FLIGHT READINESS REVIEW

Design, Development, and Launch of a Reusable Rocket and Autonomous Ground Support Equipment

Payload Option 3.1.8 Centennial Challenge – MAV

Madison West High School | *Non-Academic Team* | March 14th of 2016

Madison West High School, 30 Ash Street, Madison, Wisconsin

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Team Summary

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Launch Vehicle Summary

Length	58*in*
Diameter	3*in*
Liftoff Weight	11.1*lbs* rocket (including 1.00*lbs* of ballast)
Rail Size	1010 rail, 5*ft* long (part of AGSE)
Motor Choice	CTI J760WT (primary), CTI J449BS (backup, if primary not available)
Recovery System	dual deployment 18*in* drogue parachute at apogee 40*in* main parachute at 700*ft* Fully redundant dual event altimeters
Flysheet	http://westrocketry.com/sli2016/MSRFS_FRR_MadisonWest2016_Martians.xls

Payload/AGSE Summary

We are pursuing payload option 3.1.8: *Design, Development, and Launch of a Reusable Rocket and Autonomous Ground Support Equipment* (Centennial Challenge). The goal of the project is to develop a reusable rocket together with autonomous ground support equipment (AGSE). AGSE must be able to

- collect a container with soil sample from the ground
- insert the container into payload compartment in the rocket
- close the door of payload compartment
- raise the rocket into launch position of 5° from vertical
- insert igniter to rocket motor
- signal launch readiness

Our AGSE is all aluminum construction (8020 rails and parts), powered by linear actuators and stepper motors and controlled by Arduino microcontroller with firmware written in C++ language.

Changes made since Proposal

Changes made to vehicle criteria

- **Page 15:** Extended and updated verification plan and status, addresses *CDR feedback item #6*
- **Page 16:** Added summary table of vehicle subsystems testing
- **Page 18:** Updated verification matrix
- **Page 22:** Updated vehicle development schedule
- **Page 24:** Updated vehicle safety parameters
- **Page 23:** Updated vehicle maturity discussion
- **Page 26:** Updated mass statement
- **Page 26:** Refined ballast weight (1.0*lbs*), addresses *CDR feedback item #5*
- **Page 28:** Corrected nosecone shape in dimension drawing (*CDR feedback item #1*)
- **Page 31:** Added material stress testing (deflection, tensile), addresses *CDR feedback item #4, #6*
- **Page 39:** Updated summary table of deployment and recovery system
- **Page 43:** Added recovery/deployment subsystem testing, addresses *CDR feedback item #6*
- **Page 45:** Updated drift calculations
- **Page 46:** Updated drift calculations (now based on measured descent rates)
- **Page 46:** Updated performance predictions (now based on full scale vehicle test flights)
- **Page 46:** Updated performance predictions with anchored model
- **Page 52:** Added detailed results of full scale vehicle test flights
- **Page 52:** Refined value of drag coefficient (C_d) via full scale test flights (*CDR feedback item #*2)
- **Page 57:** Updated AGSE checklists
- **Page 57:** Added information about GPS tracker (Trackimo)

Changes made to payload criteria

- **Page 57:** Updated AGSE checklists
- **Page 89:** Update AGSE control subsystem
- **Page 94:** Added description of AGSE firmware software architecture
- **Page 102:** Added detailed verification plan for AGSE

Changes made project plan

- **Page 116:** Updated outreach information

Vehicle Criteria

Selection, Design and Verification of Launch Vehicle

Mission Statement, Requirements, Success Criteria

We will use a single stage, J-class vehicle to deliver the standard MAV payload to the target altitude of 5,280*ft*. The rocket will land using dual deployment recovery and will be reflyable on the same day. The following criteria define successful mission for vehicle:

- Rocket safely launches from AGSE under 5^o angle from vertical
- Rocket reaches but will noy exceed target altitude of 5,280*ft*
- Rocket lands safely after deployment of drogue parachute at apogee and main parachute at 700*ft* AGL
- Rocket lands within the confines of launch area (1/2*mile* radius from launch site)
- Rocket is recovered with no damage and reflyable on the same day

System Level Overview

The following subsystems are necessary to accomplish the mission:

Subsystem	Addresses	Pages
Structural	Rocket construction, material selection	26-38
Propulsion	Motor choice, performance predictions	46-51
Recovery	Parachutes, deployment electronics	39-46
AGSE	Autonomous ground support equipment	65-114

Table 1: Vehicle subsystems

The requirements for each subsystem are addressed in its own section in the document.

Verification Plan and Status

Overall Plan and Status

The sequence of verification steps for the vehicle is summarized in the table below:

#	Step	Goals	Milestone	Status
1	***RockSIM model***	• Preliminary vehicle design ○ estimate of liftoff weight ○ vehicle stability ○ preliminary performance predictions ○ preliminary mass statement	**SOW/PDR**	**PASSED**
2	***Scale model***	• Verify deployment scheme • Preliminary estimate of drag coefficient • Verify aerodynamic stability • Verify avionics selection and functionality	**CDR**	**PASSED**
3	***Design Revision***	• Using drag coefficient from scale model flight, verify that the full scale vehicle is capable of reaching altitude target • Using flight observations, verify/revise the deployment scheme • Using flight data verify that avionics performed as expected (events at correct altitude) • Update mass statement	**CDR**	**PASSED**
4	***Material selection***	• Using manufacturers specifications, verify that all selected materials are suitable for rocket construction, including ○ Body tube ○ Shockcords ○ Fin material ○ Nosecone ○ Bulkheads and centering rings ○ Motor retention ○ Anchors, shroudlines, canopies, tie rods and links • Update mass statement	**CDR**	**PASSED**
5	***Material static stress testing***	• Perform static tests on materials selected for rocket construction ○ Deflection of planar components ○ Tensile strength of	**CDR/FRR**	**PASSED**

		○ shockcords, shroudlines, tierods, anchors and links ○ Deformation of tubular components ○ Rail buttons strength and mounting method		
6	***Static tests***	• Using pressure chamber, verify that all barometric devices respond to changes in pressure • Calculate ejection charge sizes • Perform static ejection charge tests • Ground tests of tracking devices • Ground tests of parachute packing and ability to inflate • Avionics power source endurance tests (battery capacity)	**CDR/FRR**	**PASSED**
7	***Flight tests***	• Verify performance of vehicle • Verify liftoff weight • Verify deployment scheme • Verify kinetic energy of impact limits • Verify descent rates • Verify functionality of tracking devices • Verify endurance of materials used	**FRR**	**PASSED**

Table 2: Verification Plan and Status

Detailed list of all project requirements, how they are addressed and verified starts on page 118.

Subsystems Verification

The following table summarizes how the tests used to verify each of the subsystems (structural, propulsion, deployment and tracking). The tests are listed in the order in which they were performed.

Subsystem	Tests	Page
Propulsion	1. RockSIM simulations	46
	2. Scale model flight	24
	3. Full scale model flights	52
Structural	1. Material selection using manufacturer's specifications	30
	2. Static stress material testing	31
	3. Full scale model flights	52
Deployment/Recovery	1. RockSIM simulations (to determine apogee)	46
	2. Preliminary parachute size/descent rate calculations	39
	3. Ejection charge calculation	40
	4. Shockcord/parachute tensile strength static tests	31
	5. Altimeter static tests (pressure chamber)	43
	6. Avionics battery capacity tests	43
	7. Anchors/tierods/links tensile strength static tests	31
	8. Static ejection charge tests	39

	9. Ground parachute inflation tests 10. Full scale vehicle flight data analysis	43 52
Tracking	1. Ground tests 2. Battery capacity tests 3. Full scale vehicle flight tests	41 41 52

Table 3: Subsystems Testing

Verification Matrix

The verification plan is constructed based on the project requirements, pages 118-125. Each of the requirements is addressed in list form, starting on page 118.

Further, for each of the requirements, we have identified

- Component addressed by a given requirement
- Test to perform to verify that a given requirement is satisfied

The verification components for the vehicle are:

C1: Flight Electronics
C2: Recovery Systems
C3: Motor
C4: Power Supply (for electronics)
C5: Ejection Charges
C6: Tracking and Telemetry
C7: Launch System

The verification procedures (tests) for the vehicle are:

V1/Functionality: Ensure satisfactory performance of components.
V2/Integrity: Application of force to verify durability.
V3/Integration: Ensures proper fit of component within its assigned compartment, free of interference of other components.
V4/Scale Model: Verifies the predicted performance of the vehicle.
V5/Full Scale Vehicle Test Flights: verify the actual performance of the vehicle

Finally, the verification shows which test is applied to which component and which project requirement (identified by its number) is verified by carrying out that test.

	V1	V2	V3	V4	V5
C1	1.2	2.5	2.4	1.2	1.2
C2	2.5	1.3	1.4	1.4	1.4
C3	1.5	2.5	1.12	1.2	1.2
C4	1.7	1.7	1.12	1.7	1.7
C5	2.2	2.5	1.12	1.13.1	1.13.1
C6	2.11	2.5	2.11	2.11	2.11
C7	1.8	2.5	1.8	1.8	1.8

Table 4: Verification matrix for vehicle

Both the 2/3 scale model and full scale vehicle have been constructed and most of the verification tests were conducted. The remaining tests are mainly flight tests of the full scale vehicle, scheduled to start on the weekend of January 16th.

Project Requirements for Vehicle and Verification

The adherence to NASA mandated project requirements is in detailed discussed in the Project Requirements section on pages 118 to 125.

Vehicle Risks

We have over a decade of Student Launch experience and we work with highly experienced mentor and other engineers. The biggest risk is the weather that can severely limit our flight test opportunities. Motor availability and feature creep (unnecessary "just because we can" project scope expansion) have been identified as major risks as well. On the other hand, we have a 24/7 access to workshop and sufficient personnel to provide us with sufficient workshop time and all tools necessary for successful completion of vehicle construction and testing. We also work with several vendors to ensure the parts and supplies availability. The identified risks are sorted by the likelihood of each risk occurring.

Risk	Mitigation	Impact	Likelihood
Weather (affects test flights)	There is sufficient number of flight windows open in our area (about 3 windows each month). The team members are aware of the fact that some launch dates will be rescheduled due to bad weather. SL test flights are of high priority for all team members and there will sufficient ground personnel available for each launch window. We also have the option to ask a "one-time-favor" from owners of private launch sites.	**HIGH**	**MEDIUM**
Motor Supply	We work with several rocketry vendors to avoid "out-of-stock" situation. However, since the motors are produced by only a few manufacturers, this risk is higher than supply risk for parts and supplies.	**HIGH**	**MEDIUM**
Scope (feature creep)	The team will adhere to the requirements of the project and by CDR milestone will identify the minimum solution that satisfies all project requirements. Addition of features beyond this scope will not be allowed until the minimum solution is implemented and 100% functional. Mentor and educators will enforce the limits to project scope at all times.	**HIGH**	**MEDIUM**
Schedule (tasks taking longer than expected)	Team schedules workshop and classroom time according to the project status. If the project starts slipping behind original schedule, more work time will be scheduled.	**MEDIUM**	**LOW**
Budget overrun (team	The budget has been constructed and will be	**HIGH**	**LOW**

running out of money)	closely monitored as the project progresses. The team is participating in annual fundraising event to earn money and to increase community awareness of the project and its educational impact. After the conclusion of fundraising activities for this year, the team still has several options to raise more funds if needed.		
Team member injury	All team members, mentor and educators will utilize personal protective equipment for all activities. All safety related documentation is kept on hand for quick access. The team members are supervised by the mentor and educators at all times. The first aid kit is kept on-hand during all activities.	**HIGH**	**LOW**
Personnel (not being available)	We have several workshop supervisors that can work with the students and our workshop is accessible 24 hours, 7 days of week. Two or more students are assigned to each task to ensure that no task will stall because of personnel shortage. The school exam periods and break are accounted for in our schedule.	**MEDIUM**	**LOW**
Rocket Construction (the ability of the team to build a rocket that will be suitable for the mission)	The team is supervised by highly experienced mentor with previous Student Launch experience to ensure that the vehicle is constructed using proper construction techniques and materials and that sufficient time is allocated to each of the construction tasks.	**HIGH**	**LOW**
Rocket Performance	The team will perform several test flights to make sure that the rocket will reach but not exceed the target altitude. This will include computer simulations, half-scale model flights and full scale vehicle test flights. After each flight the collected data will be analyzed to evaluate the overall performance of the launch vehicle.	**MEDIUM**	**LOW**

Deployment Failure (damage to rocket, possible rocket loss)	Static ejection tests will be performed to make sure that the ejection charges are of correct size and the coupling surfaces are smooth enough. Fully redundant ejection electronics will be used to increase the probability of successful deployment of both the main and drogue parachute. The rocket flight preparations will be observed by the mentor and checklists will be used to prevent step omissions.	**HIGH**	**LOW**
Rocket Loss	The team is aware of possibility of losing the rocket during any of the test flights. A sufficient surplus of parts will be kept to allow for construction of the new vehicle. All test flights will be scheduled in sufficient advance of the final launch to allow team to recover from the rocket loss. The team mentor will supervise the team during all test flights to ensure the highest possible probability of favorable flight outcome. The weather situation will be critically evaluated before every test flight to balance the risk of rocket loss with the consequences of not making the test flight.	**HIGH**	**LOW**
Parts/Supplies Availability	We work with several vendors and use materials with normalized dimensions to avoid situations when the only vendor carrying a critical item runs out or the item is discontinued.	**HIGH**	**LOW**

Table 5: Project risks related to the vehicle

Additionally, we have performed full Failure Mode Effect Analysis (page 153) and RAC Safety Assessment (page 155) both for the vehicle and the AGSE.

Development Schedule for Vehicle

Detailed schedule of all our activities is shown starting on page 137. The dates concerning the launch vehicle development are summarized in the table below. We have allocated 2 weeks for parts acquisition for each of two vehicles (half-scale and full-scale), followed by a three week (6 workshop sessions) manufacturing period and minimum of 2 days of ground/static testing and verification. Finally each vehicle has three launch windows available. The vehicle development is now concluded and the vehicle is ready for the final launch at NASA SL 2016 event.

AGSE was developed in parallel with the vehicle and is now fully functional and launch tested.

Activity	Dates	Time allocated	Status
Scale model parts acquisition	**11/7 to 11/21**	2 weeks	**DONE**
Scale model construction	11/21 to 12/10	3 weeks	**DONE**
Scale model ground tests, verification	12/10, 12/11	2 days	**DONE**
Scale model test flights	12/12 or 12/19 or 1/9	3 launch windows; one required	**DONE**
Full scale vehicle parts acquisition	1/9 to 1/23	2 weeks	**DONE**
Full scale vehicle construction	1/24 to 2/13	3 weeks	**DONE**
Full scale ground tests, verification	2/14 to 2/19	1 week	**DONE**
Full scale test flights (minimum 2 needed)	2/20, 2/27 or 3/5	3 launch windows, two required	**DONE**
Full scale vehicle final preparations for SL launch in AL	3/6 to 4/9	5 weeks	

Table 6: Vehicle development schedule

Vehicle Development Status

The half scale vehicle has been constructed and flown – the results are described on page 24, Table 8. The full scale is now constructed, statically tested has made four test flights (results are discussed on page 52). AGSE is in a launch capable state and we have completed launch tests with gradually increasing rocket size in following order:

Launch Vehicle	Motor/Total Impulse *[Ns]*	Liftoff Weight *[g]*	Status
TARC Rocket	F-class : 60	650	**DONE**
2/3 Scale Model	H-class: 130	1200	**DONE**
Full Scale Vehicle	J-class: 1100	5000	**DONE**

Table 7: Gradual AGSE launch load testing

Each test flight is videotaped and the recordings are analyzed for any signs of AGSE instability or weakness. All tests were successful, no AGSE problems were discovered (expected result).

Figure 1: TARC rocket launched from AGSE to test AGSE's launch capability

Vehicle Design Maturity

The vehicle design is fully matured, the scale model was constructed and flown, full scale vehicle was also constructed, statically and flight tested. We have performed material strength tests for all applicable components and flight tests.

Computer Simulations: We have carried out flight simulations in OpenRocket software, with coefficient of drag set to 0.7, a typical value for single diameter, cylindrical rockets and the simulated apogee is very close to desired altitude target (target is 5280*ft,* and our simulations show predicted apogee of 5324*ft*). The scale model was flown, indicating coefficient of drag of 0.95. We have updated our simulations and performed detailed analysis to select our full scale motor (this process is described in detail on page 51). We have verified our propulsion choice by performing four test flights with the full scale vehicle. We are confident that we will be able to reach the altitude target with acceptable precision (5%) using the motor selected based on scale model flight results, computer simulations and known mass of full scale vehicle.

Scale model test flight: 2/3 scale was constructed and flown. The vehicle parameters, propulsion and flight results are listed in table below:

Vehicle Diameter	2.0*in*
Vehicle Length	40*in*
Liftoff Weight	2.3*lbs*
Motor	AT-G339N, 109*Ns*
Flight Apogee	927*ft*
Calculated C_d (effective coefficient of drag)	0.95

Table 8: Scale (2/3) model parameters and test flight results

The scale model performance was significantly worse than simulation predicted. The predicted apogee was 1,270*ft* and the actual flight peaked at 927*ft*. After anchoring the simulations to flight data, we have obtained value of coefficient of drag C_d = 0.95 (unexpectedly high, 0.75 being the average C_d predicted by RockSim for this design). To account for possibility of either result being correct, we have conducted series of simulations, both for Cd = 0.70 and Cd = 0.95 to guide our selection of full scale motor. This process is explained in detail in Table 23 on page 51. The scale model flight was stable and the deployment scheme worked as expected, necessitating no further changes to the full scale vehicle design.

Full scale test flights: after completion of the full scale vehicle we have performed four test flights, each flight using J-class motor. The results of the test flights together with the static tests and material stress tests confirm that the vehicle is flight-worthy, safe and will be able to reach the target altitude of 5,280*ft*. The vehicle reached apogee of 5,324*ft* on its final test flight (flying in the same configuration that will be used at NASA SL2016 event). The results of all test flights are discussed in detail on page 52.

Flight safety parameters: the following table shows the flight safety parameters for full scale vehicle. The table has been updated to reflect scale model flight test results and full scale parameters (as the full scale vehicle is already constructed). Thrust to weight ratio is significantly above the minimal required of 5, rocket has stability of 4.4*calibers* (stable) and the exit velocity of the 5*ft* rail is 48*mph* (above the minimum required value of 30*mph*).

Parameter	Value
Flight Stability Static Margin	4.4 *calibers*
Thrust to Weight Ratio	18.6
Velocity at Launch Guide Departure (5ft launch rail)	48.0 *mph*

Table 9: Vehicle flight safety parameters

Mission goal suitability: the vehicle was significantly redesigned to fit better the overall mission goals. The body diameter was decreased from 4*in* to 3*in* to allow the rocket become smaller and capable of taking off from a 5*ft* launch rail, thus significantly decreasing the AGSE footprint and volume. The rocket body is still wide enough to allow for easy payload insertion by a robotic arm while retaining sufficient robustness of the payload bay.

High wind performance: the flight apogee will vary by about 0.9% when flying under different conditions, ranging from wind-speed of 0*mph* to wind speed of 20*mph* (cf. Table 21 on page 47). Due to the launch angle of 5^{o} from vertical, the best performance (+0.7%) difference is for 10*mph* wind and the worst performance (-0.19%) is for 20*mph* wind.

Recovery and drift: the parachute sizes and deployment altitudes were selected so the rocket will not drift for more than 0.5*mile* even when flying under 15*mph* wind conditions while obeying the constraint of 75*ft-lb.f* maximum kinetic energy on landing for any of its section. The kinetic energy on landing for entire rocket is 79.8*ft.lb-f.* The details of drift prediction calculations are summarized in Table 20 on page 46).

Mass Statement

Estimated Mass: we have constructed the full scale vehicle and its actual liftoff weight (with primary propulsion choice, CTI J760WT motor) is 11.1*lbs,* including 1*lbs* of ballast.

Ballast: the rocket needs 1*lbs* of ballast to remain under 5,280*ft* of altitude using its primary (CTI J760WT) or backup (CTI J449BS) motor choice. The amount of ballast does not exceed 10% of rocket liftoff weight and the rocket has been flight-tested in fully ballasted configuration.

Underpowered Rocket Margin: as currently designed and loaded with primary propulsion choice (CTI J760WT) the rocket would have gain about 30*lbs* to become underpowered. As we have already constructed the full scale vehicle and know its liftoff weight (11.1*lbs*), this scenario is not considered realistic.

Structural Subsystem

The rocket is constructed from 3" thin-wall fiberglass tubing, using 1/8" G10 fins. The rocket is robust enough to endure 30+*g* of acceleration and high power rocket flight and deployment stresses. The recovery system can withstand over 50*g* shocks during deployment.

The rocket is 58 inches long, with a 3.0 inch diameter. It has liftoff mass of 11.1 pounds, including one pound of ballast. The vehicle and propulsion options are discussed in detail below. The primary propulsion choice is a J-class motor (CTI J760WT, 54*mm*) with total impulse of 1265*Ns*. The vehicle can launch from a standard size, 5*ft* launch rail.

The rocket uses dual deployment to minimize drift.

Design Goals and Approach

The rocket is designed to carry a plastic container with 4 ounces of sand to altitude of 5,280*ft.*

The rocket will be launched from AGSE (Autonomous Ground Support Equipment). Since it is beneficial (score-wise) to minimize the size of AGSE, a minimum size rocket is indicated. The dexterity of robot arm of our AGSE dictates 3" diameter vehicle at minimum. The launch rail length contributes significantly to overall AGSE size and for this reason we are looking for high thrust propulsion (to reach the safe velocity as fast as possible). Our tests so far indicate that *5ft* rail will be sufficient for safe liftoff.

High thrust motor is also desirable for altitude precision missions as the fast moving rocket is less affected by wind than a slower vehicle and leaves less opportunity for bad rail exits (when the rocket is hit by a wind gust as it exits the rail).

High thrust propulsion results in high acceleration values and requires strong and robust vehicle (necessitating fiberglass construction). High thrust propulsion will also result in high speeds (based on available data we estimate 580*mph* for our vehicle), thus requiring a suitable nosecone (we chose Von Karman/LD Haack shape designed for minimum drag). We have already designed, 3D-printed and flight tested such nosecone.

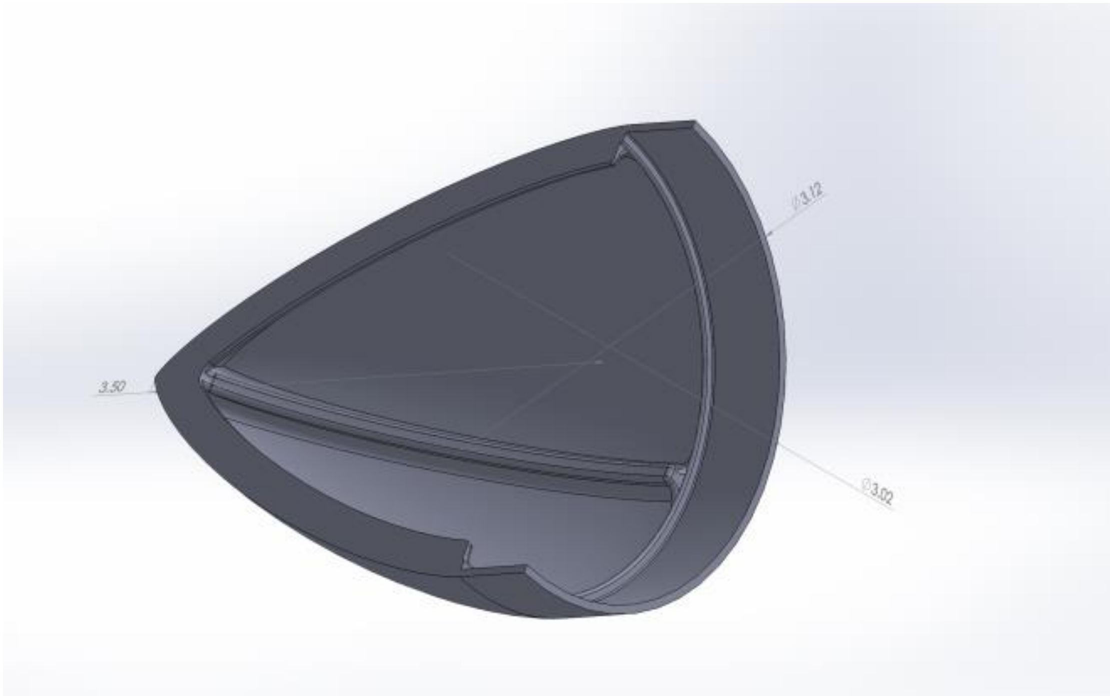


Figure 2: Von Karman (LD Haack) nosecone selected for MAV mission

Payload occupies only a minor fraction of overall vehicle length, the majority of vehicle is occupied by motor and dual recovery system. The parachute size is determined by kinetic energy of landing requirement, the shockcords are selected for maximum strength for given volume (we chose ¼" tubular Kevlar, 550*lbs* (measured) break strength).

Vehicle Design Features

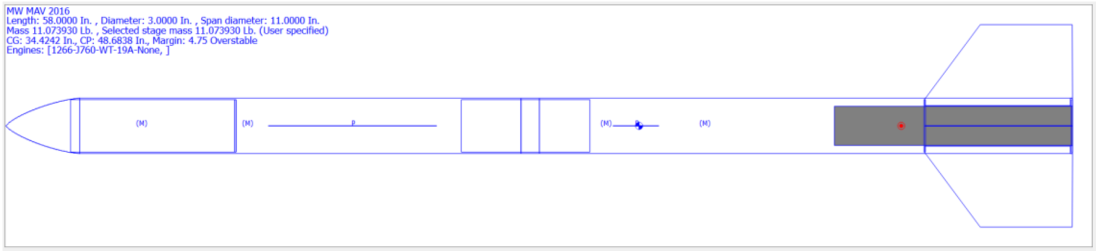
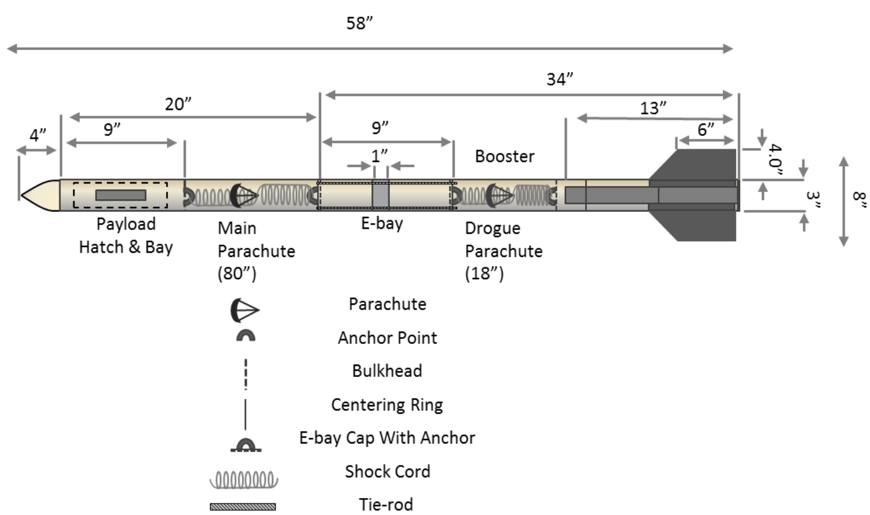


Figure 3: A two dimensional schematic of the entire rocket.

The vehicle has clipped-delta fins (with beveled leading and trailing edge), which are easy to manufacture and install. Clipped-delta fins are high performance fins (second only to elliptical fins) and will not negatively affect altitude performance of the rocket, its stability or integration with AGSE. Because rocket is expected to operate in near transonic regime (maximum velocity 580*mph,* 0.76*Mach*), we have chosen Von Karman (LD Haack) nosecone, a nosecone suitable for high speed rockets. The vehicle is all fiberglass construction to withstand 30+*g* stresses. The payload is directly below the nosecone, the avionics bay is a coupling part. The ballast can be added to bottom bulkhead of avionics bay (near center of gravity of the rocket in launch configuration).

Dimensional Drawing of the Vehicle

The figure below show dimensioned drawing of the entire vehicle, including all major components and structurally important points (such as anchors for shockcords, tie-rods or bulkheads). The location of both parachutes, motor, payload and bay with deployment electronics is also shown.



Nose Cone: ABS 3/32”, Von Karman	Bulkheads: Fiberglass 1/8”
Payload Body Tube: Fiberglass 1/8”	Attachment Points: U-Bolts 1/4”
Booster Body tube: Fiberglass 1/8”	Tie-rods: #8/32 stainless steel
Coupler Tubes: Fiberglass 1/8”	Fins: Fiberglass 1/8”
Shockcords: ¼” tubular Kevlar, 550lbs	Centering Rings: Fiberglass 1/8”

Figure 4: Dimensioned drawing of vehicle

Vehicle Parameters

The table below shows the primary design parameters of our vehicle. The values are taken from already constructed full scale vehicle. Thrust to weight ratio is calculated for maximum thrust (937*Ns*) of CTI J760WT motor (primary propulsion choice).

Length *[in]*	Mass *[lbs]*	Diameter *[in]*	Motor Selection	Stability Margin *[calibers]*	Thrust to weight ratio *(g)*
58	11.1	3	CTI J760WT	4.4	18.7

Table 10: The rocket's dimensions, stability, and primary propulsion

The following figure shows all compartments and sections of our rocket. The rocket separates into three tethered sections. The first section contains the nosecone, payload, and the main parachute. The second section is the deployment e-bay. The third section contains the drogue parachute and the rest of the vehicle. We will use standard dual deployment triggered by two fully redundant PerfectFlite StratoLogger altimeters.

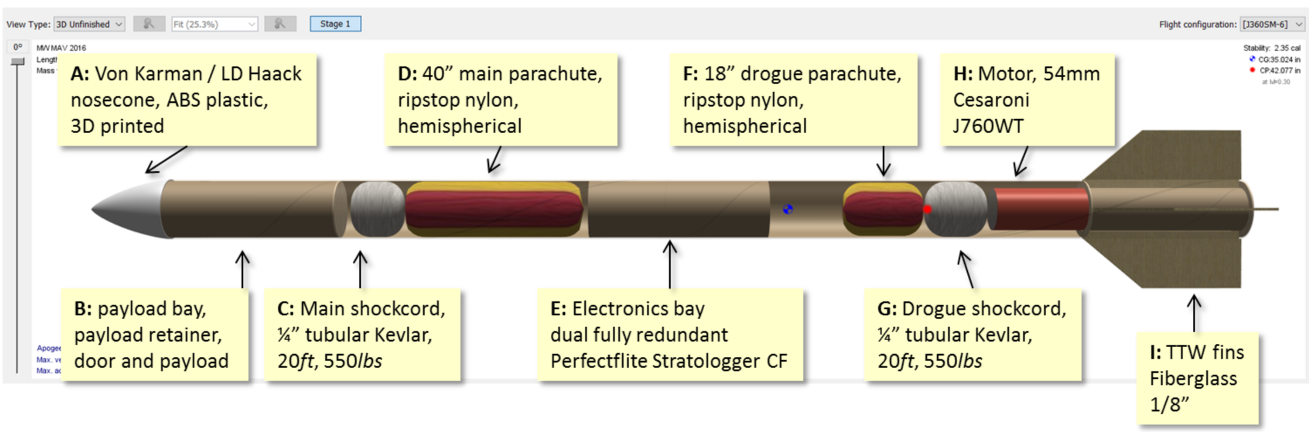


Figure 5: A three dimensional schematic of the entire rocket

Letter	Part
A	Nosecone (Von Karman, LD Haack), ABS, 3D printed
B	Payload pay, retainer, door, payload
C	Main shockcord, ¼" tubular Kevlar, 550*lbs*, 25*ft* long
D	Main Parachute (40" ripstop nylon, hemispherical)
E	Deployment E-Bay (dual PerfectFlite Stratologger CF)
F	Drogue Parachute (18" ripstop nylon, hemispherical)
G	Drogue shockcord, ¼" tubular Kevlar, 550lbs, 25*ft* long
H	Motor Mount (54mm), Aeropak retainer
I	Fins (4, 1/8" G10)

Table 11: Rocket sections and parts

Material Selection

The following table shows the selection of materials for the vehicle. We used primarily fiberglass for vehicle construction because it is easily precisely machined and glued, is light and strong. Our vehicle is 3” in diameter and we have a sufficient total impulse allowance for fiberglass construction.

The airframe (including couplers) is made out of fiberglass tubing and 1/8” G10FR (garolite, flame retardant) fins (mounted through the wall). The centering rings are also made out of 1/8” G10FR. Bulkheads are made out of ¼” G10FR. Fiberglass tubing and garolite fins are proven materials for high power rocketry construction, including transonic and supersonic vehicles.

Figure 6: Full scale vehicle loaded on the AGSE. AGSE is now partly operational and fully launch capable.

The recovery system is anchored using ¼” black steel U-bolts, with 2000*lbs* breaking force. From the flight data we calculated that the deployment subsystem will experience up to 300*lbs* force. Shockcord is made from ¼” tubular Kevlar with 550*lbs* breaking force. Both parachutes are rip-stop nylon parachutes from SpheraChute, each parachute having 8 shroudlines, each shroudline rated for 320*lbs* breaking strength (measured). Tie-rods are made out of steel 8/32 threaded rod, two tie-rods are used, each measured to withstand at least 1000*lbs* of force. In summary, our deployment system is expected to see 300*lbs* stresses and the weakest point is 550*lbs* shockcord.

The 2/3 scale model was assembled using 3,500*psi* LocTite epoxy and the full scale vehicle was built with West Marine Epoxy system (and appropriate fillers to save weight).

Rocket Part	Material	Supplier	Part No.	Strength
Nosecone	3D printed ABS	Madison West	N/A	Flight tested
Tubing	Fiberglass, 75mm tube	Wildman Rocketry	G12-3.0	Flight tested
Fins	1/8” G10 garolite, beveled, TTW	McMaster-Carr	8667K213	Flight tested
Parachutes	Ripstop nylon	Giant Leap	N/A	320*lbs* (measured) shroudlines (8), ripstop nylon
Couplers	Fiberglass	Wildman Rocketry	G12CT-3.0-9	Flight tested
Motor Mount	Fiberglass, 54mm tube	Wildman Rocketry	G12-2.0	Flight tested
Centering Rings, Bulkheads	Fiberglass, 2x1/8”	McMaster-Carr	8667K213	Flight tested
Anchors	¼” stainless steel U-bolts	McMaster-Carr	3201T45	2000*lbs*
Shockcords	½” tubular Kevlar	Wildman Rocketry	KEVLAR1/4”	550*lbs*, measured
Tie-rods	8/32 stainless steel threaded rods	McMaster-Carr	93250A05	1000*lbs* (measured) per tierod, 2 tierods used

Table 12: Material selection

Material Stress Testing

Tensile Strength

We performed tensile strength testing for following components:

- U-bolt anchors
- tie-rods
- links
- shockcords
- parachute shroudlines

Test results are summarized in the Table 13. The machine used for testing (shown on Figure 7) can exert force of up to 1000*lbs* and record *elongation vs force* profile.

Figure 7: Structural stress analyzer used for tensile strength testing

Component	Material	Strength Rating	Force tested	Result	Flight tested
Anchors	¼" stainless steel	2000*lbs*	1000*lbs*	**MAX**	**YES**
Tie-rods	#8/32 stainless steel	800*lbs*	1000*lbs*	**MAX**	**YES**
Links	QuickLink	2000*lbs*	1000*lbs*	**MAX**	**YES**
Shockcords	¼" tubular Kevlar	3600lbs	540*lbs*	**FAIL**	**YES**
Parachute shroudlines	Nylon	400*lbs*	320*lbs*	**FAIL**	**YES**

Table 13: Tensile strength test results

The **RESULT** column in the table indicates how the test was terminated: either by **MAX**ing out the force that machine can exert (1000*lbs*) or by the structural **FAIL**ure of tested component. Additionally, all components were tested during full scale vehicle flights for further verification.

The testing red flagged ¼" Kevlar shockcord, which is being sold as 3600*lbs* Kevlar, yet the stress analyzer was able to break it repeatedly using 540*lbs* force. We have investigated the issue and we have found the following:

- **Knots can weaken cord strength by as much as 70%:** we have researched topic in literature and online and knots on the cord are a source of major detriment to the strength of cord (due to bending of fibers). To avoid this issue, the cord should be spliced, rather than tied.
- **Manufacturer's provided data are likely inaccurate:** during tensile strength testing, we've measured loss of 80% of rated strength, more than any literature or online source indicated. We have also measured a smaller, 400*lbs* rated Kevlar line (from a different vendor) and it broke at 360*lbs* (significantly closer to manufacturer's rating).

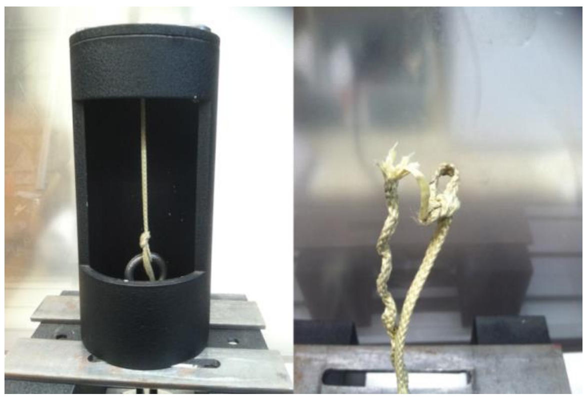


Figure 8: Shockcord tensile strength testing and material failure

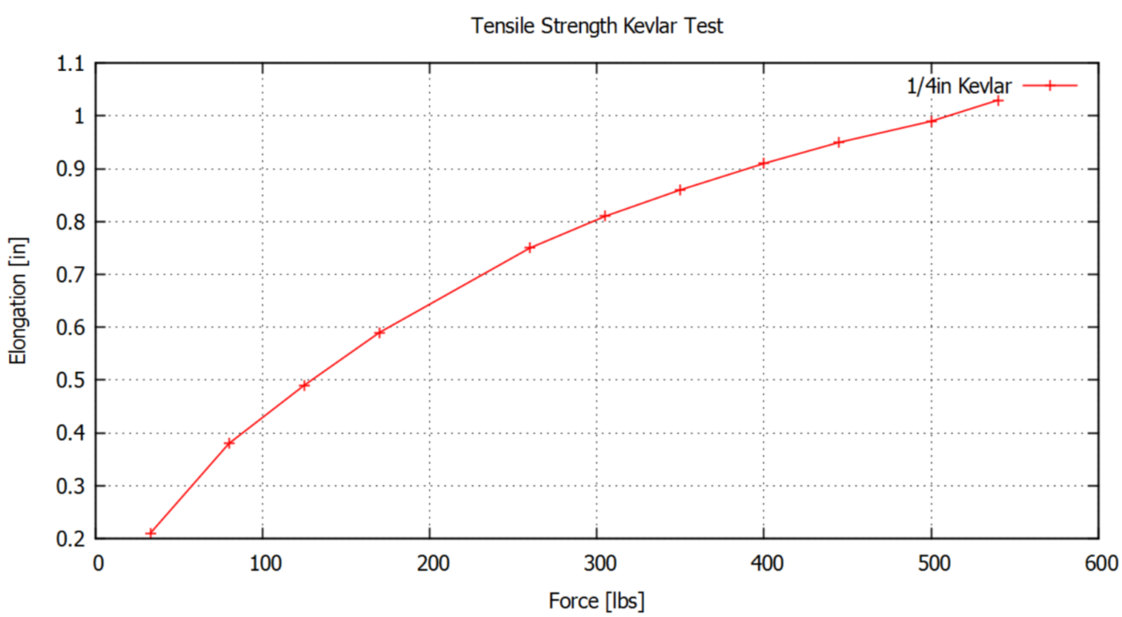


Figure 9: Kevlar shockcord tensile strength test

Since our preliminary calculations of deployment forces indicated that the shockcord can experience as much as 800*lbs,* the tensile stress results were concerning (despite successful static ejection test and test flight). For next test flight we have installed tri-axial accelerometer (Raven-3) to measure accelerations experienced by the rocket during ascent and deployment. The measured results are show in Figure 10 and summarized in Table 14.

