the nose cone of the rocket. An electromechanical system also allows for easier, repeatable ground testing.

Two Parachute Recovery Systems

The desired method of recovery for the PSAS rocket is to employ a dual parachute system. As Figure 1 shows, this breaks the task into two separate subsystems: the drogue parachute deployment (i.e. nose cone separation) and main parachute deployment (i.e. drogue parachute release). Immediately after apogee a drogue parachute is deployed, which allows the rocket to descend at a controlled rate in order to reduce the amount that the rocket drifts, and reduces the shock force experienced during parachute deployment. At a specified altitude, the main parachute is deployed, which slows the rocket to a safe descent speed.

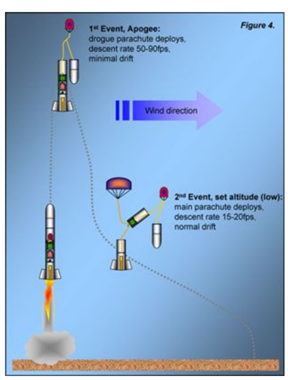


Figure 1. Example of a dual deployment parachute recovery system. The example is shown with the drogue parachute remaining attached; however, for the actual application the drogue parachute will be completely detached [1].

Mission Statement

PSAS requires a new two-stage parachute recovery system. Our capstone team will design, build, and test a flight-ready system that will successfully recover their current rocket, Launch Vehicle 3.1 (LV3.1), and scale to function as the recovery system for their future 100 kilometer rocket, Launch Vehicle 4 (LV4). The new recovery system must be fully electromechanical, eliminating the current need for pyrotechnics during parachute deployment. The final design must fit within the LV3 nose cone, and be as lightweight as possible. The parachutes must be anchored such that they withstand the shock forces during parachute deployment and support the dry mass of the rocket. Overall, the system must be capable of surviving the environments during launch and descent.

Deliverables for the project include a flight-ready system to be deployed on the next PSAS launch during the Summer of 2019. Additionally, a set of standard operating procedures (SOPs) must be written to ensure future generations of university rocketeers are able to setup and operate the system. Finally, all design decisions must be documented on the PSAS Github and Google Drive accounts. This satisfies the open-source requirement that PSAS places on all of its design and development projects.

Project Document Specifications (PDS)

The ERS will recover LV3.1; a CAD model of which can be seen in Figure 2. The rocket has a diameter of 6.6 inches and stands 11.6 feet tall. It is designed as a modular carbon fiber airframe, connected using aluminum rings clamped together. The recovery system will be stored partially in the nose cone of the rocket and partially within the adjacent module made of aluminum.

Figure 2. Launch Vehicle 3.1 (LV3.1) CAD model made by the PSAS Airframe team

Table 1 below outlines the design specifications and engineering targets continuously refined with PSAS during the course of this project.

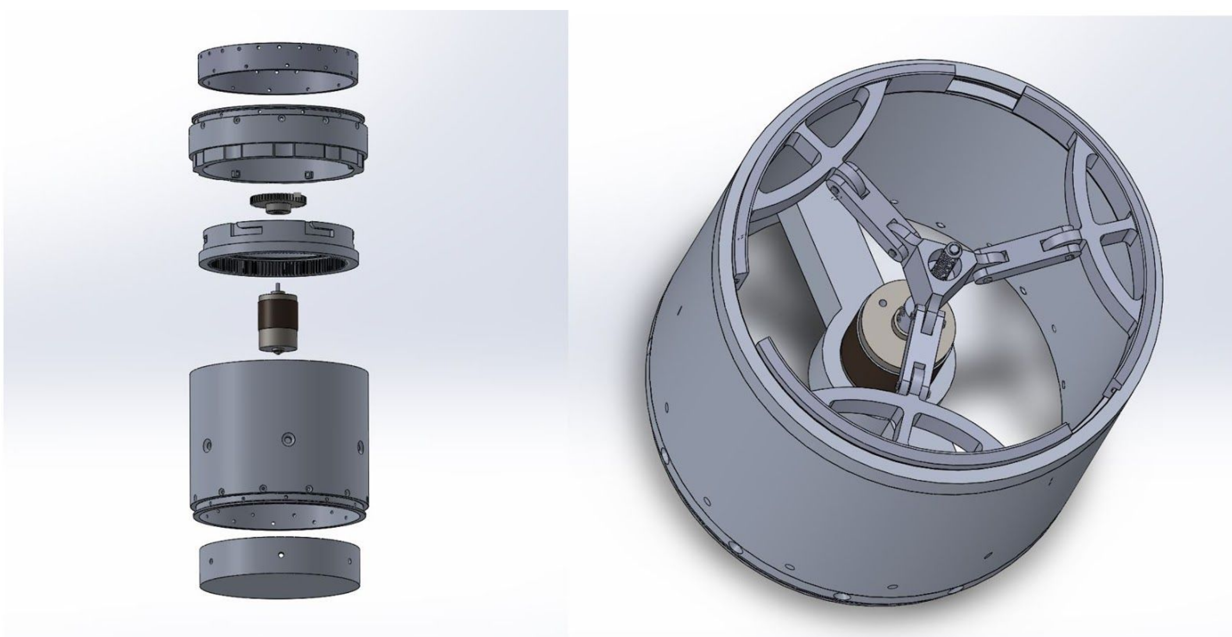
Table 1. Product Design Specifications & Engineering Targets

Category	Customer Need	Priority	Engineering Target	Final Design
Volume	Must fit in the LV3 and LV4 nose cone	High	12466.60cc	6292.63cc
Impulse	Must support LV3 and LV4 estimated dry mass	High	LV3(25kg)/LV4(>50kg)	≥68kg
Weight	Should be as lightweight as possible	High	<5kg/Max 10kg	6.4kg
Construction	Must be fully electromechanical	High	No Pyrotechnics	Fully Electromechanical
Operation	Fast drogue deployment	Med	1-3s	3s
Operation	Main parachute deployment at desired altitude	Med	1000 ft	Electronically Controlled

Conceptual Design Evaluations

Nose Cone Separation Concept Development

Two methods of actuation were evaluated for the nose cone separation. Shape memory alloy (SMA) wire offered an extremely space efficient option, but was labor intensive to train and required in depth knowledge of the material [2,3]. The other option was to use a DC motor to actuate the system, which was easy to use, but much heavier and took up additional space. The DC motor actuation scored higher in the design decision matrix (Appendix 1) and was selected as the method of actuation for the nose cone release. Based on the chosen method of actuation, designs for the nose cone separation were developed. Two designs, a twist coupling design (Fig. 3a) and a vertical central motor mount design (Fig. 3b), were compared using the weighted criteria described in Appendix 1. The twist coupling design capitalized on simplicity, ease of assembly, and space saving, and was selected for the final nose cone separation system. Full details of the design decision matrix used to evaluate these methods is found in Appendix 1.