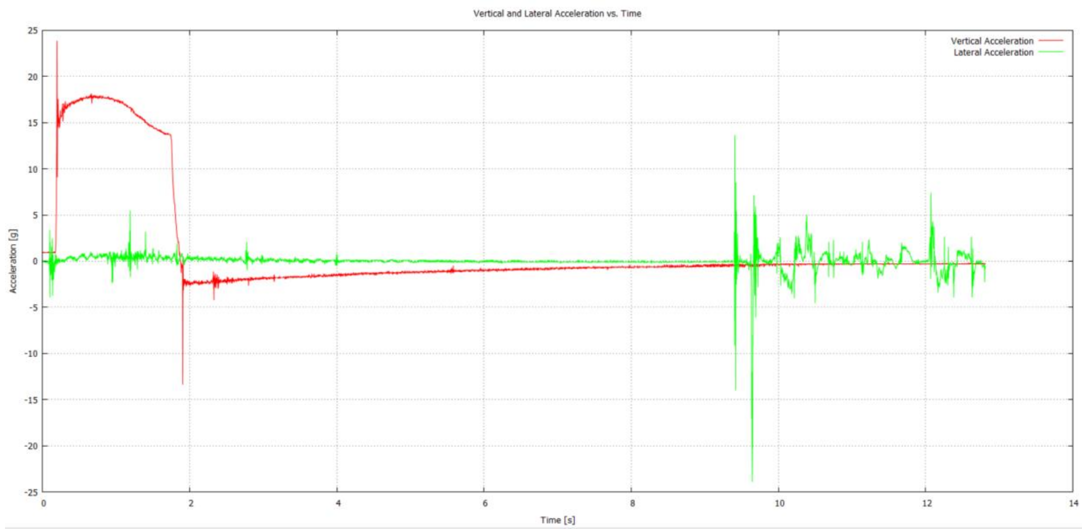


Figure 10: Vertical and Lateral Acceleration vs Time

Direction	Maximum Positive		Maximum Negative	
Vertical	+24*g*	*liftoff*	-13*g*	*burnout*
Lateral	+14*g*	*apogee event*	-24*g*	*apogee event*

Table 14: Vertical and lateral acceleration extremes

Using the formula

$$F = m \cdot a$$

for measured acceleration extreme of 24*g* at deployment and the weight of the rocket at the same moment (burnout weight, 9.8*lbs*), we get force of 236*lbs* stressing the shockcord during deployment events. In conclusion, while the chosen shockcord does not have the rated strength, it is still sufficient (at safety ratio 2:1) for our purposes. The tensile strength and measured acceleration values also qualify parachute shroudlines for flight, with safety ratio of 1.36 for each of the shroudlines, however the parachute has 8 shroudlines.

Tierods have been identified as the weakest point of the rocket during Critical Design Review. Manufacturer's specification rated #8/32 tie rods to 800*lbs* break force, however during our tensile strength testing, the #8/32 stainless steel tie-rod were stressed to 1000*lbs* without breaking. The result of the tierod test is shown on Figure 11. The test ended with stress analyzer reaching maximum force it can exert (without the tierod breaking).

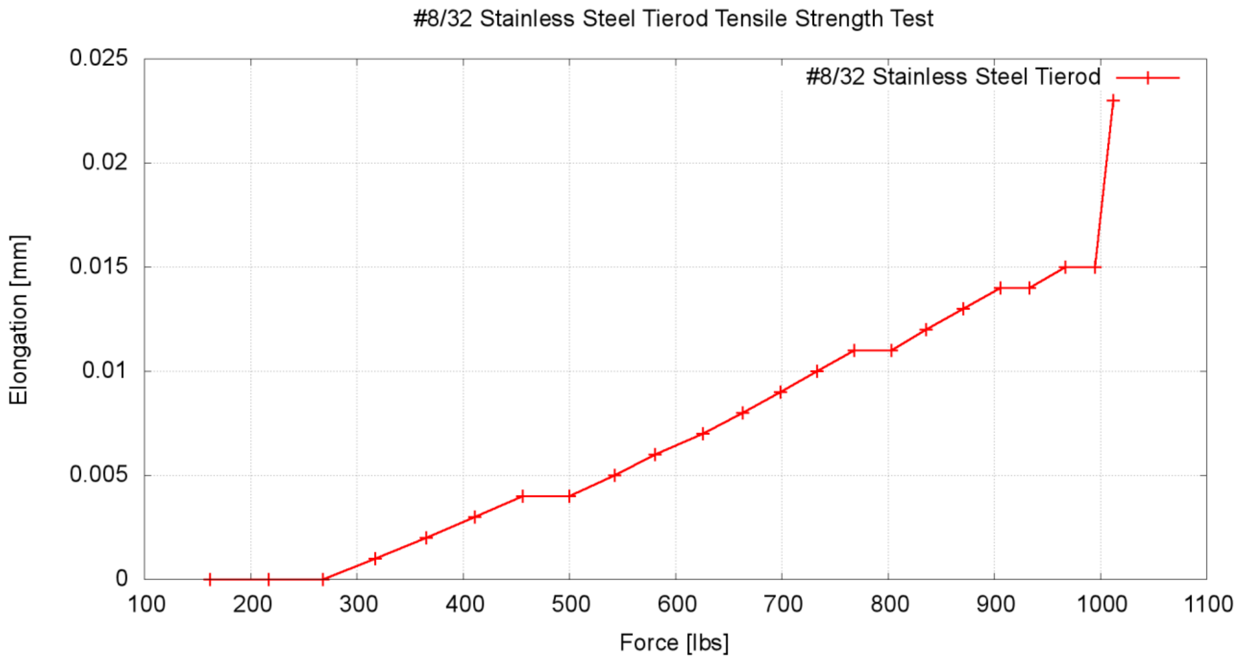


Figure 11: #8/32 stainless steel tierod tensile strength test

Based on the result of tensile strength tests we conclude that U-bolt anchors, tie-rods, links, shockcords and parachute shroudlines are strong enough to withstand flight and deployment stresses.

Deflection Tests

In addition to tensile strength testing we have performed deflection testing for following components:

- 1/8" fiberglass fins
- fiberglass body tube
- fiberglass payload tube reinforced with a coupler (to support payload door)

Figure 12: Fin deflection test setup

Fin Deflection

The results of fin-deflection test are shown in Figure 13. The upper graph shows total fin deflection vs. force applied, the bottom graph depicts deflection per pound of force applied.

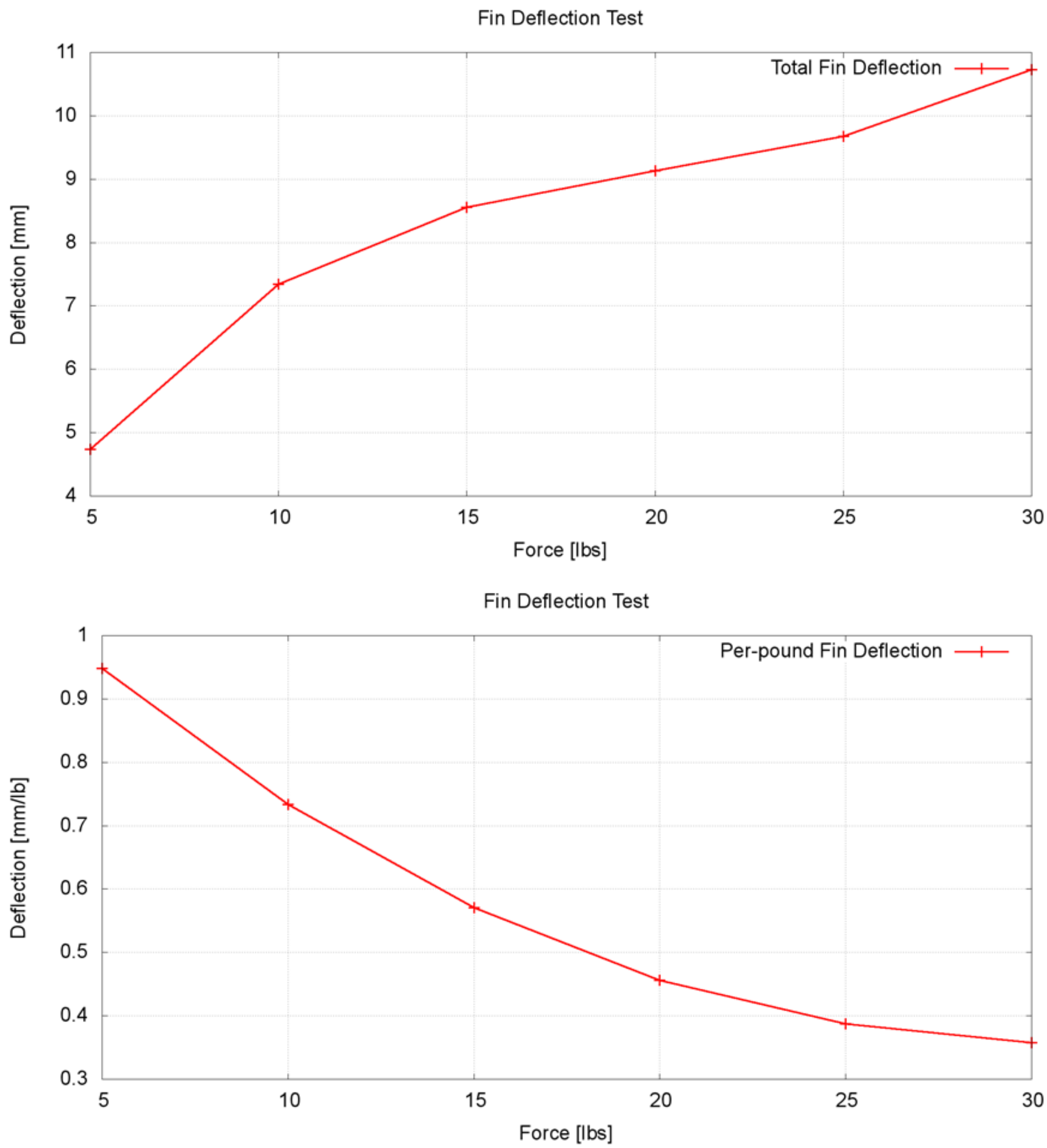


Figure 13: Fin deflection test

Body Tube Deflection

During Preliminary and Critical Design reviews a question of robustness of the payload compartment tube has been raised. The payload compartment has a door to allow for payload insertion and removal. The door construction requires removal a 120° section of tubing which weakens the tube. We counter this loss of strength by insertion of coupler both to provide rim for the door (when closed) and to reinforce the tube itself. We have performed tube deflection tests both for the plain fiberglass tube with no section removed and no coupler (the booster portion of the rocket), and the payload section of the rocket (shown on Figure 14).

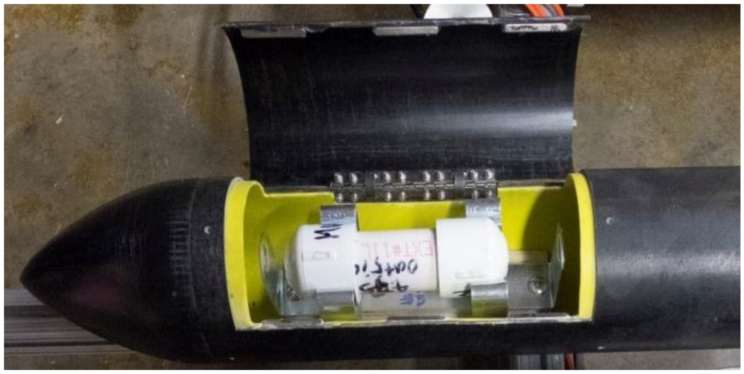


Figure 14: Payload compartment with a hinged door and a coupler (yellow) for reinforcement.

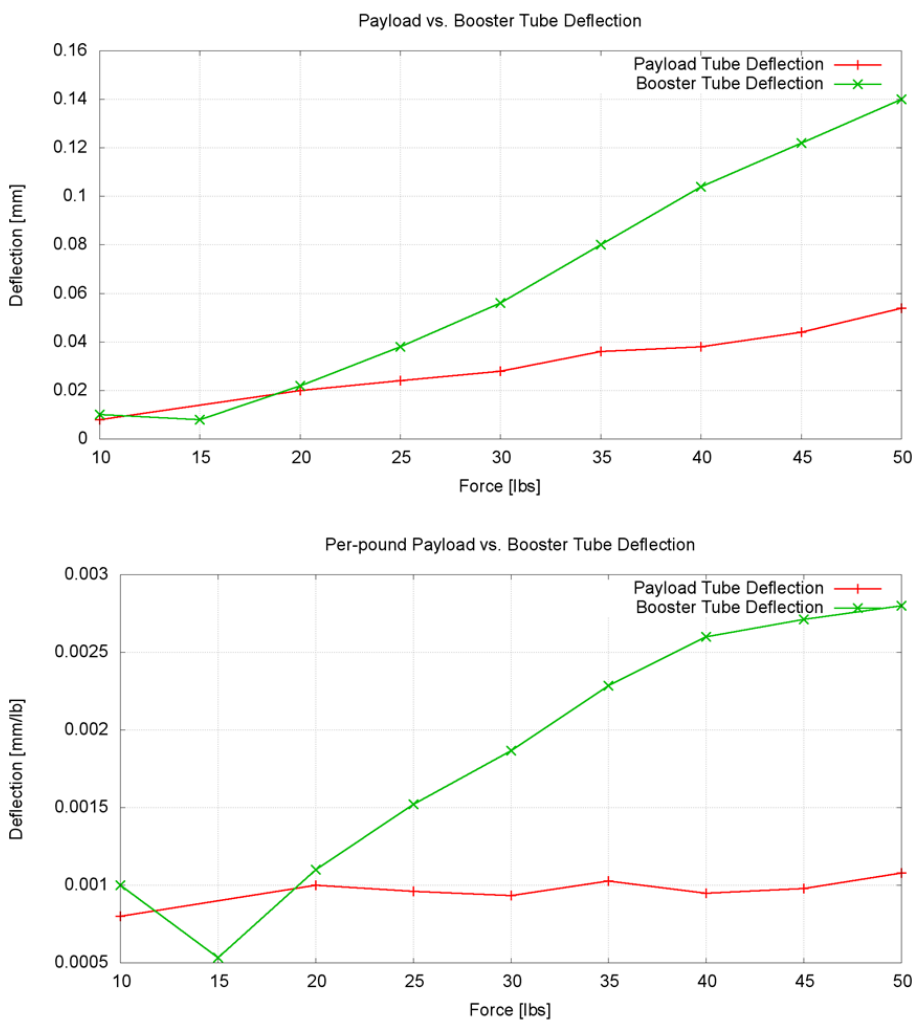


Figure 15: Results of tube deflection tests

We have used measured deflection amounts to calculate the buckling force both for the payload compartment and the booster section of the rocket. From the deflection measurements we have calculated buckling force for each section of the rocket using the following equations:

$$EI = \frac{L^3}{48}\frac{F_d}{d}$$

$$F_b = \frac{\pi^2 EI}{{L_R}^2}$$

where:

EI	section modulus	
L	length of section	*[in]*
F_d	deflecting force	*[lbs]*
d	measured deflection	*[in]*
L_R	rocket length	*[in]*
F_b	buckling force	*[lbs]*

The results of deflection measurements and buckling force calculations both for the booster and payload section of the rockets are shown in Table 16. Because of the insertion of supporting coupler, the payload section is stronger than the booster section. The entire vehicle is robust enough to withstand the expected flight stresses and has been flight-tested four times. No damage or obvious material fatigue was observed during any of the test flights.

Booster Section			**Payload Section**		
Force ***[lb]***	Deflection ***[in]***	EI	Force ***[lb]***	Deflection ***[in]***	EI
10	0.000394	4,900,609	10	0.000315	9,143,995
20	0.000866	4,455,102	20	0.000787	7,315,196
30	0.002205	2,625,328	30	0.001102	7,837,710
40	0.004094	1,884,851	40	0.001496	7,700,206
50	0.005512	1,750,219	50	0.002126	6,773,330
	$EI_{average}$	3,123,222		**$EI_{average}$**	7,754,087
	F_b *[lbs]*	14,363		F_b *[lbs]*	22,726

Figure 16: Buckling force calculations

Construction Techniques

The rocket is all fiberglass construction, including fins, centering rings and bulkheads. All anchor points are ¼" stainless steel U-bolts and tie rods are 8/32" threaded rods made out of stainless steel.

The glue used for construction of full scale vehicle is West Marine Epoxy resin (#105) with West Marine Epoxy fast hardener (#205) and West Marine colloidal silica filler (#406) to decrease the weight of epoxy bonds without weakening their strength. The working time of mixed epoxy is about 30 minutes, curing time is 24 hours.

Rocket fins are mounted through the wall, anchored at the motor tube and filleted at all three contact points: i) root edge at motor tube, ii) between fin and inside wall of body tube and iii) between fin and outside wall of body tube (cf.).

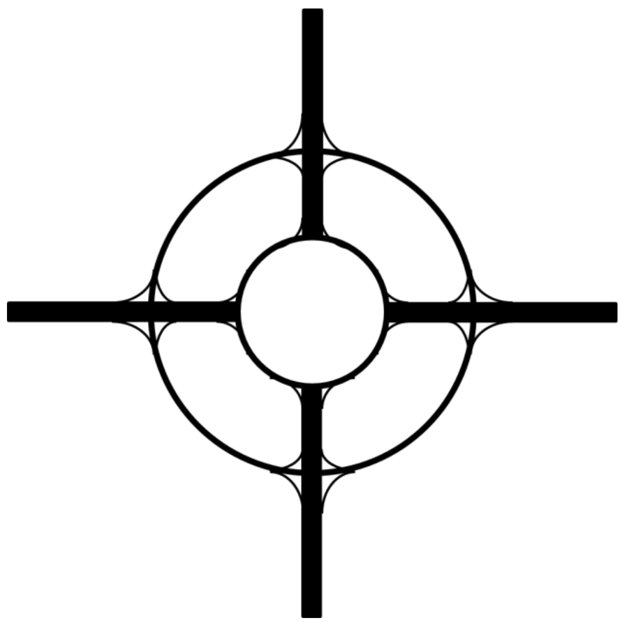


Figure 17: Through the wall mounted fins and epoxy fillets

All fiberglass surfaces that come to contact with epoxy are roughened with 80-grit sandpaper to allow for deeper epoxy penetration and stronger bond.

All nuts (such as to secure U-bolts) are tightened and secured with Loctite Threadlocker #271/red.

Shockords are mated to anchors using QuickLinks.

All avionics is mounted on fiberglass sled using #4/40 standoffs and all screws are secured using nail polish (because of the small screw size and frequent need to remove the avionics devices, nail polish provides sufficient lock-in strength yet easy removal). All wires carrying current to power avionics or fire ejection charges are at least gauge #22, insulated braided speaker wire.

All wires that connect avionics to batteries or e-bay output terminals are attached to screw mount terminal block and the connections are verified prior and after each flight.

Recovery System Design

The rocket separates into three tethered parts: upper section (containing the MAV payload), electronic bay (separating the main and drogue parachute compartments) and the booster section. The classic dual deployment scheme with drogue parachute in the lower compartment is used. Parachutes are deployed using black powder ejection charges triggered by two fully redundant barometric altimeters (PerfectFlite StratoLogger CF). The figure below illustrates the vehicle separation scheme.

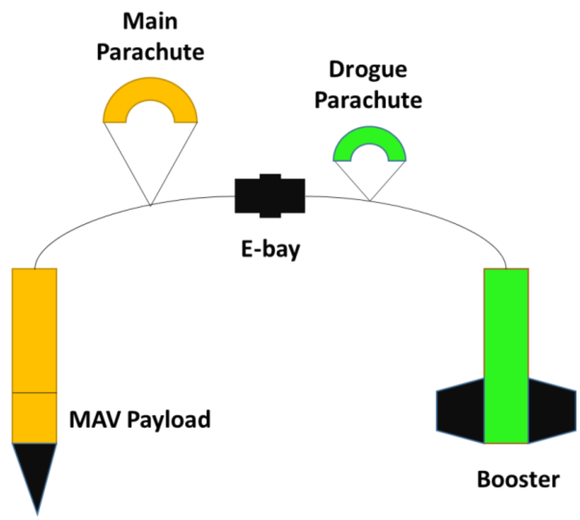


Figure 18: Vehicle separation scheme

Our rocket uses the standard dual deployment scheme. At apogee, the drogue parachute located directly below the payload will be deployed. The rocket will descend under the 18-inch parachute until 700 *ft* AGL, at which point the 40-inch main parachute will be deployed. The total kinetic energy for the rocket landing under 40-inch main parachute is 79.8*ft.lb-f*. None of the three tethered parts lands with kinetic energy higher than 75*ft.lb-f*.

Parachutes and Ejection Charges

The following table shows the summary of recovery system, including parachute size, descent rates (estimate), ejection charges and impact energy for each section. Table 15 shows the finalized parameters of recovery subsystem, as both statically and flight tested. The descent rates for both parachutes were measured during test flights (detailed results available on page 52), the charges were statically tested (and upgraded as necessary). The calculations used to design the recovery system are shown later in this section.

Parachute	Diameter *[in]*	Descent Rate *[fps]*	Ejection Charge *[g]*	Nylon Shear Pins	Deployment Altitude *[ft]*	Descent Weight *[lb]*		Impact Energy *[ft.lb f]*
Drogue	18	49	1.50	2 x #2/56	5324		8.8	332.6
Main	40	23	1.50	2 x #2/56	700	*E-bay*	0.9	7.8
						Payload	3.6	23.0
						Booster	5.3	49.0

Table 15: Summary of recovery system: parachute sizes, ejection charges and impact energy

The impact energy is calculated using the following formula:

$$E = \frac{1}{2} \cdot m \cdot v^2$$

Where

E	impact energy	*[ft.lb f]*
m	rocket descent weight (measured)	*[slug]*
v	descent rate (measured)	*[ft/s]*

The ejection charge sizes are calculated using the following formula:

$$W = \frac{dP \cdot V}{R \cdot T} \cdot \frac{454}{12}$$

where

W	ejection charge size		*[g]*
dP	ejection pressure	15	*[psi]*
V	pressurized volume		*[in^3]*
R	universal gas constant	22.16	*[ft-lb $^oR^{-1}$ lb-mol^{-1}]*)
T	temperature	3307	*[^oR]*

Table 16 below shows the calculated values of ejection charges for full scale vehicle. Bay length refers to the length of parachute bay that has to be pressurized during ejection, primary charge is calculated using the formula above and backup charge is 125% of primary charge (to increase the likelihood of deployment should the primary charge fail).

Parachute	Bay Length *[in]*	Volume *[in^3]*	Diameter *[in]*	Primary *[g]*	Backup *[g]*
Drogue	13	70.69	3	0.71	0.89
Main	11	84.82	3	0.60	0.75

Table 16: Calculated ejection charges, backup charges are set to 125% of primary charge

Finally, all ejection charges were statically tested to assure that they are powerful enough to deploy the recovery system without damaging the rocket (due to excessive pressure inside parachute compartments). We have found that the addition of shear-pins requires a significant upgrade to ejection charge size in both compartment and we were able to obtain a reliable deployment after upgrading both ejection charges to 1.5 grams (as shown in Table 15).

The recovery system principal components are listed in the table below:

Component	Material	Breaking force
Shockcords	¼" tubular Kevlar	550*lbs*
Thermal protectors	Nomex sheets	N/A
Parachutes	Rip-stop nylon, 8 nylon shroudlines	320*lbs* per shroudline (× 8)
Anchors	¼" stainless steel U-bolts	2,000*lbs*
Bulkheads (anchor hosts)	½" G10FR fire retardant garolite	
Tie-rods	#8 stainless steel threaded rods	800*lbs* (× 2)
Tie-rod nuts	#8 brass knurled nuts	N/A
Electrical matches	M-tek, electrical current 0.3A no-fire, 0.7A all-fire	N/A
Terminal blocks	Nylon screw terminals	N/A

Table 17: Main components of recovery system

The weakest point of the recovery system is the shockcord that has tensile strength of 550*lbs*. The maximum expected stress on shockcord during deployment is 240*lbs*, based on the acceleration measured during a test flight.

The electrical components of the recovery and tracking subsystem are listed in Table 18.

Component	Count	Product	Manufacturer/Vendor	Battery Endurance
Altimeter	2	Stratologger CF	PerfectFlite	24 hours
GPS tracker	1	Trackimo	Trackimo	12 hours
On/Off Switch	2		Missile Works	N/A
Braided, #22 speaker wire	6		RadioShack	N/A

Table 18: Electrical components of recovery subsystem

We have simplified our tracking setup by use of Trackimo GPS trackers. The trackers use cellular network to deposit its current location into data cloud and an app (available for mobile and portable devices) is used to show the location of the tracker, the direction and speed of its movement as well as battery status. We extensively tested Trackimo devices, when used actively (constantly moving) they have about 12 hours of battery life with 1 minute periodic location reporting. When location of the tracker does not change, the tracker does not transmit periodically (energy saving mode). The trackers are dependent on presence of cellular network, however that requirement is satisfied at our launch sites suitable for SL project launches in our area and at the location of NASA SL2016 event.

Trackimo devices comply with Part 15 of FCC rules, the radio waves exposure is limited to guidelines as referenced in FCC Part 1.1310.

Figure 19: Trackimo GPS tracker

Electrical Schematics for Recovery System

The figure below shows fully redundant recovery electronics. Two fully independent circuits are used: primary and backup. Each circuit provides complete deployment functionality, including deployment of drogue and main parachutes. Each circuit has its own power source, external switch and set of ejection charges. The charges attached to the backup circuit are 25% larger than primary charges to provide additional deployment force should the primary deployment fail. If the primary deployment succeeds, the backup charges fire into open air, causing no damage.

The primary drogue charge is fired at apogee and backup drogue charge fires one second after apogee (Perfectflite Stratologger provides this functionality). The primary main charge fires at 700*ft AGL*, backup main charge is activated at 500*ft AGL*. This assures proper sequencing of charges and avoids using oversized backup charges when not necessary.

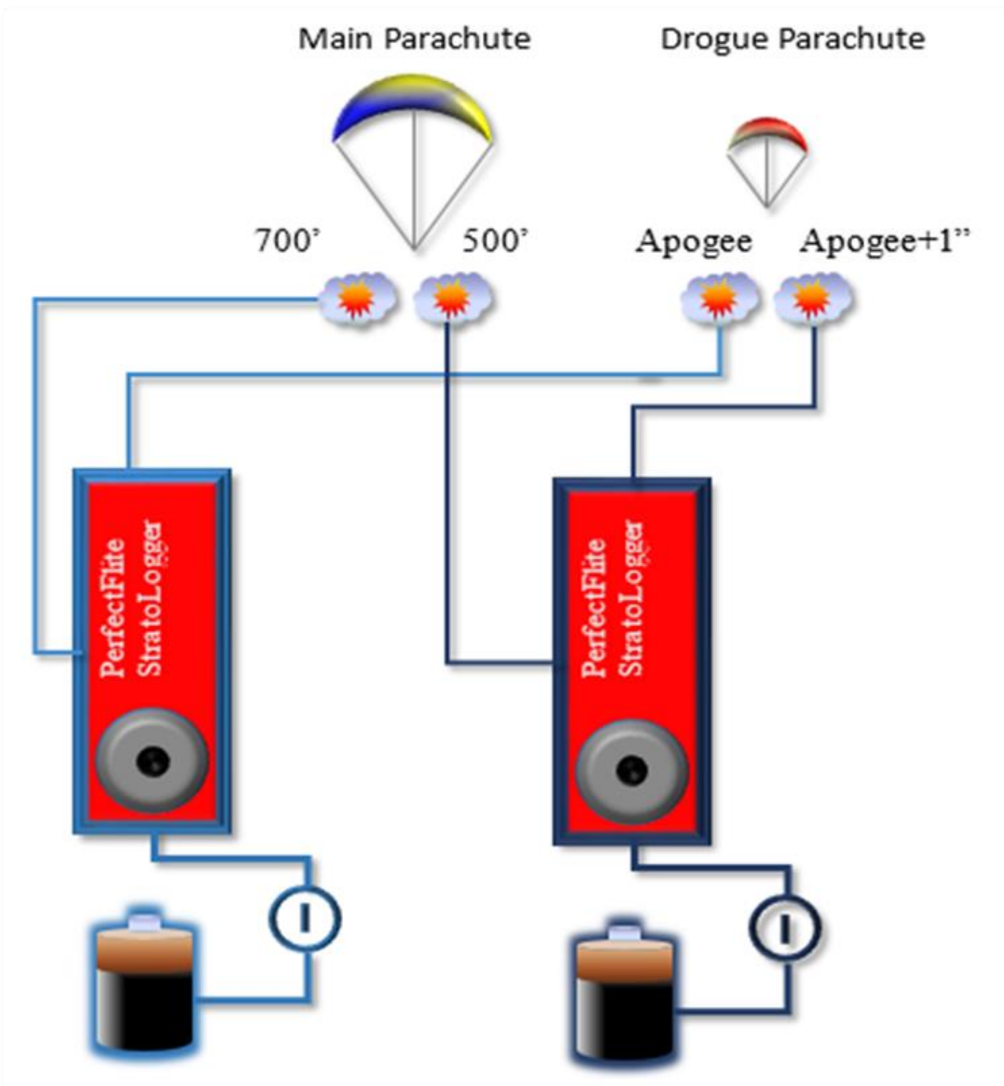


Figure 20: Recovery system electrical schematics (fully redundant deployment)

Static Testing of Deployment and Recovery Subsystem

Because of its critical role in mission, we have subjected the deployment subsystem to static tests to verify its proper functionality.

Altimeter Pressure Test: we have built a small baro-chamber (cf. Figure 21) for the altimeter, using a pasta jar with screw-on lid and a large syringe. The syringe is used to either withdraw air from the chamber (decreasing pressure, simulating altitude increase) or to push more into chamber (increasing pressure, simulating pressure increase). We have attached light bulbs to each of the altimeter output ports (one for drogue parachute charge and another for main parachute charge), the bulbs simulating the ejection charges. Using the syringe we have simulated rocket flight and watched how altimeter responds and whether it “fires charges” (light bulbs switching on). We have repeated this test 15 times and observed no failure or irregularities.

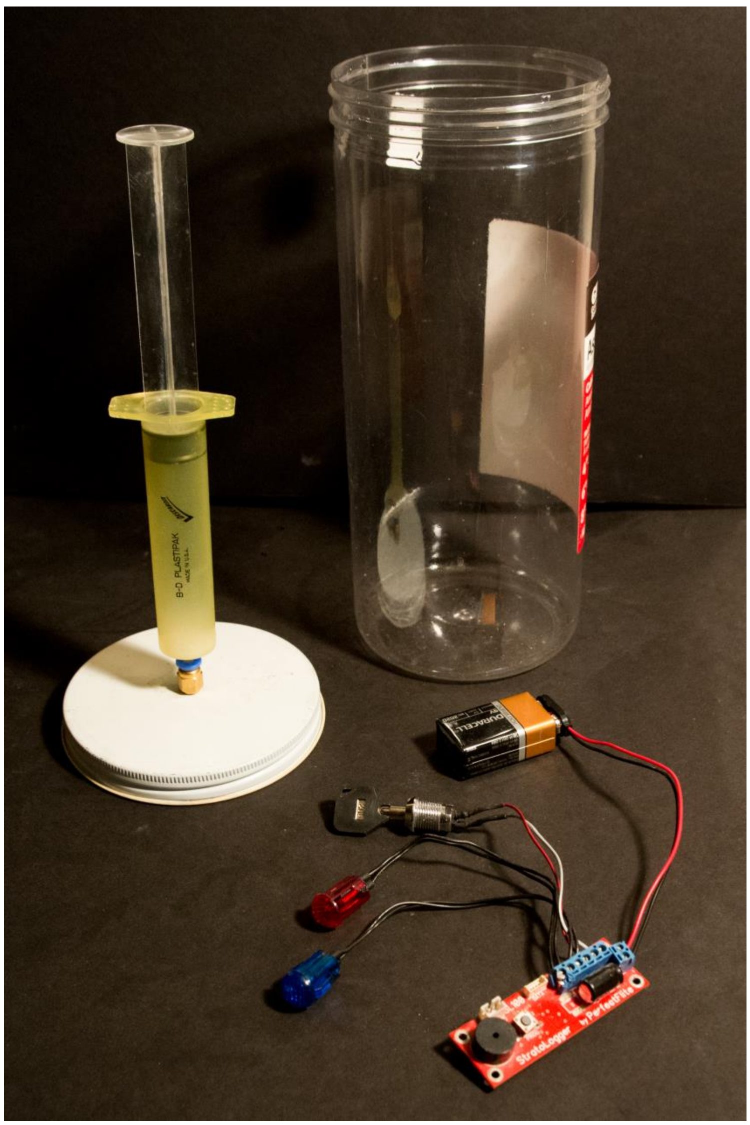


Figure 21: Baro-chamber for altimeter testing including the altimeter instrumented for output port testing

Altimeter Output Test: we have measured current on the altimeter output when the ejection is fire. Firing event can be triggered using desktop application provided with the altimeter. Using a fresh Duracell 9V battery we have observe on average (out of five firings) 5.3A on the altimeter outputs. The M-tek e-matches that we are using reliably fire using 1A of electrical current.

E-match Safety and Reliability Test: M-tek e-matches that we are using are rated for 0.3A *no-fire* (no e-match will fire until current exceeds 0.3A) and 0.7A *all-fire* (all e-matched will fire after receiving this current). The *no-fire* limit is important to ensure that the e-match will not fire during continuity test, the *all-fire* threshold is to match the trigger device (altimeter) with the e-match to provide reliable firing during operation. We have measured 10 e-matches, the results are summarized in Table 19).

	No Fire [A DC, 9V]	All Fire [A DC, 9V]
Product specification	0.300	0.700
Measured	0.420	1.030

Table 19: E-match no-fire/all-fire testing (sample size: 10 e-matches)

Altimeter is using current of only a few milliamps to test continuity of the ejection charge and can output over 5A to fire a charge. Thus, the M-tek e-matches are a good choice: they will not fire during continuity tests and they will reliable fire when a flight event is triggered by the altimeter.

Altimeter Battery Capacity Test: we have connected a fresh battery to altimeter with the light bulbs attached to its output ports. The bulbs are used to simulate ejection charges. After powering the altimeter up we left ON for 24 hours and then used the PerfectFlite desktop app to test fire both ports. Both ports fired successfully. This is in agreement with manufacturer's specification of expected battery lifetime.

Parachute Inflation Test: to assure that the parachutes will inflate correctly and the canopy is symmetrical, we have performed inflation test on all parachute (an example of such test is shown on Figure 22). The inflation tests can be easily performed in windy weather by allowing the wind to enter the parachute canopy or in windless weather by running with the parachute and letting it open.

Figure 22: Parachute inflation test

Drift Calculations

Table 20 below shows drift estimates for wind speeds ranging from 0*mph* to 20*mph*. There are two components contributing to apparent drift (distance of the landing location from the launch pad). During ascent, the rocket travels upwind (against the wind) due to the weathercocking effect. After parachute deployment, the rocket travels downwind (drift). The distance from launch pad to the landing location is a sum of upwind travel (negative value, if rocket travels against wind) and downwind travel (positive value, if rocket drifted downwind). Due to the mandated 5^o launch angle, most upwind travel values (except one for 20mph wind speed) are positive for our project (weathercocking is compensated by launch rail angle). Figure 23 illustrates this concept.

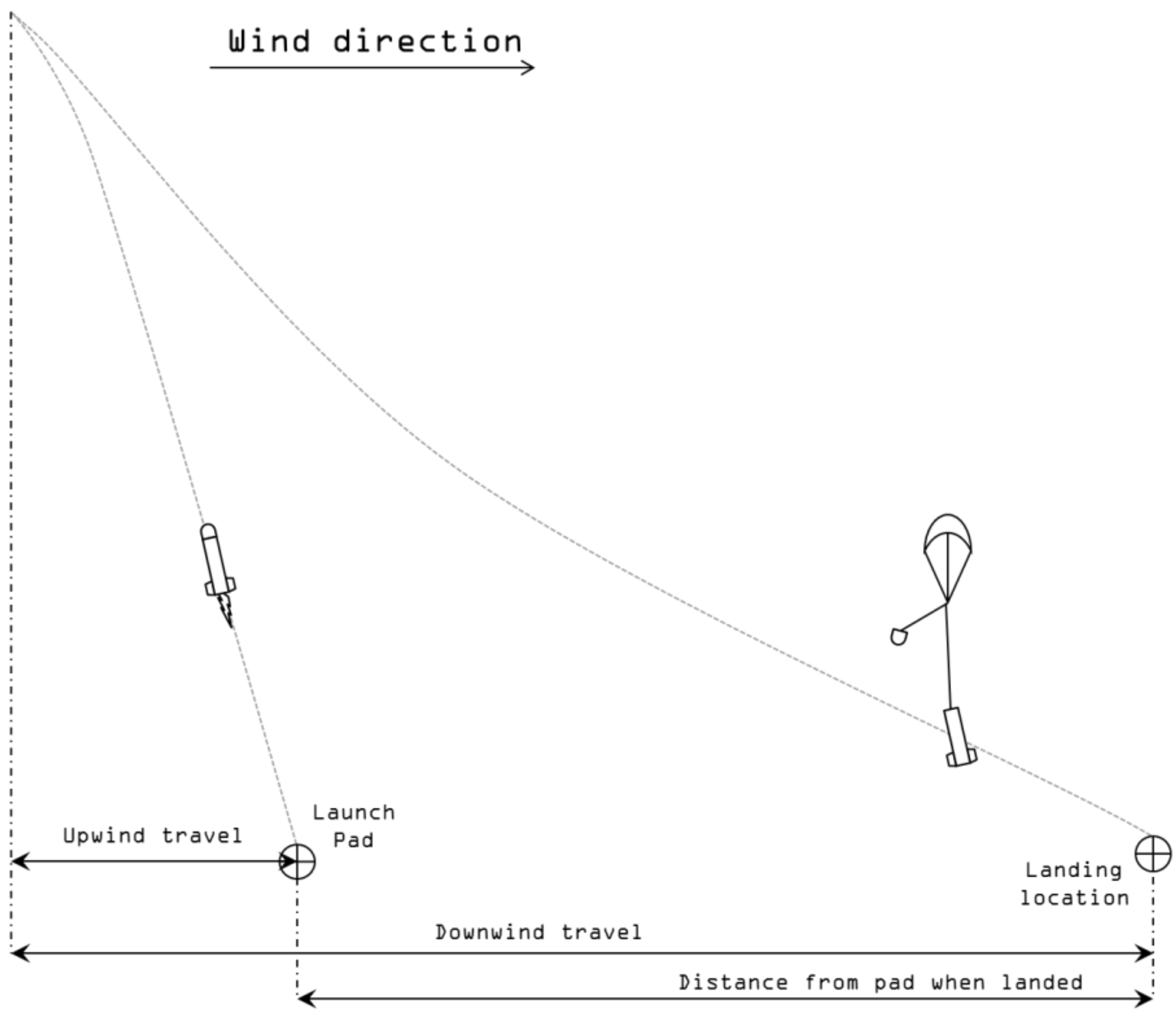


Figure 23: Drift calculations

We have calculated upwind and downwind components and the distance of landing location from the launch pad for wind speeds 0, 5, 10, 15 and 20*mph*. The upwind travel calculations are provided by OpenRocket software, assuming the 5^o downwind launch guide angle. The rocket will remain within the confines of the launch site even if the wind speed reaches 20*mph*, drifting 0.468*mile*.

Wind speed [mph]	Upwind Travel [ft]	Downwind Travel [ft]	Distance from pad when landed [ft]	Distance from pad when landed [mile]
0	743	0	743	0.141
5	537	771	1308	0.248
10	318	1545	1863	0.353
15	129	2301	2430	0.436
20	-96	3064	2968	0.562

Table 20: Estimated drift

Performance Predictions

We have used RockSim to carry out flight simulations of the proposed vehicle. The simulations are now anchored to test flights of the full scale vehicle (C_d = 0.780) and known liftoff weight of already constructed full scale vehicle (11.1*lbs,* including 1.0*lbs* of ballast). The test flight results are in detail discussed on page 52. The simulation results are discussed below.

Mission Performance Criteria

The delivery mission is successful if:

- Launch vehicle launches safely from AGSE
- Launch vehicle ascents in a stable manner
- Launch vehicle reaches but does not exceed target altitude of one mile
- Launch vehicle deploys drogue parachute at apogee and main parachute at 700*ft* AGL
- Launch vehicle lands safely and is reflyable on the same day

Altitude Profile

The graph below shows the simulated flight profile for the CTI J760WT motor. The simulated vehicle reaches the apogee of 5324*ft* sixteen seconds after the ignition. Based on the full scale vehicle flight results, the coefficient of drag is set to C_d = 0.78. The entire flight duration is estimated at 105*s* and the drift under 15*mph* wind conditions is 0.436*mi* (accounting for travel upwind due to weathercocking).

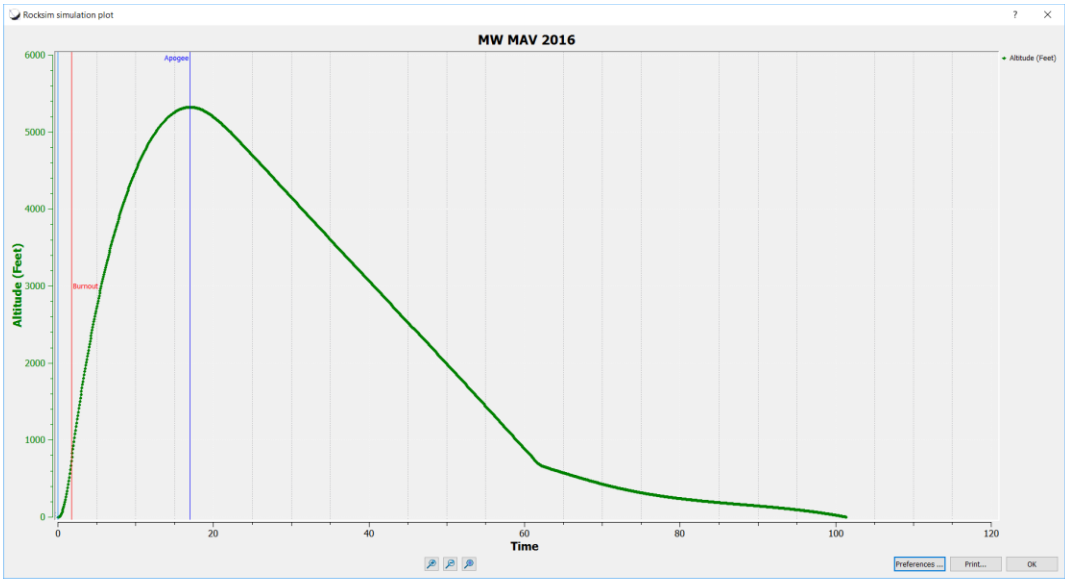


Figure 24: Simulated altitude profile for CTI-K760WT motor

Wind Speed vs. Altitude

The effect of the wind speed on the apogee of the entire flight is investigated in the table below. Due to the mandated launch rail angle of 5^o downwind, the altitude performance of the rocket improves from wind speed 0*mph* to wind speed 15*mph* (as the weathercocking compensation becomes beneficial) and the largest apogee difference (0*mph* vs. 15*mph*) is less than 0.7%. The values in the table were calculated for best estimate of coefficient of drag (C_d = 0.95) and known liftoff weight of already constructed full scale vehicle (10.1*lbs*).