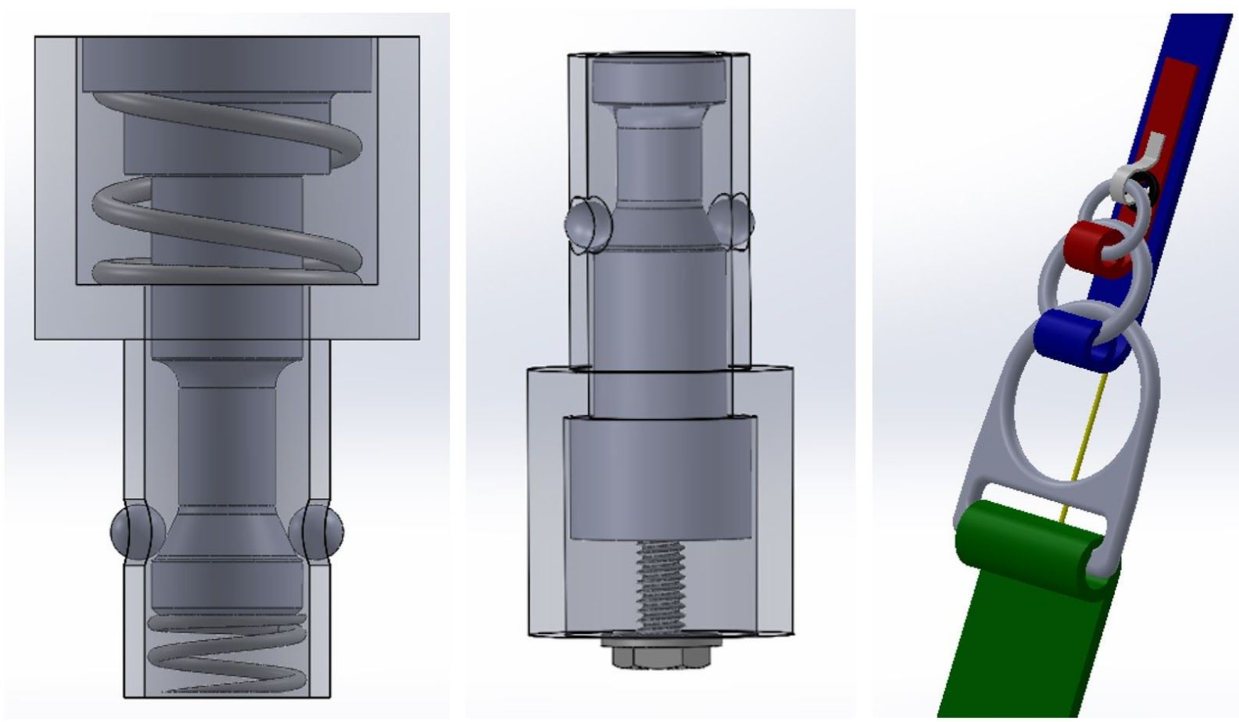


(a) (b)

Figure 3. (a) Twist Coupling Nose Cone Release Design and (b) Vertical Central Motor Nose Cone Design

Drogue Parachute Release Concept Development

Three initial concept designs were developed to actuate the drogue parachute release system. The first was designed to use SMA wire formed into a spring as the actuator (Fig 4a). Incorporating a bias compression spring on the opposite end, the design is intended to mimic the plunger of a socket wrench [4]. The second concept replaced the SMA wire with a DC motor and a threaded rod (Fig. 4b). The combination holds the plunger in place during launch and descent until it is released by turning the motor. The last conceptual design applied a three ring release system commonly used by skydivers [5]. The system can withstand high shock forces while still being actuated with relatively low force. This is done by pulling the release cord shown in yellow at the back of Fig. 4c. These designs are detailed below and were evaluated based on criteria shown in Appendix 1.



(a) (b) (c)

Figure 4. (a) SMA Plunger Design, (b) Motor Driven Plunger Design, and (c) Three-Ring Drogue Parachute Release System.

Final Design

Full Assembly

The final assembly of the ERS is shown in Figure 5. The nose cone (1) surrounds the parachute cups (2,3), which house the folded drogue and main parachutes. The nose cone is rigidly attached to the upper ring (6) which acts as the separation point for the nose cone and the body of the rocket. The surgical tubing assembly (4) is attached to the upper ring, and provides the tension needed to propel the nose cone away from the body of the rocket. The electronics, parachute anchors, linear actuator (9), motor (10), and power supply (11) are housed on the Kepper Ring. The twist coupling joins the upper and lower rings, and the three ring (eRing) system is the connection between the drogue parachute and rocket body during initial descent.

Once at apogee, the flight computer onboard LV3.1 sends a signal to our electronics, which activates the motor to spin. This turns the twist coupling until the retention nubs on the upper ring align with the slots in the twist coupling. Once aligned, the tension applied from the surgical tubing pulls the upper ring and nose cone away from the rocket body. The nose cone is attached to the drogue parachute cup via a nylon cord, which flips the drogue cup and deploys the drogue parachute. Once the flight computer receives a signal from the altimeter at 1000 ft it sends a signal to our electronics which retracts the linear actuator, releasing the eRing system. This allows the drogue parachute to separate, simultaneously pulling the main parachute cup off and deploying the main parachute.