Wind Speed *[mph]*	Altitude *[ft]*	Percent Change in Altitude
0	5326	0.00
5	5356	0.56
10	5365	0.73
15	5324	-0.04
20	5316	-0.19

Table 21: Flight apogee vs. wind speed

Thrust Profile

The graph below shows the thrust profile for the Cesaroni J760WT. The CTI J760WT motor reaches its maximum thrust of 937*N* after 0.05*s* and burns at approximately constant thrust level for about 1.8*s* (the average thrust-to-weight ratio is 15.1, maximum thrust to weight ratio is 18.6). The rocket requires a standard five-foot rail for sufficient stability on the pad and leaves the 5*ft* rail at about 48*mph*.

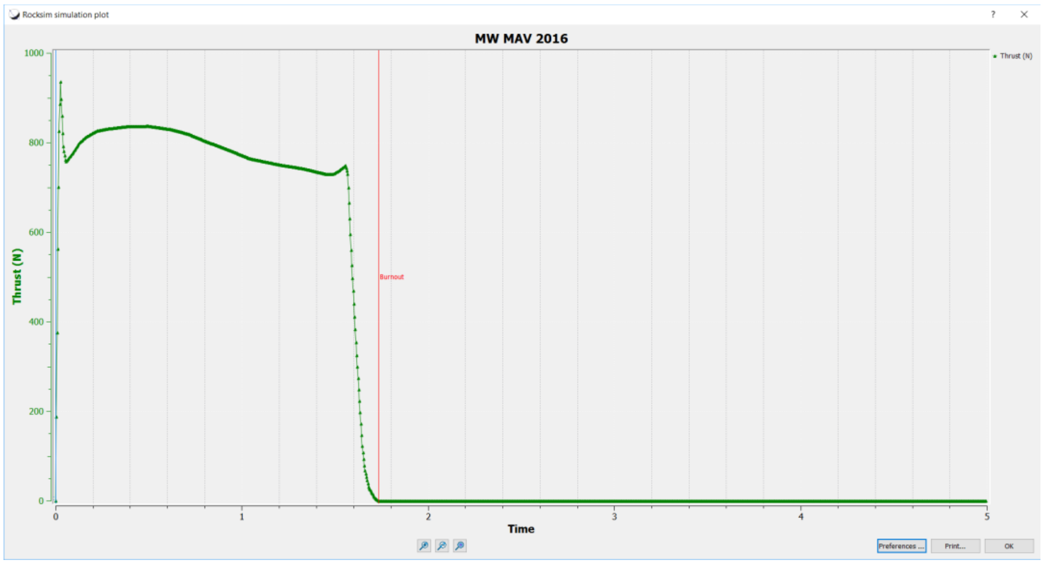


Figure 25: Thrust profile for CTI-K760WT motor

Velocity Profile

According to the velocity profile (next graph), the rocket will reach maximum velocity of 540*mph* shortly before the burnout (1.8*s*). The rocket remains subsonic for the entire duration of its flight. Because the rocket will reach close-to-transonic speed, a Von Karman (LD-Haack) nosecone was chosen for this mission (cf. Figure 2 on page 27).

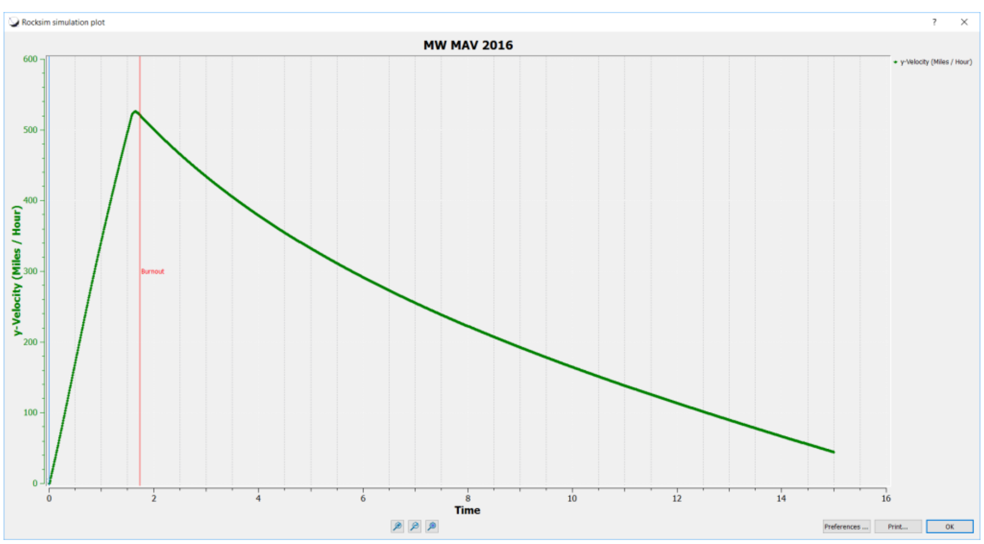


Figure 26: Velocity profile for CTI-K760WT motor

Acceleration Profile

The graph below shows that the rocket will experience maximum acceleration of about 19*g*. Our rocket is robust enough to endure 30*g*+ acceleration shocks. All-fiberglass construction provides necessary robustness for the rocket (cf. Table 12 on page 30).

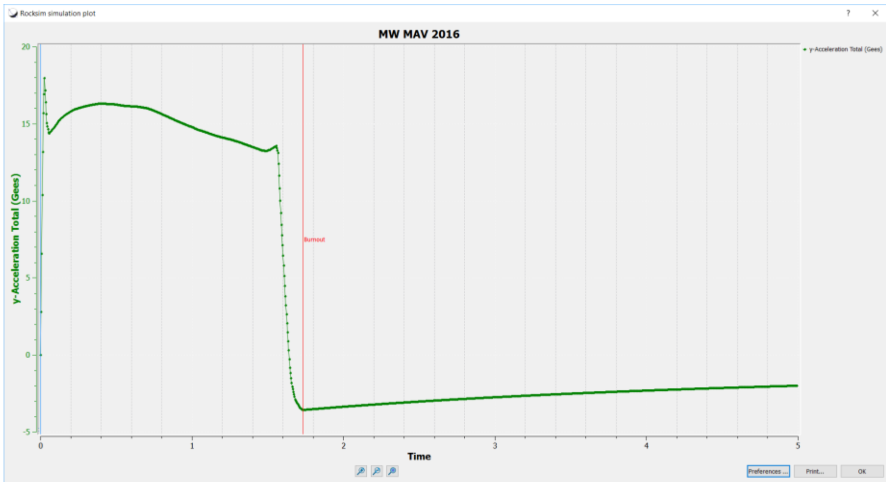


Figure 27: Acceleration profile for CTI-K760WT motor

Flight Sequence

The following figure and table describe the expected sequence of flight events. The motor burns out at 880*ft* AGL and rocket will reach apogee in 16.18*s* after ignition. The drogue parachute is deployed at apogee and the rocket descent for 57*s* until reaching the main parachute deployment altitude of 700*ft*. The main parachute deploys at 700*ft* and the rocket lands approximately 103*s* after launch.

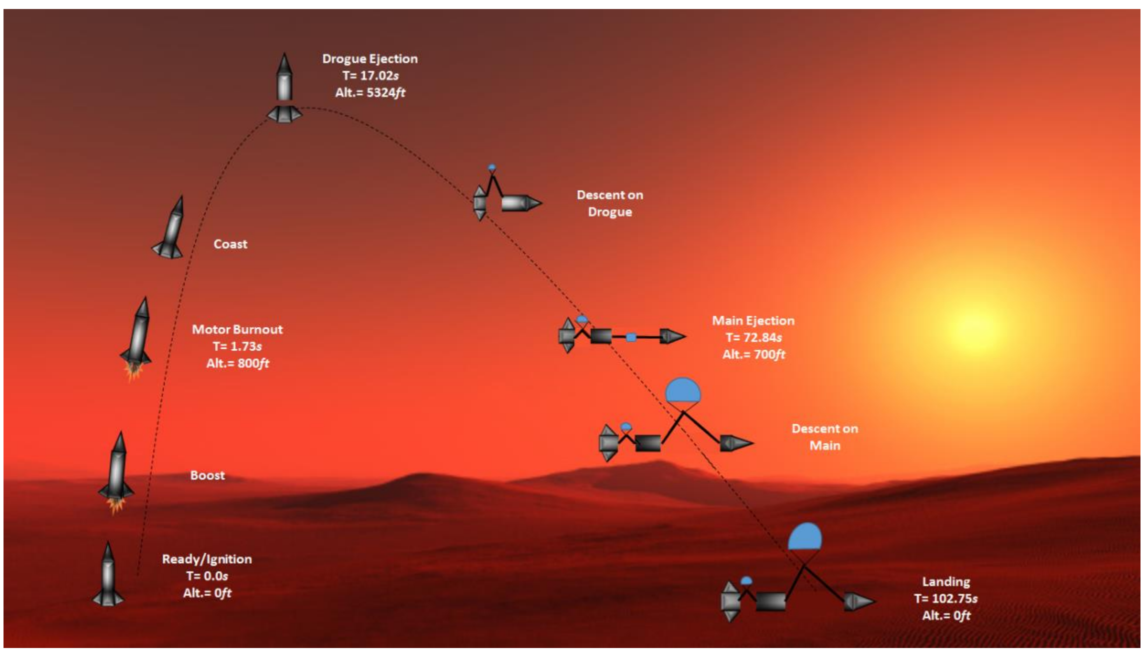


Figure 28: Mission Profile Chart

Event	Time *[s]*	Altitude *[ft]*
Ready	0.00	0
Ignition/Take-off	0.00	0
Motor Burnout	1.73	800
Coast	1.73 to 17.02	80 to Apogee
Drogue Ejection	17.02	5125
Descent on Drogue	17.02 to 72.84	5324 to 700
Main Ejection	72.84	700
Descent on Main	72.84 to 102.75	700 to 0
Landing	102.75	0

Table 22: Flight Events

Propulsion Selection

Selection of motor for the full scale vehicle is based on computer simulations (using RockSim CAD package), results of test flight of 2/3 scale model and finally test flight results with full scale vehicle (cf. page 52). By anchoring the scale model flight results (cf. Table 8 on page 24) we obtained

$$C_d = 0.95$$

However, due to the weather conditions, the flight had to be limited to low apogee (927*ft AGL*) and thus we are leaving a wide margin of error for possible inaccuracies in coefficient of drag measurements. A typical value of C_d for single diameter cylindrical rocket is ~0.7. We have run simulations for all suitable motors, both for C_d = 0.95 (measured value) and C_d = 0.70 (typical value) to find the motor that will work for both values without adding excessive amount of ballast or requiring longer launch rail. The simulation results are summarized in the table below:

	Cd = 0.70		Cd = 0.95		
Motor	**Apogee**	**v_{exit}**	**Apogee**	**v_{Exit}**	**Balast**
	[ft AGL]	*[mph]*	*[ft AGL]*	*[mph]*	*[lbs]*
J449BS	5944	42	5134	42	1.4
J295C	5578	37	4876	37	0.3
J355RL	5462	37	4784	37	0.3
J380SS	4570	35	4062	35	N/A
J1520VM	4986	77	4321	77	N/A
J760WT	6009	55	5157	55	1.6

Table 23: Motor selection rationale, v_{exit} is the launch guide departure velocity

The two clear favorites, CTI J760WT and CTI J449BS are highlighted in the table. The *Ballast* column indicates ballast weight necessary to bring the altitude of the rocket (assuming drag coefficient of 0.7) down to 5,280*ft AGL*. Addition of ballast only decreases rail exit velocity by 1*mph* both for CTI J760WT and CTI J449BS motors. Ballast (if necessary) will be added to the bottom bulkhead of electronics bay to minimize its effect on vehicle stability (the bottom bulkhead is closest anchor above center of gravity).

In the absence of results of full scale vehicle flights (CDR motor selection deadline), we have made our propulsion choice based on the scale model flight results and simulations detailed above. Our primary propulsion choice is CTI J760WT and the backup choice if CTI J449BS. Both motors provide safe and stable flight, altitude reach of 1*mile* (for case of C_d = 0.95) or can be ballasted for apogee of 1*mile* (for C_d between 0.70 and 0.90).

Motor	Diameter *[mm]*	Total Impulse *[Ns]*	Burn Time *[s]*	Stability Margin *[calibers]*	Thrust to weight ratio	5ft rail exit velocity *[mph]*
CTI K760WT	54	1276	1.80	4.4	20.5	48.0
CTI J449BS	54	1260	2.80	4.4	12.8	37.0

Table 24: Motor selection, including backup choices

Full scale vehicle test flights

After making the propulsion choice using 2/3 scale model test flight results in tandem with computer simulations, we have finished the construction of the full scale vehicle and performed four test flights of the full scale vehicle to verify the performance of the rocket and the propulsion choice.

#	Motor	Wind	Ballast	Apogee	Prediction (C_d = 0.7)	Anchored C_d	Drogue Descent Rate	Main Descent Rate	E_k payload ebay booster
		[mph]	*[lbs]*	*[ft AGL]*	*[ft AGL]*		*[ft/s]*	*[ft/s]*	*[ft.lb-f]*
1	***J449BS***	10	0.00	5867	5951	0.719	48	19	30.3 2.5 19.9
2	***J360SK***	15	1.00	3552	3892	0.885	47	22	42.1 7.1 29.0
3	***J380SS***	18	0.00	4451	4448	0.701	49	24	47.5 8.1 23.3
4	***J760WT***	7	1.00	5330	5624	0.780	49	23	43.1 7.3 29.3

Table 25: Full scale vehicle test flight results

Because of the propellant availability issues we had to perform each of the test flights using a different motor. However, the simulation results correlate with the measured flight data well and we were able to confirm our initial motor selection (as presented at Critical Design Review).

All flight results were compared against simulations with coefficient of drag set 0.7 (column *Prediction*) and also the effective coefficient of drag (column *Anchored C_d*) was calculated by anchoring the simulations to flight data. Descent rates both under drogue and main parachutes were measured and the kinetic energy of each tethered section of the rocket was calculated.

Descent rates are calculated from altitude profiles for each flight as slopes of the corresponding part of the profile. The concept is illustrated in Figure 29.

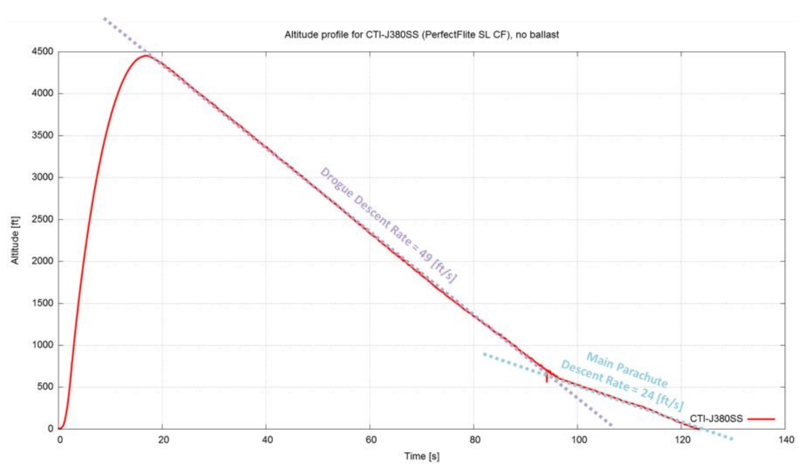


Figure 29: Descent rate calculation from altitude profile

Flight results, including comparison against simulations with coefficient of drag fixed to 0.7 are shown in Figure 30.

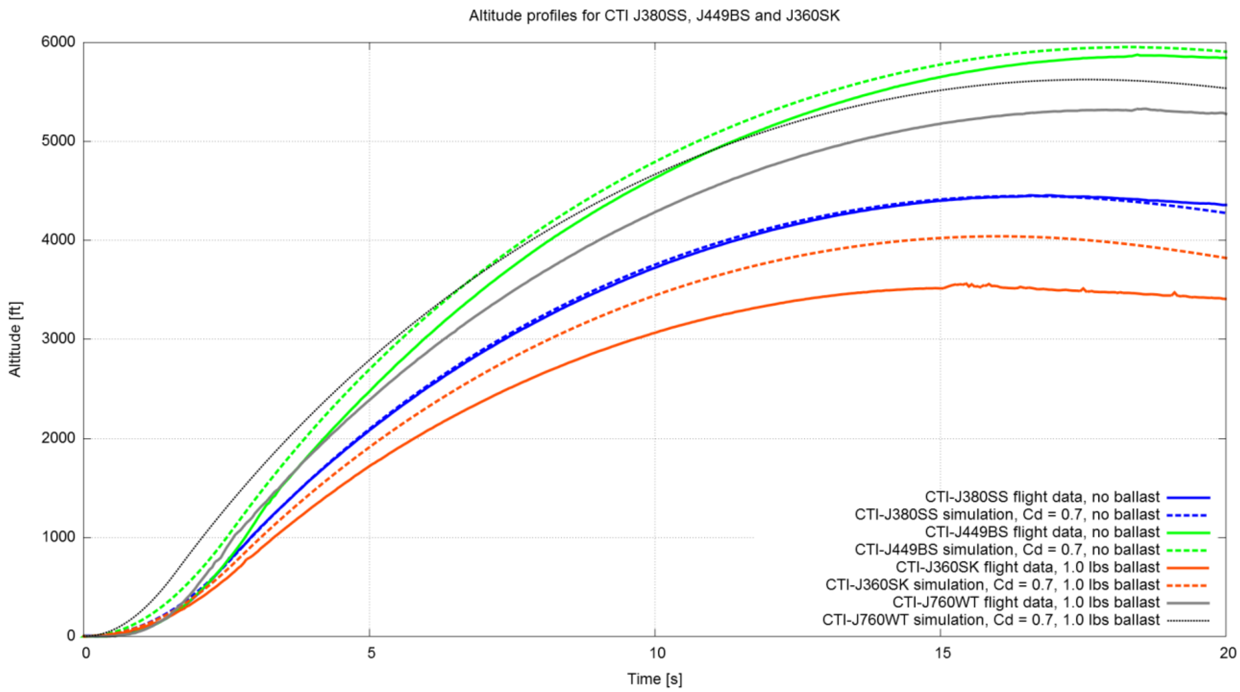


Figure 30: Flight data vs. simulation with Cd = 0.7 for full scale vehicle and CTI J380SS, J360SK, J449BS and J760WT motors.

Our verified propulsion choice, including the amount of ballast necessary is listed in Table 26.

	Motor	**Ballast *[lbs]***
Primary Propulsion Choice	CTI J760 WT, 54mm	1.00
Backup	CTI J449BS, 54mm	1.00

Table 26: Finalized motor choice

The rocket has been fully flight-tested, proven stable and having sufficient rail exit speed. The dual deployment recovery system works as designed. The rocket is ready for final launch at NASA SL2016 event.

Interfaces

Interfaces and Integration

The payload is located in the booster section, above the motor and below both parachutes. The payload will be separated from the motor and parachute sections by plywood bulkheads. There are no electrical connections from payload to the rest of the rocket. The payload structural subsystem will be 3D printed and will fit perfectly (with no free play) inside the payload compartment in the rocket. Payload installation inside the rocket consists from payload insertion and securing of the bulkheads.

The only **internal interfaces** are electrical connections from deployment altimeters to ejection charges. These interfaces consist from terminal blocks mounted on the e-bay caps.

The **interfaces between launch vehicle and ground launch system** are rail buttons (for attachment of the rocket to launch rail), cradle supporting the rocket during payload insertion and fin stabilizers on the blast deflector supporting the rocket during rail erection. The rocket is fully autonomous and does not need any other interface.

The **interfaces between launch vehicle and ground** are radio beacons used for tracking the rocket and CAT (Cloud Aided Telemetry) system. Both interfaces are wireless.

Safety

Safety Officer

Safety officer for the team is William. He will supervised and tutored by the team's mentor, Mr. Brent Lillesand. The duties of safety officer are described in details in the Project Requirements section, page 133.

Vehicle Checklists

Final Assembly

- ❖ Propulsion
    - ☑ Receive assembled motor from team's mentor
    - ☑ Insert motor to motor mount
    - ☑ Secure motor with retainer ring
    - ☑ Verify that the motor is secured and the retainer is tightened
- ❖ Drogue parachute
    - ☑ Using a QuickLink, attach drogue parachute to shockcord
    - ☑ Using the same QuickLink, attach Nomex sheet
    - ☑ Using a QuickLink, attach one end of shockcord to booster section anchor
    - ☑ Using a QuickLink, attach the other of shockcord to e-bay bottom anchor
    - ☑ Verify that parachute is 1/3 of shockcord length from e-bay and 2/3 of shockcord length from booster anchor
- ❖ Main parachute
    - ☑ Using a QuickLink, attach main parachute to shockcord
    - ☑ Using the same QuickLink, attach Nomex sheet (thermal protection)
    - ☑ Using a QuickLink, attach shockcord to e-bay top anchor
    - ☑ Using a QuickLink, attach shockcord to payload compartment bottom bulkhead anchor
    - ☑ Verify that that parachute is 2/3 of shockcord length from e-bay and 1/3 of shockcord length from payload bulkhead anchor
- ❖ Ejection charges
    - ☑ Receive assembled ejection charges from mentor
    - ☑ Put on goggles to protect eyes
    - ☑ Verify that all avionics is switched OFF
    - ☑ Attach primary drogue charge to terminal block marked D1 on bottom e-bay cap
    - ☑ Attach backup drogue charge to terminal block marked D2 on bottom e-bay cap
    - ☑ Attach primary main charge to terminal block marked M1 on top e-bay cap
    - ☑ Attach backup main charge to terminal block marked M2 on top e-bay cap
- ❖ Vehicle Assembly
    - ☑ Insert both drogue charges in the booster of the rocket, all the way to the motor top closure
    - ☑ Insert first 2/3 of drogue shockcord, neatly coiled, above the drogue charges
    - ☑ Pack the drogue parachute, wrap in Nomex sheet and insert above the bottom part of the shockcord
    - ☑ Neatly coil the remaining shockcord and insert on top of the parachute
    - ☑ Insert e-bay to booster section

- ☑ Install booster section shear pins
- ☑ Insert both main charges all the way under the payload bay bulkhead
- ☑ Insert top 1/3 of main shockcord, neatly coiled, under main ejection charges
- ☑ Fold the main parachute, wrap in Nomex sheet and insert under the top part of the shockcord
- ☑ Neatly coil the remainin shockcord and insert under the main parachute
- ☑ Insert e-bay into the top portion of the launch vehicle
- ☑ Install top shear pins

Launch Procedure

- ❖ Payload loading
  - ☑ Verify the AGSE is OFF
  - ☑ Install rocket on the launch rail and verify that it is secure
  - ☑ Open the payload door
  - ☑ Put payload in starting position
  - ☑ Upon instruction from NASA, activate AGSE
  - ☑ Wait until the AGSE completes payload loading, launch rail erection and igniter insertion
  - ☑ Visually verify that the AGSE is in launch capable position
- ❖ Avionics check
  - ☑ Using external switch, activate primary altimeter
  - ☑ Verify drogue and main parachute deployment setting (reported by altimeter beeps)
  - ☑ Verify continuity of ejection charges (reported by altimeter beeps)
  - ☑ Switch primary altimeter OFF
  - ☑ Using external switch, activate secondary altimeter
  - ☑ Verify drogue and main parachute deployment setting (reported by altimeter beeps)
  - ☑ Verify continuity of ejection charges (reported by altimeter beeps)
  - ☑ Switch primary altimeter ON and allow it to complete its boot procedure
- ❖ Igniter continuity check
  - ☑ Notify the team mentor that the rocket is ready
  - ☑ Mentor will connect the igniter to alligator clips
  - ☑ Mentor or launch official will verify the continuity of the igniter
- ❖ Rocket Launch
  - ☑ All team members will retire to safe distance from the launch pad
  - ☑ Launch official will execute final countdown and launch the rocket
  - ☑ In event of misfire, the team will wait at least one minute and upon instruction from launch official the mentor will approach the rocket for connection check and igniter replacement
- ❖ Landing
  - ☑ After the rocket lands, the mentor will approach the rocket to switch avionics OFF and to remove all ejection charges that might have fail to fire during flight.
  - ☑ Team can now approach the rocket for postflight inspection

AGSE Checklists

Pre-operation checklist

- ☑ Check that battery is fully charged.
- ☑ Check/inspect all wire connections, connectors, including remote dongle.
- ☑ Check that placement laser is working and aligned correctly to robot arm.
- ☑ Ensure that all mechanical fastenings are tightened on AGSE.
- ☑ Remove any temporary lashings, especially but including the launch rail to superstructure lashing.
- ☑ Check AGSE structure for levelness and adjust feet if needed.
- ☑ Check area underneath AGSE to ensure surface is sufficiently flat for launch rail “bottom tee” ground clearance.
- ☑ Check area in payload pickup area for debris or non-levelness. Adjust feet or surrounding area if necessary.
- ☑ Inspect launch rail for damage or defects. Spray launch rail with 3M silicone dry lube and wipe down with dry cloth.
- ☑ Load igniter into insertion tube using baby powder. Ensure ignitor head emerges from end of tube. Bend wires at based of tube. Use masking tape to secure bent wires at end of tube.
- ☑ Check alignment of insertion rod to insertion carriage.
- ☑ Perform all of vehicle pre-launch readiness checklist.
- ☑ Inspect robot arm for range of motion and interference in both rotary and vertical directions.
- ☑ Inspect door closer for range of motion.
- ☑ Inspect rail for range of motion.
- ☑ Inspect ignitor insertion for range of motion.

Pre-Autonomous procedure

- ☑ Ensure AGSE master power switch is in OFF position and E-STOP is pushed IN (engaged).
- ☑ Turn on locating laser.
- ☑ Place payload as per laser crosshairs.
- ☑ Check ignitor location against marked fiducials on rail. Ensure that tip of igniter is just above hole in blast plate.
- ☑ Detach erection motor from control box and attach to battery box.
- ☑ Retract motor slightly to allow launch vehicle fin clearance.
- ☑ Load launch vehicle on upward facing side of rail, sliding into lower-most position.
- ☑ Ensure that fins are placed between the vehicle stabilizing angle brackets on blast deflector plate.
- ☑ Extend motor so that rail is in positioning slit in AGSE base. Ensure launch vehicle is properly secured in bosses.
- ☑ Detach erection motor from battery box and attach to control box
- ☑ Open the payload door. Rotate the payload section if needed to meet the fiducials on the payload nest/bosses. Check condition of bistable hinge and magnets.

- ☑ Leave door in open position. Inspect that rocket location on rail is matched to fiducials for payload location. Check that wheels on door closure linear motor are lined up correctly.
- ☑ Verify all external AGSE connections are correct and secure.

Autonomous procedure

- ☑ Inspect area for personnel and foreign objects.
- ☑ Pull/rotate E-STOP OUT to disengage.
- ☑ Flip master switch upwards to power AGSE.
- ☑ Wait for red lamp to extinguish while setup routine executes.
- ☑ Check that LCD does not show any errors and that status lights indicate ready (amber) condition.
- ☑ Wait for NASA official to give official go-ahead.
- ☑ Press Green START button.
- ☑ Watch system perform procedure. Press yellow button if instructed or judged necessary to do so.
- ☑ Only press the red E-stop in case of dire emergency (threat of damage to people or the AGSE itself).
- ☑ In case of ERROR (solid red lamp), evaluate the AGSE state in tandem with NASA official and safely power down the AGSE.

Post-autonomous procedure launch instructions

- ☑ Check indicator lights and LCD for “launch ready” condition.
- ☑ Inspect entire area for personnel or foreign objects.
- ☑ Check launch rail angle in both axes with goniometer.
- ☑ Check wind and weather conditions.
- ☑ Check that personnel in charge of launch is “all clear” with verbal communications. By touching ends of igniter source check for any sign of spark by touching ends together.
- ☑ Connect stripped wires of igniter to ignitor voltage source with clips or wire nuts.
- ☑ Inspect connection carefully. Have second person check connection carefully.
- ☑ Walk away from the AGSE. Check that area is clear of personnel following NAR safety rules.
- ☑ Allow NAR safety official to perform final safety and clearance check and to perform ignition.
- ☑ Perform tracking and recovery procedures for Maxi-MAV vehicle

Post-Launch Homing Procedure

- ☑ Check area around AGSE for non-authorized personnel or other hazards.
- ☑ Press blue homing button and monitor AGSE progression.
- ☑ Press yellow button if judged necessary to do so. Only press the red E-stop in case of dire emergency (threat of damage to people or the AGSE itself).
- ☑ SCARA arm will clear rocket carriage by moving to uppermost end stop, rotating to outermost end stop, and moving to lowermost end stop.
- ☑ Door actuator will retract fully
- ☑ Igniter insertion actuator will retract fully
- ☑ Erection motor will extend fully, lowering rocket.
- ☑ Power down AGSE by flipping master switch to OFF. Push E-STOP IN to engage.

Hazard Analysis

The table below shows the preliminary hazard analysis. Additionally, the following codes are observed to ensure safety all of participants:

- NAR Model Rocket Safety Code, http://www.nar.org/safety-information/model-rocket-safety-code/
- NAR High Power Rocket Safety Code, http://www.nar.org/safety-information/high-power-rocket-safety-code/
- FAR 14CFR F/101/C, http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title14/14tab_02.tpl
- NFPA 1127 Code for High Power Rocket Motors, http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=1127

We maintain a collection of project related MSD sheets online to allow for easy access. A printed version of this collections is kept in the workshop.

MSDS COLLECTION: http://westrocketry.com/sli2016/safety/safety2016r.php

Hazard	Mitigation	Likelihood	Severity
Workshop tools and machinery hazards	Personal Protective Equipment (PPE) will be used at all times in the workshop. All students will be periodically briefed on workshop safety procedures and supervised by adults at all times. First aid kit is on-hand.	**LOW**	**MEDIUM**
Dangerous substance hazards	MSD sheets are required for all chemicals use during the project. Appropriate protective equipment must be used when working with hazardous substances. Students will be supervised by adults at all times.	**LOW**	**HIGH**
Payload integration failure	Team will verify before every launch that the payload fits into payload compartment and that the payload door closes without any misalignment.	**LOW**	**HIGH**
Vehicle assembly failure	The day before every launch the team will run through complete vehicle assembly procedure, using a checklist, to verify that there are no problems that would prevent vehicle from being assembled into launch ready state.	**LOW**	**HIGH**
Missed procedure	Checklist will be used for all vehicle related operations and two members will run the same checklist in parallel. Mentor will provide additional	**MEDIUM**	**HIGH**

	checklist run after all operations were completed.		
Missed attachment	Checklist will be used to make sure that no attachment point was missed. After vehicle assembly mentor will go over the list of attachment points and verify that there all attachment points were addressed.	**MEDIUM**	**HIGH**
AGSE structural failure	AGSE will be inspected prior to every launch, both the night before and at the launch site.	**LOW**	**HIGH**
Unexpected ejection charge activation	Personal protective equipment will used at all times when handling the ejection charges. Mentor will be the only person handling ejection charges. Avionics will be only activated after the rocket has been placed into launch position.	**LOW**	**HIGH**
Unexpected motor ignition	Personal protective equipment will used at all times when handling motors. Mentor will be the only person handling motors. Motor nozzle will be always pointing away from people and the igniter will not be inserted until the rocket is in the launch position and the avionics has been activated.	**LOW**	**HIGH**
Electrical shock	Only properly insulated cables will be used. The ignition circuit will be activated only after the rocket is fully ready for launch and all connections have been made.	**LOW**	**HIGH**
Avionics powerup failure	Avionics batteries will be checked prior every launch and a fresh set of batteries will be used for each launch.	**LOW**	**HIGH**
Misfire	Alligator clips will be cleaned periodically and igniters will be expected before insertion into motor.	**MEDIUM**	**LOW**
Rail bite (poor takeoff)	Rail button alignment and launch rail condition will be checked prior every launch. The rail will be dry-lubricated and periodically cleaned.	**MEDIUM**	**MEDIUM**
Motor catastrophic failure	Only commercially produced motors will be used. Mentor will assure the proper assembly of the motor. All launches will be made from the safe	**LOW**	**HIGH**

	distance, as required by NAR HPR safety code.		
Deployment failure	Ejection charge connections will be checked prior each launch, using the altimeters continuity reports. Fully redundant deployment system will be used for all flights. Ejection charge sizes will be verified by static testing.	**LOW**	**HIGH**
Recovery system failure	Shockcords, Nomex protectors, attachment points and parachutes will be inspected prior each flight.	**LOW**	**HIGH**
Landing with live ejection charge	Ejection charge connections will be checked prior each launch, using the altimeters continuity reports. Mentor will be the first person to approach the rocket after landing to verify that all charges were fired or to safely remove remaining live charges. Mentor will wear PPE while inspecting rocket after landing.	**LOW**	**HIGH**
Landing in inaccessible location	Wind direction and weather conditions will be evaluated prior each launch. The minimum launch size distance will (according to NAR safety code) will be observed. The drift assessment will be made prior each launch to estimate the landing zone. NAR safety code regulations for rocket landed in inaccessible location will be strictly adhered to.	**MEDIUM**	**HIGH**

Table 27: Hazard analysis

Environmental Concerns

Rocket launches can negatively affect the environment if the necessary precautions and mitigations are not observed. Below we list several aspects that needs to be considered prior launching a rocket at specific area.

We only launch in areas specifically designated for rocket launch and only during official launch windows (with active FAA waiver). We cooperate closely with Wisconsin Department of Natural Resources to ensure that our activities are not damaging to the environment. Additionally, all applicable regulations (NAR safety codes, FAA regulations, NFPA regulation and local laws) are strictly observed during all our launches.

Vehicle Loss

The vehicle is built from inert materials which can last for long time in natural environment without decay. Vehicle will not contain any chemicals that could quickly leach into environment and cause immediate problems, however all efforts will be made to recover the vehicle after each launch and leave no traces of our activities at the launch location. We are using attached Nomex sheets for thermal protection of parachutes (instead of wadding material that would be expelled into environment). All our rockets are tracked using either radio-beacon (combined with a sonic beacon, where permissible) or GPS tracker (Trackimo) to maximize the probability of vehicle recovery. If the vehicle lands in inaccessible place or is lost, we work with the launch site owner to ensure swift vehicle location and recovery or at minimum a report of lost vehicle.

Dangerous Chemicals

The only potentially dangerous substance is the black powder used for ejection charges. We use it only in amounts absolutely necessary and it is always handled by our certified mentor.

Human Presence

A typical high power rocket launch is conducted by a team of students accompanied by educators and mentors, thus causing measurable car and foot traffic at the launch site. WI Dept. of Natural Resources (WI DNR) has conducted study of human presence during rocket launches in Richard Bong Recreational Area and has not identified the traffic as excessive or negatively impacting the species living in the area, as long as the number of launch dates is controlled by the park management. We strictly follow the launch calendar for each launch site as well as the local ground rules for each location.

Rocket Exhaust and Litter

The exhaust from rocket motors has not been identified as environmental concern by Department of Natural Resources in Wisconsin. We follow all federal, state and local regulations for use of a given launch site (we mostly launch at dedicated launch site in Bong Recreation Area, Kansasville, WI or agricultural fields in Princeton, IL). Additionally, all our launches are strictly carry-in/carry-out, we remove all our litter and with the exceptions of necessary traffic impact (which has been classified as acceptable by WI DNR) we leave no impact on the area.

Fire Hazard

We actively mitigate all possibilities of fire hazard by using well designed and thoroughly test blast deflector, launching only in designated areas with inert surface (usually concrete) and having firefighting equipment (water fire extinguishers, shovels and matts) on hand at all our launches. The fire extinguishers are primed prior each launch to ensure that can be used immediately. Prior each launch three selected people are fully dedicated to observing the launch and being ready to extinguish any fires that may result from the launch.

Noise

The noise from rocket launches has not been identified as environmental concern by WI DNR as long as the number of launches and launch dates are controlled by the nature park (launch site management). We have also worked with WI DNR on providing noise measurements in support of establishment of new launch site at Sauk Prairie, WI and we were told by DNR official that the data we provided indicate less noise from rocket launches than other activities considered for the area (motor-bikes, hunting).

Material Damage

Damage to environment or man-made structures can be a result of failed rocket flight or failure of deployment system. We subject every rocket to thorough preflight testing – including computer simulations, careful material selection, static ejection tests and rocket inspection, in effort to minimize the likelihood of bad or catastrophic flight. We only launch at established launch sites which conform to NAR safety code and FAA regulations for operation of model and high power rockets.

Concern	**Impact**	**Likelihood**	**Mitigations**
Vehicle loss	**MEDIUM**	**MEDIUM**	GPS/radio tracking
Dangerous chemicals	**HIGH**	**LOW**	Avoidance
Human presence	**LOW**	**CERTAIN**	Only use designated launch sites, work with site owners
Rocket exhaust and litter	**MEDIUM**	**MEDIUM**	Carry-in/carry out, work with site owners
Fire hazard	**HIGH**	**LOW**	Firefighting equipment always on-hand, avoid dry sites, follow local laws and regulations
Noise	**LOW**	**CERTAIN**	Only use designated launch sites, work with site owners
Material damage	**HIGH**	**LOW**	Only use designated sites, follow safety codes and regulations, verify rocket design via computer simulations and ground testing, insurance

Table 28: Environmental concerns summary

Payload and AGSE

Per section 3 of the requirements for non-academic teams, we choose payload Task 2, Centennial Challenge, option 3.1.8. The technical design for this task is discussed below.

Overall approach

The Maxi-MAV solution we have begun prototyping we expect will address the core technical challenge but also the associated limitations associated with a very limited timeline and project budget. We have begun to tackle all three of these aspects by maximizing the use of commercial-off-the-shelf (COTS) components and subsystems as much as possible and ensuring that the engineering team addresses the core requirements only, without allowing “scope creep” of additional features that are not required in the NASA specification. The focus of this document is to address SoW §3.3.3.1 although we necessarily refer to the launch vehicle in relation to the payload compartment and securing of the payload within the vehicle.

To this end, we divide the challenge into the following pieces:

- Vehicle design to meet payload, size, altitude, and landing requirements
- Payload compartment design including securing the payload and ensuring rocket integrity (door closure/sealing)
- Overall superstructure to support the vehicle and associated robotic elements, meeting envelope and mass requirements
- Payload acquisition, manipulation, and insertion
- Launch rail erection and securing
- Igniter insertion
- Autonomous control of subsystem, user interface, power control/management
- Safety (of motion control system, launch vehicle, as well as all materials used and electrical systems)

We have prototyped and tested various aspects of each of the above subsystems or elements at this point, although complete integration of the elements into a final working solution remains for the next phase of the program, including detailed full programming of the entire routine into the microcontroller and debugging the interactions of the various mechanisms.

In this section we’ll combine a report of the progress we’ve achieved on the design, subsystem by subsystem and outline what we have accomplished and expect to accomplish.

Payload compartment design

This subsection describes how the vehicle payload compartment is expected to meet §3.3.5.1-.3 of the MAV statement of work and complies with the dimensions, mass, and other specified design aspects of the payload.

In addition to the explicit NASA-defined requirements, the payload compartment design must also address additional derived requirements:

- Balance the forces of inserting/retaining the payload against the force that the robotic arm and end effector (robotic gripper mechanism used to hold payload) are capable of sustaining
- Balance the force required to hold the door closed against the force allowed to be placed on the rocket
- Have an overall design methodology that is highly tolerant of placement error of the payload initial location, placement error owing to tolerances from the arm and end effector, and tolerant of the placement of the rocket on the launch rail, as well as potential variation from payload to payload.

To that end we intend to address the payload retention with a straightforward metal spring-based design. A solid model of the internal retention design is shown below. This sled was measured to weigh 4.6 ounces without payload or other support structures.

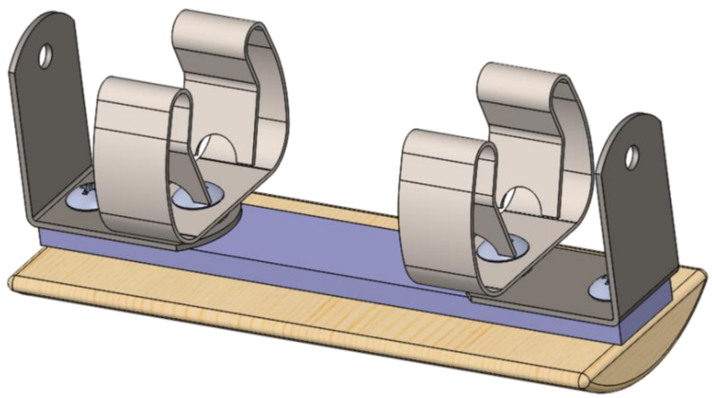


Figure 13. Sled used to retain payload.