Figure 5. Final Design Components

Nose Cone Separation

The twist coupling design capitalizes on simplicity, ease of assembly, space savings, and weight savings, leading to its selection as the final design. Another significant benefit of the twist coupling is its open body design. A largely open channel through the center of the design allows for easy placement and assembly of the internal components, and any possible variations. The channels in the twist coupling utilize the concept of lost motion; they are intentionally longer than needed to lock the upper and lower rings in place, allowing for small amounts of movement due to vibration without unintentionally releasing the nose cone.

The upper, lower, and surgical tubing rings are made from 6061 T6 Aluminum, which is the standard for PSAS parts for its strength to weight ratio. The twist coupling and pinion gear are made from delrin, which was chosen for its strength and low coefficient of static friction on the aluminum rings. The diametral pitch and number of teeth were selected to actuate the system in ~1 second. Testing confirmed the actuation time to be 1.15 seconds, which meets our design specifications.

The system is fully electromechanical, and uses no consumable components. The fully assembled final system weighs in at 6.5kg, which is greater than our preferred target, but less than our maximum of 10kg. This design meets all of the applicable PDS requirements, and is easily scalable to the LV4 size in the future.

eRing Release

The eRing release system is based on a design patented by Bill Booth in 1979 [6], but modified for automation. Originally designed for skydivers, the three metal rings shown in Figure 6 are intertwined and held in place with a fabric retaining loop and wire release cord. When the system is triggered, the two small rings unfurl and release the top, largest ring from the assembly. The two small rings stay attached to the rocket body while the largest ring carries the main parachute cup away with the drogue parachute. Since the number of rings and their size can vary, three separate ring sets were created for prototype testing. The release cord was tested for straight and angled actuation, and the shock force was measured for drogue parachute deployment. The setup and procedure for each of the prototype tests can be found in Appendix 2.

Figure 6. eRing ring system at each stage of release

Figure 7 is a box-whisker plot of the maximum recorded force during each run for the straight pull tests. The Large ring set requires less force to actuate than the Small and Two ring sets. The ratio of the Small ring data to the Large data is approximately 1.9, suggesting that diametral reduction from the Large Ring set to the Small Ring set equates to almost doubling the required pull force. Calculating the ratio between the Large and Two Ring sets analyzes the effect of removing a ring from the system. The ratio of 0.47 indicates that removing a ring nearly doubles the required pull force. Comparing the Small and Two ring data by their mean ratio suggests that the systems have a similar effect on the required pull force since their ratio is 0.9.

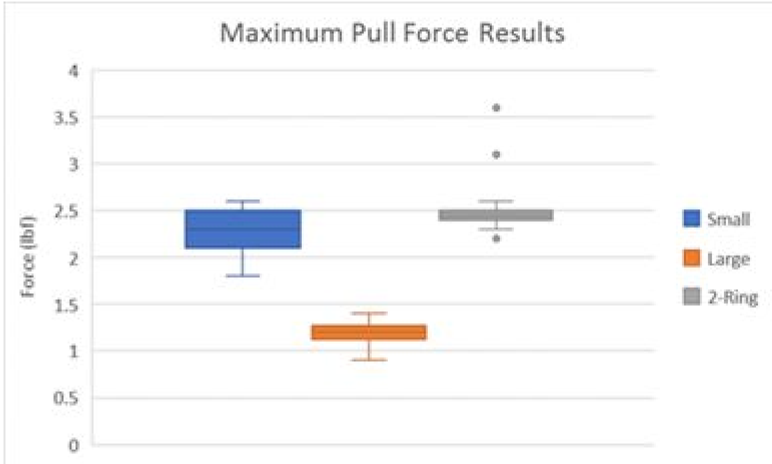


Figure 7: Box-whisker plot of the maximum recorded force during each run for the straight pull/static force tests

To better understand the change in required pull force given the release system ends up mounted off-center with respect to the cross-sectional area of rocket body, the pull force was measured for three discrete angles. As the results show in Figure 8, the required pull force increased as the angle relative to the load application was increased. Again, the Large Ring set required less force than the other two prototypes and the Two Ring and Small Ring sets produced similar results.

Figure 8. Pull force as a result of the angle of pull relative to the direction of load application

Other testing completed to justify the final component selection for the eRing Release was the shock force imparted on the hardware during drogue parachute deployment. The force was measured for various deployment speeds by replacing the release system with a load cell. Figure 9 displays the results from the parachute testing. There is a positive trend in the data; more importantly, the forces detected by the load cell were all on the same order of magnitude as the weight of the rocket - rather than the magnitude of the total energy change during the parachute deployment. This means that testing the ring releases using a static weight equivalent to the anticipated rocket or more should be sufficient to cover the expected loads that the system might experience during flight.

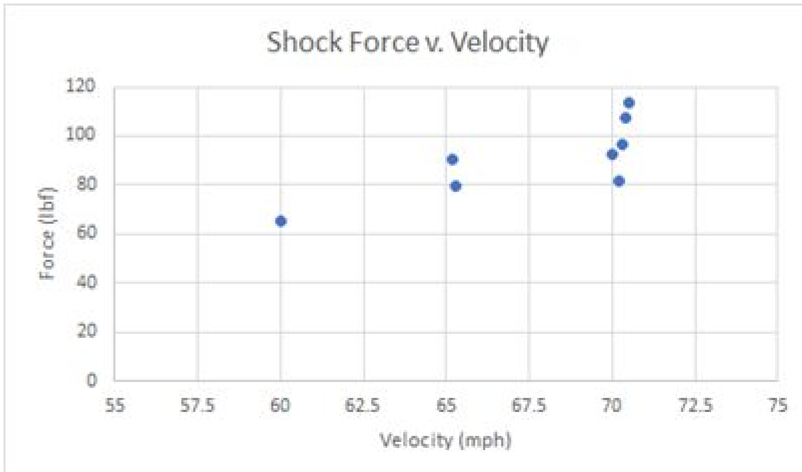


Figure 9. Shock Force v. Velocity as measured during parachute deployment testing

After comparing the results of each of the three prototypes (Appendix 3), the “Small Three Ring” set was chosen for the final design. This set had a straight pull force of 1.8-2.6 lbf, with a maximum measured angled pull force of 3.4 lbf. It was chosen for its smaller size compared to the other two prototypes. Even though the Small set required more pull force, the linear actuator selected to retract the release cord can produce more than three times the required force. The linear actuator was also chosen for its simplicity in function and space saving capability. The linear actuator is easier to implement vertically, which leaves more room for mounting other recovery components.