The clips in the middle are commonly-available garden rake or broom retention clips used for holding tubular objects to a tool rack or wall. These were chosen and slightly adjusted to accommodate the payload end cap outer diameter. The clips and brackets are secured onto an aluminum bar which is in turn screwed onto the plywood base. The plywood mounts to the inner diameter of the launch vehicle.

The end effector will place the payload into the clips and the greater force of the clips will remove the payload from the end effector and secure it during flight. Two brackets at either end of the sled will prevent the payload from sliding out.

The image below shows the payload retainer subassembly mounted in the rocket payload compartment, as well as the payload door and other details of the design.

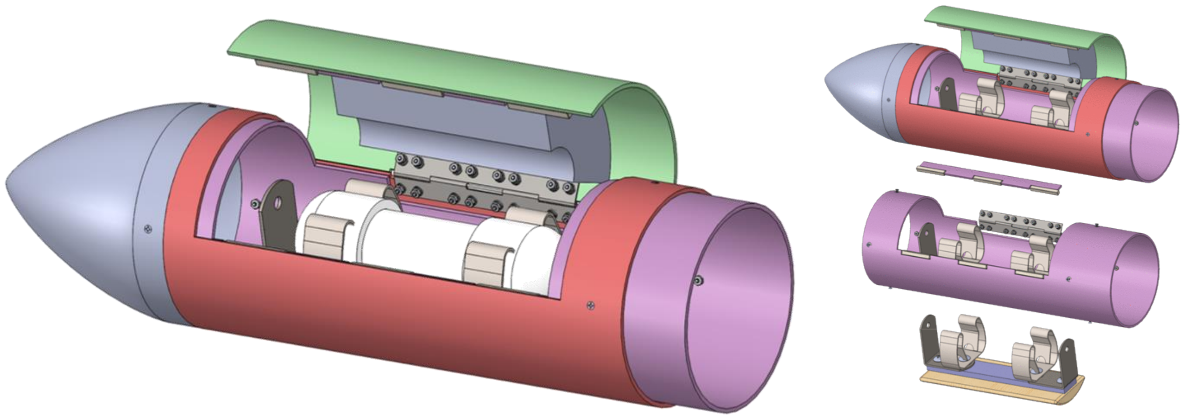


Figure 31. Detail showing 3D render of payload retention in vehicle bay.

To ensure structural strength of the vehicle bay, the payload area will be reinforced with fiberglass coupling tube with a rectangular cutout smaller than the payload door. This will act as a seat for the door when it is closed, a means to mount the magnets securely, and a strengthening member when open. In addition, we use the inner coupling section of the nose cone to support the forward end of the door section and a section of coupler tube to support the aft end of the door while closed. The inner coupler tubing will be secured with West Systems epoxy and four #0-80 screws equally spaced above and below the payload bay (8 total).

Before constructing the full-scale compartment, a partial-scale payload compartment was first fully constructed and tested in the scale model launches. It included all of the key features of this design, scaled appropriately (door length and subtended arc, reinforcing coupler, struts, epoxy, etc.). Due to space limitations, this design used a hybrid magnet and metal plate approach to hold the door closed, and we estimate that the holding force for that design was approximately 3 pounds. Results from this test flight indicated that our methodology works and that the door will remain closed during flight conditions even with this very low force.

Then a full scale compartment, as designed above, was constructed. This design demonstrated that the end effector only needs an opening that is 150° of the circumference of the rocket instead of the original 180°. With all-fiberglass construction, a short payload door, minimal mass in the nosecone forward of the payload compartment, and doubled wall thickness in the walls of the non-door portion of the rocket, we will have sufficient strength to support launch forces despite the inherent structural weakness induced by the large door opening.

This full-scale model was tested qualitatively on the ground by manually applying force laterally and axially. We applied approximately 20 pounds of lateral force and observed no obvious deformation of the tube as judged by any gap closure observed between the door and main tube. We also applied approximately 30 foot-pounds of rotational torque above and below the compartment and observed no visible deformation of the tubing.

Because we are using a 3" tube, great care was taken with alignment of the launch buttons since the door, while open, may come close to the payload gripper.

The sled shown above was secured using 3M DP420NS epoxy to the inner coupler tubing. Four wood screws are inserted from the outside of the rocket into the wood body of the sled as well.

Figure 32. Image of completed full-scale payload retention bay showing door in open position (foam on door not present).

The payload door is hinged with an integral over-sprung mechanism, making it bistable (i.e., equally stable in the open or closed position). This aspect serves two key functions: ensuring that the door stays open or closed without the aid of gravity, and lowers the tolerances required by the robot arm and gripper in the process of the closing the door.

For the hinge we harvested the bistable hinge found in hard-shell glasses cases; these are roughly 6 inches long and will open to 100° and can close to 180° opening angle. We have already acquired these from a local Costco optical shop as surplus discards, and the hinge is “harvested” from the case by removing the fabric covering and removing the retaining metal flaps. It is secured with #0-80 screws with a washer, lock washer, and nut. Eight screws are used on each flap of the hinge (16 total) to attach the door to the hinge and the hinge to the body tube.

The door itself is body tube section cut from the main body itself with a razor saw and Dremel tools. On the inside of the door, a square of memory foam may optional be used to keep the payload in place and keep it from shifting during flight if necessary. We have acquired the memory foam with the needed density and resilience already; it will be attached with hot melt glue to the door.

We will use a linear electric actuator attached to the AGSE frame to initiate the closing movement of the payload hatch. After the hatch passes its stable point, the bistable hinge will close it the rest of the way. The bistable hinge already provides all of the force required to close the door, but given the forces that the rocket will endure during flight and the mass of the door, magnets were added to secure the door once it is in the closed position. Small, neodymium magnets are readily available and inexpensive. They were bonded to the door and the body tube and coupler tube using 3M DP420 epoxy. We used six of the following magnets, described below. The pull force of each magnet should exceed 4.5 lbs once the door is closed.

- Dimensions: 1" x 1/8" x 1/8" thick (±.004 in tolerance)
- Material: NdFeB, Grade N42
- Plating/Coating: Ni-Cu-Ni (Nickel)
- Magnetization Direction: Thru Thickness
- Weight: 1.92 g
- Pull Force, Case 1: 4.80 lbs
- $0.74 per magnet in small quantities

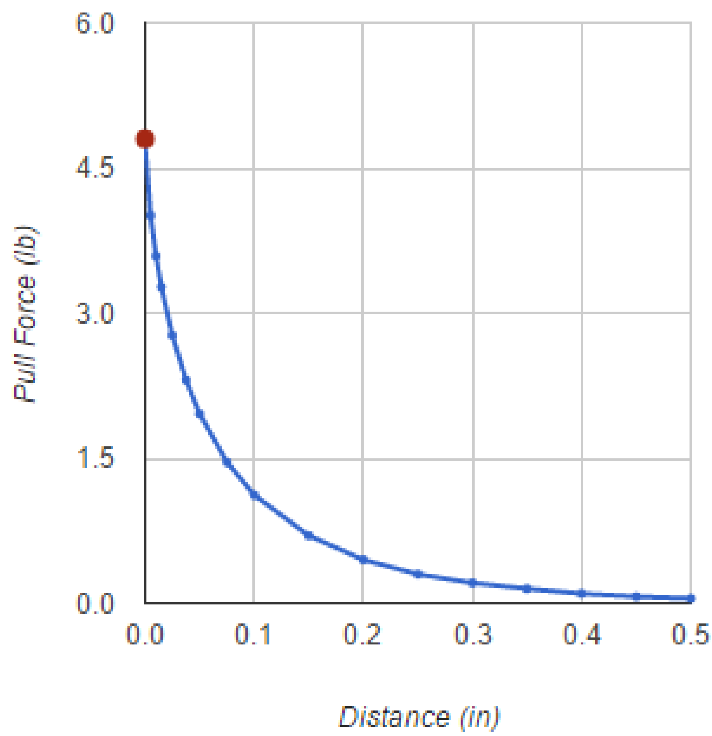


Figure 33. Pull force of single magnet to magnet plate versus distance.

Combining the force of the six magnets plus the bistable spring force we estimate that the six magnets provide over 30 pounds of closing force. We will quantitatively measure this force directly in the next phase to verify these estimates; we have found it difficult to open the door and have made a special tool to pry it open after closing, and we believe the force is at least this much qualitatively.

To assess that this is sufficient force to hold the door closed, we calculated the dynamic pressure resulting on the door at peak launch velocity, assuming the payload/door were completely sealed, enabling a maximum pressure differential to build up. The 30 pounds of closing force is comparable to the calculated force, however the payload compartment is far from sealed, with air gaps in the hinge and door sections. For extra surety that this dynamic pressure cannot build up on the door, several small holes will be drilled around the payload/door section as is common practice to ensure accuracy of barometric altimeter electronics.

AGSE Superstructure

We have built the superstructure using low cost and readily available 8020 extrusions, secured with bolts and fasteners, reinforced with angle struts. The main outer frame is constructed from 1020 (1x2 inch) section for rigidity, and many of the struts are made from 1020 or 1010 (1x1 inch) depending on the application. Modular framing such as this has demonstrated the appropriate strength-to-weight characteristics, cost, and modular aspects for this design. The team has several years of experience designing a variety of launch platforms with sufficient robustness for high power rockets of Level 1 (H-I class) and Level 2 (J-L class).

Figure 34 below shows several dimensioned views of the AGSE in the payload-loading configuration. It is shown in the horizontal "loading" position, ready for the launch vehicle to be installed on the rail (§3.3.2.1.1).

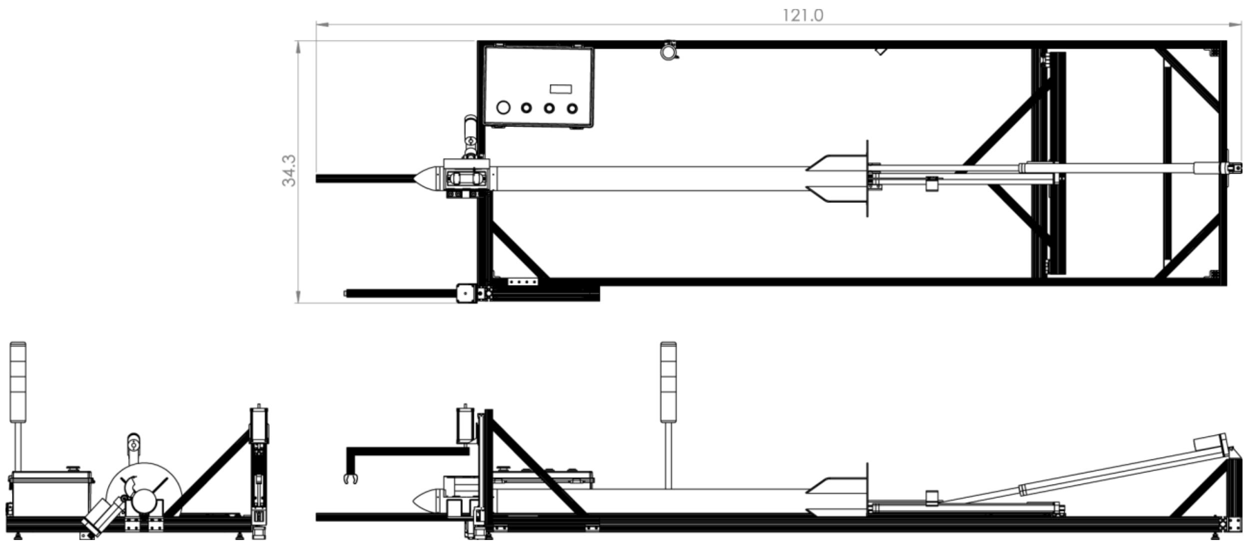


Figure 34. Line drawing views of AGSE superstructure in horizontal payload-loading configuration. The structure is 121 x 34.3 inches the horizontal configuration. Payload manipulator robot arm and body tube stabilizer are shown.

In the image below we show the AGSE in the launch-ready position. The entire maximum rectangular envelope of the AGSE in either configuration does not exceed 121 x 34.2 x 97.7 inches, well below the NASA specification of 144 x 144 x 120 inches.

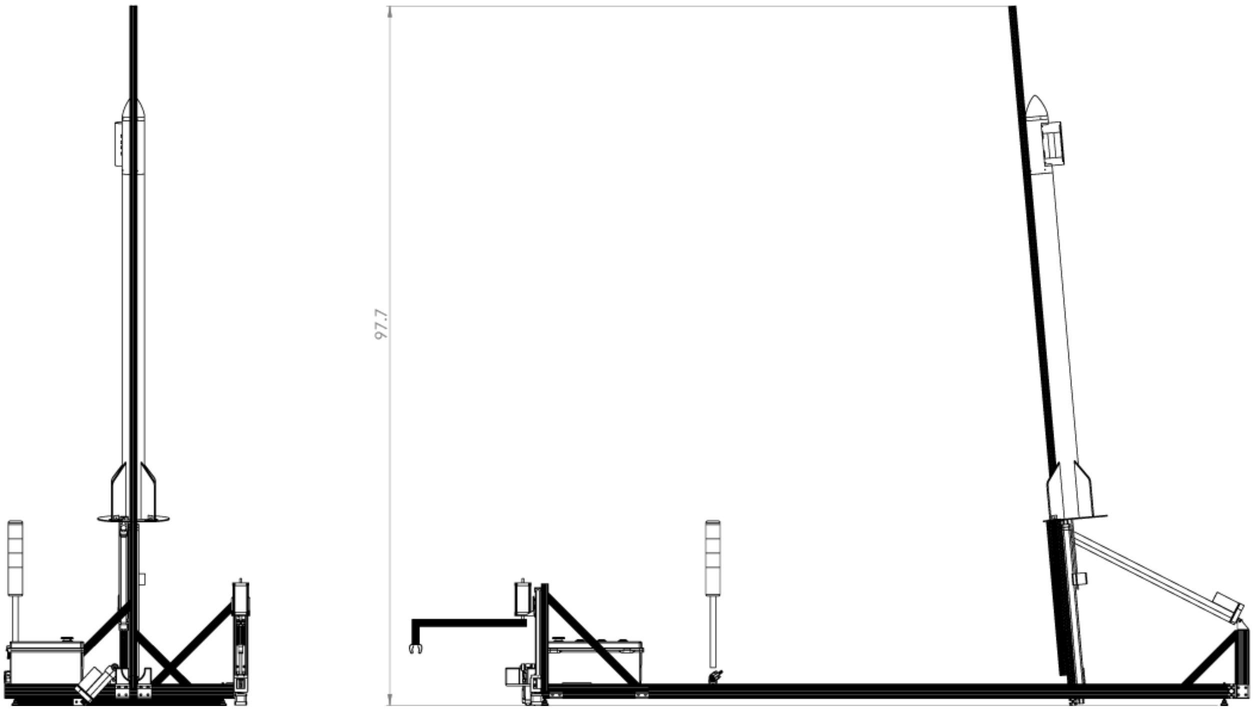


Figure 35. Line drawing views of AGSE superstructure in vertical (85º) launch-ready configuration. The structure is 121 x 34 x 98 inches in the launch-ready configuration.

The structure also provides a reference point for the motion control elements: payload pickup and insertion, launch rail erection, and igniter insertion. Each of these tasks dictates a unique design element of the proposed superstructure. Additional 8020 brackets and components are used to securely mount these subsystems to the superstructure.

Figure 36. Top view of nearly-fully-assembled AGSE superstructure.

The igniter insertion approach (detailed below) necessitates a launch platform that is approximately 45 cm (18 inches) above ground level. The requirement that the payload sit on the ground, at least 30 cm (12 inches) outside the AGSE envelope provides another constraint on the platform (SoW §3.3.5.4). The inherent benefit of short throw arms (which reduces torque and motor mass) for payload manipulation suggests an approach that places the payload compartment of the rocket as near to the ground as possible.

The drawings shown above illustrates some of the elements of the superstructure. Some of key aspects are:

- Use of lightweight modular "80/20" aluminum extrusions with low-cost off-the-shelf connecting mechanisms. Reinforcing triangular cross-bracing is used as necessary to provide strength against launch forces and torque during rail erection. A long extrusion is used as the guide rail for the launch vehicle.
- A small extension attached to the main superstructure will hold the payload insertion arm and end effector. This same extension will also have a "nest" to support the launch vehicle during payload insertion and prevent those forces from being entirely supported by the launch rail and rail buttons.
- An aluminum sheet blast shield. This is securely fixed to the launch rail with a hole for ignitor insertion. The shield provides sufficient area to protect the linear actuator for ignitor insertion and any associated micro switches and other gear near the blast area. Some customization or venting of the blast exhaust may be considered after completion of the detailed design.

Figure 37. Image demonstrating ready portability of the AGSE superstructure even under adverse weather conditions.

Body Tube Stabilizer

To ensure the rocket is both stable and does not experience untoward forces on the delicate rail launch buttons, a small plastic saddle will provide additional support to the rocket while it is in the pay-loading horizontal position. The body tube stabilizer is a near half-circumference plastic tray affixed to the fixed lower portion of the AGSE superstructure. The launch rail will sit between the "halves" of the body tube stabilizer and support the outer diameter of the rocket only while the payload is being inserted and the door is being closed.

Its position and shape will serve to relieve stress on the launch buttons, prevent the rocket from rocking from side to side while the door is being pushed closed, and locate the rocket axially to reduce the variation in tolerances for payload insertion and alignment with our passive system.

The body tube stabilizer is a fixed plastic piece with loose tolerances and low strength requirements and is currently being rapid-prototyped on one of the workshops' 3D printers as of the writing of this report.

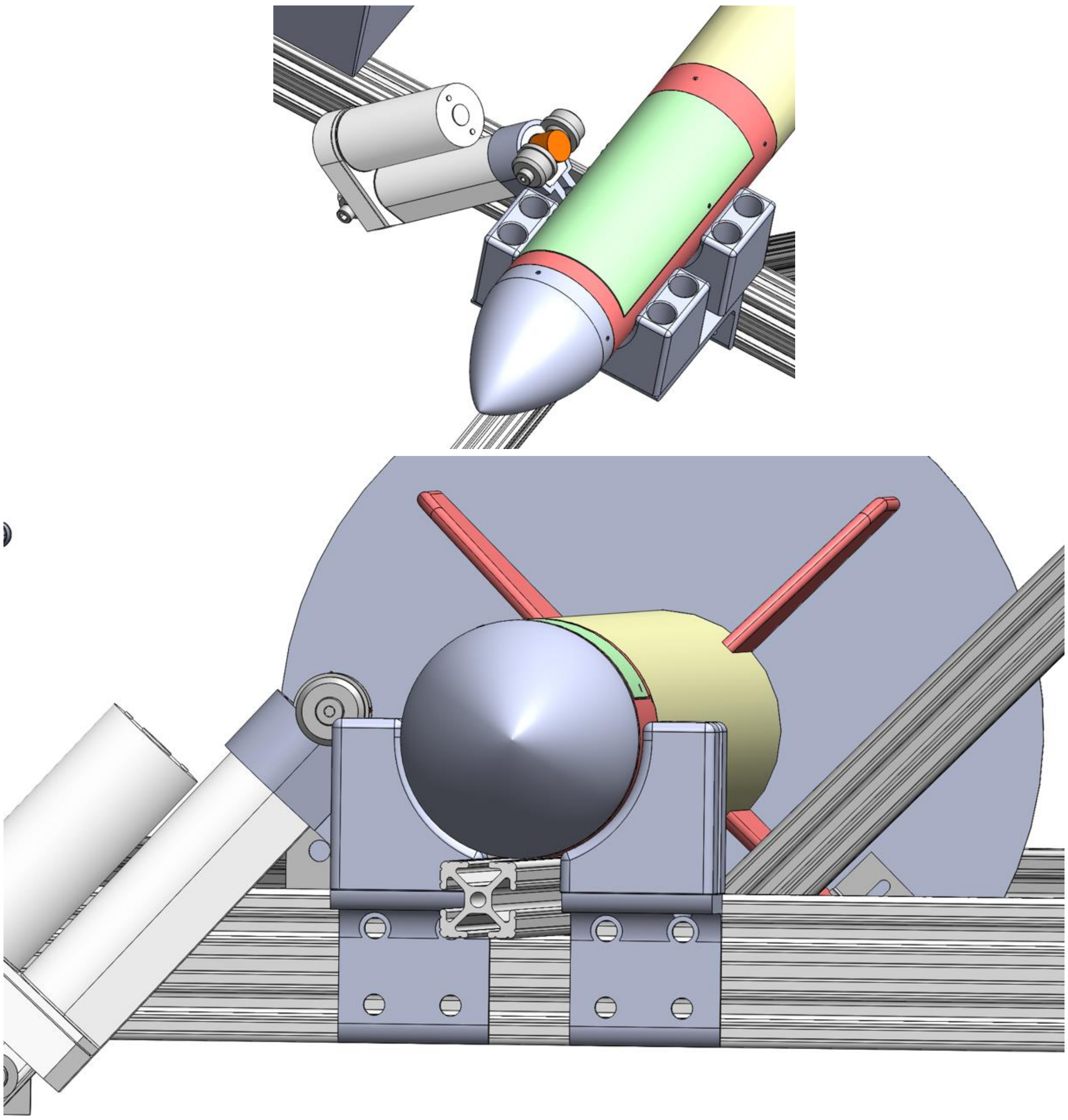


Figure 38. Renderings of body tube stabilizer ("saddle"); above, top oblique view; bottom, end view.

Figure 38 shows how the rocket will restrained from roll motion when in horizontal position. This is important to protect the rail buttons and rail from damage, should the rocket roll to the side.

Payload transport and insertion

Concept and inspiration

Our approach to these tasks is to minimize the complexity of the motion control by (1) actively guiding the location of the initial payload placement and (2) maximizing the tolerances of the payload bay and capture mechanism. This allows for passive, non-guided motion control while ensuring that the payload is securely placed using positive latching mechanisms. Feedback from the motion control system's encoders as well as embedded switches ensure that every aspect of the payload grabbing and insertion complete correctly before proceeding to the next step.

During the PDR phase we carefully examined several of the commercially available off-the-shelf low-cost hobbyist robots that appeared to meet the specification requirements including reach, load capacity, cost, weight, and integration. The field of options meeting both cost and weight requirements limits the field considerably, despite there being a great deal of commercial activity in this area.

Ultimately, along with several other design explorations, this analysis led us to consider a simplified SCARA (Selective Compliance Assembly Robotic Arm) robot. SCARA robots are widely used in industrial automation for placement of items on industrial conveyor-belt lines, semiconductor industry, and adhesive dispensing/assembly. One example is shown below, with the typical 4 axes (two rotary to move the arm into location, one vertical to move the end effector up and down, and a 4th rotary that moves the end effector in a circular fashion.)

Figure 39. Example of industrial SCARA robot.

What we proposed for the AGSE is a simplified version with only two axes: a single rotary motor, rotor vertical, placed ~18 inches from rocket center axis, riding on a vertically-mounted linear travel stage.

Payload placement

To ensure the design requirement §3.3.5.4 of the MAV SoW is met, we intend to use laser triangulation to reinforce the proper location of the payload for pickup by the AGSE. (This aspect is not shown in concept rendering of the AGSE). This will use a widely available commodity structured laser light diffuser commonly used in drill presses and cutoff saws to place a laser "+" for payload placement prior to autonomous loading. This should ensure that the payload is within approximately ±0.5 cm (±0.2 in) of the required location and ensures that the payload sits fully beyond the 12-inch requirement.

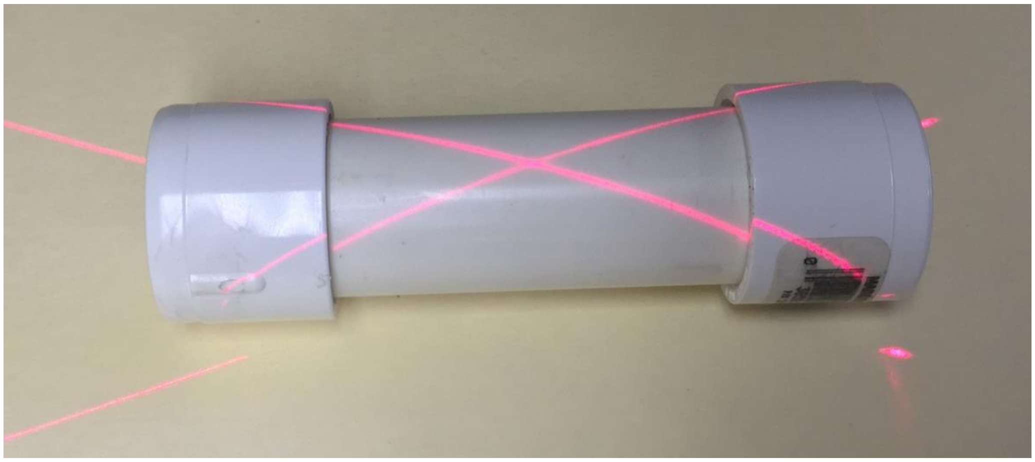


Figure 40. Photograph showing "pre-prototype" of household drill press with laser line projectors on dummy payload.

In Figure 40 above we show a photograph of a common laser line pair projector from a home workshop drill press showing the projected laser line image on the payload. This was photographed under ambient fluorescent lighting and demonstrates viability of the concept in the following ways:

- Laser line is clearly visible on white PVC payload under wide range of lighting conditions
- Projected line pair from unmodified subassembly has dimensions and crosshair angle that are compatible with the payload overall size.
- Placing payload outsize of projected laser zone is clearly obvious as being out of place laterally and having the wrong payload positioning angle.

During this phase we acquired and tested a standard drill-press laser line pair projector and mounted it temporarily to the AGSE near the SCARA subassembly. We found that many different configurations of the laser line pair were both suitable and compatible with the AGSE/SCARA. We are currently finalizing the mounting configuration and projection scheme (is an “X” or “+” more suitable and which produces minimal error in placement of the payload)

Arm

We are using a commercial linear motion stage for the vertical motion, mounted to the AGSE with a fixed metal bracket. This vertical linear travel stage has the required 8.1 inches of travel and possesses a small pre-load since it operates vertically. The advantage here is that it can be acquired as a complete solution commercially for reasonable cost and the stage mass is less of a consideration.

A rotary stepper motor is mounted to the vertical travel stage, keeping all of the mass of this mechanism concentrated on the AGSE superstructure rather than cantilevered. The central rotary stepper motor moves an arm, 17” long. The motor is operated in a common microstep configuration, providing sufficient angular resolution despite the roughly 13” radius of swing.

The passive gripper and arm is made from lightweight 80/20 rail. The cantilevered mass of this solution is considerably lower, reducing the requirements on the rotary motor, only adding to the load of the vertical linear stage.

Before the automatic cycle starts, the arm is swung inward, parallel the long axis of the AGSE (parallel to the rocket), maintaining the slim envelope of the AGSE.

The 15" swing arm is fabricated from 80/20 rail. The arm is sufficiently long to meet the 12 inch envelope requirement yet short enough to use commonly available motors and materials and low-cost construction methods.

Payload motion

In the payload acquisition (extended) position, the gripper sits over the payload. The controller actuates the linear stage downward, pushing the gripper on to the payload, securing it in the clamp. The “gripper” we are using is a passive spring clip nearly identical to that used to secure the payload in the launch vehicle. It is modified to reduce the spring force to be just sufficient to securely contain the payload mass during pick-up and transport.

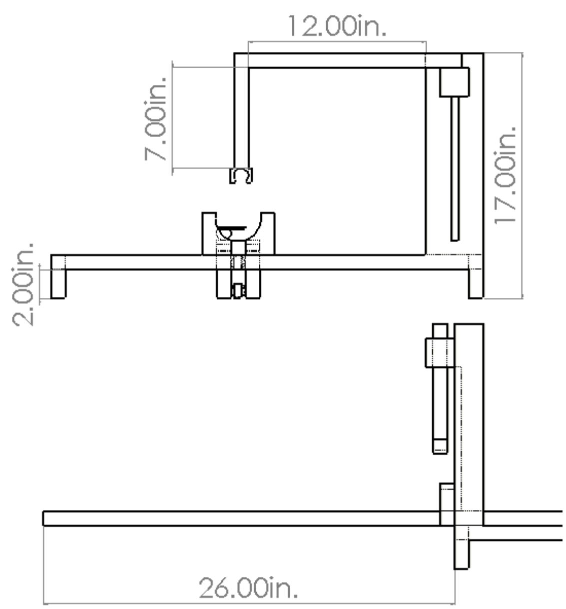


Figure 41. Scaled schematic views of the proposed payload transport and insertion system (top: end view showing rocket stabilizing saddle; bottom: side view showing launch rail across middle).

The downward force will be just a pound or two to overcome the passive retainer clip. The upward force required is the payload plus friction and the force required by the passive gripper, just a few pounds.

Once the payload is secured, we raise the vertical stage, then rotate the main arm 180°. Now the arm and payload sit atop the rocket payload compartment.

The linear vertical stage is moved down again, but only a short distance, to push the payload into the rocket. This requires a downward force of approximately 10 pounds to overcome the securing spring inside the payload compartment. Note that this ensure sequence does not rely on gravitational forces, meeting §3.3.5.5 of the SoW.

The vertical stage that is both compact for mass, but also capable of the axial and torsional loads is shown below in Figure 42 (THK series 26 with stepper motor, 8.1" travel).

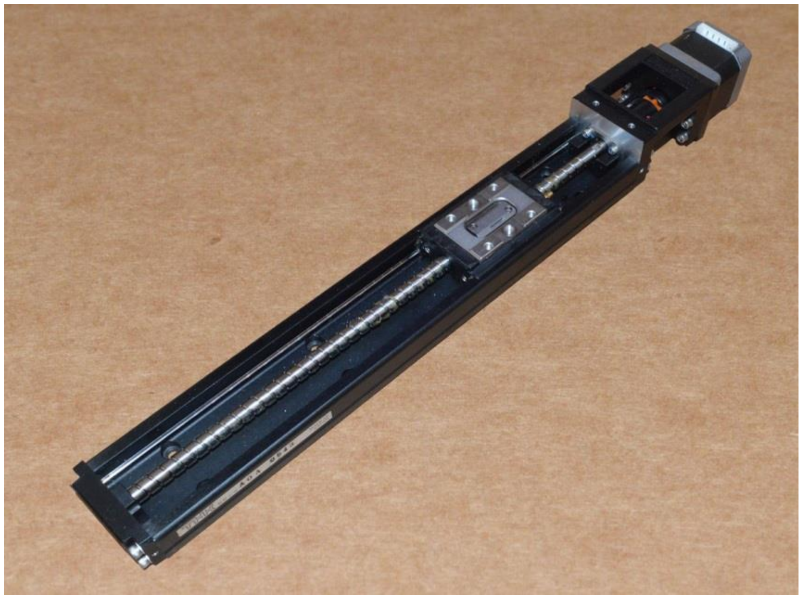


Figure 42. Compact linear stepper-motor driven vertical travel stage.

To this stage we mounted a rotary stepper motor to actuate the arm across a 180° arc, from the payload "pickup location" to the insertion and loading position into the launch vehicle. Based on the arm length, payload, arm, and gripper mass, and taking into account safety factors we are using a NEMA 23-sized stepper motor. An example motor and off-the-shelf right-angle mounting bracket are shown in Figure 43 below.

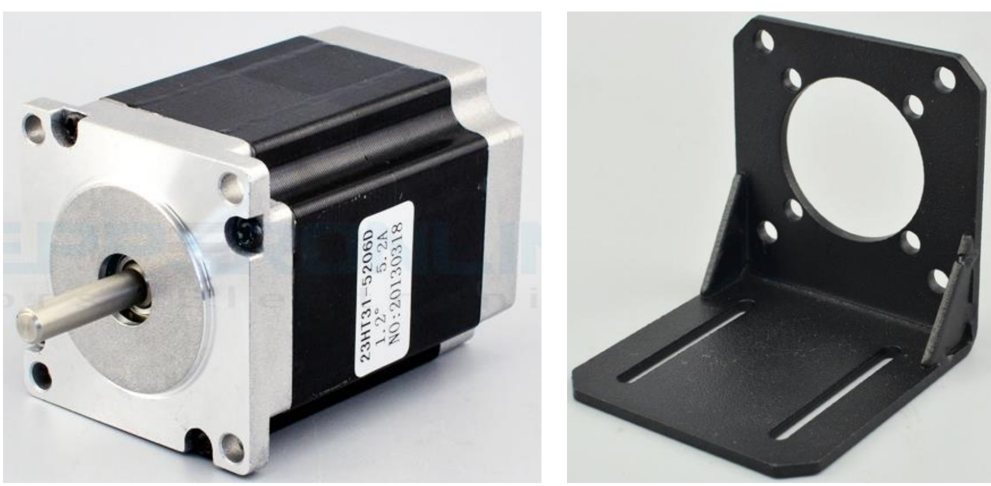


Figure 43. NEMA 23 sized stepper motor and accompanying angle mounting bracket.

The SolidWorks rendered sequence shown in Figure 44 and its detailed caption below details the major steps in loading and unloading the payload with the 2-axis SCARA robot implementation.

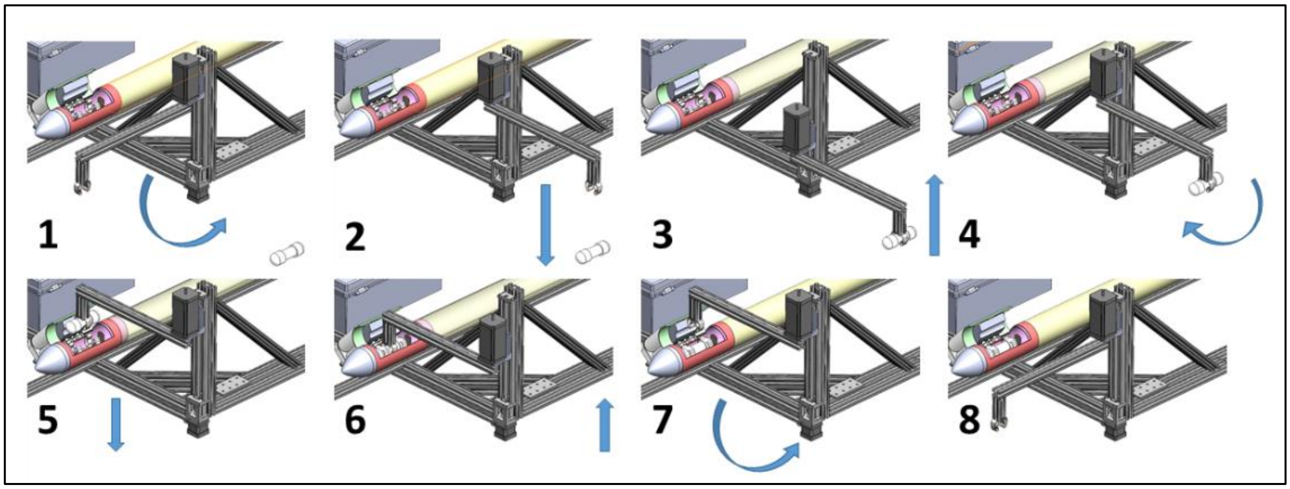


Figure 44. Payload pickup and insertion sequence. (1) arm extended to begin payload pickup. (2) vertical stage lowered over payload for pickup. (3) vertical stage raised with payload. (4) arm rotated 180° over vehicle payload compartment. (5) arm lowered to insert payload in compartment. (6) arm raised, leaving payload in compartment. (7) arm moved back to extended position, out of the way. (8) payload door closed.

To prove out the concept of the passive spring gripper and differential spring force we used the "pre-prototype" of the rocket payload section along with a pre-prototype gripper assembly. Figure 45 below shows both in schematic section view (top) and photographic 3D view (bottom) of this insertion sequence.

We have acquired and assembled the vertical stage, rotary motor, angle brackets, stepper motor controllers, and all associated assembly hardware. We have demonstrated the full operation of the SCARA robot through the entire operational sequence under Arduino control. This subassembly testing has proven out:

- Compatibility of stages and motors with low-cost stepper drivers
- Full operation of the SCARA robot over the entire required motion envelope
- Demonstrated placement accuracy and tolerances required to load the payload
- Demonstrated stability and rigidity of entire structure while under load of picking up and inserting payload into compartment
- Demonstrated robustness of the arm, motors, and drivers to minor workspace envelope incursions by unexpected intrusions or obstacles
- Demonstrated integration of Arduino driver code, stepper driver, and power supplies. Speed control with acceleration and deceleration demonstrated

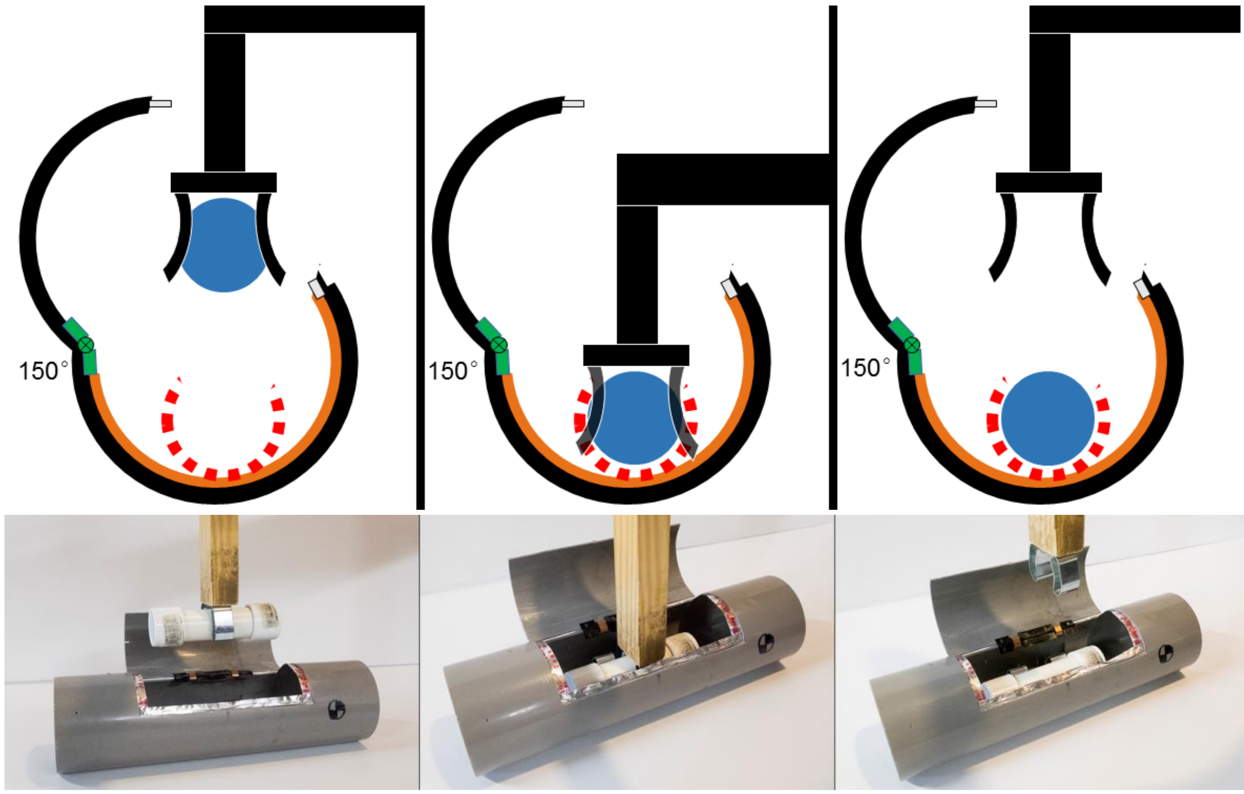


Figure 45. Picture series of payload integration using "pre-prototype."

Door closure

We are using a short-throw linear electric motorized "piston" stage to close the payload hatch. This is mounted in a fixed position to the AGSE superstructure beneath the launch rail and serves only to close the door, extending itself and pushing the payload door well past its bistable angle, then retracting.

The small linear actuator will be mounted at a roughly 45° angle to the rocket as shown in the figure, which maximizes the perpendicular force on the door while remaining out of the way at the end of the closure push cycle (above the payload door). Figure 46 shows an image of an actual 2-inch throw compact electric linear actuator suitable for this task.

Figure 46. Example short-throw (2" stroke) electric linear actuator for closing payload door.

The cartoon sequence shown below shows the operation of the linear piston to close the door and retreat. The door actuator will retract when the door is closed, completely out of the way of the rocket and fins during take-off.