Conclusion

The final ERS system meets all of the product requirements set by PSAS. The system is fully electromechanical and therefore repeatable for testing. All of the components fit within the given volume of the nose cone and weigh less than 10 kg. Each subsystem releases in less than 3 seconds and can support the payload.

More testing is necessary to ensure reliable deployment. In an attempt to simulate a launch scenario, the PSAS recovery team will drop the completed system from a helicopter. A non-flight rated nose cone will be used with one module beneath it to carry a weight approximate to that of the rocket. Following a successful drop test, the ERS will be integrated into the PSAS LV3.1 rocket and launched during Summer 2019. Concepts from this design will be integrated into the LV4 system architecture.

Future Work and Suggestions

The eRing design was never tested against a model of itself. Three different designs were analyzed, but it was suggested in prior research that the pull force of the release system is very sensitive to the construction. Therefore, it is strongly suggested that several models of the same design are made with relatively loose accuracy and then tested against one another to inspect any differences in pull force. The chosen ring release design is also just one configuration that works. It is possible that a stronger motor could be found that allows for smaller and/or fewer rings to be used in the design. Space turned out to be extremely limited in the overall assembly, so any reduction is useful for the entire recovery system.

The current nose cone release design will be used for the next PSAS launch, with modifications to reduce the weight through strategic material reduction. Additionally, all but a few of the parts will be made from aluminum, while the parachute cups, surgical tubing cap, twist coupling ring, and the parachute support platform will be 3D printed using high strength filament. We recommend machining a new pinion gear out of aluminum in order to prevent the set screw that fits the pinion to the motor shaft from loosening.

Bibliography

1. Photo credit: “(75) Madison West Rocketry - Home” Available: https://www.facebook.com/madison.west.rocketry.
2. Yoo, Y. I., Jeong, J. W., Lim, J. H., Kim, K.-W., Hwang, D.-S., and Lee, J. J., “Development of a non-explosive release actuator using shape memory alloy wire Related Articles Development of a non-explosive release actuator using shape memory alloy wire,” REVIEW OF SCIENTIFIC INSTRUMENTS, vol. 84, 2013, p. 15005.
3. Activating Nitinol with electric current. (n.d.). Retrieved December 14, 2018, from https://www.imagesco.com/articles/nitinol/06.html
4. Song, H., Kubica, E., & Gorbet, R. (2011). RESISTANCE MODELLING OF SMA WIRE ACTUATORS, 10.
5. Ernst, G. R., “Wrench socket holder,” US6092655A, May 10, 1999.
6. “Means for releasably attaching strands,” Dec. 1979.

Appendix 1 - Design Decision Tables

Table 1A. Design criteria outlined as necessary for a successful system

Criteria	Importance
Vibration Resistance	LV3.0 destruction at the last PSAS launch was caused by airframe resonance.
Accidental Actuation	Small but intense vibrations from the Mach forces during ascent that can vibrate hardware and other components loose.
Simplicity	The fewer number of parts, especially moving ones, the better the design. Electronics used to control the system should be easy to debug and operate. The final concept should be relatively intuitive for other future generations. Longevity and durability are evaluated through simplicity.
Ease of Assembly	The final assembly and operation of the design should be easy to understand and carry out. The success of the operation should not depend on any assembly step that is commonly forgotten or easy to perform incorrectly. Avoid requiring extra, especially unique, tools for assembly.
Commercial-off-the-shelf (COTS) Parts	Incorporates more COTS parts than custom will be considered more favorable. It is also important that the COTS part not be too unique; that there be several variations allowing for improvements to the prototype for the final design. The manufacturer should be reputable and likely continue to be in business.
Internal Space Saving	The design must allow for actuation of both the nose cone release and drogue release without impeding the operation of either system, or cause undue wear and tear on parts, especially parachute lines.
Lightweight	Efficiency of a design is partially dependent on the overall weight - the more compact, the lighter, and thus the more efficient.

Table 2A. Decision Matrix for the Method of Actuation

Criteria	Weight	SMA Weighted Values	DC Motor Weighted Values
Vibration Resistance	5	10	25
Accidental Actuation	5	15	20
Simplicity	4	12	12
Ease of Assembly	3	9	9
COTS parts (use and availability)	3	6	12
Space Saving	2	10	6
Lightweight	2	10	6
Total		72	90

Table 3A: Decision Matrix for the Nose Cone Separation Design

Criteria	Weight	Twist Coupling Weighted Values	Vertical Motor Weighted Values
Vibration Resistance	5	15	25
Accidental Actuation	5	20	25
Simplicity	4	20	8
Ease of Assembly	3	15	6
COTS parts (use and availability)	3	9	12
Space Saving	2	10	4
Lightweight	2	10	6
Total		**99**	**86**

Table 4A: Decision Matrix for the Drogue Parachute Separation Design

Criteria	Weight	SMA Plunger Weighted Values	Screw and Motor Weighted Values	3 - Ring Release Weighted Values
Vibration Resistance	5	20	25	20
Accidental Actuation	5	20	20	10
Simplicity	4	8	16	16
Ease of Assembly	3	9	9	12
COTS parts (use and availability)	3	6	6	15
Internal Space Saving	2	8	8	10
Lightweight	2	4	2	10
Total		**75**	**86**	**93**

Appendix 2 - Prototype Testing Procedures

Parachute Testing

Testing Apparatus

Depicted in Figure #, a 300 kg S-bar load cell was attached to the roof rack of a vehicle using two eye bolts, several carabiners, and a small amount of 200 lb strength line. Not shown is the drogue parachute that is attached to the other end of the last carabiner in the assembly line. A camera was attached to the roof to take footage of the drogue parachute as it deployed.

Figure 1A. Parachute testing apparatus

Shock Force Measurement

Most of the shock experienced during drogue parachute deployment is theoretically absorbed by the parachute inflating; which implies not much more than the weight of the rocket is actually imparted on the hardware connecting the parachute to the payload (i.e. the ring release system). To prove this, a deployment test was developed using a larger strain gauge and a car driving at various speeds.

An Arduino with an SD card attached was used to log the data during testing. The parachute was folded using the "z-fold" technique that will be employed during launch and thrown out the window once the car reached the test speed (60-70 mph).

Ring Release Testing

Testing Apparatus

Shown in Figure #, a bucket of concrete was hooked to one end of each ring release design while the other end was looped over another eye hook at the top of the apparatus. An extending line was used on the bottom end of the assembly to reduce the distance from the floor to the base of the concrete bucket and make it easier to access the tension gauge during each test. The main frame of the apparatus was made of 2 x 4 wooden beams combined with two sawhorse brackets. The frame stands approximately six feet tall and three feet wide. Pads were placed below the weight to cushion the impact when the weight falls at the end of each run.

Figure 2A. Ring release apparatus

The concrete weight was made of an 80 pound bag of mix, which over approximates the anticipated weight of the PSAS LV3.1 rocket. A   40 kg tensiometer with hooks at either end was used to measure the pull force required to actuate. The releasecord was started in the same position for each run and pulled through the retaining loop in approximately three seconds.

Actuation Force Measurement

The actuation force was measured for straight pull and angled pull tests. For each test the ring design was set up according to the assembly procedure, then the smaller ring side of the assembly was looped over the eye hook in the top member of the apparatus frame and the concrete weight was hooked onto the largest ring side.The straight pull tests were designed to evaluate the difference in required pull force to actuate between each of the three prototypes. This pull force translates to the required strength of the motor that will pull the yellow release cord. The “straight pull” was defined by pulling the yellow release cord as parallel to the main webbing as possible. The angled pull settings are depicted in Figure #. The tests were guided by pulling in line with the scribed angles, designed to mimic some of the possible angles of the motor relative to the yellow release cord due to off-center mounting within the actual rocket. The more the system is mounted away from the center axis of the rocket, the more the payload will tilt during descent. The pull angle was offset at 20, 30, and 40 degrees, measured from inline with the main webbing.