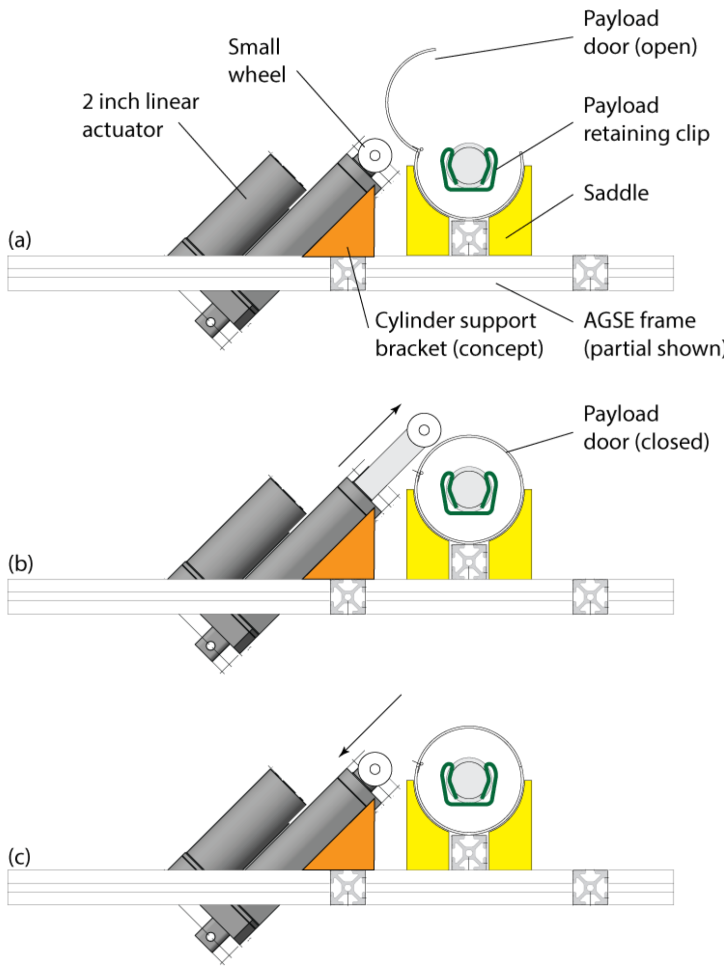


Figure 47. Cartoon sequence showing door-closing using linear cylinder.

The photo sequence below shows the cylinder successfully closing the door on the full-scale rocket compartment. Note that the student's hand in the photo below was only supporting the rocket to proxy for the not-yet-fabricated stabilizer/nest parts and was not imparting action to the rocket body during the testing.

Figure 48: Real sequence of the door closing using the linear cylinder

Tolerance Analysis

We have chosen a passive approach to acquiring and inserting the payload, relying upon careful placement of the payload and savvy choice of end effector and overall motion control design.

We must address the overall tolerances of the placement of the payload, both in the capture zone as well as the placement within the payload compartment.

Many linear dimensional factors will be taken into consideration:

- Placement error of the payload in the capture zone (axial, lateral, and angle)
- Error (absolute and repeatability) of the end effector, factoring in angular encoder error or the rotary motor, arm length, sag and linearity of the vertical stage, and mechanical tolerances of the parts themselves
- Size of the payload door/compartment (axial length and angular subtend of the door cut-out)

- Location and repeatability of the location of the rocket body on the rail/AGSE
- Location, spacing, and angle of the end effector/passive clip
- Location, spacing, and angle of the payload compartment retaining clips
- Payload-to-payload variability

And many mass and force factor will be taken into consideration:

- Mass and variability of the payload
- Center of gravity of the payload
- Insertion and retention force of the end effector clip (and variation with wear)
- Insertion and retention force of the payload retaining clips (and variation with wear and from prototype to prototype)
- Mass, axial load capability of the linear stage
- Mass, later load capability, axial (shaft) load capability of rotary motor
- Length and mass of manipulator arm

The dimensions, relative location, insertion/removal forces of the end effector and retaining clips will be readily adjustable through the prototyping phase, whereas due to time and budget constraints the limits of the linear and rotary stations will be locked early.

Based on very preliminary testing we believe we have roughly ±0.3 inch tolerances laterally and up to ±5, possibly ±10° laterally in passive payload placement. To guide the placement of the payload, we are using a pair of simple line generators, commonly used in consumer drill presses, to provide visible triangulation point(s) to provide a visual placement guide for the payload.

Direction	Payload Axial	Payload Radial
Allowable Tolerance	±0.3 inches	±0.5 inches

Table 29. Payload placement/insertion estimated tolerances.

Rail erecting

After the payload has been inserted in the payload pay and payload door has been closed and latched, the controller will instruct the launch rail to erect. A range of approaches were examined for this task that meet the mass, size, cost, and complexity implied by the specification. Ultimately we settled upon a DC electric linear actuator. This mechanism is readily available and has the ideal specifications for this application: 12-volt DC motor, compact/low-mass mechanism, more than sufficient force for the rail length and rocket mass, and sufficient speed given the window for time completion of the entire task. The current required by such motors will be readily controlled with available relays.

Previously we had considered directly actuating the rail at the pivot, primarily to keep the rail and igniter insertion clear of interferences from other mechanisms. However, the combination of selecting a smaller rocket body diameter scaled the entire system down such that the rocket could feasibly be placed on the rail distant from the pivot, leaving a substantial lever arm and location to mount the pivot for a linear actuator. This significantly reduces the requirements on the motor required for erection as well as simplifies the control electronics and power requirements, while still using the same principle of a worm and rotary gear mechanism.

A schematic and key dimensions are shown below. The chosen linear electric actuator is also shown below.

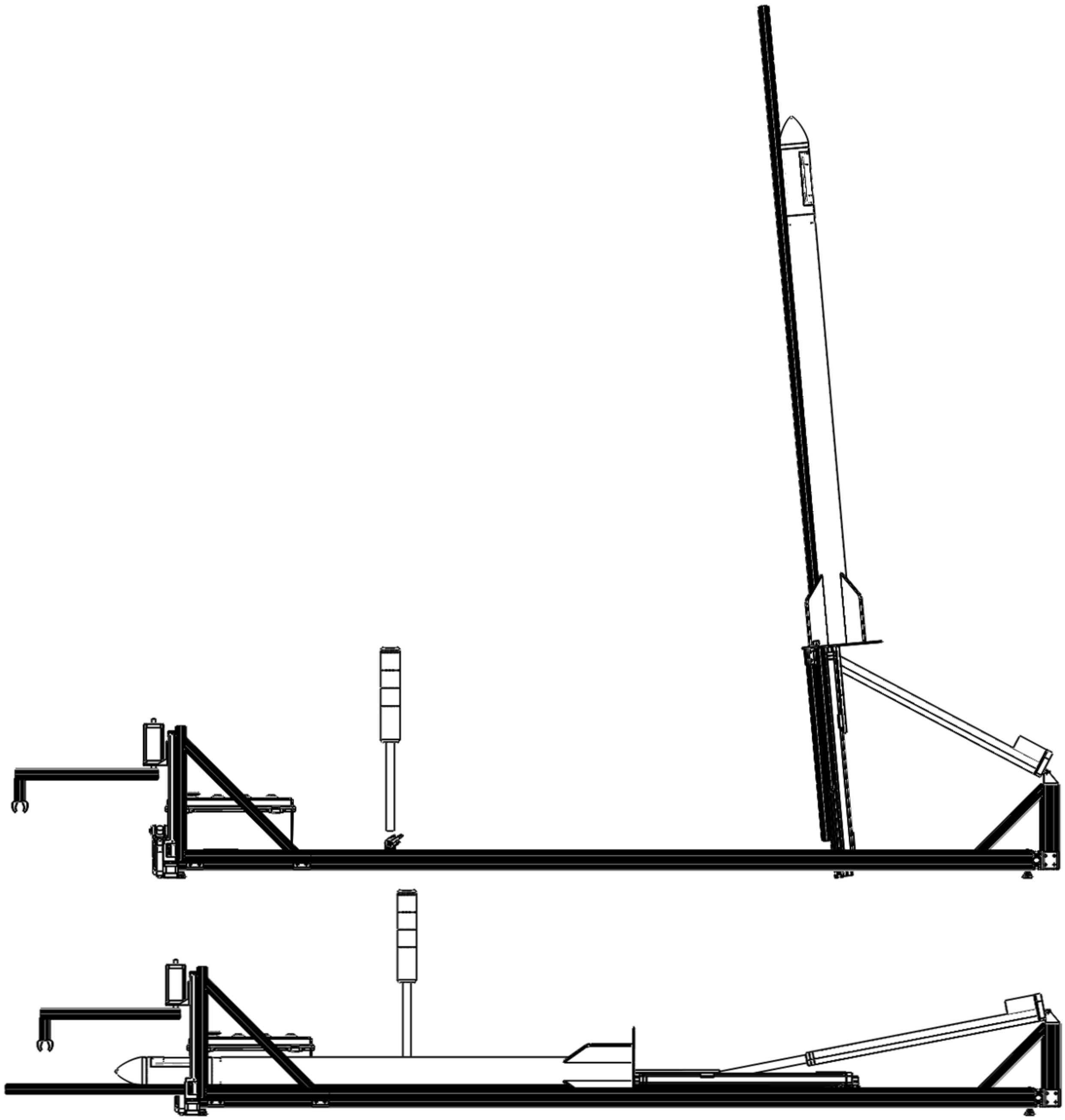


Figure 49. Schematic of launch erecting mechanism and approach.

Figure 50. Long-stroke (24 inch) linear electric actuator for raising/lowering launch rail.

Two simple heavy-duty 8020 compatible hinges are used in association with the linear actuator mechanism to support the rotation of the rail and the launch forces of the rocket engine. When in the erect position, the base pivot will be slightly above the ground, enabling it to act as a direct contact support to the ground given minimal flexure from the AGSE base.

The pivot horizontal rail itself has two diagonal reinforcing struts running in the direction perpendicular to the direction of the linear actuator, giving the entire design a very secure tripod-style support.

Figure 51. Key hardware elements used in rail pivot for erecting mechanism.

External micro-switches mounted to the superstructure will be used to provide location feedback on “raised” and “lowered” status. Rubber bumpers will be mounted as hard limit-stops in both locations.

During prototyping and testing of the erection mechanism several changes were proposed and implemented to overcome the forces induced during the erection process. Specifically, the linear motion stage pivot point was moved higher above the rail pivot to improve leverage from the horizontal position. In additional, braces were added to strengthen the rail against the initial lifting forces.

The entire completed erection system was load-and stress-tested by adding 20 pounds of aluminum plates to the rail just above the blast plate, simulating an approximate 2x overload by the rocket. The erector system worked perfectly albeit slightly more slowly, under these extreme conditions. The system was cycled to fully horizontal to nearly full vertical several times and the flexure of various members observed and recorded by many team members.

The image below shows the completed prototype AGSE being used by freshman and sophomore members of the Madison West rocket club both to erect smaller “TARC” rockets but also to launch them.

Figure 52. Freshman and sophomore members of Madison West SLI team testing the AGSE erection/launch system with F-class motor driven rockets.

Igniter insertion

A range of alternatives were explored for this task. Additional embedded constraints/requirements for this task beyond those provided by NASA are:

- Implicit self-restriction (for safety) to use the manufacturer-supplied ignitors and wiring without modification
- Stiffness and design of the ignitor and wiring
- Nozzle and bore diameter of the proposed rocket motor, and tolerances
- Depth of the rocket motor and required igniter insertion depth, and tolerances
- Conditions inside and outside the motor pre- and post-launch
- Safety considerations

After considering a range of mechanisms and methods, we have selected an electrically-driven linear actuator to move the igniter into position. This type of linear actuator is quite precise, low cost, and can be driven from a 12 or 24V DC supply with moderate currents. A variety are available that include 12, 15, 18 inch strokes or longer, and can be acquired with position indication in some cases. These are commonly used in high-end audiovisual installations or raising and lowering aerodynamic spoilers in sport road vehicles.

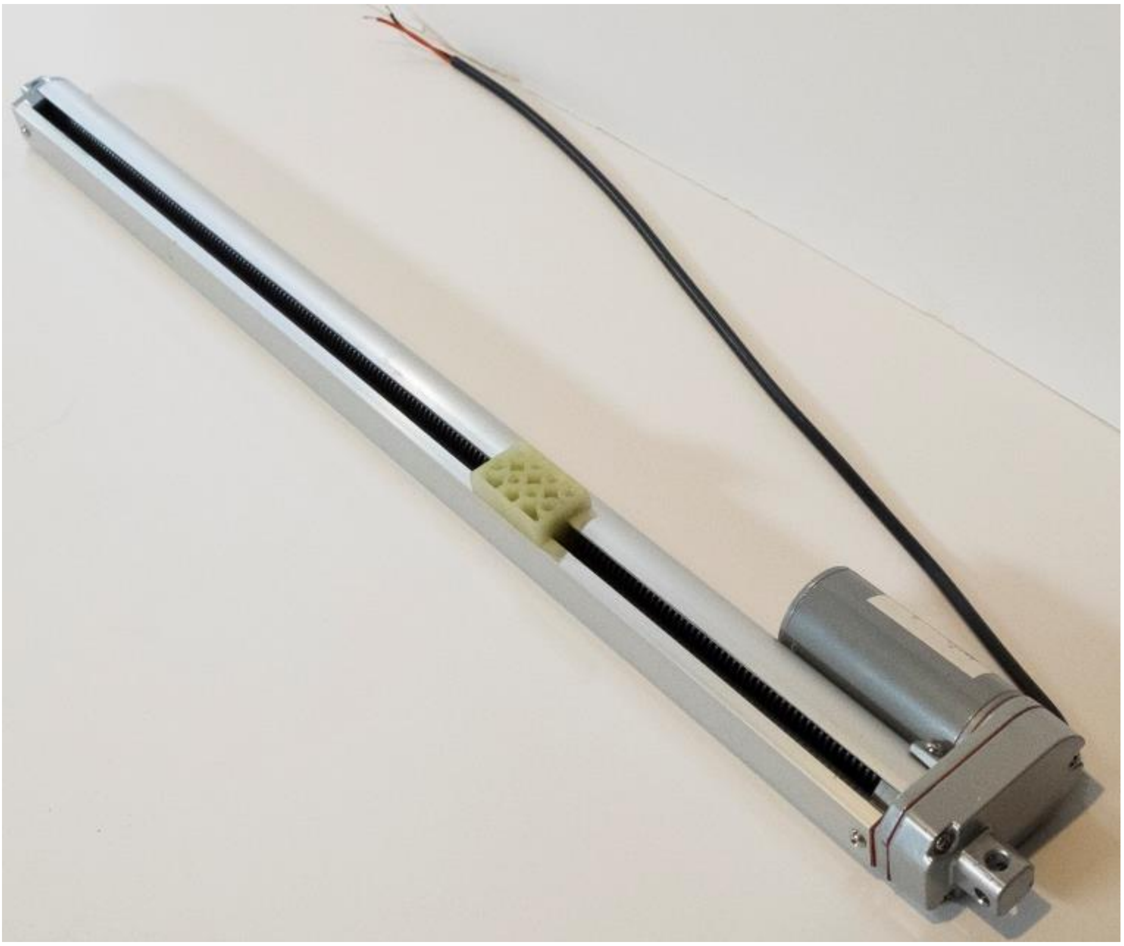


Figure 53. Photograph of actual igniter insertion linear stage.

The image above shows the actual selected insertion stage with 20 inches of travel. The stage has initial incoming testing performed and verified that the stage is compatible with the power from the 12Vdc gel-cell battery, and requires less than 1A current draw without any load. A load of approximately 10-20 pounds caused the motor to draw just over 2A momentarily. The stage is not expected to have loading beyond a pound or two owing to gravity on the ignitor, bracket, and carbon tube. The stage was measured to take approximately 16 seconds to move the entire 20 inch length with no added axial load.

The image below shows a cutaway schematic of the ignitor insertion approach and key support components. In this image you can see the carbon fiber igniter tube fully inserted into a 4-grain engine compartment, penetrating the blast plate.

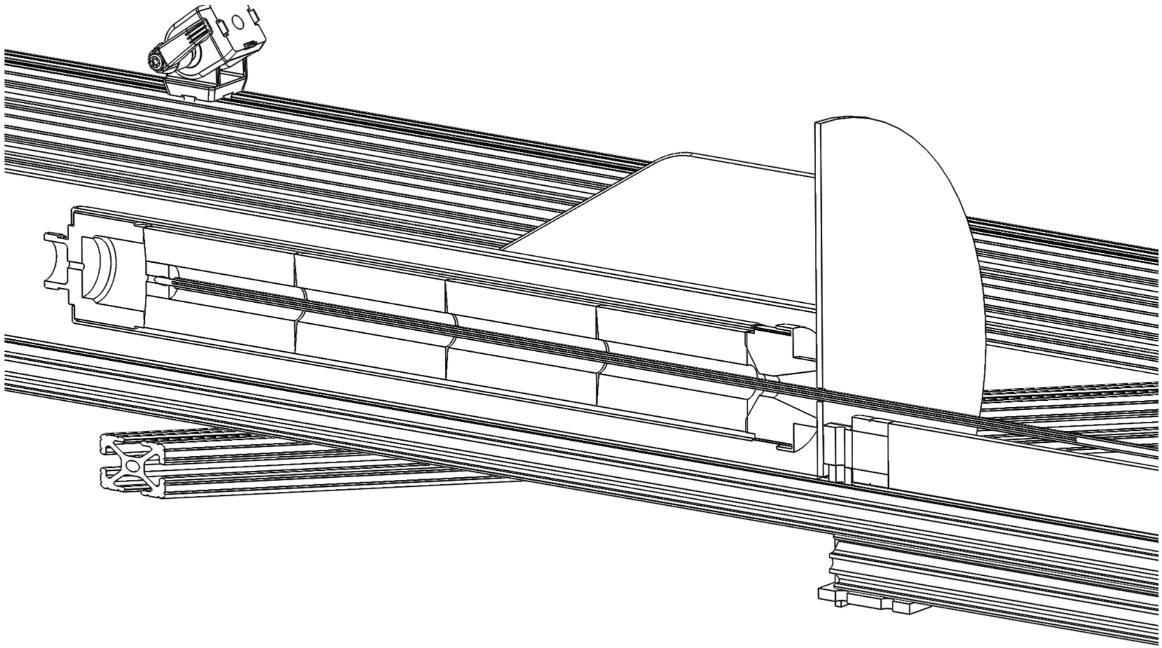


Figure 54. Schematic of igniter insertion approach.

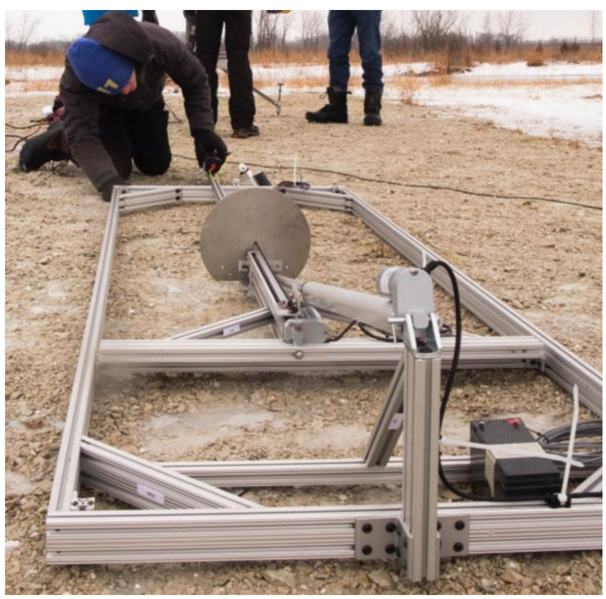


Figure 55. Close-up photo showing details of erector and ignitor subsystems in operation.

The support for the igniter is accomplished with a small-diameter (0.125” to 0.1875” outer diameter) carbon-fiber tube. These are low-cost, exceptionally stiff, hold acceptable straightness tolerances without modification, and are sufficiently sized to allow the igniter wiring to be threaded through the inner bore. The carbon-fiber tube OD (outer diameter) to rocket motor ID (inner diameter) tolerance is large (nozzle ID approximately 0.375 in and propellant bore ID approximately 0.75 inches). This tolerance, along with the travel straightness of the linear actuator, ensures that the ignitor will travel smoothly through the engine bore without getting caught.

Prior to the start sequence, the carbon tube will be loaded with the igniter, using baby powder as a dry lubricant, and manually hand-test fitted into the engine and rocket already loaded on the launch platform. The depth will be manually adjusted with a simple slider and secure thumbscrew. This ensures that the final endpoint of the igniter rests precisely on the surface of the pellet, not lower or higher.

This end location is reinforced both with the fixed travel range of the linear actuator but also by a separate micro switch. This ensures that the microcontroller has positive feedback that the igniter has reached the required, safe location before the “sequence complete” LED is lit on the control panel.

The use of a small bore carbon tube to hold the igniter in place is considered safe as the additional material present in the bore is only slightly more than that of the igniter wire itself. The high carbon content of the tube ensures safety through limited volatility – the epoxy resin binder is less flammable than the igniter wire itself. A fresh carbon-fiber tube will be prepared and used for every launch (the carbon-fiber tube is considered disposable, like the igniter and wires themselves). It should be noted that the added cost per launch of the carbon-fiber tube is negligible compared to the cost of the expendable motor itself (less than $4 per tube length).

The tube is mounted to the linear stage with miniature “P” type tube clamps and an aluminum L-bracket. The holes are oversized so that screws with washers can be used to fine-tune the alignment of the carbon tube with the blast plate.

Figure 56. Preliminary field testing of AGSE with F-class rocket.

The aluminum blast plate is reinforced with a modified abrasive wheel to provide additional blast/shielding from the rocket exhaust during launch. A small washer will be added to the carbon-fiber tube to add an additional "labyrinth-style" secondary blast shield to block direct exhaust from the hole in the blast shield.

As of this CDR we have fully built the ignitor insertion system, tested the motion of the system, tested ignitor insertion into the tube, and tested the efficacy of the blast shield against several F-class motor exhaust launches.

Control System

All of the subsystems described above are tied together with an Arduino-based control system. The benefits of this approach are low cost and simplicity of the code, as well as the rich ecosystem of Arduino-affiliated drivers and code libraries. This extends with the overall design philosophy of using off-the-shelf components, creatively combined to achieve the overall goals of the system.

Control

The control box has been assembled to integrate the Arduino Mega 2560 controller with battery power, stepper motor controllers, relay control boards, debounce/isolation input ICs, input switchgear, and interface to connectors/wiring. The internal view of the controller is shown in the photograph below. Key specifications of the Mega 2560 board are given in Table 30.

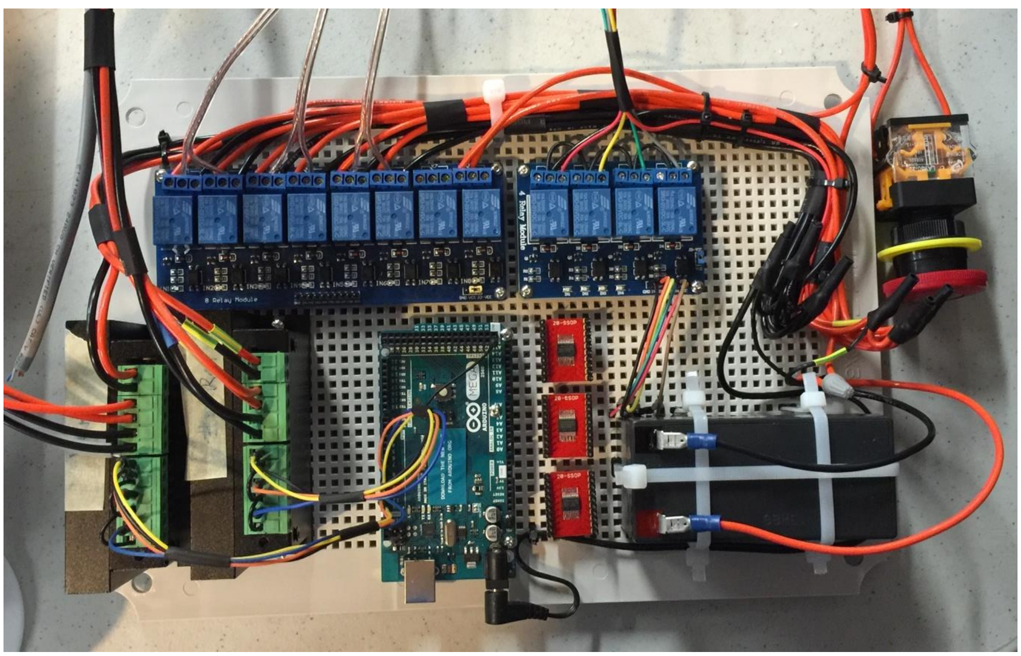


Figure 57. Partially-wired controller system internal view.

Arduino Mega 2560	
Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage	7-12V
Digital I/O Pins	54
Flash Memory/SRAM	256 KB/8 KB
Clock Speed	16 MHz
Weight	37 g

Table 30: Arduino Mega 2560 Manufacturer Specifications

At center is the Arduino Mega 2560, with enough IO pins to drive all of the components of the AGSE without requiring any additional stack-on shields. It only requires drivers for each of the stages. The two stepper motor drivers are mounted vertically at left (black with green connectors). A bank of 8 and 4 high-current relays for driving the linear motion stages appears across the top. The lower right has the very small sealed lead-acid battery for powering the entire system. The 3 red rectangles in the middle are integrated debounce/isolation ICs for all of the button and microswitch inputs. The E-stop switch, not yet mounted in the chassis in this image, is at upper-right. A block diagram of the overall control system is given in Figure 58.

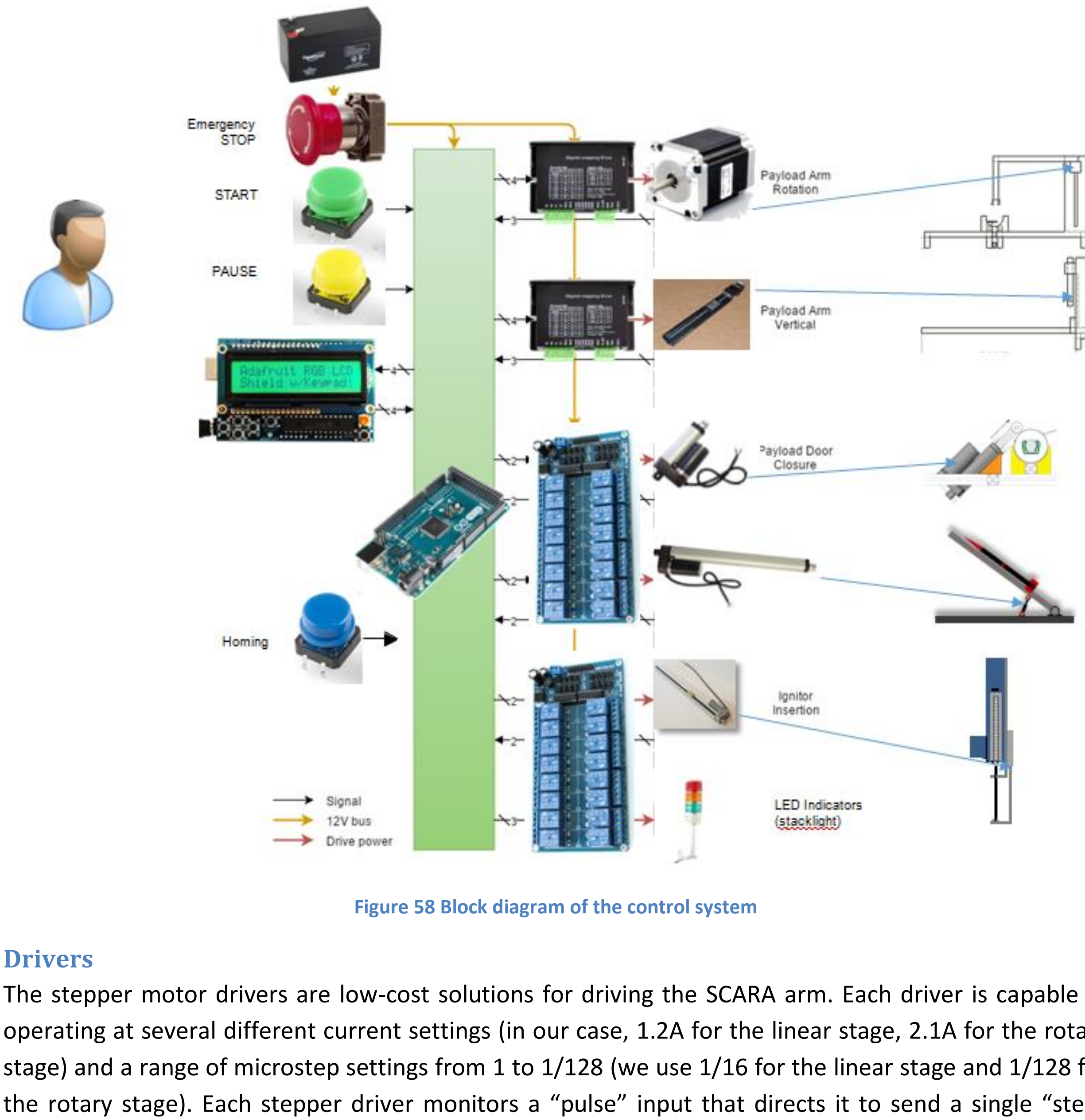


Figure 58 Block diagram of the control system

Drivers

The stepper motor drivers are low-cost solutions for driving the SCARA arm. Each driver is capable of operating at several different current settings (in our case, 1.2A for the linear stage, 2.1A for the rotary stage) and a range of microstep settings from 1 to 1/128 (we use 1/16 for the linear stage and 1/128 for the rotary stage). Each stepper driver monitors a “pulse” input that directs it to send a single “step” command to the motor, these pulses are timed and delivered using custom functions on the Arduino.

Direction of the motor is controlled by a "direction" input on the driver. Main power for the drivers is pulled from the 12V battery.

Power

The system uses a 12-volt DC bus for power, derived from a small lead-acid gel cell battery. This is a fully-sealed, reliable, low-cost, rechargeable, and commonly available battery type. Both the high peak currents (no more than 5A for the actuators and motors we have chosen) are satisfied readily with this type of battery with no degradation or need for secondary means of storing energy. The capacity (watt-hours/amp-hours) of this type of battery is more than sufficient to allow the entire sequence to run over ten times before a recharge is required.

This choice forms a nice balance between cost of the power source and the convenience and risk related to operating and developing the system with a mixed set of skills and background. For example, we could choose to minimize the mass of the battery by using a lithium-polymer or other lithium-ion chemistry, however, the costs would be slightly higher and the risks of battery damage during development are much higher.

The power requirements for the Arduino microcontroller board will be derived from the 12V supply using high-efficiency buck converters on the Arduino board itself to provide 5 V low-current bus voltages.

Interface

A control box mounted on the AGSE superstructure contains all of the switchgear and indicators required by the specification as well as house the drivers and power source and the connections to and from the system. In addition to the required indicators and switches, the panel holds:

- A hard emergency stop ("E-stop") locking pushbutton that immediately, physically cuts all power to the entire system. This is in addition to the Pause button required by the specification.
- A 4-line matrix LCD display to indicate details of the process, primarily for debugging but also for a richer set of information to the operator.

This design for the control panel and the underlying implied firmware code to support the operation satisfy: §3.3.2.1.2 (start button), §3.3.2.1.3/§3.3.6.1.2 (pause button), §3.3.6.1.1 (master power switch). Figure 59 displays the completed front panel.

Figure 59. Concept of control box front panel.

An additional, important safety aspect of the control system is an industrial-style status indicator beacon pole (sometimes referred to as a "stacklight"), providing 360° visibility of the operational status of the AGSE. These are commonly used in industry, with the lights mounted atop a pole for visibility in the busy factory. Figure 60 below shows a concept of this for the AGSE. We anticipate using a low-cost LED indicator pole, driven via relay from the Arduino board in a similar fashion to the linear motor stages, but with lower current.

The indicators on this pole are intended to satisfy §3.3.6.1.3 (amber safety light, 1 Hz flash while AGSE is powered, solid when paused). The satisfies §3.3.6.1.4 (all systems go light). The remaining red light is used to indicate an error condition or failure code for the AGSE (reinforced with an error message on the LCD display).

Figure 60. Status indicator beacon pole integrated with AGSE, control box, and full-scale launch vehicle.

The entire sequence is pre-programmed and requires no human intervention after the start button is pressed (SoW §3.3.3.2).

Event Sequencing

The flowchart below shows the actions required to be performed by the controller code. The first column of actions are performed by the controller outside of the timed sequence, and serve to place the ASGE in the correct starting position, suitable for loading the launch vehicle and fresh igniter, as well as having the payload correctly placed.

The next column begins the timed, 10-minute limit sequence, triggered by the master control switch.

The third column outlines the key steps required of the robotic arm and gripper to grasp the payload and insert it into the rocket, secure it, close the door, and return to a neutral position.

The final column outlines the lifting of the launch rail to the required 5° vertical angle and igniter insertion sequences.

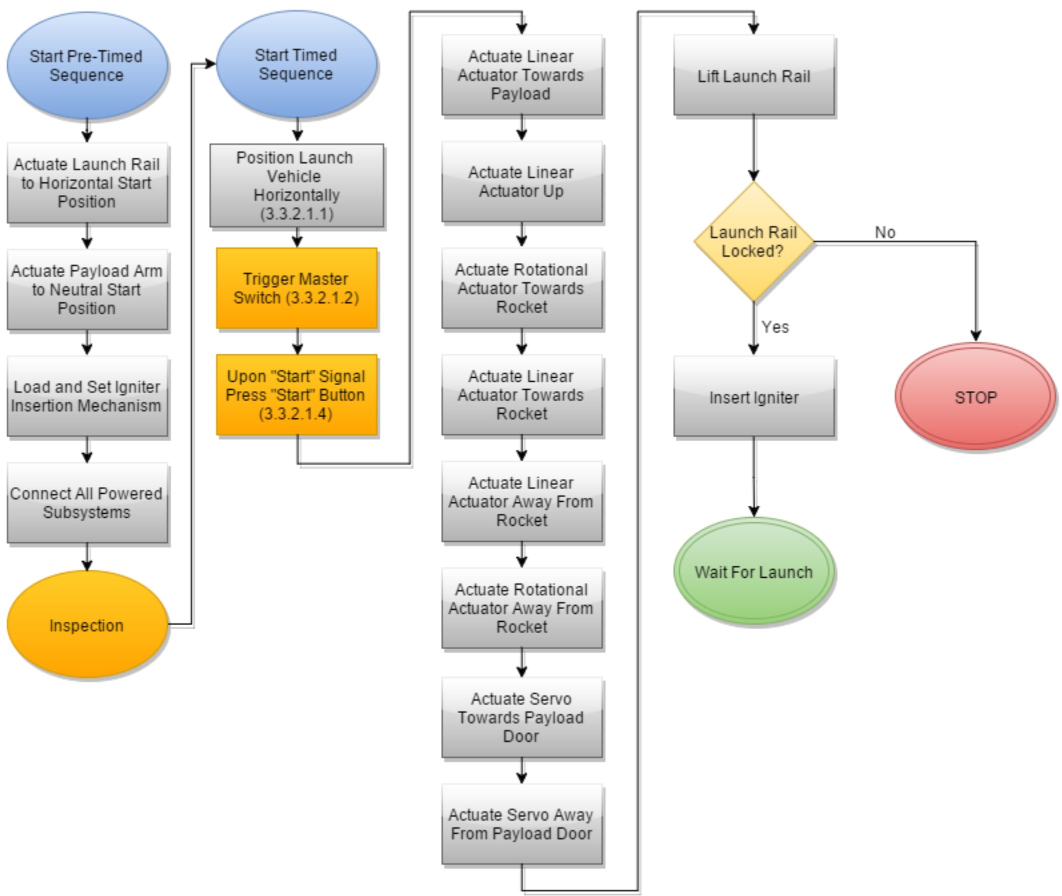


Figure 61. Flowchart for main process control; blue/red/green are start/end of sequence; orange reflects human interaction step.

The main Arduino board will be used to drive the LEDs and sense the input switches on the control panel. The micro switches and position indicators on the drive motors/actuators will be sensed from the shield boards primarily.

In addition to the sequential actions shown in the flowchart, a "Pause" functionality is also implemented into the AGSE controller. The system can be paused and resumed at any point in the autonomous operation procedure as dictated by §3.3.2.1.4 of the SoW. As a backup to provide an additional level of safety, the controller also possesses a separate "hard E-stop" locking pushbutton which removes power from the controller and all motion control.

The current timeline for execution of autonomous procedures is listed in Table 31. The system easily meets the SoW time limit of 10 minutes (§3.3.5.6).

Action	Duration [sec]	Running Time [min:sec]
Move to "Home" Position	38	0:38
Payload Capture	37	1:15
Payload Dropoff	81	2:36
Clear SCARA Arm	35	3:11
Close Payload Door	14	3:25
Erect Rocket	47	4:12
Ignitor Insert	21	4:33
TOTAL	**273**	**4:33**

Table 31: Autonomous AGSE operations timeline.

Firmware

The Arduino development environment streamlines much of the code upload process that would be required for an industrial microcontroller, allowing us to focus on the program structure and logic rather than non-essential details (i.e. specifying correct header files, ensuring a working bootloader, etc.). This high-level focus allowed extremely rapid development of the firmware, and, since the AGSE hardware was near completion at an early stage in the project, a tight "write-test-update" cycle was maintained throughout the implementation of the code.

The "Arduino language" consists of a library of C/C++ functions that are known to the integrated development environment (IDE) and can be included in an "Arduino Sketch." For example, to read a GPIO pin, the Arduino function *digitalRead(PIN)* can be used, while the Arduino function *micros* returns the current time in microseconds. These built-in functions allow easy access to low-level functionality of the microcontroller. Custom C++ functions and classes can also be incorporated into the sketch, giving us a great deal of flexibility in how to write our code.

For this project, we decided to use a top-level Arduino file (file extension ".INO") to control main program flow, while C++ classes handle all hardware interfaces to the SCARA arm, linear actuators, and output devices. This allowed easy segmentation of work between team members, a modular method to test each subsystem independently, and simplified development of the program logic by hiding details of the implementation. The SCARA arm, for example, requires hundreds of lines of code simply to make a single motion, but can be commanded to make that motion with a simple call to a function of that class. The object-oriented approach also made it easy to keep track of the internal state of the SCARA arm, which was a vital requirement in order to enable the pause/resume capability required by §3.3.2.1.3. A flow diagram of the program and its associated classes is shown in Figure 62.

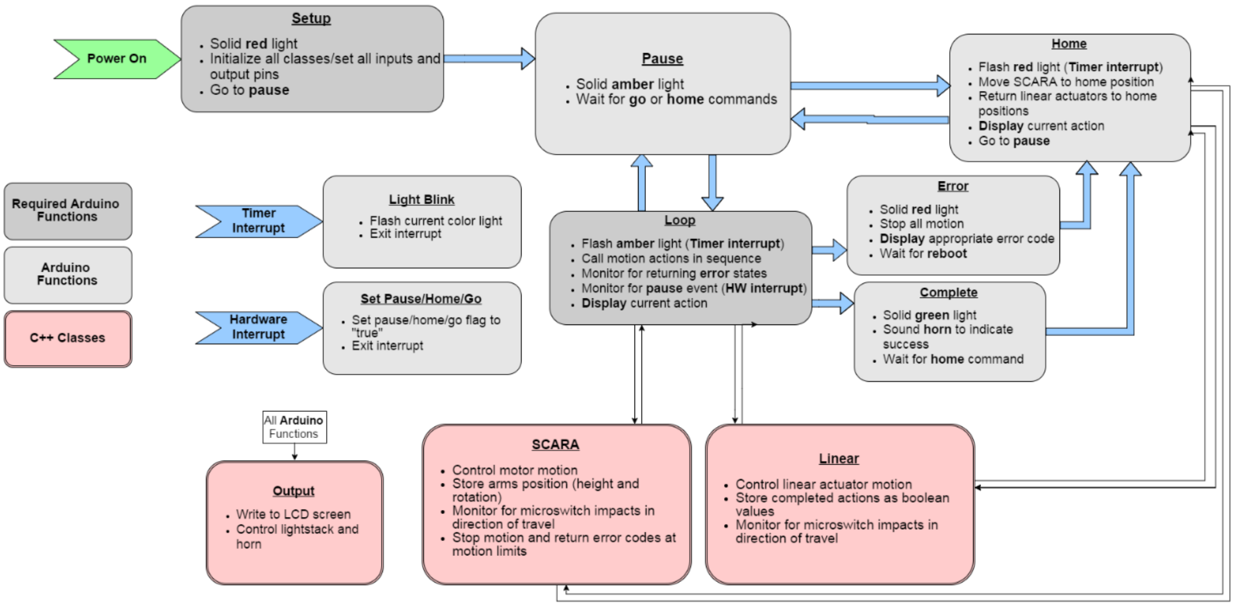


Figure 62: AGSE Firmware Program Organization and Execution. Required Arduino functions are shown in dark gray, added custom function in light gray, and C++ hardware interface classes in red.

The main program execution process along with the details of each interface class will now be described. For further detail, a full version of the AGSE controller code is available for examination at the Madison West Rocketry Github Repository.

Main Execution

The order of operations for the AGSE is handled in the *setup* and *loop* functions, with additional functions such as *pause*, *error*, etc. dedicated to handling state flow of the Arduino. Upon bootup, the Arduino will call *setup* in order to perform any required initialization functions. It is here that all input and output pins are set appropriately and the SCARA arm is assigned its predetermined set of motions for payload pickup. Over and above the requirements of §3.3.6.1, the red stack light is illuminated during the setup phase to indicate the AGSE is not set to run. Once setup is complete, the program passes control to the *pause* function.

Pause simply holds in place until the **GO** or **HOME** buttons are pressed (interrupt detection is discussed in a separate section). Control is passed to the appropriate function once either of these events occurs. The amber light is illuminated while *pause* is active, per §3.3.6.1.3.