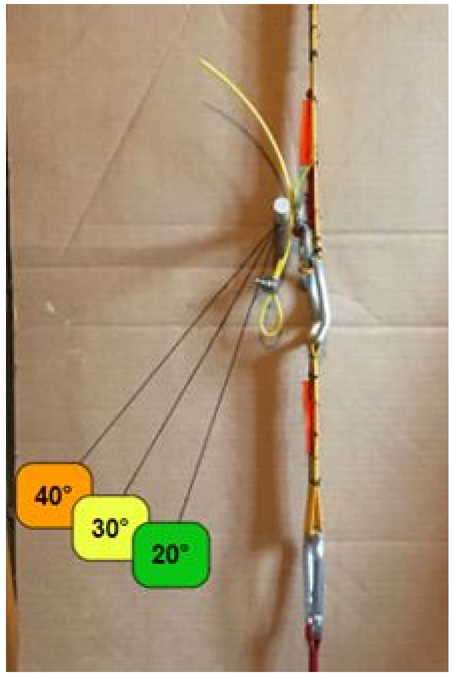


Figure 3A. Angled ring release apparatus

Appendix 3 - Prototype Pictures

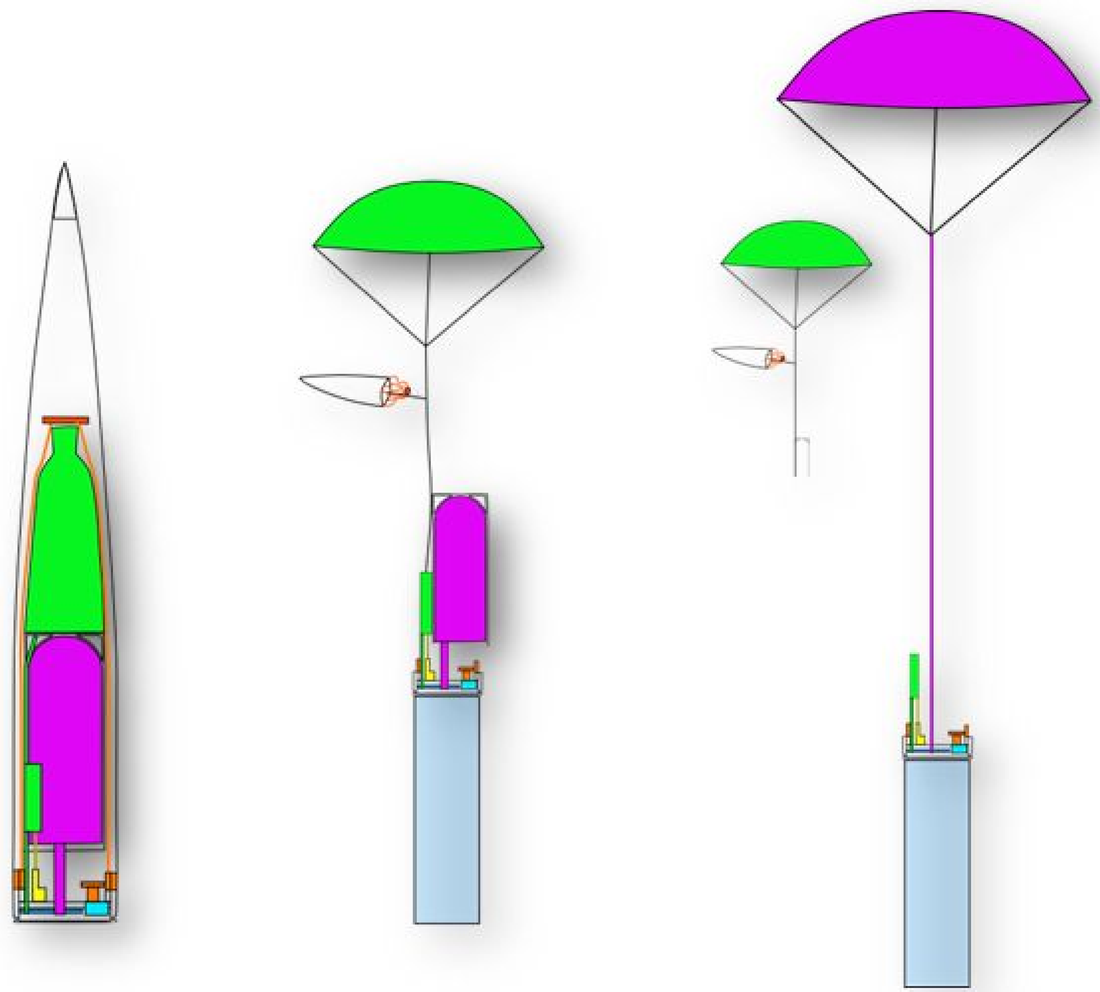


Figure 4A. Stages of the Final Recovery System Design

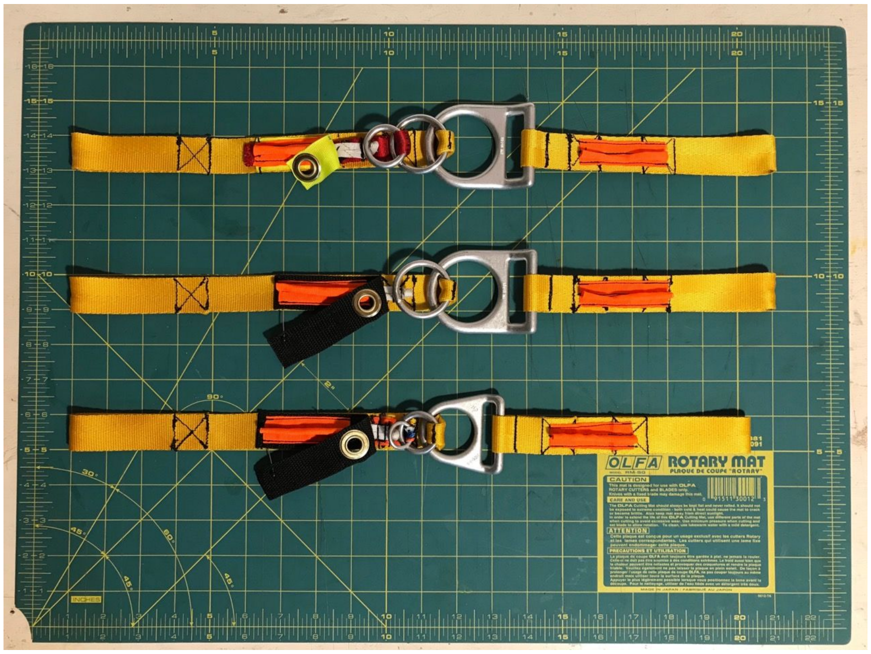


Figure 5A. Three prototyped ring releases

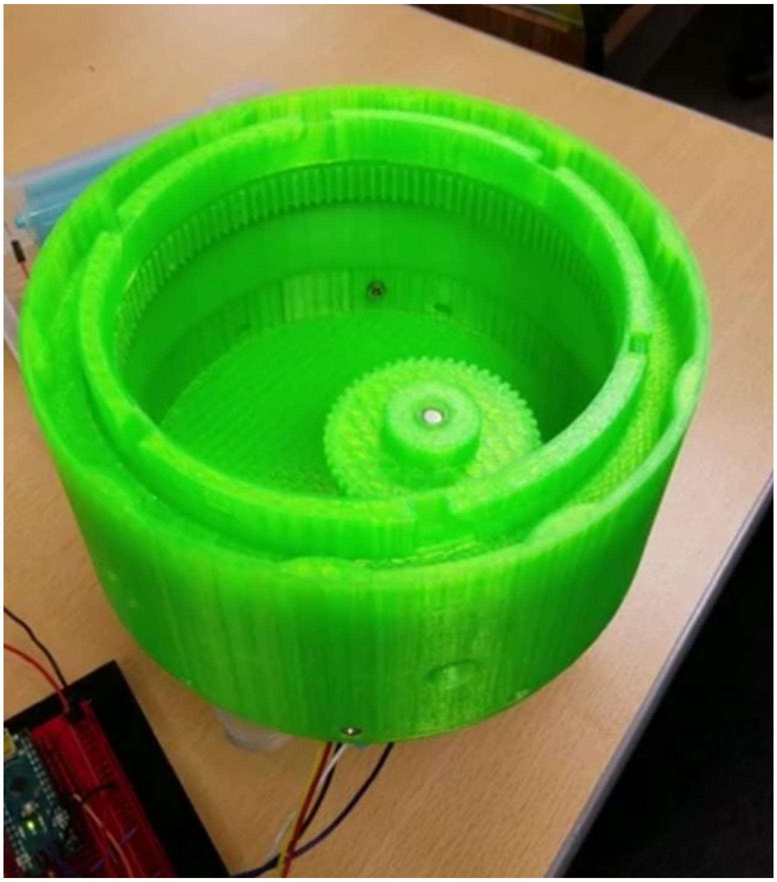


Figure 6A. Lower ring and Twist Coupling Prototypes

Appendix 4 - Bill of Materials

Electromechanical Recovery System (ERS) - Bill of Materials (BOM)						
Part	**Part Name/No.**	**Description**	**Qty**	**Unit**	**Unit Price**	**Vendor**
Electronics						
Arduino Nano Board	1050-1001-ND	ARDUINO NANO ATMEGA328 EVAL BRD	2	each	$22.00	Digikey
Assorted Hookup Wire Pack	1568-1357-ND	HOOK-UP WIRE ASSORT SOLID 22AWG	1	each	$16.95	Digikey
Brushless Gear Motor	4EB71A2AC4F F68AD8ACA79 2C2D68F73B	Fetcus DC Brushless Gear Motor Diameter 37mm 12V 24V (100RPM)	1	each	$60.09	Amazon
Wire Connectors	B07BF8154S	Padarsey 2 Pair XT60 Connector Female/Male W/Housing 10CM Silicon Wire 14AWG	1	2-pk	$7.99	Amazon
Mini Solder-able Breadboard	B0778G64QZ	Gikfun Mini Solder-able Breadboard Gold Plated Finish Proto Board PCB for Arduino Electronic DIY (Pack of 5PCS) GK1009	2	5-pk	$9.58	Amazon
Rechargeable Battery	B07GDVV3BK	GOLDBAT 3S 11.1V 1500mAh 100C Softcase Lipo Rechargeable Battery with XT60 Plug for RC Car, Skylark m4-fpv250, Mini Shredder 200, Qav250, Vortex, Airplane Helicopter Drone and FPV (1 pack)	2	each	$16.99	Amazon
Linear Amplifier	ICL7641ECPD +-ND	General Purpose Amplifier 4 Circuit Rail-to-Rail 14-PDIP	3	each	$3.75	Digikey
zip ties						
10K-Ohm Resistor		10K-Ohm resistor, 1%, purchase from EPL	4	each		EPL
JST SM Plug	43222-15127	Hilitchi 520Pcs 2.5mm Pitch 2 3 4 5 Pin JST SM Male & Female Plug Housing and Male/female Pin Header Crimp Terminals Connector Kit	1	set	$14.99	Amazon
DCR						
Ring - small	H3860B	NO. 3 STYLE RING	1	each	$6.50	ParaGear
Ring - medium	H3840B	NO. 2 STYLE RING	1	each	$10.00	ParaGear
Ring - large	H3880B	NO. 4 STYLE RING	1	each	$4.65	ParaGear