The main contest execution – items §3.3.2.1.1 to §3.3.2.1.4 – is performed in the *loop* function. The SCARA arm actuation and linear actuators are called in sequence. The amber light flashes at 1 Hz in accordance with §3.3.6.1.3. In the event of a **PAUSE** command, execution is halted and control returns to the *pause* function. The SCARA arm tracks its current internal state and can properly resume from pause without losing its place in the internal sequence. The linear actuators do not have an internal state but will simply actuate until encountering a microswitch in the appropriate direction. This means that the linear actuators do not need to be tracked in order to resume gracefully from pause.

If the SCARA arm encounters a limit microswitch during payload loading, execution will cease and control will pass to the *error* function. Since the AGSE has no way to determine the cause of an unexpected microswitch encounter, *error* will simply hold in place and wait for a reboot and human intervention. If an error state is reached, the red stacklight will illuminate as notification.

Upon completion of the MAV requirements, control passes to the *complete* function, which simply illuminates the green “all systems go” light per §3.3.6.1.4 and waits for further instruction. From this state, **GO** has no functionality, but **HOME** can be used to return the AGSE to a secured position.

The *home* function will, in sequence,

- Clear the SCARA arm of the rocket carriage by traversing to the uppermost stop, rotating full outboard, and traversing to the lower stop
- Ensure the door actuation motor is fully retracted
- Ensure the igniter insertion motor is fully retracted
- Fully extend the erection motor in order to lower the rocket

The red stacklight will flash at 1 Hz during the homing procedure to indicate autonomous operation not associated with the MAV competition. **PAUSE** may be used at anytime during the homing procedure in order to cease operation. Once the home process is completed, the SCARA internal state is reset, control is passed to *pause*, and the autonomous procedures may be repeated again if desired.

Hardware/Timer Interrupts

Several interrupts are used in the AGSE firmware in order to achieve the required functionality. First, a timer interrupts set to a 1 Hz interval is always active. The interrupt service routine tells the *output* class to toggle a currently selected light – either the amber or red stack light – every time the interrupt occurs. For situations in which no light should be flashed, the interrupt still triggers, but the *output* class simply returns immediately rather than toggling a light.

Interrupts are also invaluable for handling user inputs. Three hardware interrupts are associated with each of the three user input buttons and are triggered when any of these buttons are pressed. An appropriate global flag is then triggered so that any function can check whether a current state exists or not. This is most applicable to the “pause” flag, since the SCARA and linear actuators must stop immediately should the pause button be pressed. Using interrupts on the input buttons is superior to active checking for a variety of reasons, including timing interference with the stepper motors and the relative likelihood of missing a pause command.

Unlike the user input buttons, microswitches do not rely on interrupts, simply because there are too many to use on the 5 available interrupt pins. Instead, a single microswitch corresponding to the direction of motion is monitored by the SCARA or linear actuators. Interrupts would again be a superior option for the microswitches, however, given the choice between using hardware interrupts for the input buttons or the end stops, the input buttons were a more logical selection.

SCARA Class

The SCARA class actuates the linear and rotary stepper motors associated with the SCARA arm. Open-loop control based on the number of commanded steps is used to determine the travel distance, and two modes of operation are available.

In the "manual" mode, each motor is commanded to move a certain distance and stop. If a microswitch is hit, the arm stops, but takes no other action. This mode is used by the homing routines to run up against the end stops and "home" the arm. Travel speed of the arm is low enough to avoid motor damage when coming to a sudden stop.

In the "automatic" mode, a series of movement commands is fed to the SCARA class and executed on command. After each action is complete, the total distance covered is subtracted from the stored set of distances. This means that, if the arm is paused at an intermediate point, it can resume operation precisely from where it left off. This mode is used for the main payload pickup/dropoff routines and is essential to enabling the pause/resume behavior of the AGSE. If a microswitch is triggered during automated motion, this indicates a programming error or other unforeseen problem in the system, so the SCARA arm stops and is no longer able to move using its set of internal motion commands. For this reason, microswitch triggers during the payload manipulation are treated as unrecoverable errors.

The stepper motors themselves are actuated by pulsing the appropriate GPIO pins at an appropriate frequency. The motors follow a trapezoidal velocity profile by steadily accelerating to a maximum speed before steadily decelerating to the target location. Directional control is handled by setting each driver's "DIR" pin to 5V or 0V as necessary.

Linear Actuator Class

The linear actuators for closing the payload door, erecting the rocket, and inserting the ignitor must function in sequential order with microswitch triggered program stops, built in hard stops, as well as backup timed stops. Each linear actuator is associated with two function within the class, one of which extends the actuator while the other retracts it. In order to control the direction of the motor, the actuators two relay pins are set to either (+5V, 0V) or (0V, +5V).

Each linear actuator shares similar functionality within the code. Each function will start by allowing power to be applied to the corresponding linear actuator movement. The functions will continuously check three conditions:

- Has the pause button been pressed?
- Has the corresponding microswitch which indicates end of movement been triggered?
- Has the movement been going longer than a designated amount of time?

Should any of these conditions be met, power will be cut from the linear actuator and the program will return from the current function to proceed with the next instruction.

Output Class

The output class manages operation of the lights and LCD screen. The stacklights are operated using a single GPIO pin for each light, this pin in turn activates the appropriate power relay associated with that light. In addition to the ability to turn on, turn off, and toggle each light, the output class can also store a "current light" that flashes at 1 Hz in accordance with the Arduino timer interrupts. During normal operation, the current light is set to amber, while during homing operation, it is set to red. While the *pause*, *error*, and *complete* states have control of the AGSE, the current light is set to "none" and no 1 Hz flashing occurs.

The LCD allows simple messages to be printed to the top of the screen, bottom of the screen, or both. In general, the top of the screen is used to display the current stage of operation – e.g. "Loading Payload", "Closing Door," – while the bottom stage displays the state of the system – "PAUSED," "RUNNING," or "ERROR."

Unit Tests and Verification

A "unit test" function was written for each class in order to fully check its function independently from the other program components. These unit tests have allowed successful verification of the code after major hardware or software changes, and will be essential to ensuring the AGSE operates correctly after transport to Huntsville. Full verification of the autonomous routines has also been performed, as shown in the included video.

Safety

We will address all aspects of safety through materials selection, process control, and by design of the controls and mechanisms. Provided elsewhere in this proposal are the MSDS sheets for the proposed materials used; this section focuses on the design aspects of safety.

A key safety aspect worth amplifying is that the control system proposed here does not include launch of the vehicle itself nor does it include anything addressing the aspects of ignition. The igniter, while inserted into the engine autonomously, is not electrically wired to the system nor is the system capable of firing the igniter.

As highlighted before, the physical aspects of safety related to motion-control system are addressed through a combination of active feedback from the motion stages (in some cases), integrated micro switches, and physical hard stops. Furthermore, the control box contains both a physical pause button to stop the code from executing as well as an E-stop that cuts power from the entire system. The code will be written in a fashion to enable the sequence to be stopped anywhere along the way in needed for safety reasons.

The control box, while mounted to the superstructure, is located well-away from the moving parts and any pinch points. Potential pinch points in all of the moving parts will be clearly labeled and/or painted brightly to call attention to that safety aspect.

As for electrical safety, the choice of a low-voltage, battery-based approach ensures fundamental safety to the students and educators during all phases of development. By using off-the-shelf drivers and relays to direct the higher currents required directly to the motors, this minimizes design work and interaction with the high-current parts of the circuits; the remaining aspects of the electrical work are lower voltage (3.3V) and lower current (<100mA).

The assembly and packaging of the electronics will be carefully overseen and inspected to ensure proper assembly, solder, and insulation techniques are used to prevent shorts or overheating of components or subsystems.

During assembly, test, and debug, safety of the team will be given the utmost importance, ranging from protocols for distance from the system envelope during operation to using non-live engine loads for insertion testing. Furthermore, given the 10-minute performance budget for the sequence, it is anticipated that all motion in the system will be slow and deliberate, giving any humans near the device time to move to safety in the unlikely case of collision.

Mass Statement

Using the draft concept detailed bill of materials we have revised our estimate of the mass of the structure and vehicle. This is still a preliminary estimate based on a mixture of actual measurements of acquired parts, datasheet statements of masses, and engineering estimates based on prior knowledge or common-sense based on the size and type of materials.

Analysis

The AGSE fixed superstructure is by far the largest contributor to the total system mass, primarily because of the scale of the design. The structure needs to be long enough to accommodate the length of the rocket plus igniter insertion, amplified by the fact that the payload will be inserted just below the vehicle nose cone, and thus all of the payload handling equipment is at the fore end of the rocket and the erection and igniter insertion are aft. Further constraints on the superstructure size are the need for stability of the ground interface footprint of the launch pad given the length of the rail and the thrust of the engine at take-off, and the distance of the structure’s feet from the axis of the launch rail.

The robotics and motion control for grabbing the payload, inserting it, and closing the door are the next major mass contributor, dominated by the sturdy stages needed to move the payload and effect the torque required to secure the payload in the rocket.

The rail erection and controller are the next major mass contributions. The erection motion control and brackets dominate that mass contribution, whereas the controller’s main contribution is the relatively dense gel-cell battery.

In Figure 63 and Table 32 below we summarize the latest, revised mass estimates for the entire system, vehicle and launch apparatus. We divide the aspects into the logical subsystems as described above, including separating vehicle-related and the payload aspects of the vehicle, and the logical subsystems required to support each of the motion control aspects.

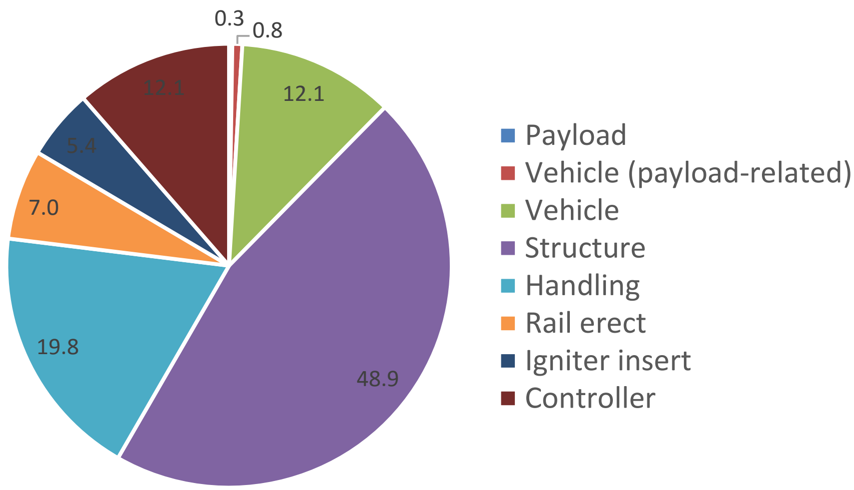


Figure 63. AGSE Mass Allocation.

Subsystem	Mass (lbs)	Comment
Payload	0.3	just the PVC payload and weighting
Vehicle (payload-related)	0.8	includes items required to retain and secure the payload
Vehicle	12.1	all aspects of the rocket including structure, propulsion, recovery, telemetry
Structure	48.9	the static superstructure of the ASGE
Handling	19.8	the robotic motion control for acquiring and depositing the payload
Rail erect	7.0	lifting the launch rail into a near-vertical position
Igniter insert	5.4	insertion of the igniter into the engine
Controller	12.1	all aspects of control including microcontroller, drivers, indicators, safety lights, housing, and po
TOTAL	**106.4**	

Table 32. Summary of mass contributions to Maxi-MAV and AGSE.

This is still a preliminary estimate of the masses, and puts us well under the 150 pound specification limit. Our estimate includes line items for mass overage error for each subsystem, roughly proportional to the mass of that subsystem, attempting to buffer against errors or creep as the design is fully developed and matured.

Examining each of the subsystem, we believe the highest-risk subsystem is the superstructure itself, not only because it is the largest contributor, but as the design is refined and built, it may be determined that additional cross-bracing or struts are needed beyond the current design plan to ward against twist/deformation during payload motion and insertion, as well as overall dimensional stability of the entire structure.

Because we estimate we are well below the specification budget, we see this as a low risk to meeting the specification, but constant focus is maintained on minimizing system mass as far below specification as possible. These estimates leave us confident that the system will end up below the SoW requirement of 150 pounds total (§3.3.3.3).

Key components and subsystems

The table below lists key components and subsystems that we have made a preliminary down-selection towards, and believe will support the overall goals of the Maxi-MAV challenge.

Subsystem	Description	Manufacturer/Supplier	Model
Payload retention	Dowel holder / spring steel clip	True value	
Payload retention	Eyeglass case spring hinge	Donation from local Costco	n/a
Payload retention	Magnet	KH magnetics	
Structure	8020 rail	club inventory, McMaster-Carr	
Structure	8020 assembly hardware	McMaster-Carr	
Handling	Laser line generator	Craftsman/Amazon	
Handling	Gripper	True value	
Handling	Linear motor stage (8") / vertical	THK/eBay	N/A
Handling	Stepper motor with encoder	StepperOnline (NEMA 17/23 size)	N/A
Handling	Linear actuator (2") / door closer	Everest Supply or Firgelli	
Erection	Linear actuator (18")	Everest Supply or Firgelli	N/A
Erection	Pillow sleeve bearing	McMaster-Carr	
Erection	Shoulder bolt	McMaster-Carr	
Insertion	Linear actuator with track mount	Firgelli	
Insertion	Carbon-fiber tube	McMaster-Carr	
Controller	Microcontroller	Sparkfun	Arduino Uno R3
Controller	Relay shield	Sparkfun	
Controller	Stepper driver with microstep	TBD	
Controller	Battery, 12 Pb-acid/gel	Tenergy or similar	e.g., TB12120
Controller	Indicator tower	uxcell/Amazon	12V tricolor

Table 33 List of selected key components

During this phase, every key component has been defined, the requirements for that component and flow-down specifications unique to that component have been at least outlined and defined. We feel that a key driving principle of the design is to use simple passive components wherever possible, minimizing the number of active components and moving parts wherever possible.

None of the components used or subsystems we implement violate any of the subclauses of SoW §3.3.4.

A related aspect is “design re-use,” seeking to re-use or re-purpose components and subsystems wherever possible. This has a dual benefit, since this approach usually enables the use of consumer or hobbyist components which have a much higher production volume and therefore lower costs. Given the limited life and number of cycles required of the entire system, this is a very reasonable tradeoff.

Below we call out some of the specific component aspects in this regard:

Re-purposed/creative use

- Hard glasses case hinge/spring closing mechanism (payload compartment in vehicle)
- Spring clip used for retaining brooms/rakes (payload compartment and gripper)

- Laser line generator from drill press (payload location)

Surplus

- Linear vertical motion stage (payload transport)
- 80/20 construction rail (AGSE superstructure, payload transport, erection and launch rail)

Traditional components applied in a novel fashion

- Linear actuators (often used in home automation/audiovisual systems, race car spoiler raise/lowering) used for igniter insertion, rail erection, payload door closure
- Rugged door hinges used for launch rail pivot
- Low-cost stack lights from industrial machinery
- Low-cost high-strength magnets used to retain payload door during launch

AGSE Verification plan

Overall Plan and Status

The sequence of verification steps for the vehicle is summarized in Table 34.

#	Step	Goals	Milestone	Status
1	***Concept design***	• Preliminary structure/launcher design • Preliminary payload manipulation & insertion approach • Preliminary control system approach • Preliminary power source and architecture • Preliminary vehicle payload retainment approach • Preliminary weight estimate • Preliminary budget estimate	**SOW**	**PASSED**
2	***Solid Modeling and Development***	• Use SolidWorks® software to develop full AGSE assembly • Determine required dimensions for each component • De-conflict ranges of motion for robotic subsystems	**PDR/CDR**	**PASSED**
3	***Hardware Familiarization***	• Assemble critical subsystems in isolation • Gain proficiency with hardware assembly techniques • Verify motor functionality and suitability	**PDR/CDR**	**PASSED**
4	***Assembled Hardware Test***	• Assemble full AGSE • Manually actuate robotic components through required MAV procedures • Perform live launches from AGSE	**CDR**	**PASSED**

5	***Firmware Verification - Component***	• Verify correct firmware function prior to use with robotic subsystems • Check stepper motor controller using oscilloscope trace • Check linear actuator controller with multimeter • Check microswitches, control inputs, and general functionality with serial print commands	**FRR**	**PASSED**
6	***Hardware/Firmware Integration - Component***	• Test subsystems individually • Verify correct microswitch function for stepper and linear motors • Verify correct travel distances and speeds for stepper motors • Ensure functionality of stack lights and LCD • Test payload placement procedure	**FRR**	**PASSED**
7	***Full System Verification***	• Perform fully autonomous MAV Challenge routine • Pause and resume during every phase of autonomous motion	**FRR**	**PASSED**

Table 34: Verification Plan and Status

Table 35 summarizes the testing completed on the AGSE portion of the Maxi-MAV system. Following this summary table we describe in detail the testing performed and results achieved from that testing, as well as how some of the preliminary testing influenced or caused revision of the the design through the SoW/PDR/CDR phases.

Subsystem	Tests	Page
AGSE Structure	1. General rigidity and stiffness verification 2. Launch rail testing; vehicle and wind loading 3. Wind stability load testing 4. Full scale launches and environmental testing 5. Weight assessment	104 106 107 108 108
SCARA Arm	1. Load testing 2. Motion accuracy tests 3. Microswitch functionality tests 4. Full payload pickup procedure	109 110 111 112
Linear Motors	1. Range of motion tests 2. Microswitch functionality 3. Igniter insertion	112 113 113
Outputs: Stacklight/LCD	1. Light operation tests 2. LCD operation tests	113 114
Power/control	1. Pause/interrupt testing 2. Procedure length/timing	114 114

Table 35: Subsystems Testing

AGSE Structure

General rigidity and stiffness verification

An extruded aluminum system of parts rich with available sizes and accessories was chosen, called 80-20. Preliminary beam deformation calculations were performed to select the profile size for the main frame and other key structural members. For the outermost rectangular frame, 1 inch by 2 inch rail was chosen to provide adequate structure strength for the long, unsupported section (8 feet). The 2-inch direction is mounted vertically to provide stiffness, while the 1-inch section is horizontal, since less strength is needed laterally owing to the cross-beams and box/girder construction techniques.

The general rigidity and integrity were tested semi-quantitatively once the overall structure was assembled, to determine that the structure was robust for general handling, transport by van, accommodating various field conditions, etc. During assembly, transport during repeated field testing and evaluation the structure was subjected to approximately 100 pounds of force in axial twist, compressive loading from the side, and from the ends. The structure did not sustain deformation or structural change of note during this qualitative testing.

The main structure was subjected to quantified vertical loading and deflection measurements for two key design criteria: stability of the structure to static loads (rocket and all other stages) and to dynamic loads (rocket takeoff). Two critical load levels should be noted here, approximately 10 pounds, the weight of the rocket, and approximately 200 pounds, the estimated peak load during rocket lift-off from the launch platform. Test conduct is shown in Figure 64.

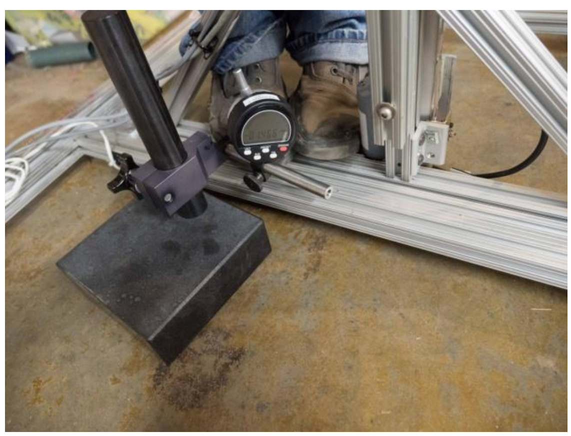


Figure 64. Deflection measurement testing of the AGSE structure using 10 pound (*top*) and 200 pound (*bottom*) loads

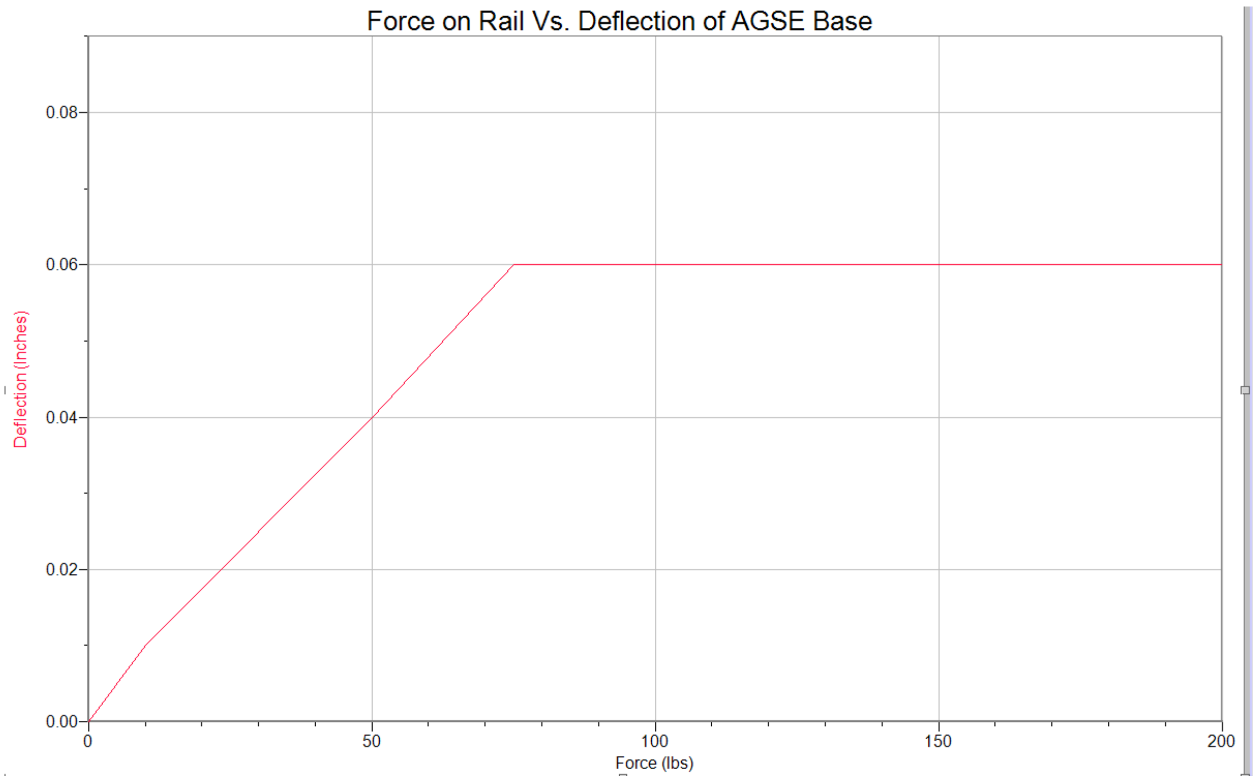


Figure 65. Deflection data of The AGSE base frame under static load.

As can be seen from Figure 65, the deflection even under peak load is only 0.06 inches. Note that the center horizontal support for the launch rail is designed to touch the ground at 0.06 inches of deflection. All of this structural deflection is well within the elastic limits for the 6061T6 aluminum used in the design.

Launch rail testing

The launch rail and erection system must be able to support the weight of the vehicle and payload as well as itself at every angle of erection from 0 to 85 degrees. For the linear motor and pivot design used, the highest load on the linear motor is at the 0 degree (horizontal) position, so this was the focus of our testing.

Testing was performed two ways: preliminary testing during design verification and final testing prior to FRR.

Preliminary design testing is shown in Figure 66; aluminum plates, with measured weight of 23 pounds, were carefully stacked at the calculated center of weight of the rocket onto the launch rail. The erection motor was actuated and the ability to move the plates as well as the current draw from the motor were recorded. As can be seen in the image, the rail was successfully able to rise even with the approximately 2 times load of 23 pounds. Peak motor current was measured at 3.2 amperes.

Figure 66. Representation of Preliminary load testing performed during PDR/CDR design phases.

It is notable that this preliminary testing proved quite important in driving modification to our vertical erection cylinder mounting location and mounting method, to ensure that adequate vertical lift force was provided by the cylinder while still maintaining a minimal overall physical AGSE envelope size (height especially here).

Final testing was performed with a dial-based flexure load measurement instrument as shown in Figure 67.

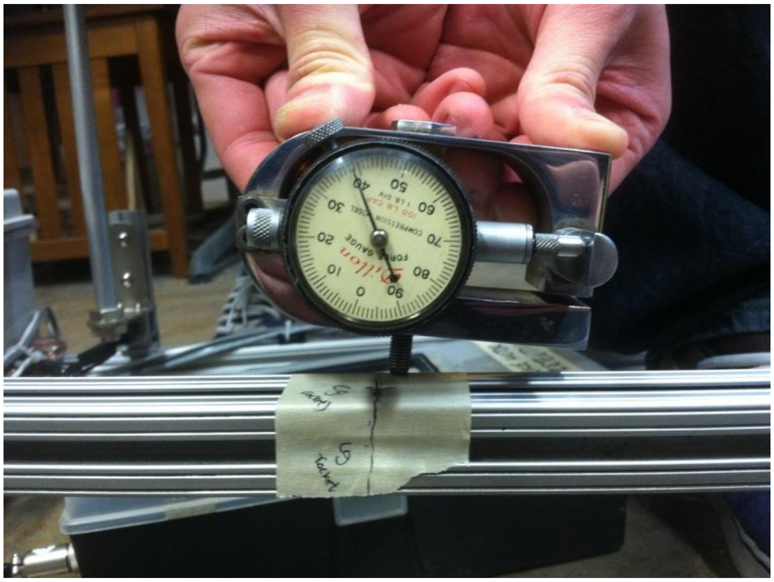


Figure 67. Rail load testing with calibrated dial gauge.

AGSE Stability Testing

Stability of the structure against wind loads was evaluated. The stability of the entire AGSE to wind loads for tipping was also tested from both sides of the AGSE (which are the shortest legs and thus the most likely to lead to tipping of the AGSE. The rail required 20 lbs of force before the legs lifted off of the ground.

Figure 68. AGSE wind stability testing.

Full-scale vehicle and environmental exposure testing

The AGSE has been exposed to the forces and stresses of both outdoor operation in Wisconsin winter as well as the stresses of vehicle launch exposure. The results of this “real-world” testing have resulted in some notable changes/modifications during the PDR/CDR/FRR phases:

- Rusting of the exposed lead screw in the igniter insertion stage – silicone dry-film lubricant has been added to resolve this
- Minor damage to the aluminum blast protection plate – a permanently-affixed blast reinforce made from an abrasive grinding disc has been added
- Improvement to the tolerances for aligning the igniter insertion rod to the blast plate by adding a small funnel to guide the igniter/rod into the blast hole

The AGSE has been used for dozens of launches of rockets ranging from E to K class motors and it has proven stable and durable across all of these launches. The environmental conditions have ranged from rain to sub-zero cold temperatures with high winds.

Figure 69. AGSE platform launching a J-class rocket in inclement Wisconsin weather.

Weight Assessment

The AGSE and subsystems have been measured to verify the overall weight. The system is compact enough that it can be placed on a bathroom scale for weight assessment. Note that during previous design phases, individual subsystems were measured separately from the fully-assembled system for verification.

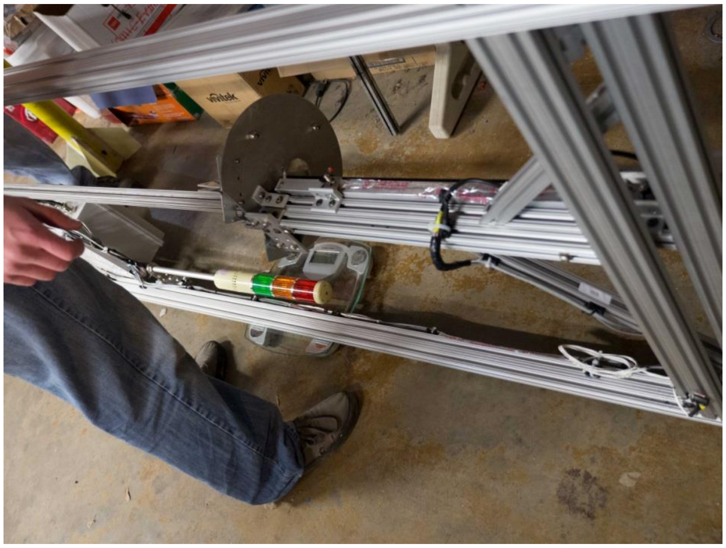


Figure 70. Weight assessment of the full-assembled AGSE.

The final weight of the AGSE was measured to be 72.25 pounds, weighed using a Healthometer dual load-cell digital bathroom scale

SCARA Arm

Load Testing

The individual stages were load tested to ensure they met the manufacturer specifications and our requirements. At the time these were tested using a Healthometer dual load-cell digital bathroom scale

The vertical stage was tested to 20 pounds as judged by the ability to continue to apply force to the scale.

Figure 71: SCARA vertical stage load test

The rotary stage was tested to 5 ounces using the 16 inch long arm and a 5kg capacity load pull tester. It was tested until the rotary stage stalled.

Figure 72: Measurement of SCARA arm peak force using load pull tester

Motion accuracy

The vertical stage motion was calibrated and verified in two ways: by using the microstep size of the stepper motor, counts indicated in the firmware, and the pitch of the leadscrew used in the linear stage. Many tens of thousands of counts were used and the distance of travel was verified by measuring with a ruler. Note that the vertical stage resolution is much finer than required for this application.

Figure 73: Accuracy of vertical stage being measured with ruler

The rotary stage's effective linear resolution when outfitted with the approximately 16-inch long arm and operated at a 1/128 step size was verified by taking 4-10 steps and measuring the motion at the end of the arm with a ruler. These measurements, combined with successful conduct of the payload placement procedure, confirm the accuracy of the open-loop step-based motion control.

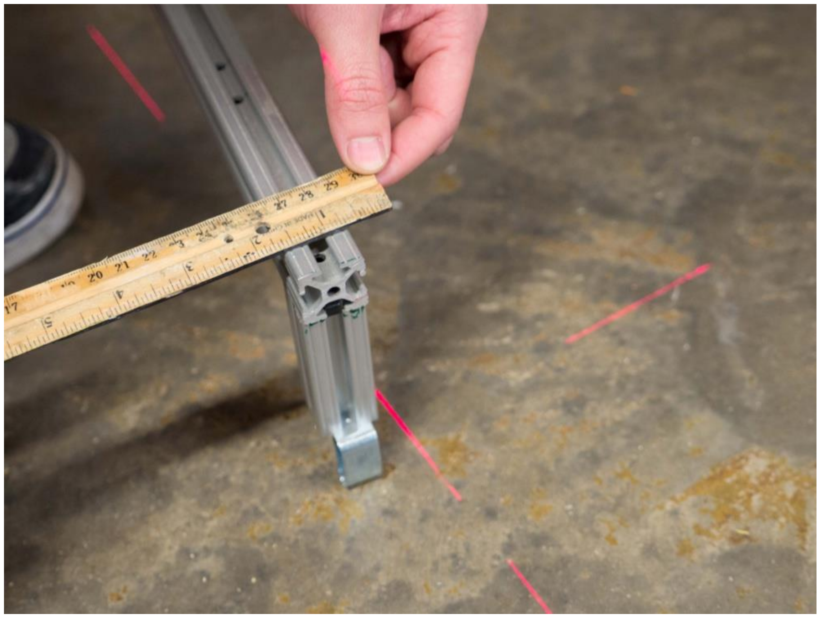


Figure 74: Accuracy of rotary stage being measured with ruler

Microswitch function

The microswitch functionality on the two SCARA motion stages is the most critical in the system since the stepper motors do not have any knowledge of their location without them.

The microswitches were verified both electrically with continuity tests as well as with the firmware to verify signal integrity. Analog signal integrity was verified both at DC to measure signal levels high and low into the Arduino, but also at AC to look for spikes or bounce in the signal. This also served to verify the functionality of the debounce switches.

The microswitch functionality for mechanical location was tested for both stages to verify that the microswitch closed when the stage was in the required/expected location. During design, adjustments were made to the location and in some cases the mounting and solidity of the switch mounting were improved.

Note that a routine built into a subset of the homing firmware tests the functionality all of the microcontroller-connected microswitches.

The homing routine which is part of the autonomous procedure has been run repeatedly and verifies the location, functional, and sufficiency of the microswitches for these two stages every time the procedure is run.

Full pickup/load procedure

The full procedure using the SCARA involving the loading of the payload, motion, and unloading was run many times to verify full operation of this subsystem. Snapshots of the load sequence are shown in Figure 75. This all-in testing verifies many key design parameters:

- Sufficiency of laser crosshair and human interaction to adequately locate/register payload with respect to SCARA arm and AGSE
- Vertical stage force capability to push arm clip over payload
- Capability of SCARA to transport payload and maintain payload registration to clip
- Clearances of SCARA motion with respect to ground, AGSE, rocket, and rocket/payload securing door
- Capability of SCARA to provide sufficient force to push the payload into the bay
- Capability of the payload bay retention clips to retain payload once arm retreats
- Capability of SCARA to maintain counts under load and thus maintain knowledge of location during motion sequence

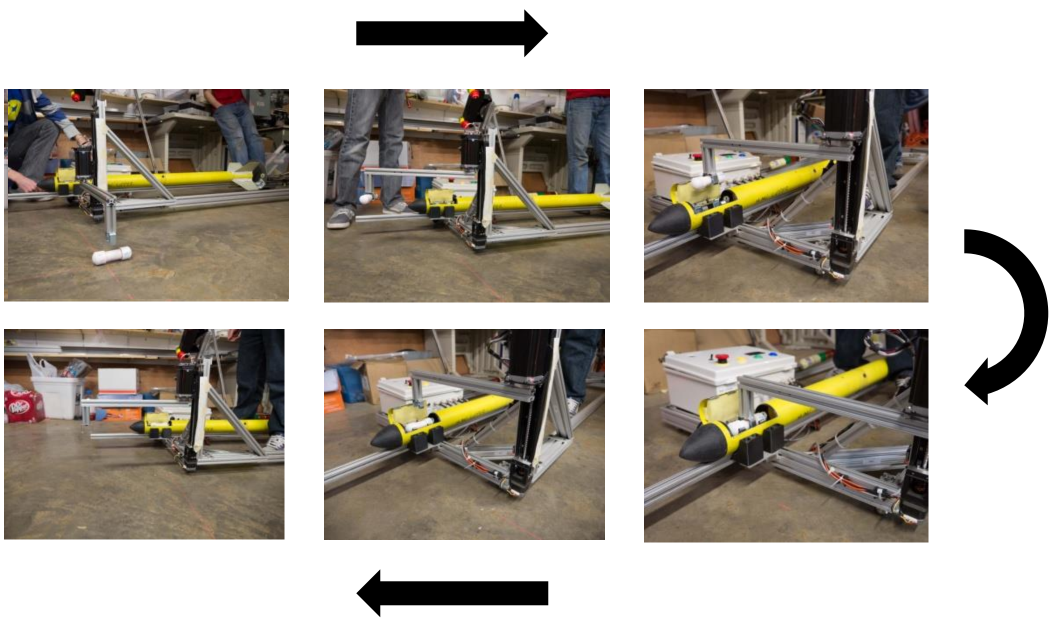


Figure 75: Payload Loading Sequence

Linear motors

Range of motion

There are 3 linear motors used, one of which is used to their full range of motion and two are necessarily limited by design.

The door closure motor was tested for range of motion, both for sufficient travel as well as compatibility with the rocket door and ability to close the door, and found to be fully adequate, demonstrating the full 2 inch range of travel.

The igniter motor was tested for range of travel and meets the manufacturer requirements. During PDR/CDR adjustments were made to ensure free and clear motion from two unexpected sources: end-of-travel microswitches and alignment of the igniter insertion rod to the blast deflection shield. Minor adjustments to the design ensured full range of travel and this was fully tested after the modifications were made.

The erector motor was also tested for range of travel and found sufficient. This stage is used for a limited set of travel and the limits are discussed in the next section.

Microswitch function

There are two sets of microswitches in this design, a pair integrated into each linear stage, and a set that sit outside the stage that are monitored by the microcontroller. The integrated pair on each linear stage acts as hard stops, cutting power to the motor when engaged; functionality of each pair was fully verified for each stage. The external microswitches were verified both electrically with continuity tests as well as with the firmware to verify signal integrity. Analog signal integrity was verified both at DC to measure signal levels high and low into the Arduino, but also at AC to look for spikes or bounce in the signal. This also served to verify the functionality of the debounce switches.

The microswitch functionality as for mechanical location was tested for each stage, to verify that the microswitch closed when the stage was in the required/expected location. During design, adjustments were made to the location and in some cases the mounting and solidity of the switch mounting were improved.

Note that a routine built into a subset of the homing firmware tests the functionality all of the microcontroller-connected microswitches.

Igniter insertion

The igniter insertion functionality was tested during one launch to verify: sufficiency of motion travel, diameter of insertion rod, lack of interference, and ability to achieve ignition and rocket takeoff. The insertion method proved completely adequate and the igniter support method did not interfere with the launch in any way.

Outputs

Stacklights

The flashing rate, colors, and functionality of the stacklights were verified against both the specification, as well as additional functionality imposed by our own requirements as follows:

- 1 second ON, 1 second OFF for all flashing modes of all lights
- Amber – flashing only during operational procedure, solid during pause
- Red – flashing only during homing procedure (solid if homing itself is paused)
- Green – on solid only at end of successful autonomous procedure

LCD

The LCD messages during the operation were verified for contrast, visibility. The content of the messages was verified for relevant to the particular phase of the process it reflected.

Interrupt operation

Interrupt functionality was tested repeatedly over multiple runs of the autonomous procedure and incurred during every single phase of the procedure to ensure that the functionality is fully working and seamless.

Procedure length/timing

The procedure was run and a stopwatch was used. The process from end to end was measured to take 4 minutes 33 seconds.

Requirements

All payload requirements are in detail addressed in Project Requirements section, with Payload Requirements starting on page 126. The detailed description of the proposed payload starts on page 114.

Major Technical Challenges and Solutions

The technical challenges related to selected payload option (Task 2, Centennial Challenges) are described together with suggested solutions earlier in the above section (pages 114-99). The proposed design has been checked for compliance for with project requirements.

Next steps

The detailed technical description above included major aspects of progress already achieved for each area or subsystem. This section aims to briefly outline the next steps in order to prove the design ready for FRR and full-scale operation.

The subsystems need to be fully secured to the AGSE and verified, namely the SCARA arm subassembly, control box, and wiring harnesses secured to the frame. The control box and associated connectors and wiring must all be completed through all soldering stages and integrated into the project box. All of the microswitches for feedback must be mounted, wired, and integrated with the connectors as well.

The payload compartment is fully constructed but has not yet been subjected to full-scale flight testing – this will fully prove out all aspects of the payload confinement and door closure.

The SCARA arm must be tested with the full-scale payload compartment and exercised for many cycles (dozens to hundreds) for load testing and debugging of the code. This testing cycle will also allow for integration of the microswitch feedback.

The door closure means has not been tested with the newly-fabricated payload nest and will be done. Erection has been fully tested under load but should be tested with the full-scale vehicle to verify operation. Similarly igniter insertion with the full-scale vehicle must be tested and exercised many times to verify operation.

The code base currently consists of bits and pieces that can control each aspect of the sequence, but must be tied together as a complete sequence, tied in to button inputs, LCD and light outputs, and the pause/interrupt functionality implemented. The task of homing the AGSE before the autonomous sequence is performed is a task of similar magnitude and must address that stages or motors may be in an unknown or erroneous state when starting the homing procedure.

The entire sequence must be run many dozens to hundreds of times to find bugs, weaknesses, decay of alignment tolerances, etc. in order to verify that the sequence will work under the pressure of NASA judges and operating in a foreign environment.

Supporting measurements and evaluation must also be completed including correct/detailed mass measurements of the ASGE, current draw for various phases, timing of entire sequence, and better quantification of loads and forces during SCARA operation.

Educational Engagement

Status

We have already participated in three outreach events:

1. **Boy Scouts Pack #302:** we have displayed many of our rockets and payloads, helped the participant to build and launch pneumatic rockets and participated in about a 30 minute long discussion about our program and projects. *Estimated reach of 50 people.*
2. **Homecoming Parade:** the parade is traditionally held in October and it is an opportunity to inform Madison Community about our projects in a fun and visual-rich way. *Estimated reach of 200 people.*
3. **Wisconsin Science Festival:** is a major outreach events held in many location across Wisconsin. Our station was located in Wisconsin Institute of Discovery, Madison, WI. We have displayed several of our past Student Launch projects, helped participants to build and launch pneumatic rockets and engaged in impromptu discussions with all interested festival visitors. *Estimated reach of 3000 people over two days.*
4. **Science Bowl:** is a science contest for middle schools and we were invited to provide activities for teams currently not competing (each team has an hour break period). We have displayed semi-functional AGSE and several of our past SLI projects. All visitors of our station were invited to build and launch a pneumatic rocket.
5. **Physics Fair:** is a major public outreach event running concurrently with Wonders of Physics show. This was our third year at the event and we were provided with entire classroom for our displays and activities. AGSE was demonstrated to fair visitors and as usual, everybody had a chance to build and launch a pneumatic rocket. We have also displayed several of our project and invited fair visitors to ask questions and discuss the projects.
6. **Wingra School Science Night:** We displayed selection of our SLI and R4S projects, as well as TARC rocket. Each participant can explore our displays, have a discussion with Madison West students, build and launch a pneumatic rocket or any combination of these activities. This events runs for one hour and is very fast paced. This was our second year at this event.
7. ***Super Science Saturday at Randall School:*** Randall School holds annual Super Science Saturday event and we have been participating for last 7 years. We bring both Alka Seltzer and pneumatic rockets as hands on activities, in addition to displays of our current and recent projects. Our students interact in one-on-one setting with event participants and help them build and launch either pneumatic or Alka Seltzer rocket. Our students also answer all questions about our displays.

We have also helped with construction tasks at new Madison Museum of Science and in connection with this volunteer activity we have been awarded a grant from Madison Civics Club, while the club members were afforded the opportunity to meet with Mimi Gardner Gates, a stepmother of Bill Gates. The grant will help us to improve the displays and activities that we offer at our outreach events. The first project related to this grant will be a working display of a plasma thruster, built in cooperation with Prof. Amy Wendt from Dept. of Engineering at UW, Madison.

Overall Plan

Each year we participate in numerous outreach events, ranging from a single classroom activity to large public events, such as Physics Open House at UW Madison or multiday state-wide Wisconsin Science Festival. For years we have been steadily building selection of outreach opportunities and now we reach approximately 3,000 people each year. We provide all supplies and materials for our outreach events, utilizing minimum cost designs (such as pneumatic rockets) or surplus materials from our previous season.

We keep in contact with our local communities via our *Raking for Rockets* fundraising program. Last year the students in our program rake close to 100 yards in exchange for donations to their projects. Several times during our fundraising season (October-December) our raking and yardwork teams help those who could not afford yardwork services otherwise.

Besides these programs, we continuously recruit new members for our club at Madison West High School (our current membership is above 50 students mark) in a number of recruitment events which include organized recruitment events and posters advertising the location and time of the first informational meeting. Our major source of new members comes from personal referrals, either students bringing their friends or parents sharing information about our club with other families or neighbors.

The table below shows the outreach programs that we have planned for this year. The programs target primarily elementary and middle schools. We will most likely add several events to this program as the year progresses (we have become well known for our outreach activities and are steadily receiving requests from schools and organization that we have never worked with before).

Date	School	Outreach	# of People (estimated)
Oct. 8, 2015	Boy Scouts	Pneumatic rockets, Alka-Seltzer rockets	50
Oct. 16, 2015	Randall Elementary	School Homecoming Parade	200
Oct. 24/25, 2015	Wisconsin Science Festival	Pneumatic rockets, Alka-Seltzer rockets	7500
Feb. 13, 2016	Physics Open House	Displays, pneumatic rockets	600
Mar. 12, 2016	Randall and Franklin Elementary – Super Science Saturday	Pneumatic rockets, Alka-Seltzer rockets	200
Mar. 14, 2016	Kennedy School Science Night	Pneumatic rockets, project displays	100
Mar. 19, 2016	O'Keeffe Middle School Super Science Saturday	Pneumatic rockets, Alka-Seltzer rockets	80
April 1, 2016	Kids Express	Pneumatic rockets, Alka-Seltzer rockets	50
			Total: 8780

Table 36: Planned outreach events

Project Plan

Project Requirements

The following is a list of all vehicle related project requirements, listing the requirement itself (in **bold**), how the requirement will be addressed (in plain text) and how it will be verified (where applicable, in *italics*).

1.1. The vehicle shall deliver the payload to an apogee altitude of 5,280 feet above ground level (AGL).
The current simulation predicts that the rocket will reach 5,264*ft*. The coefficient of drag is set to C_D = 0.7. We have obtained this experimentally measured value from our previous experiments using a similar constant diameter K-class delivery vehicle. The performance predictions will be updated as data from scale model flight and half-impulse flight become available. If necessary, the rocket will be ballasted to prevent it from exceeding altitude of 1 mile. The amount of ballast will not exceed 10% of rocket liftoff weight. – *Verified by computer simulations and test flights*

1.2. The vehicle shall carry one commercially available, barometric altimeter for recording the official altitude used in the competition scoring. The altitude score will account for 10% of the team's overall competition score. Teams will receive the maximum number of altitude points (5,280) if the official scoring altimeter reads a value of exactly 5,280 feet AGL. The team will lose two points for every foot above the required altitude, and one point for every foot below the required altitude. The altitude score will be equivalent to the percentage of altitude points remaining after any deductions.
The vehicle will carry two identical barometric altimeters (PerfectFlite StratoLogger CF), each capable of serving the role of official scoring altimeter. The team will designate and visually identify one of the altimeters as the official scoring altimeter, before the actual flight. – *Verified be visual inspection, checklist and audio feedback when the altimeters are powered up before flight.*

1.2.1. The official scoring altimeter shall report the official competition altitude via a series of beeps to be checked after the competition flight.
We will use PerfectFlite StratoLogger CF altimeter which satisfies this requirement. – *Verified by inspection*

1.2.2. Teams may have additional altimeters to control vehicle electronics and payload experiment(s).
We will have two fully redundant barometric altimeters to ensure successful deployment of parachutes. – *Verified by inspection and checklist*

1.2.2.1. At the Launch Readiness Review, a NASA official will mark the altimeter that will be used for the official scoring.
We will select our scoring altimeter prior to the Launch Readiness Review to enable NASA officials to mark the altimeter. – *Verified by inspection*

1.2.2.2. At the launch field, a NASA official will obtain the altitude by listening to the audible beeps reported by the official competition, marked altimeter.

Following the recovery of our vehicle, we will report to NASA officials so they may record the altitude of our flight. – *Verified by postflight checklist*

1.2.2.3. At the launch field, to aid in determination of the vehicle's apogee, all audible electronics, except for the official altitude-determining altimeter shall be capable of being turned off.
All of our flight electronics will have individual switches which will allow us to turn off the altimeters. – *Verified by preflight inspection*

1.2.3. The following circumstances will warrant a score of zero for the altitude portion of the competition:

1.2.3.1. The official, marked altimeter is damaged and/or does not report an altitude via a series of beeps after the team's competition flight.
We will take proper precautions to ensure no altimeters are damaged during the flight. – *Verified by preflight inspection*

1.2.3.2. The team does not report to the NASA official designated to record the altitude with their official, marked altimeter on the day of the launch.
After recovery of our vehicle, we will report to the NASA official designated to record the altitude. – *Verified by postflight checklist*

1.2.3.3. The altimeter reports an apogee altitude over 5,600 feet AGL.
Test flights and computers simulations will be performed prior the official SL launch to ensure that our rocket does not exceed the target altitude of 5,600 feet AGL.

1.2.3.4. The rocket is not flown at the competition launch site.
Our rocket will be flown at the competition launch site.

1.3. The launch vehicle shall be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.
The vehicle is designed as reusable and can be launched several times a day. The maximum flight preparation time is 2 hours. – *Verified by postflight checklist*

1.4. The launch vehicle shall have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.
The vehicle consists of three tethered sections (nose cone, compartment housing both the payload and main parachute and the booster section). – *Verified by design and inspection*

1.5. The launch vehicle shall be limited to a single stage.
Our launch vehicle will utilize only one stage throughout the duration of the flight. – *Verified by design*

1.6. The launch vehicle shall be capable of being prepared for flight at the launch site within 2 hours, from the time the Federal Aviation Administration flight waiver opens.

The maximum preparation time for the rocket is 2 hours. The team will practice the vehicle preparation in order to assure their ability to ready the vehicle for launch within allocated time. – *Verified by dry runs and during test flights (the preparation period will be timed)*

1.7. The launch vehicle shall be capable of remaining in launch-ready configuration at the pad for a minimum of 1 hour without losing the functionality of any critical on-board component.

The launch vehicle can remain in launch ready configuration for several hours. The altimeters are rated for 24 hours of wait time. Battery capacities and available standby time will be tested extensively during project development. – *Verified by test in workshop*

1.8. The launch vehicle shall be capable of being launched by a standard 12 volt direct current firing system. The firing system will be provided by the NASA-designated Range Services Provider.

The vehicle is using Cesaroni motor which is compatible with 12V igniters. Electrical current of 3A is sufficient to fire the igniter. The vehicle can be launched from the standard 12V launch system. – *Verified during test flights*

1.9. The launch vehicle shall use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).

Only motors satisfying this performance target are used in design, testing and operation of the vehicle. Currently, Cesaroni K760WT motor is the primary propulsion choice. – *Verified by inspection and design*

1.9.1. Final motor choices must be made by the Critical Design Review (CDR).

We will select our final motor prior to the Critical Design Review. – *Will be verified by documentation review prior CDR package submission*

1.9.2. Any motor changes after CDR must be approved by the NASA Range Safety Officer (RSO), and will only be approved if the change is for the sole purpose of increasing the safety margin.

If a change of motor is necessary after the CDR, we will communicate with the NASA Range Safety Officer in order to have the modification approved. We will comply with instructions given by NASA.

1.10. The total impulse provided by a launch vehicle shall not exceed 5,120 Newton-seconds (L-class).

Our primary propulsion choice is CTI K760WT with 1412Ns of total impulse. – *Verified by manufacturer's provided motor data*

1.11. Pressure vessels on the vehicle shall be approved by the RSO and shall meet the following criteria:

Not applicable.

1.11.1. The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) shall be 4:1 with supporting design documentation included in all milestone reviews. Any pressure vessels in our vehicle will have a factor of safety above the minimum requirement of 4:1.
Not applicable.

1.11.2. Each pressure vessel shall include a pressure relief valve that sees the full pressure of the tank.All pressure vessels will include a pressure relief valve which sees the full pressure of the tank.
Not applicable.

1.11.3. Full pedigree of the tank shall be described, including the application for which the tank was designed, and the history of the tank, including the number of pressure cycles put on the tank, by whom, and when.
Not applicable.

1.12. All teams shall successfully launch and recover a subscale model of their full-scale rocket prior to CDR. The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale shall not be used as the subscale model.
We will construct a subscale model of our rocket and launch it prior to the CDR. Our subscale model will be a one half scale representation of our full vehicle as accurately as possible. Test flight of a subscale model is a standard part of our project development cycle. – *Verified by scale model test flight, project log and documentation review*

1.13. All teams shall successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The rocket flown at FRR must be the same rocket to be flown on launch day. The purpose of the full-scale demonstration flight is to demonstrate the launch vehicle's stability, structural integrity, recovery systems, and the team's ability to prepare the launch vehicle for flight. A successful flight is defined as a launch in which all hardware is functioning properly (i.e. drogue chute at apogee, main chute at a lower altitude, functioning tracking devices, etc.). The following criteria must be met during the full scale demonstration flight:
We plan to conduct at least one test of a subscale vehicle and two test flights of the full scale vehicle prior the FRR due date. The final test flight will be in full vehicle/payload configuration using the full impulse motor. – *Verified by full scale vehicle flights, project log and documentation review*

1.13.1. The vehicle and recovery system shall have functioned as designed.
The vehicle recovery system will be operated in full configuration on all planned test flight. – *Verified during half scale and full scale vehicle test and static ejection tests on the ground*

1.13.2. The payload does not have to be flown during the full-scale test flight. The following requirements still apply:

1.13.2.1. If the payload is not flown, mass simulators shall be used to simulate the payload mass.
Before the payload is ready for flight, payload will be simulated by mass simulators during test flights. – *Verified by inspection prior each test flight*

1.13.2.2. The mass simulators shall be located in the same approximate location on the rocket as the missing payload mass.
Payload mass simulators, if used, will represent the predicted mass of the payload and will be located at the payload's intended location within the vehicle to maintain the same mass distribution. – *Verified by inspection prior each test flight*

1.13.2.3. If the payload changes the external surfaces of the rocket (such as with camera housings or external probes) or manages the total energy of the vehicle, those systems shall be active during the full-scale demonstration flight.

Our payload does not change any of the external surfaces and it does not manage the total energy of the vehicle. Not applicable.–

1.13.3. The full-scale motor does not have to be flown during the full-scale test flight. However, it is recommended that the full-scale motor be used to demonstrate full flight readiness and altitude verification. If the full-scale motor is not flown during the full-scale flight, it is desired that the motor simulate, as closely as possible, the predicted maximum velocity and maximum acceleration of the competition flight.
We intend to fly our demonstration flight with the exactly same motor that will be used for our flight at the SLI launch in Huntsville. – *Verified by the flight data from final test flight of the full scale vehicle*

1.13.4. The vehicle shall be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the same amount of ballast that will be flown during the competition flight.
The vehicle will be fully ballasted (if ballast is necessary) for the final full scale test flight. Requirement 1.13 will be observed. – *Verified by preflight inspection and checklist*

1.13.5. After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components shall not be modified without the concurrence of the NASA Range Safety Officer (RSO).
Except for necessary repairs, there will not be any changes made to the launch vehicle after the full scale demonstration flight. If any repairs are necessary, the NASA Range Safety Officer will be contacted before making any changes to the vehicle. – *Verified by documentation review*

1.14. Each team will have a maximum budget of $7,500 they may spend on the rocket and its payload(s). (Exception: Centennial Challenge payload task. See supplemental requirements at: http://www.nasa.gov/mavprize for more information). The cost is for the competition rocket and

payload as it sits on the pad, including all purchased components. The fair market value of all donated items or materials shall be included in the cost analysis. The following items may be omitted from the total cost of the vehicle:

- **Shipping costs**
- **Team labor costs**

Our budget will not exceed $7,500 for construction and flight of the rocket and payload. – *Verified by detailed accounting of all project expenses*

1.15. Vehicle Prohibitions

1.15.1. The vehicle shall not utilize forward canards.

Vehicle does not have forward canards.

1.15.2. The vehicle shall not utilize forward firing motors.

Vehicle does not utilize forward firing motors.

1.15.3. The vehicle shall not utilize motors which expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)

Sparky motors are not used.

1.15.4. The vehicle shall not utilize hybrid motors.

Hybrid motors are not used.**1.15.5 The vehicle shall not utilize a cluster of motors.**

The vehicle is propelled by a single motor.

2. Recovery System Requirements

2.1. The launch vehicle shall stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee and a main parachute is deployed at a much lower altitude. Tumble recovery or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue-stage descent is reasonable, as deemed by the Range Safety Officer.

Dual deployment recovery method is used for the vehicle (drogue parachute deploys at apogee and main parachute 700*ft* (or other predetermined altitude). The vehicle has two fully independent and redundant deployment circuits. The backup charges are 25% larger than primary charges to increase the chance of deployment in the event of primary charge failure. – *Verified by preflight inspection and checklist*

2.2. Each team must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full scale launches.

Static ejection test are the standard step in our vehicle development process, starting with the subscale model and extending to the full scale vehicle as well.

2.3. At landing, each independent sections of the launch vehicle (as described in requirement 1.5) shall have a maximum kinetic energy of 75 ft-lbf.

The parachute sizes will be so chosen than no section of the rocket lands with kinetic energy greater than 75*ft-lbf*. – *Verified by measurement and calculations after the completion and first test flight of the full scale vehicle. Mass of each section and descent rates need to be measured to complete this verification. Preliminary verification has been completed using data from OpenRocket software.*

2.4. The recovery system electrical circuits shall be completely independent of any payload electrical circuits.

This performance target is a standard requirement for all Madison West projects and will be satisfied. – *Verified by inspection and preflight checklist.*

2.5. The recovery systems shall contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers.

We only use commercially available altimeters for deployment of recovery devices. Full redundancy of deployment electronics is a standard requirement for all Madison West sounding rocket projects. This performance target will be satisfied and documented. – *Verified by inspection and preflight checklist*

2.6. Motor ejection is not a permissible form of primary or secondary deployment.

Motor ejection charges are not used for the deployment, all deployment events are triggered by barometric altimeters. – *Verified by documentation review and preflight checklist and inspection. The motor charge will be removed from the motor.*

2.7. Each altimeter shall be armed by a dedicated arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.

Independent external switches are standard requirement for all Madison West sounding rocket projects. This performance target will be satisfied and documented. – *Verified by design and preflight inspection*

2.8. Each altimeter shall have a dedicated power supply.

Independent and dedicated power supplies for each deployment altimeter are standard requirement for all Madison West sounding rocket projects. This performance target will be satisfied and documented. – *Verified by design and preflight inspection*

2.9. Each arming switch shall be capable of being locked in the ON position for launch.

We use switches operated by a key. None of the switches can be moved after the key has been removed. None of the switches is momentary. – *Verified by preflight inspection*

2.10. Removable shear pins shall be used for both the main parachute compartment and the drogue parachute compartment.

Removable shear pins will be used at all separation points. The shear pins will be tested during static ejection tests to assure that they will hold but not interfere with the separation of the corresponding compartment. – *Verified by preflight checklist and inspection*

2.11. An electronic tracking device shall be installed in the launch vehicle and shall transmit the position of the tethered vehicle or any independent section to a ground receiver.

Each section of the rocket is equipped by one radio and one sonic beacon. – *Verified by preflight checklist and inspection*

2.11.1. Any rocket section, or payload component, which lands untethered to the launch vehicle shall also carry an active electronic tracking device.
Target satisfied within 2.11.

2.11.2. The electronic tracking device shall be fully functional during the official flight on launch day.
All tracking devices will fully operational during official flight in Huntsville and if possible for all full scale vehicle test launches. – *Verified by preflight test and checklist*

2.12. The recovery system electronics shall not be adversely affected by any other on-board electronic devices during flight (from launch until landing).
There will be no interference between recovery deployment circuitry and payload or tracking circuitry. Shielding will be used as necessary. – *Verified during vehicle development and prior each flight.*

2.12.1. The recovery system altimeters shall be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.
The recovery system altimeters are housed in a dedicated e-bay, separate from all other electronics. – *Verified by inspection*

2.12.2. The recovery system electronics shall be shielded from all onboard transmitting devices, to avoid inadvertent excitation of the recovery system electronics.
Shielding will be used as necessary. All electronics will be ground tested for possible interference. – *Verified by inspection*

2.12.3. The recovery system electronics shall be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system.
There are no magnetic wave generators on-board.

2.12.4. The recovery system electronics shall be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.
Shielding will be used as necessary. All electronics will be ground tested for possible interference. – *Verified by inspection and ground tests*

3. Competition and Payload Requirements

Each team shall choose any 2 payloads from Task 1, or have the choice to participate in the Centennial Challenge competition (Task 2).

We chose Task 2, the Centennial Challenge. Our rocket will be flown with a standard Centennial Challenge payload. – *Verified by project documentation review*

3.1. The payload shall be designed to be recoverable and reusable. Reusable is defined as being able to be launched again on the same day without repairs or modifications.
We will launch our rocket with a standard Centennial Challenge payload provided by a NASA official. – *Verified by postflight inspection*

3.2. (Task1) The team may choose to participate in 2 of the following payload options.
Not applicable.

3.2.1. A payload that shall gather data for studying the atmosphere during descent and after landing, including measurements of pressure, temperature, relative humidity, solar irradiance and ultraviolet radiation.
Not applicable.

3.2.1.1. Measurements shall be made at least once every second during descent, and every 60 seconds after landing. Data collection shall terminate 10 minutes after landing.
Not applicable.

3.2.1.2. The payload shall take at least 2 pictures during descent, and 3 after landing. The payload shall remain in orientation during descent and after landing such that the pictures taken portray the sky towards the top of the frame and the ground towards the bottom of the frame.
Not applicable.

3.2.1.3. The data from the payload shall be stored onboard and transmitted wirelessly to the team's ground station at the time of completion of all surface operations.
Not applicable.

3.2.2. A payload that scans the surface continuously during descent in order to detect potential landing hazards.

Not applicable.

3.2.2.1. The data from the hazard detection camera shall be analyzed in real time by a custom designed on-board software package that shall determine if landing hazards are present.
Not applicable.

3.2.2.2. The data collected shall be stored on board and transmitted wirelessly to the team's ground station.
Not applicable.

3.2.3. Liquid sloshing research in microgravity to support liquid propulsion systems.
Not applicable.

3.2.4. Structural and dynamic analysis of airframe, propulsion, and electrical systems during boost.
Not applicable.

3.2.4.1. The team must use and array of electrical sensors to measure structural vibration and to measure the stress and strain of the rocket in the axial and radial directions.
Not applicable.

3.2.4.2. At a minimum, structural analysis shall be performed on the fins/fin joints, all separation points, and the nose cone.
Not applicable.

3.2.5. A payload fairing design and deployment mechanism.
Not applicable.

3.2.5.1. The fairings and payload must be tethered to the main body to prevent small objects from getting lost in the field.
Not applicable.

3.2.6. An aerodynamic analysis of structural protuberances.
Not applicable.

3.2.7. Design your own payload (limit of 1). Must be approved by NASA review team.
Not applicable.

3.3. (Task 2) Centennial Challenge NASA University Student Launch Initiative is collaborating with the NASA Centennial Challenges Mars Ascent Vehicle (MAV) Project to offer teams the chance to design and build autonomous ground support equipment (AGSE). The Centennial Challenges Program, part of NASA's Science and Technology Mission Directorate, awards incentive prizes to generate revolutionary solutions to problems of interest to NASA and the nation. The goal of the MAV and its AGSE is to capture a simulated Martian payload sample, seal it within a launch vehicle, and prepare the vehicle for launch without the input from a human operator. For specific rules regarding the MAV project, and to learn more about Centennial Challenges, please visit the Centennial Challenge website at http://www.nasa.gov/mavprize and review their project handbook.

NOTE: The Centennial Challenge handbook is meant to be a complement to this handbook. If a team chooses to participate in the Centennial Challenge, they must abide by all the rules presented in this document.

3.3 Student Launch (Task 2) Centennial Challenge

3.3.1 Introduction

3.3.2 MAV Project – Competition and AGSE Requirements

3.3.2.1 The MAV Project will provide each team with the opportunity to develop a unique method to capture, contain, and launch a payload with limited human intervention. In addition, teams will develop a launch system that erects a rocket from a horizontal to vertical position, and has its igniter autonomously installed. The AGSE will be demonstrated at LRR and will follow this general procedure.

Requirements 3.3.2.1.1 – 3.3.2.1.4 shall be conducted autonomously from start to finish within a 10 minute time limit. The only allowed human interaction is the activation of the master switch.

Requirements 3.3.2.1.1 - 3.3.2.1.4 will be conducted autonomously from start to finish within a 10 minute time limit, and only activation of the master switch will involve human interaction. – *Verified by design and inspection*

3.3.2.1.1 Teams will position their launch vehicle horizontally on the AGSE.

Our launch vehicle will be positioned horizontally on the AGSE before demonstration. – *Verified by inspection before AGSE activation*

3.3.2.1.2 A master switch will be activated to power on all autonomous procedures and subroutines.

The central control will have a master switch that will be used to power on all autonomous procedures and subroutines. – *Verified by design and inspection*

3.3.2.1.3 All AGSEs will be equipped with a pause switch in the event that a judge needs the AGSE to be temporarily halted for any reason. The pause switch halts all AGSE procedures and subroutines. Once the pause switch is deactivated the AGSE resumes operation.

Our AGSEs will have a pause switch that halts all AGSE procedures and subroutines temporarily for any reason. Once the pause switch is deactivated all AGSEs will resume its operation. – *Verified by design and inspection*

3.3.2.1.4 Once the judge signals "START", the AGSE will begin its autonomous functions in the following order: 1) capture and containment of the payload; 2) erection of the launch platform from horizontal to 5.0 degrees off vertical (85.0 degrees), 3) insertion of the motor igniter. The judge may re-enable the pause switch at any time at his/her discretion. If the pause switch is re-enabled all systems and actions shall cease immediately. The judge will only do this if there is a question about safe operation of the AGSE. The judge and team leader will discuss and decide if the team will be allowed to continue their attempt. No modifications to the hardware or software will be allowed prior to a rerun.

The AGSE will proceed with its autonomous functions in the following order:

1) Capture and containment of the payload

2) Erection of the launch platform from horizontal to 5.0 degrees off vertical (85.0 degrees)
3) Insertion of the motor igniter once the start signal is given.

3.3.3 The Autonomous Ground Support Equipment (AGSE)

3.3.3.1 For the purpose of this challenge, the AGSE is defined as all mechanical and electrical components not part of the launch vehicle, and is provided by the teams. This includes, but is not limited to, the payload containment and igniter installation devices, computers, electric motors, batteries, etc.

We understand that the AGSE includes all mechanical and electrical components not part of the launch vehicle and will be provided by our team. – *Verified by inspection*

3.3.3.2 All AGSE systems shall be fully autonomous. The only human interaction will be if the judge pauses the AGSE.

All our AGSE systems will be fully autonomous and will not require any human interaction. The AGSE is fully described on pages 114-99 in this document. – *Verified by inspection*

3.3.3.3 The AGSE shall be limited to a weight of 150 pounds or less and volume of 12 feet in height x 12 feet in length x 10 feet in width.

Our AGSE will meet all weight, volume, and height requirements. Preliminary design has length of 11.5*ft*, width 4*ft* and height 10.5*ft*. – *Verified by measurement and inspection*

3.3.4 Prohibited Technology for AGSE

3.3.4.1.1 As one of the goals of this competition is to develop equipment, processes, and technologies that could be implemented in a Martian environment, the AGSE and any related technology cannot employ processes that would not work in such environments. Therefore, prohibited technologies include:

The following prohibited technologies (3.3.4.1.2- 3.3.4.1.6) will not be included in our AGSE or any related technology.

3.3.4.1.2 Sensors that rely on Earth's magnetic field

3.3.4.1.3 Ultrasonic or other sound-based sensors

3.3.4.1.4 Earth-based or Earth orbit-based radio aids (e.g. GPS, VOR, cell phone).

3.3.4.1.5 Open circuit pneumatics

3.3.4.1.6 Air breathing systems

None of the listed prohibited technologies is used in AGSE. Cf. pages 114-99 for full description of AGSE and technologies used. – *Verified by inspection*

3.3.5 Payload

3.3.5.1 Each launch vehicle must have the space to contain a cylindrical payload approximately 3/4 inch inner diameter and 4.75 inches in length. The payload will be made of ¾ x 3 inch Schedule 40 PVC tubing filled primarily with sand and may include BBs, weighing approximately 4 ounces and capped with domed PVC end caps. Each launch vehicle must be able to seal the payload containment area autonomously prior to launch.

The launch vehicle will have the space to contain a cylindrical payload approximately ¾ inch inner diameter and 4.75 inches in length. The payload will be made of Schedule 40 PVC tubing with the required elements. The launch vehicle shall be able to seal the payload containment area autonomously prior to launch. – *Verified by design and inspection*

3.3.5.2 A diagram of the payload and a sample payload will be provided to each team at time of acceptance into the competition. In addition, teams may construct practice payloads according to the above specifications; however, each team will be required to use a regulation payload provided to them on launch day.

A regulation payload will be used on launch day. – *Verified by inspection*

3.3.5.3 The payload will not contain any hooks or other means to grab it.

Our payload does not contain any hooks or other means to grab the payload. A gripper is used to grab the payload. – *Verified by inspection*

3.3.5.4 The payload shall be placed a minimum of 12 inches away from the AGSE and outer mold line of the launch vehicle in the launch area for insertion, when placed in the horizontal position on the AGSE and will be at the discretion of the team as long as it meets the minimum placement requirements.

Our payload shall meet the minimum placement requirements. – *Verified by measurement*

3.3.5.5 Gravity-assist shall not be used to place the payload within the rocket. If this method is used no points shall be given for payload insertion.

Gravity-assist is not used to place the payload within the rocket. The proposed AGSE can fully function without gravity. – *Verified by design and observation of AGSE functioning*

3.3.5.6 Each team will be given 10 minutes to autonomously capture, place, and seal the payload within their rocket, and erect the rocket to a vertical launch position five degrees off vertical. Insertion of igniter and activation for launch are also included in this time. Going over time will result in the team's disqualification from the MAV Project competition.

We will only require up to 10 minutes to autonomously capture, place, and seal the payload within their rocket, and erect the rocket to a vertical launch position five degrees off vertical. Preliminary calculations were made to assure that this constrain can be satisfied by proposed AGSE. – *Verified by timing of the AGSE operation*

3.3.6 Safety and AGSE Control

3.3.6.1 Each team must provide the following switches and indicators for their AGSE.

3.3.6.1.1 A master switch to power all parts of the AGSE. The switch must be easily accessible and hardwired to the AGSE.

We will have a master switch to power all parts of the AGSE. It will be easily accessible and hardwired to the AGSE. – *Verified by inspection*

3.3.6.1.2 A pause switch to temporarily terminate all actions performed by AGSE. The switch must be easily accessible and hardwired to the AGSE.

A pause switch will be created which will temporarily terminate all actions performed by the AGSE. The switch will be easily accessible and hardwired to the AGSE. – *Verified by inspection*

3.3.6.1.3 A safety light that indicates that the AGSE power is turned on. The light must be amber/orange in color. It will flash at a frequency of 1 Hz when the AGSE is powered on, and will be solid in color when the AGSE is paused while power is still supplied.

We will have an amber/orange safety light which indicates that the power on the AGSE is turned on. It will flash at a frequency of 1 Hz when the AGSE is powered on, but will be solid in color when the AGSE is paused while power is still supplied. This is currently not shown on the pictures illustrating the AGSE but will be part of the AGSE. – *Verified by inspection*

3.3.6.1.4 An all systems go light to verify all systems have passed safety verifications and the rocket system is ready to launch.

We will have an all systems go light which will verify that all systems have passed safety verifications and the rocket system is ready to launch. This is currently not shown on the pictures illustrating the AGSE but will be part of the AGSE. – *Verified by inspection*

3.3.7 Failure of the MAV Project

3.3.7.1 Any team who fails to complete any of the procedures in requirement 3.3 will be ineligible of obtaining Centennial Challenges prizes.

We understand that any team who fails to complete any of the procedures in requirement 3.3 will be ineligible of obtaining Centennial Challenge prizes.

3.3.7.2 The head judge and the MAV Project Manager will have the final decision authority to determine if the procedures in requirement 3.3 have been met.

We understand that the head judge and the MAV Project Manager will have the final decision authority to determine if the procedures in requirement 3.3 have been met.

3.3.8 General Requirements Unique to Centennial Challenge MAV Project

3.3.8.1 Any academic team or non-academic team may participate in the MAV Project, however, to be eligible for prize money, less than 50% of the team make-up may be foreign nationals and the team entity must be a United States entity.

The team entity is a US entity (Madison West High School) and the team has less than 50% of foreign national students.

3.3.8.2 Name of person or business or entity who will be receiving the award check in the event the team places in the competition and address. If a business or other entity is to receive the check then also provide a tax identification number.

Ms. Christine Hager
Madison West High School
30 Ash St, Madison, WI 53726

3.3.8.3 In addition to SL requirements, for the CDR presentation and report, teams shall include estimated mass properties for the AGSE.

Our team shall include estimated mass properties for the AGSE. The current estimate is 106lbs. – *Verified by documentation*

3.3.8.4 In addition to SL requirements, for the FRR presentation, teams shall include a video presented during presentation of an end-to-end functional test of the AGSE. The video shall be posted on the team's website with the other FRR documents. Teams shall also include the actual mass properties for the AGSE.

We will produce a video which will be presented of an end-to-end functional test of the AGSE. We will post the video on the team's website with other FRR documents. – *Verified by website inspection*

4. Safety Requirements

4.1. Each team shall use a launch and safety checklist. The final checklists shall be included in the FRR report and used during the Launch Readiness Review (LRR) and launch day operations.
We will use a launch and safety checklist. The final checklist will be included in the Launch Readiness Review, and our list will be used during launch day operations. – *Verified by documentation review*

4.2. For all academic institution teams, a student safety officer shall be identified, and shall be responsible for all items in section 4.3. For competing, non-academic teams, one participant who is not serving in the team mentor role shall serve as the designated safety officer.
We will select a student safety officer, who will be responsible for all items in section 4.3. – *Verified by documentation review*

4.3. The role and responsibilities of each safety officer shall include but not limited to:

4.3.1. Monitor team activities with an emphasis on Safety during:

4.3.1.1. Design of vehicle and launcher

The safety officer will work with the AGSE team leader and vehicle team leader to assure that AGSE meets the needs for safe vehicle launch, including sufficient rail length, motor strength (for AGSE operation) and overall AGSE stability. Safety officer will also enforce inclusion of emergency stop switch (hard disconnect) and PAUSE button (both must be functional before any AGSE operation). Safety officer will work with the AGSE team leader on developing AGSE self-test, an automated procedure that the AGSE will execute prior any operation and failure of which will prevent any further operation of AGSE.

4.3.1.2. Construction of vehicle and launcher

Safety officer will oversee all construction work on vehicle and launcher ensuring that appropriate personal protective equipment is needed, the safe practices are followed and all chemicals are used in accordance with their material safety datasheets. Maintaining proper ventilation and overall cleanliness and organization of tools, parts and supplies in the workshop is also a responsibility of safety officer. Safety officer will maintain the online and hard-copy collection of all necessary datasheets and will work with vehicle and AGSE and team leaders to ensure timely additions and updates of the collection.

4.3.1.3. Assembly of vehicle and launcher

4.3.1.4. Ground testing of vehicle and launcher

4.3.1.5. Sub-scale launch test(s)

4.3.1.6. Full-scale launch test(s)

4.3.1.7. Competition launch

During final assembly of the vehicle and launcher (4.3.1.3), ground testing (4.3.1.4) and all launches (4.3.1.5-7), the safety officer will enforce use of checklists for each procedure, use of appropriate personal protective equipment, presence and readiness of firefighting equipment/crews, and will coordinate with the team mentor regarding use of energetics (motors and ejection charges). Safety office will also coordinate with range safety officer (RSO) and launch control officer (LCO) regarding the final launch permission, considering both the weather and condition of the launch site. Safety officer will direct movement of team members during launch preparations and will only clear the team for launch after all launch preparations procedures were completed (according to the checklist), team members retreated to safe launch distance and RSO/LCO cleared the rocket for launch. Safety officer will enforce the strict adherence to NAR Model Rocket Safety Code, NAR High Power Rocket Safety Code, FAA regulations (14 CFR F/101/C) and NFPA 1127 Code.

4.3.1.8. Recovery activities

During recovery activities the safety officer will accompany the team and will enforce strict adherence to safety codes, preventing team members from entering dangerous areas or attempting to recover the rocket from unsafe places (such as power lines or water bodies). The safety officer makes the final decision whether the vehicle recovery is safe to attempt or whether additional help/tools need to be brought in. Upon the location and recovery of the rocket, the safety officer will oversee proper execution of post-launch procedure (rocket power-down) and post-flight inspection of the rocket.

4.3.1.9. Educational Engagement activities

During educational activities, the safety officer will ensure that all educational displays are installed in a secure manner and are completely inert. Safety officer will oversee the maintenance of the pneumatic launchers, ensuring that safety valves of proper rating (10*psi*) are installed and functional and that all electrical connections (launch controller) are properly insulated. Safety officer will be present at each pneumatic rocket launch, directing the crowd and running the range. All outreach participants are required to use safety goggles when launching pneumatic rockets, enforced by safety officer.

4.3.2. Implement procedures developed by the team for construction, assembly, launch, and recovery activities.

Safety officer will enforce strict adherence to construction, assembly, launch and recovery procedures, as detailed on pages 55 to 56.

4.3.3. Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.

Safety officer will maintain the online and hard-copy collection of all necessary datasheets and will work with vehicle and AGSE and team leaders to ensure timely additions and updates of the collection. The MSDS collection for this project is accessible at all times publicly online at http://westrocketry.com/sli2016/safety/safety2016r.php and a hardcopy of all MSDS is kept at workshop and inside the toolbox used during launches.

4.3.4. Assist in the writing and development of the team's hazard analyses, failure modes analyses, and Procedures.

Our team's safety officer, William, will complete the listed tasks. William will be supervised by both official educators, Dr. Williamson and Mr. Schoneman**4. Each team shall identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The mentor shall be certified by the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle, and the rocketeer shall have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to the launch at the competition launch site. One travel stipend will be provided per mentor regardless of the number of teams he or she supports. The stipend will only be provided if the team passes FRR and the team and mentor attend launch week in April.**

Mr. Brent Lillesand will serve as a mentor for this team. He is L3 certified, and is a member of both NAR and TRA. He will accompany the team to SL launch In Huntsville.

4.5. During test flights, teams shall abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA University Student Launch Initiative competition launch does not give explicit or implicit authority for teams to fly those certain vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.

During all test launches, we will abide by the rules and guidance of the RSO. Prior to any launch, we will communicate with the RSO to ensure that we will be able to test our vehicle as we require.

4.6. Teams shall abide by all rules and regulations set forth by the FAA.

We will abide by all rules and regulations set forth by the FAA.

5. General Requirements

5.1. Team members (students if the team is from an academic institution) shall do 100% of the project, including design, construction, written reports, presentations, and flight preparation. The one exception deals with the handling of black powder, ejection charges, and installing electric matches. These tasks shall be performed by the team's mentor, regardless if the team is from an academic institution or not.

Students will do 100% of the work on our vehicle, except for all tasks involving energetics. These tasks will be performed by our mentor.

5.2. The team shall provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assigned, educational engagement events, and risks and mitigations.

We will maintain a project plan, which will include all of the required information listed above.

5.3. Each team shall successfully complete and pass a review in order to move onto the next phase of the competition.

We will complete and pass each review prior to continuing the next phase of the competition.

5.4. Foreign National (FN) team members shall be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during launch week due to security restrictions. In addition, FN's will be separated from their team during these activities. If participating in the MAV task, less than 50% of the team make-up may be foreign nationals.

All foreign national team members will be identified prior to the Preliminary Design Review.

5.5. The team shall identify all team members attending launch week activities by the Critical Design Review (CDR). Team members shall include:

5.5.1. Students actively engaged in the project throughout the entirety of the project lifespan and currently enrolled in the proposing institution.

All students are actively engaged for the entire duration of the project.

5.5.2. One mentor (see requirement 4.4).
Mr. Brent Lillesand is the mentor for the team.

5.5.3. No more than two adult educators per academic team.
Not applicable.

All team members will be identified prior to the Preliminary Design Review.

5.6. The team shall engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities, as defined in the Educational Engagement form, by FRR. An educational engagement form shall be completed and submitted within two weeks after completion of each event. A sample of the educational engagement form can be found in the handbook.
Our education engagements plan includes over 2500 students from local elementary and middle schools. At least 300 of those are middle school students. Educational engagement form will be completed and submitted within two weeks of each event's completion.

5.7. The team shall develop and host a Website for project documentation.
We will develop and host a Website for project documentation.

5.8. Teams shall post, and make available for download, the required deliverables to the team Web site by the due dates specified in the project timeline.
All required documents will be made available for download on our Website by the due date as specified in the project timeline.

5.9. All deliverables must be in PDF format.
All documents on our Website will be available in PDF format.

5.10. In every report, teams shall provide a table of contents including major sections and their respective sub-sections.
Every report will contain a table of contents listing major sections and all sub-sections.

5.11. In every report, the team shall include the page number at the bottom of the page.
Every report will contain the page number at the bottom of the page.

5.12. The team shall provide any computer equipment necessary to perform a video teleconference with the review board. This includes, but not limited to, computer system, video camera, speaker

telephone, and a broadband Internet connection. If possible, the team shall refrain from use of cellular phones as a means of speakerphone capability.
We will be using fully equipped teleconference rooms in Engineering Hall at UW Madison.

5.13. Teams must implement the Architectural and Transportation Barriers Compliance Board Electronic and Information Technology (EIT) Accessibility Standards
The Section 508 is in detailed described on page 149.