Webbing - main	W9910	YARD - TYPE 6 NYLON WEBBING (Orange)	5	yard	$3.00	ParaGear
Webbing - secondary	1873163626A	Simplicity, Trim, ~ 3/4 in / 19.05 mm 9 ft / 2.74 m	9	feet	$5.49	Joann Fabrics

Webbing - grommet	14888341	Offray 7/8"x21' Grosgrain Solid Ribbon	1	each	$5.99	Joann Fabrics
Webbing - guide	14889463	Offray 1.5"x21' Single Faced Satin Ribbon	1	each	$7.99	Joann Fabrics
Grommet	9604K24	Fabric Grommets - with Washer, Brass, Trade Size 2, for 0.14" Material Thickness (pk of 50)	1	pack	$6.92	McMaster
Crimp - release cord	3896T3	Wire Rope Compression Sleeve for 1/8" Rope Diameter - Not for Lifting (pk of 50)	1	pack	$10.60	McMaster
Yellow release cord	M5825	YELLOW 3 RING RELEASE CABLE	1	yard	$2.25	ParaGear
White retaining loop	W9680	YARD - TYPE IIA SLEEVING WHITE	1	yard	$0.35	ParaGear
Thread	B00HVPT65M	Tex-70 Size 69 Nylon Thread - Black (color not important) - 1500 yard spool	1	spool	$8.30	Amazon
Linear Actuator	RB-Fir-165	P16 Linear Actuator, 50mm, 64:1, 12V w/ Potentiometer Feedback	1	each	$90.00	Robot Shop
LinAct Mount Left	N/A	3D print	1	each		
LinAct Mount Right	N/A	3D print	1	each		
LinAct Mount Nuts	90480A005	Low-Strength Steel Hex Nut Zinc-Plated, 4-40 Thread Size	1	pk of 100	$0.89	McMaster -Carr
Hardware for squishing mount	91253A117	Black-Oxide Alloy Steel Hex Drive Flat Head Screw 4-40 Thread Size, 1-1/4" Long	1	pk of 25	$12.70	McMaster -Carr
Hardware for mounting to kepper	92210A113	18-8 Stainless Steel Hex Drive Flat Head Screw 4-40 Thread Size, 3/4" Long	1	pk of 100	$4.30	McMaster -Carr
NCS						
Keeper Ring	keeper_ring_V3	Please See Quote, Keeper Ring V3, $238.00 for the Keeper Ring, $250 additional charge for NRE FEE, "Kepper Ring"	1	each	$488.00	WPP
Lower Ring	lower_ring_V3	ALUM, NCS,	1	each	$660.56	WPP
Motor						
Twist Coupling Ring	twist_coupling_V3	ALUM, NCS,	1	each	$296.94	WPP/Premier Gear
Upper Ring	upper_ring_V3	ALUM, NCS,	1	each	$349.88	WPP
pinion gear						
motor mount						
motor to mount hardware						

motor mount screws	90272A153	Steel Pan Head Phillips Screws 6-32 Thread, 1" Long	1	pk of 100	$3.64	McMaster -Carr
motor mount washers	92141A011	18-8 Stainless Steel Washer for Number 10 Screw Size, 0.203" ID, 0.438" OD	1	pk of 100	$2.33	McMaster -Carr
motor mount nuts	90631A011	Low-Strength Steel Nylon-Insert Locknut Zinc-Plated, 10-24 Thread Size	1	pk of 100	$3.31	McMaster -Carr
spacer ring						
kepper ring hardware	91263A556	Zinc-Plated Alloy Steel Hex Drive Flat Head Screw 1/4"-20 Thread Size, 5/8" Long	1	pk of 25	$7.99	McMaster -Carr
pinion gear set screw						
Parachutes						
Anchor	89535K87	304/304L Stainless Steel Rod, 3/8" Diameter machined to size	2	each	$4.51	McMaster -Carr
#6 1" Pan Head Machine Screws	90272A153	Steel Pan Head Phillips Screws 6-32 Thread, 1" Long	1	pk of 100	$3.64	McMaster -Carr
#6 Nylock Nuts	91831A007	18-8 Stainless Steel Nylon-Insert Locknut 6-32 Thread Size	1	pk of 100	$4.43	McMaster -Carr
Main chute	N/A	120in. Rocketman Iris Chute / $315, pink/green	1	each	$315.00	Rocketma n
Drogue chute	N/A	5 ft Ballistic Mach II Parachute	1	each	$135.00	Rocketma n
shock cord 10ft	SCN-688	Large Shock Cord, 9/16 3000lb Nylon Webbing 10 yards (30ft) in length	1	each	$30.13	Fruity Chutes
shock cord 14ft	SCN-688	Large Shock Cord, 9/16 3000lb Nylon Webbing 14 yards (42ft) in length	1	each	$35.73	Fruity Chutes
drogue cup	N/A	3D print	1	each	-	Donation
main cup	N/A	3D print	1	each	-	Donation
pizza table	N/A	3D print	1	each	-	Donation
pizza hardware	91772A115	Passivated 18-8 Stainless Steel Pan Head Phillips Screw 4-40 Thread, 1" Long	1	pk of 100	$5.29	McMaster -Carr
Surgical Tubing Assembly						
ST Cap	N/A	3D print	1	each	-	Donation
ST Bottom	N/A	3D print	1	each	-	Donation
Surgical Tubing	B01LYF949F	AIRSOFTPEAK Natural Latex Rubber Tubing Speargun Band Slingshot Catapult	1	33 ft	$15.99	Amazon

		Surgical Tube Rubber Hose 0.2" OD 0.12" ID, 3ft/ 33ft				
ST Ring	tube_ring_V3	ALUM, NCS,	1	each	$238.89	WPP
#4-40 (for ring)	91253A112	Black-Oxide Alloy Steel Hex Drive Flat Head Screw 4-40 Thread Size, 5/8" Long	1	pk of 100	$9.59	McMaster -Carr
1/4-20 for cap	91263A556	Zinc-Plated Alloy Steel Hex Drive Flat Head Screw 1/4"-20 Thread Size, 5/8" Long	1	pk of 25	$7.99	McMaster -Carr
8-32 for cap	91772A201	Passivated 18-8 Stainless Steel Pan Head Phillips Screw 8-32 Thread, 1-1/4" Long	1	pk of 100	$10.47	McMaster -Carr
8-32 nylock nuts for cap	91831A009	18-8 Stainless Steel Nylon-Insert Locknut 8-32 Thread Size	1	pk of 100	$5.55	McMaster -Carr

Appendix 5 - Standard Operating Procedure (SOP)

1. Surgical Tubing Assembly
    1.1. Metal Surgical Tubing Ring
        1.1.1. Feed one length of surgical tubing through one hole of the metal surgical tubing ring from the inside to the outside. Then continue it into the next hole (or however many are skipped in a predetermined pattern), feed it from the outside to the inside. Repeat this step for the rest of the tubing ring.
    1.2. Surgical Tubing Cap
        1.2.1. Make sure the surgical tubing cap is oriented so that the point is facing downward toward the metal surgical tubing ring.
        1.2.2. Feed the top of the tubes used in the metal surgical tubing ring into the surgical tubing cap, making sure there is even spacing between the holes you choose to use.
        1.2.3. Insert the metal surgical tubing pins into the ends of the tubing that were fed through the surgical tubing cap holes, and push the pins down while pulling the tubing so that the are secure in the holes and will not come loose.
2. Parachutes & Parachute Cups
    2.1. Main Parachute/Cup
        2.1.1. The main parachute can be stuffed into the cup, but make sure the lines are oriented to the bottom of the cup, and the parachute is oriented such that when it is released it is all in the same direction.
    2.2. Drogue Parachute/Cup
        2.2.1. Do a z-fold of the drogue parachute (reference parachute packing SOP)
        2.2.2. Stuff the drogue parachute into the cup with the top of the parachute toward the top of the cup.
3. 3-Ring Assembly
    3.1. Feed the smallest ring through the middle ring, then the middle ring through the largest ring.
    3.2. Flip the cover with the guiding track for the for the yellow release cord up over the 3-ring assembly.
    3.3. Feed the yellow cord through the guiding track.
4. Kepper Ring
    4.1. Linear Actuator & Motor
        4.1.1. Put the linear actuator through the oval cutout on the Kepper ring, place the linear actuator brackets around it, feed the wires through the top of the brackets, and screw the brackets into place.
        4.1.2. Put the motor through the large opening, place the motor bracket around it, and the wires should stay below the bracket in the small cutout.
        4.1.3. Feed the wires from both the linear actuator and the motor through the hole in between the two
    4.2. Mounting Bars
        4.2.1. Screw the two mounting bars on their respective spots.
5. Screw the radial holes of the bottom ring.
6. Insert the twist coupling into the spacer ring.
7. Insert the top ring.

8. Attach the Kepper ring.
    8.1. Insert the webbing
    8.2. Install bars
    8.3. Install pizza table
9. Attach the surgical tubing ring.
10. Stuff the parachute into the main parachute into the main parachute cup.
11. Install the main parachute cup and the 3-ring assembly for the drogue release.
    11.1. Make sure it is oriented so the largest ring is at the top and fits in the cut-out in the main parachute cup.
    11.2. The top loop should go through a hole along the top edge of the main parachute cup.
12. Install the drogue parachute cup above the main parachute cup.
13. Attached the end of the drogue parachute lines to the 3-ring release assembly.
14. Put the surgical tubing cap point in the divet of the drogue parachute cup, and pull the surgical tubing and ring down over the parachute cups.
    14.1. Screw the surgical tubing ring to the other rings.