Development Schedule

	NASA Date (documentation deadline, teleconference, SL2016 events)
	Classroom (writing session, data analysis, design meeting)
	Launch (test flight)
	Fundraising activity (raking or other manual work)
	Outreach event
	Workshop session (rocket building or repair, launch preparations)
	Organizational meeting (scheduling, past events review)
	Vacation time (holidays, school breaks)

Table 37: Color code for timeline

Project Timeline

	August 2015
Aug 7	RFP goes out
Aug 9	Writing Session
Aug 16	Writing Session
Aug 23	Writing Session
Aug 30	Writing Session
	September 2015
Sep 3	Robotics Workshop
Sep 4	Workshop
Sep 6	Writing Session
Sep 7	Organizational Meetings
Sep 10	Robotics Workshop
Sep 11	**SOW due**

Sep 11	Workshop
Sep 13	Writing Session
Sep 14	Organizational Meeting
Sep 17	Robotics Workshop
Sep 18	Workshop
Sep 20	Writing Session
Sep 21	Organizational Meeting
Sep 24	Robotics Workshop
Sep 25	Workshop
Sep 27	Writing Session
Sep 28	Organizational Meeting
	October 2015
Oct 1	Robotics Workshop
Oct 2	Awarded proposals announced
Oct 2	Outreach
Oct 2	Workshop
Oct 4	Writing Session
Oct 5	Organizational Meeting
Oct 7	Kickoff and PDR Q&A
Oct 8	Outreach
Oct 8	Robotics Workshop
Oct 9	Workshop
Oct 10	Fundraising (raking)
Oct 11	Writing Session
Oct 12	Organizational Meeting
Oct 15	Robotics Workshop
Oct 16	Workshop
Oct 17	Fundraising (raking)
Oct 18	Writing Session
Oct 19	Organizational Meeting
Oct 22	Robotics Workshop
Oct 23	**Team web presence established**
Oct 23	Workshop
Oct 24	Fundraising (raking)
Oct 24	Outreach
Oct 25	Writing Session
Oct 25	Outreach
Oct 26	Organizational Meeting
Oct 29	Robotics Workshop

Oct 30	Workshop
Oct 31	Fundraising (raking)
	November 2015
Nov 1	Writing Session
Nov 2	Organizational Meeting
Nov 5	Robotics Workshop
Nov 6	**PDR due**
Nov 6	Workshop
Nov 7	PDP practice
Nov 7	Fundraising (raking)
Nov 8	Writing Session
Nov 9	Organizational Meeting
Nov 12	Robotics Workshop
Nov 13	Workshop
Nov 14	Fundraising (raking)
Nov 9-20	PDP teleconferences
Nov 15	Writing Session
Nov 16	Organizational Meeting
Nov 19	Robotics Workshop
Nov 20	Workshop
Nov 21	Fundraising (raking)
Nov 22	Writing Session
Nov 23	Organizational Meeting
Nov 26	Robotics Workshop
Nov 27	Workshop
Nov 28	Fundraising (raking)
Nov 29	Writing Session
Nov 30	Organizational Meeting
Nov 21-Dec 11	Scale Model Building
	December 2015
Dec 3	Robotics Workshop
Dec 4	CDR Q&A
Dec 4	Workshop
Dec 5	Fundraising (raking)
Dec 6	Writing Session
Dec 7	Organizational Meeting
Dec 10	Robotics Workshop
Dec 11	Workshop
Dec 12	Scale Model Flight

Dec 13	Analysis of Flight Data
Dec 14	Organizational Meeting
Dec 17	Robotics Workshop
Dec 18	Workshop
Dec 20	Writing Session
Dec 27	Writing Session
	January 2016
Jan 3	Writing Session
Jan 4	Organizational Meeting
Jan 7	Robotics Workshop
Jan 8	Workshop
Jan 10	Writing Session
Jan 11	Organizational Meeting
Jan 14	Robotics Workshop
Jan 15	**CDR due**
Jan 15	Workshop
Jan 16	CDP practice
Jan 17	Writing Session
Jan 18	Organizational Meeting
Jan 21	Robotics Workshop
Jan 22	Workshop
Jan 24	Writing Session
Jan 19-29	CDP teleconferences
Jan 25	Organizational Meeting
Jan 28	Robotics Workshop
Jan 29	Workshop
Jan 30	Outreach
Jan 19- Feb 19	Full Scale Building
	February 2016
Feb 1	Organizational Meeting
Feb 3	FRR Q&A
Feb 4	Robotics Workshop
Feb 5	Workshop
Feb 7	Writing Session
Feb 8	Organizational Meeting
Feb 11	Robotics Workshop
Feb 12	Workshop
Feb 13	Outreach
Feb 14	Writing Session

Feb 15	Organizational Meeting
Feb 18	Robotics Workshop
Feb 19	Workshop
Feb 20	Full Scale Half Impulse Flight
Feb 21	Analysis of Flight Data
Feb 22	Organizational Meeting
Feb 25	Robotics Workshop
Feb 26	Workshop
Feb 27	Full Scale Full Impulse Flight #1
Feb 28	Analysis of Flight Data
Feb 29	Organizational Meeting
	March 2016
Mar 3	Robotics Workshop
Mar 4	Workshop
Mar 5	Full Scale Full Impulse Flight #2
Mar 6	Analysis of Flight Data
Mar 7	Organizational Meeting
Mar 10	Robotics Workshop
Mar 11	Workshop
Mar 12	Outreach
Mar 13	Writing Session
Mar 14	**FRR due**
Mar 14	Organizational Meeting
Mar 19	FRP practice
Mar 19	Outreach
Mar 21	Organizational Meeting
Mar 17-30	FRP teleconferences
Mar 28	Organizational Meeting
	April 2016
Apr 1	Outreach
Apr 4	Organizational Meeting
Apr 11	Organizational Meeting
Apr 13	Teams travel to Huntsville, AL
Apr 13	LRR’s
Apr 14	Safety Briefings
Apr 14	LRR’s
Apr 15	Rocket Fair
Apr 16	Launch Day
Apr 17	Back-up Launch Day

Apr 18	West Rocketry travels home
Apr 23	Writing Session
Apr 24	Writing Session
Apr 25	Organizational Meeting
Apr 29	**PLAR due**

Table 38: Project timeline

Gantt Chart

GANTT chart below shows the sequence, dependencies, overlaps and possible conflicts between different phases of the project. We use this chart to determine optimal schedule that will lead to successful and timely completion of our project.

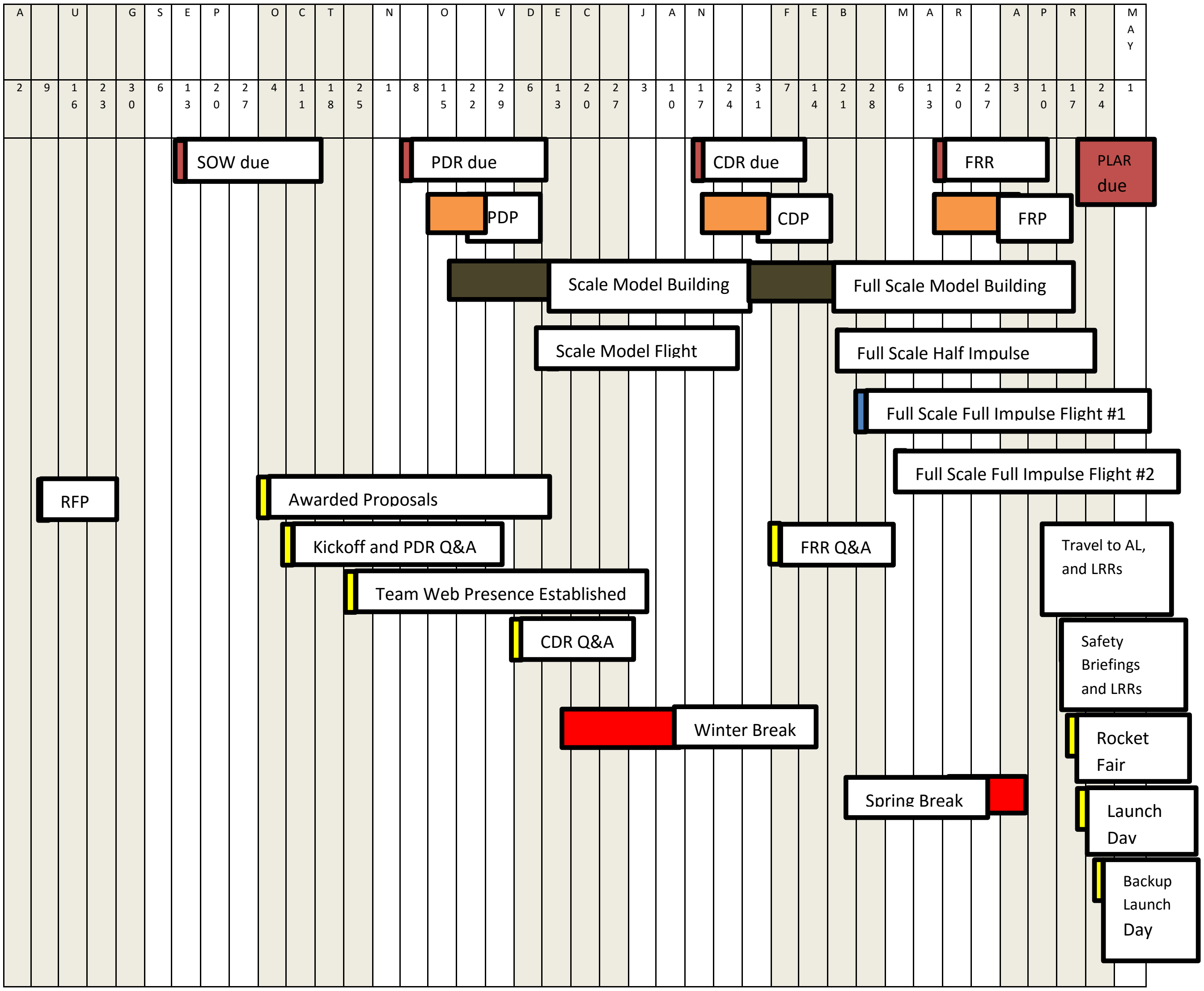


Figure 76: GANTT chart for SL2016 project

Project and Travel Budgets

Our Bill of Materials (BOM) for the entire Maxi-MAV including payload, rocket, and AGSE has been updated extensively as the system has been prototyped and parts have been acquired to support this. The extensively detailed BOM table attempts to track every item required for the construction of the system. We estimate that at time of CDR we have acquired at least 90% of the items needed to complete the construction of the AGSE.

Methodology

We will assess the cost of the Maxi-MAV solution in two ways: bottoms-up using the extensively detailed bill of materials (BOM), and top-down using the detailed costs recorded in acquiring the items during this phase.

Below, bottoms-up, we have broken down the anticipated costs of the delivered by subsystem and show a summary of those costs both in tabular and chart form below. Our methodology for this analysis has been to consider only the parts that will appear in the final Maxi-MAV system (vehicle and autonomous ground support). Therefore, we include just one instance of expendable items (charges, rocket motors, ignitors). We do not include costs related to purchasing items due to minimum order quantities (e.g., nuts and bolts) nor do we include prototyping yield losses or related prototyping costs (buying multiple Arduino controller boards to cover damage and allowing for parallel development of subsystems.)

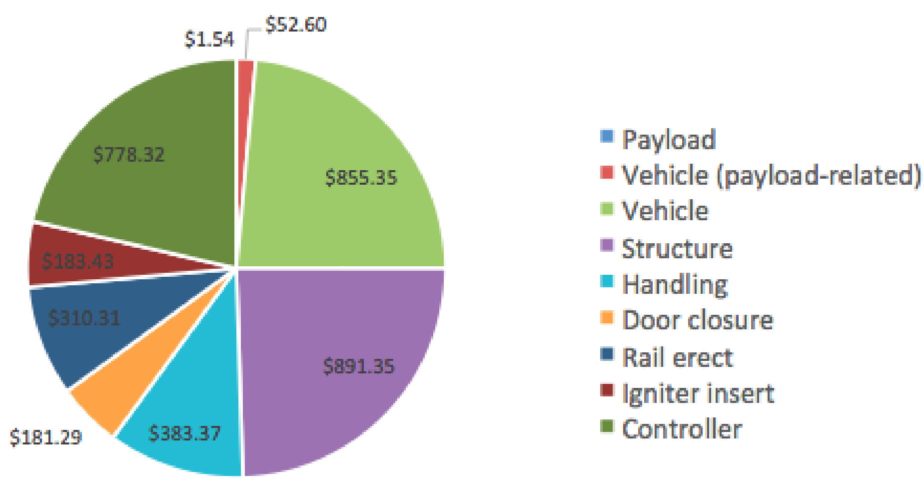


Figure 77. Cost breakdown by subsystem.

Subsystem	Cost	Comment
Payload	$1.54	just the PVC payload and weighting
Vehicle (payload-related)	$52.60	includes items required to retain and secure the payload
Vehicle	$855.35	all aspects of the rocket including structure, propulsion, recovery, telemetry
Structure	$891.35	the static superstructure of the ASGE
Handling	$383.37	the robotic motion control for acquiring and depositing the payload
Door closure	$181.29	means for closing door and holding rocket
Rail erect	$310.31	lifting the launch rail into a near-vertical position
Igniter insert	$183.43	insertion of the igniter into the engine
Controller	$778.32	all aspects of control including microcontroller, drivers, indicators, safety lights, housing, and power
	$3,637.55	

Table 39. List of costs for delivered prototype.

Materials Acquisition

Due to the cost constraints of the program budget we use commercially available off-the-shelf items (COTS) wherever possible. We have generally focused on vendors who serve the hobbyist market and consumer markets and thus have lower costs. One advantage of this approach is that these vendors all tend to provide accessories compatible with the components being purchased, limiting the number of custom parts required to assemble the system.

Top-down, we have tracked every out-of-pocket expenditure related to the Maxi-MAV program to date, more specifically, the AGSE itself. Note clearly that these expenses form an upper-bound for the costs of the system since they include costs that do not necessarily go into the AGSE or rocket, such as excess materials that must be ordered in minimum quantity, or parts acquired for prototyping or development that do not necessarily appear in the AGSE or vehicle.

To-date, AGSE expenditures have been $3586 which includes $332 in shipping costs, thus $3254 in materials costs expended. All of these are new, commercially-available parts with one exception, a THK vertical motion stage, that was a surplus purchase for $175. The estimated fair market value for this item is $1200, putting the "fair market" costs for the program (i.e., repeat but the surplus item had to be purchased new) at approximately $4300. Given the overages or minimum order quantities, this bounds the value of the AGSE solution at between $3500 and $4000.

Our detailed BOM lists many of the key vendors anticipated to be used, many of whom the team has a lot of experience with already.

A vast majority of the BOM was purchased commercially and we have used club funds to obtain these parts – these fundraising activities are described elsewhere. Some commercial items, such as 80/20 rail, mechanical hardware, and some piece parts have been donated by parents or local businesses, and the AGSE design intends to re-use/incorporate these parts as much as the design will allow.

The team's workshop has basic tools for modifying plastic and metal parts suitable for some of the customizations and fabrications. The workshop also owns several ABS-based extrusion-type rapid-prototyping machines that will be used to fabricate small or low-strength parts for the vehicle and some parts for the AGSE. Costs included in the budget are estimates for the raw material (e.g., ABS filament for the 3D printers or metal stock to be machined or modified) but not the depreciation of the machines used to perform the fabrication.

Through this prototyping and design prove-out phase, we were able to find commercial, off-the-shelf parts for nearly every required item, and no custom machined parts ended up being required. All modifications were accomplished with commonly available, low-cost shop tools such as Dremel tools and blades, band saw, table saw, chop saw, and drill press.

These custom efforts and designs are supported indirectly by the solid modelling capability of the team, with sufficient academic licenses for multiple team members to contribute directly to the mechanical design of the rocket and AGSE, and generate the files required for our rapid prototyping machine shop vendors and the 3D printers in the shop.

Description	QT	uom	Cost ea	Cost extend
Payload				**$1.54**
PVC pipe, schedule 40	0	ft	$1.50	$0.50
PVC end cap	2	ea	$0.32	$0.64
Bead shot, copper/lead	0.05	bottle	$5.49	$0.27
Sand	2.50	oz	$0.05	$0.13
Vehicle - Payload retention				**$52.60**
Clip, payload retention, chrome steel	2	ea	$0.95	$1.90
O-ring	2		$0.05	$0.10
8-32 screw SHCS, long	2		$0.10	$0.20
L-bracket	2		$0.70	$1.40
8-32 screw, pan head, __ long	2		$0.10	$0.20
Aluminum strip, 6061T6, 3/16 x 7/8"	1		$2.00	$2.00
#6 flat head wood screws	2		$0.10	$0.20
Wood semicircle boss, 1/2" plywood	1		$1.00	$1.00
Coupler section	1		$12.00	$12.00
Magnet, high-strength	6	ea	**$0.74**	$4.44
Payload door	1		$3.00	$3.00
Eyeglass hinge	1	ea	$0.50	$0.50
0-80 FH Philips screw, __ length	32		$0.08	$2.56
#0 washer	1		$0.02	$0.02
#0 lock washer	1		$0.03	$0.03
0-80 hex nut	1		$0.05	$0.05
Epoxy, 3M DP420NS	1		$3.00	$3.00
Other	1	lot	$20.00	$20.00
Vehicle				**$855.35**
Tube, fiberglass, 3 inch OD	78	in	$0.80	$62.40
Nose cone	1	ea	$30.00	$30.00
Payload door	1	ea	$3.00	$3.00
Fin	4	ea	$5.00	$20.00
Altimeter	2	ea	$55.00	$110.00
Locator beacon/radio	1	ea	$80.00	$80.00
Battery	1	ea	$5.00	$5.00
Switchgear/wiring	1	ea	$20.00	$20.00
Parachute, main	1	ea	$35.00	$35.00
Parachute, drogue	1	ea	$25.00	$25.00
Ejection charge	1	ea	$3.00	$3.00
Motor casing	1	ea	$30.00	$30.00
Motor	1	ea	$112.95	$112.95
Rail bead	1	pr	$7.00	$7.00
Altimeter bracket	1	ea	$12.00	$12.00
Other	1	lot	$300.00	$300.00
AGSE Superstructure				**$891.35**
Foot, swivel	6	ea	**$5.95**	$35.70
1010 profile, 2 inches long, tapped end	4	2	$0.55	$2.20
Bracket, 1" x 2"	4		**$8.47**	$33.88
1020 profile rail, 8 feet	2	96	$44.64	$89.28
1020 profile rail, ~30 inches	4	26	$18.03	$72.12
1020 profile 45° brace, 12 inch (for main)	6	12	**$18.49**	$110.94
1020 profile, 12 inches	2	12	$9.13	$18.26
1010 profile, 6.5 feet	1	78	$26.38	$26.38
1010 profile, approx 4 feet	2	78	**$14.20**	$28.40
45 deg adapter ends, zinc	2	pr	**$18.00**	$36.00
Wiring holders	20		$15.00	$300.00
2 x 2" extrusion bracket	1		$8.79	$8.79
Single 80/20, 2 inches, for feet	4	2	$5.85	$23.40
Screws and bolts	1	lot	$20.00	$20.00
Nest, plastic, for rocket body	3	ea	$12.00	$36.00
Braces and brackets, misc	1	lot	$50.00	$50.00
Payload handling				**$383.37**
Laser, structured lighting	1	ea	**$39.99**	$39.99
Bracket, laser to frame	1	ea	**$8.83**	$8.83
1010 short length	1	30	$5.00	$5.00
1010 short length #2	1	32	$12.00	$12.00
fixed angle pivot	1		$17.00	$17.00
hardware for fastening	1		$30.00	$30.00
Nut, 1/4-20	2	ea	**$0.09**	$0.19
Vertical linear motion stage, >8" travel	1	ea	**$174.95**	$174.95
Rotary stepper motor, NEMA housing	1	ea	**$30.54**	$30.54
1020 45 degree support, 18"	1	18	**$19.84**	$19.84
1010 45 degree support, 12"	1	12	**$17.15**	$17.15
1020 short length (2"?) for support	1	2	$3.00	$3.00
8-32 T-nut	8	ea	$0.16	$1.28
8-32 SHCS, 3/8" long	8	ea	$0.12	$0.99
Motor to linear stage mounting bracket	1	ea	**$6.34**	$6.34
10-32 SHCS, 1/2" SS	4	ea	**$0.18**	$0.71
10-32 nuts	4	ea	**$0.10**	$0.42
M4 x 8 screws	4	ea	**$0.09**	$0.37
Flanged shaft support block	1	ea	**$6.37**	$6.37
8-32 SHCS, 1/2" long	2	ea	$0.13	$0.26
Arm, 16" long 80/20	1	16	$5.00	$5.00
Payload clip	1	ea	**$0.95**	$0.95
O-ring, 0.25" ID	2	ea	**$0.03**	$0.06
Screw, 1/4-20, button head, SS	1	ea	**$0.14**	$0.14
Payload vertical ext, 1x1 8020, 3 in	1	3.75	$2.00	$2.00
Door closure				**$181.29**
Payload door closure linear cylinder	1	ea	**$41.95**	$41.95
End ball or roller	1	ea	$10.00	$10.00
End mount bracket	1	ea	**$15.95**	$15.95
Door closure cylinder mounting	1	ea	$35.00	$35.00
Braces and brackets, misc	1	lot	$50.00	$50.00
Screws and bolts	1	lot	$50.00	$50.00
Cable ties for wire retention	1	lot	$2.00	$2.00
Mini microswitch, roller lever	2	ea	**$1.25**	$2.49
Mini microswitch, lever	2	ea	**$1.98**	$3.95
Mini microswitch, offset lever	2	ea	**$1.48**	$2.95
Mini microswitch mount, A	2	ea	**$0.90**	$1.79
Mini microswitch mount, B	2	ea	**$1.79**	$3.58
Mini microswitch mount, C	2	ea	**$1.79**	$3.58
Rail erecting				**$310.31**
Pivot, 80/20	2	ea	**$18.15**	$36.30
10 series 10-32 std t-nut	2		**$0.84**	$1.68
10-32 SHCS x 1-3/8" long, SS	2		**$0.23**	$0.46
#10 washer	2		$0.15	$0.30
Angle bracket for agse end	2		**$8.79**	$17.58
Angle bracket for launch rail end	2		$15.00	$30.00
means to attach microswitches	10		$2.00	$20.00
Microswitch	2	ea	$3.00	$6.00
Linear actuator, 24" stroke	1	ea	**$119.99**	$119.99
Rubber bumper hard stop	2	ea	$4.00	$8.00
Latch/retainer	1	ea	$30.00	$30.00
Wiring harness, erecting	1	ea	$10.00	$10.00
Bracket, MB6	1	ea	**$11.00**	$11.00
Bracket, MB1	1	ea	**$7.00**	$7.00
Screws and bolts	1	lot	$10.00	$10.00
Cable ties for wire retention	1	lot	$2.00	$2.00
Igniter insertion				**$183.43**
Carbon tube, cut to length	0.4	ea	**$13.13**	$5.47
Linear actuator, 20" stroke	1	ea	**$119.99**	$119.99
Blast deflector shield	1	ea	**$15.00**	$15.00
Angle bracket	4	ea	**$0.69**	$2.76
8-32 screw	8	ea	$0.08	$0.64
8-32 acorn nut	8	ea	$0.15	$1.20
Wiring harness, igniter insertion	1	ea	$5.00	$5.00
Bracket, actuator to rail	2	ea	$8.00	$16.00
L-Bracket, tube to actuator	1	ea	**$4.92**	$4.92
Loop clamp with vinyl coating	2	ea	**$0.22**	$0.44
Screws and bolts	1	lot	$10.00	$10.00
Cable ties for wire retention	1	lot	$2.00	$2.00
Controller and interface				**$778.32**
Project housing	1	ea	$35.00	$35.00
Project internal tray for housing	1		$22.00	$22.00
Battery	1	ea	**$15.13**	$15.13
Jack, power (battery)	1	ea	**$10.53**	$10.53
Plug, power (battery)	1		**$17.01**	$17.01
Arduino Mega 2560 R3	1	ea	**$45.95**	$45.95
Shield, relay driver	3	ea	**$19.03**	$57.09
Stepper driver	2	ea	**$21.44**	$42.88
LCD Button Shield	1	ea	**$12.95**	$12.95
E-stop button	1	ea	**$7.15**	$7.15
Pushbutton, yellow	1	ea	**$1.95**	$1.95
Pushbutton, green	1	ea	**$1.95**	$1.95
Hookup wire, 20ga, red and green	1	lot	$15.00	$15.00
PCB adapter, 0.1" header to 20SSOP	3		**$2.50**	$7.50
Debounce chip, octal	3		**$7.00**	$21.00
Jack, stepper 1, 8pos	1		**$11.48**	$11.48
Plug, stepper 1, 8pos	1		**$19.80**	$19.80
Jack, stepper 2, 8pos	1		**$17.24**	$17.24
Plug, stepper 2, 8pos	1		**$16.84**	$16.84
Jack, panel, linear stage	3	ea	**$9.90**	$29.70
Plug, cable, linear stage	3	ea	**$14.18**	$42.54
Jack, panel, light tower	3	ea	**$9.15**	$27.45
Plug, cable, light tower	3	ea	**$13.85**	$41.55
DC 12V Industrial Red Green Yellow Alarm	1	ea	**$26.65**	$26.65
length of 80/20 1x1	1	6	$1.00	$1.00
Locking pivot	1	ea	**$18.98**	$18.98
Wire harnesses	1	ea	$50.00	$50.00
Mounting for Arduino and shields	1	ea	$50.00	$50.00
Bracket from housing to 8020	1	ea	$100.00	$100.00
Screws and bolts	1	lot	$10.00	$10.00
Cable ties for wire retention	1	lot	$2.00	$2.00
Cable jack		ea	**$13.02**	$0.00
Remote control				**$74.12**
Project housing	1	ea	$35.00	$35.00
E-stop button	1	ea	**$7.15**	$7.15
Pushbutton, yellow	1	ea	**$1.95**	$1.95
Pushbutton, green	1	ea	**$1.95**	$1.95
Cable jack	1	ea	**$13.02**	$13.02
Ethernet cable length	1	ea	**$15.05**	$15.05

Other costs

Not included in the total costs for the single AGSE + Maxi-MAV "deliverable" are the prototyping costs, shipping charges and estimated local sales taxes where applicable. Nearly all items will be acquired through on-line retailers located out of state so only a portion of the purchased BOM is subject to in-state taxes.

We estimate these additional (not part of project budget limit of $7500) costs as follows:

- Scale model costs $350
- Motors for test flights $370
- Shipping (vehicle-related shipments) $100
- Sales taxes (5.5% on 10% of vehicle expenditures) $5
- Other $300
- **TOTAL $1125**

Table 40: Project budget

Travel Budget	
Flight	
$400/Person * 13 People	$5,200.00
Rooms	
$119/Room * 7 Rooms * 5 Nights	$3,094.00
Car Rental (Ground Support Vehicle)	
$500 rental+ $600 gas	$1570.00
Total	$9,864.00
Cost per Team Member	**$ 986.40**

Table 41: Travel Budget

Funding Plan

Madison West Rocket Club has sufficient money earning opportunities (raking leaves/yardwork and donations from families or local companies) to earn enough money to cover the estimated budget and cover for possible discrepancies between the estimated budget and actual project expenses. Additionally, it is our policy to provide necessary economic help to all SLI students who cannot afford the travel expenses associated with the program. Every year we award several full expense travel scholarships both to our SLI and TARC students. The monetary amounts and the names of recipients are not disclosed.

SL program is extremely well received by Madison community and we enjoy significant support from local companies, families of students and researchers and labs at University of Wisconsin. We maintain and expand our network of supporters via various venues, mostly through our participation in public outreach events.

Based on our last year data and estimated costs for this years, we expect the following breakdown of funds and expenses:

	Expenses	
Project cost	$6,500.00	
Workshop rental	$1,000.00	
Workshop insurance	$400.00	
Teleconferencing fees	$0.00	Venue and equipment provided at no cost by Chemical Engineering Dept.
Outreach costs	$500.00	
Travel expenses	$9,864.00	
Total Expenses	***$18,264.00***	
	Funds	
Raking fundraiser	$4,000.00	
Donations from families	$3,000.00	
Material support from companies	$1,500.00	
Material support from UW	$1,000.00	
Travel funds	$9,864.00	Students pay the travel expenses associated with SL launch
Total Funds	***$19,364.00***	

Table 42: Funding plan

Safety and Risks (project-wide)

Written Safety Plan

Safety officer responsible for enforcement of the safety plan is William. He will be aided and supervised by educators, Dr. Rob Williamson, Mr. Joseph Schoneman and mentor Mr. Brent Lillesand.

We have identified the following risks that could endanger the successful completion of our project (listed with proposed mitigations):

- **Facility Risks:**
    - ***Workshop inaccessible:*** we have singed rental agreement for our workshop space and should it become temporarily inaccessible, we will work with our landlord to resolve the issue in a timely manner. Rocket construction can be also temporarily moved to Mr. Lillesand's house.
    - ***Classrooms unavailable:*** the classrooms are provided by Engineering Dept. and Physics Dept. of UW, Madison. This provides sufficient redundancy. We can also utilize other options, such as reserving meeting room in a local library or temporarily meeting in club member's house.
    - ***Launch site unavailable/inclement weather:*** we routinely schedule redundant launch windows to ensure that we will have enough opportunities to carry out all necessary flights. We are currently working with three rocketry organizations (NAR Section WOOSH, TRA WI and TRA QCRS) to maximize our launch opportunities.

- **Project Risks:**
    - ***Project behind schedule:*** project progress is constantly compared against list of required milestones and working hours are extended as necessary to meet all milestones. All deadlines are considered hard.
    - ***Key team member unavailable:*** no task is assigned to a single team member; all tasks are carried out by a pair or small group of equally knowledgeable students. Students are not allowed to limit their participation in the project to a single area of expertise.
    - ***Unsolvable technical problem:*** a thorough feasibility review is conducted before the Statement of Work is submitted. Alternative solutions will be sought.
    - ***Unresolvable personal disagreements:*** should the students involved fail to reach an acceptable compromise, the educators will protect the progress of the project, regardless of the interests of the parties in the dispute. All students were informed of this rule before admission to the program.
    - ***Part unavailability:*** all purchasing is conducted as soon as practically possible. We are also working with several vendors, trying to maintain part availability redundancy as much as possible.
    - ***Budget overrun:*** the initial fundraising goal is set at 140% of estimated project expense.

- **Vehicle risks:**

- **Repeated test flight failure:** rocket design review, performance prediction evaluation, static stability check and static ejection tests will be carried out before each test flight. A due consideration will be given to weather conditions to maximize the probability of safe flight and successful recovery. All flight data will be analyzed to identify problems before next flight.
- ***Vehicle lost/irreparably damaged during test flight:*** a sufficient time reserve will be built into project schedule to allow for vehicle replacement. All team members will participate in additional workshop hours. The airborne vehicle will be tracked using three different methods: CAT (Cloud Aided Telemetry), radio beacon and sonic beacon.

- **AGSE Risks:**
  - ***Mechanical runaway, failure to pause:*** the system will be equipped with an emergency stop button that will physically cut all power to the AGSE. The pause functionality will be implemented in AGSE firmware, the emergency stop functionality will be a physical disconnection from power source. There are no moving parts that can be moved by gravity force alone, once the power is cut from the system, all movement stops immediately.
  - ***Failure to stop motion:*** should any of the end-stop microswitches fail, the operator still retains the option of pausing or completely stopping the system. System can continue operation from a paused state, however it will reset from the stopped state, before it can start the operation again (a system self-check at power up will recognize this state).
  - ***Structural failure:*** the superstructure of the AGSE will be inspected prior each demonstration for weakened parts or loosened screws.
  - ***Electrical shock:*** AGSE power comes from batteries and all electrical connections will be properly insulated and inspected on regular basis. AGSE will not be powered up until all team members are in the safe distance. Fuses will be used to prevent short-circuits.
  - ***Unauthorized use of AGSE or accidental activation:*** the control panel has a key operated master switch, preventing unauthorized use.

- **Personal risks:**
  - ***Physical injury:*** the use of Personal Protective Equipment is mandated during all construction tasks and preparation of the rocket for flight or static test. Adult supervision is provided at all times. The use of headphones and personal electronics during rocketry activities and workshop hours is strictly prohibited. The safe distance from AGSE will be maintain at all times when the AGSE is powered.
  - ***Toxicity:*** MSDS documentation is available for all chemicals used in the project and dangerous chemicals are avoided as much as possible. Adult supervision is provided at all times, PPE use is mandated.

NAR/TRA Personnel

Mr. Brent Lillesand (L3 certified, NAR and TRA member) is the mentor for the team and designated owner of the rocket for liability purposes. Mr. Lillesand will accompany the team to Huntsville, AL.

All hazardous materials will be purchased, handled, used, and stored by Mr. Lillesand or project educators (Dr. Williamson or Mr. Schoneman). Mr. Lillesand will be the only person purchasing and handling energetics. The use of hazardous chemicals in the construction of the rocket, will be carefully supervised by NAR mentor and project educators. MSDS data will be available both as a hardcopy and online materials.

In the construction of our vehicle, only proven, reliable materials made by established manufacturers, will be used under the supervision of the mentor and educators. We will comply with all NAR standards regarding the materials and construction methods. Reliable, verified methods of recovery will be exercised during the retrieval of our vehicle. Motors will be used that fall within the NAR HPR Level 2 power limits as well as the restrictions outlined by the SL program.

Additionally, All HPR flights will be conducted only at public launches covered by an HPR waiver (mostly the WOOSH/NAR Section #558 10,000ft MSL waiver for Richard Bong Recreation Area launch site and 15,000ft MSL waiver for Princeton, IL, TRA QCRS site). We will be assisted by members of hosting section (WOOSH, TRA WI or TRA QCRS) and follow all instructions provided by their range personnel and our mentor.

All LMR flights will be conducted only at the launches with the FAA notification phoned in at least 24 hours prior to the launch. NAR and NFPA Safety Codes for model rockets and high power rockets will be observed at all launches.

Team Members Safety Briefing

Mentor, educators and experienced rocketry team members will take time to teach new members the basics of rocket safety. All team members will be taught about the hazards of rocketry and how to respond to them; for example, fires, errant trajectories, and environmental hazards. Students will attend mandatory meetings and pay attention to pertinent emails prior participation in any of our launches to ensure their safety. A mandatory safety briefing will be held prior each launch. During the launch, adult supervisors will make sure the launch area is clear and that all students are observing the launch. Our NAR mentor will ensure that any electronics included in the vehicle are disarmed until all essential pre-launch preparations are finished. All hazardous and flammable materials, such as ejection charges and motors, will be assembled and installed by our NAR-certified mentor, complying with NAR regulations. Each launch will be announced and preceded by a countdown (in accordance with NAR safety codes)

Safety Documentation Procedures

In all working documents, all sections describing the use of dangerous chemicals will be highlighted. Proper working procedure for such substances will be consistently applied, including the required PPE (Personal Protective Equipment), such as using protective goggles and gloves while working with chemicals such as epoxy. MSDS sheets will be on hand at all times to refer to for safety and emergency procedures. All work done on the building of the vehicle will be closely supervised by adult mentors, who will make sure that students use proper protection and technique when handling dangerous materials and tools necessary for rocket construction.

Compliance with Federal, State and Local Laws

All team members and mentors will conduct themselves responsibly and construct the vehicle and payload with regard to all applicable laws and environmental regulations. We will make sure to minimize the effects of the launch process on the environment. All recoverable waste will be disposed properly. We will spare no efforts when recovering the parts of the rocket that drifted away. Properly inspected, filled and primed fire extinguishers will be on hand at the launch site.

The team is cognizant and will abide with the following federal, state and local laws regarding unmanned rocket launches and motor handling:

- Use of airspace: Federal Aviation Regulations 14 CFR, Subchapter F, Part 101, Subpart C
- Handling and use of low explosives: Code of Federal Regulation Part 55
- Fire Prevention: NFPA1127 Code for High Power Rocket Motors

All of the publications mentioned above are available to the team members and mentors via links to the online versions of the documents.

http://westrocketry.com/sli2016/safety/safety2016r.php

Energetics Purchase, Storage, Transport and Use

NAR/TRA mentor, Mr. Lillesand, holds a Level 3 HPR certification. Mr. Lillesand has Low Explosives User Permit (LEUP). If necessary, the team can store propellant with Mr. Goebel (Level-3 certified), who owns a BATFE approved magazine for storage of solid motor grains containing over 62.5 grams of propellant. In most cases, the motors and electrical matches are purchased from the on-site vendor, Mr. Tim Lehr of Wildman Rocketry and used on the same day. Mr. Lillesand will be the sole person to purchase and handle energetics (motors, ejection charges and igniters). Mr. Lillesand will be responsible for depositing unused propellant with Mr. Goebel, should the need arise. Only NAR/TRA certified motors will be used.

Written Safety Statement

All team members and educators understand and will unconditionally abide by the following safety regulations

Range Safety Inspection

Range safety inspections of each rocket before it is flown. Each team shall comply with the determination of the safety inspection.

RSO Ruling Compliance

The Range Safety Officer has the final say on all rocket safety issues. Therefore, the Range Safety Officer has the right to deny the launch of any rocket for safety reasons.

Team Compliance with Safety Requirements

Any team that does not comply with the safety requirements will not be allowed to launch their rocket.

Failure Mode Effect Analysis

Failure Modes Effect Analysis (FMEA)

#	Subsystem	Potential failure mode *How this process step or input could go wrong*	Effects of this failure mode *what is the effect?*	Effect *10 = severe* *1 = no impact*	Occurrence *10 = frequent* *1 = rare*	Controls *Identify the controls in place to detect/control the issue*	Control *1 = excellent* *10 = none*	RPN
30	**Controller**	Bug in firmware causes sequence to stop	Fail to complete sequence	7	5	Thorough testing of code	3	105
18	**Payload handling**	Payload location varies with respect to robot arm	Gripper may miss the payload entirely or knock it out of the way	6	5	Use laser projector and/or template to locate the payload correctly before starting sequence	3	90
11	**Vehicle**	Parachute tangles	Rocket plunges to earth dangerously/high energy	7	4	Follow proper procedures for inspecting and folding parachute and lines	3	84
3	**Payload/ Containment**	Payload location varies with respect to robot arm	Payload is not within tolerances of compartment	5	2	Design sufficient margin on axial and radial capture of clips and end L-brackets Homing routine performed before each payload pickup and placement	8	80
31	**Controller**	Failures in soldering or harnesses cause interruption of sequence	Fail to complete sequence	7	5	Test all harnesses and inspect all solder joints	2	70
32	**Controller**	Battery dies during operation	Fail to complete sequence	7	5	Charge battery before commencing operation	2	70
33	**Controller**	Light bulb fails during operation	Sequence does not meet NASA specifications	7	5	Check all lights at beginning of sequence during homing	2	70
14	**Vehicle**	Engine impulse too high/low	Altitude target over/under run	2	7	Scale launch and full-scale tests	4	56
10	**Vehicle**	Backup rocket doesn't perform similar to main rocket	Altitude target over/under run	2	5	Design reviews and careful inspection before launch of either rocket	5	50
12	**Vehicle**	Ejection charge too small	Failure to deploy, dangerous energy on ground	8	3	On-ground ejection test with same ejection charge	2	48
27	**Igniter insertion**	Igniter jams against side of rocket motor during insertion	Fail to complete sequence	7	2	Careful alignment and inspection pre-launch	3	42
24	**Rail erecting**	Rail jams on obstacles during erection (saddle, bearings, actuator)	Error in launch attitude	3	4	Inspection pre-launch sequence	3	36
1	**Payload/ Containment**	Test payload has different dimensions than what we expected	May not be able to be secured in compartment or gripped	3	5	Clips are made narrow to accommodate range of lengths	2	30
23	**Payload handling**	Loose screws cause gripper to be in wrong configuration	Payload not inserted completely or at all	5	2	Inspection pre-launch sequence	3	30
28	**Igniter insertion**	Ignitor motor overruns its travel	Rocket is lifted off platform; launch rail shortened	5	3	Use microswitch to limit travel	2	30
20	**Payload handling**	Payload arm collides with rocket	Damage to rocket door or fins	7	2	Use of homing microswitches and inspection pre-sequence	2	28
22	**Payload handling**	Stepper motors fail	Fail to complete sequence	7	1	Choose good quality motors and test them	4	28
26	**Rail erecting**	Erecting motor stage fails	Fail to complete sequence	7	1	Choose good quality motors and test them	4	28
29	**Igniter insertion**	Ignitor stage fails	Fail to complete sequence	7	1	Choose good quality motors and test them	4	28
19	**Payload handling**	Payload transport arm deforms during insertion	Payload not inserted completely or at all	6	2	Design for appropriate strength and use microswitches to prevent damage during operation	2	24
25	**Rail erecting**	Microswitch fails to stop motion at 85 degree position	Error in launch attitude	3	2	Choose good quality motors and switches and test them	4	24
5	**Payload/ Containment**	Rocket rotates in saddle, putting door or opening in way of gripper	Door or payload compartment prevents SCARA arm from inserting payload	5	2	Payload compartmnent contains alignment hole to check rotation at time of rocket insertion on launch rail	2	20
7	**Vehicle**	Parachute does not deploy	Rocket plunges to earth dangerously/high energy	8	2	Use redundant deployment system	1	16
13	**Vehicle**	Ejection charge too large	Potential damage to recovery system	2	4	On-ground ejection test with same ejection charge	2	16
4	**Payload/ Containment**	Clip retention force varies over time or from rocket to rocket	Rocket clips may not "grab" payload from weaker SCARA clips	2	3	Tolerance force differential to be large enough (~2) to accommodate variation and degradation	2	12
15	**Superstructure**	Structure twists/deforms while robot is inserting payload	Damage to rocket door or fins	3	2	Perform full inspection of payload compartment and fins after launcher is erect with igniter inserted	2	12
16	**Superstructure**	Structure deforms during takeoff	Error in launch attitude	2	3	Launch rail tee is in near-contact with ground to limit conformational changes during launch	2	12
17	**Superstructure**	Structure changes shape or configuration when re-assembled at test site location	Error in launch attitude, failure of robot to insert payload or close payload door	6	1	Extensive load testing and operational testing beyond normal operational parameters	2	12
21	**Payload handling**	Rocket moves when payload door cylinder moves to close door	Payload not inserted completely or at all	3	2	Use of saddle to hold rocket in place during door closure	2	12
2	**Payload/ Containment**	Center of mass of payload changes from test to final	May be harder to grip or changes CoG of rocket	2	5	Ensure strength of clips exceeds impact of center of mass change Use L-brackets to ensure payload cannot shift more than 0.25 inch after placement Ensure rocket stability margin large enough to accommodate center of mass changes	1	10
6	**Vehicle**	Engine explodes	Destruction of rocket and damage to AGSE	10	1	Choose known/proven engine suppliers Store engines carefully and use promptly after purchase	1	10
8	**Vehicle**	Altimeter fails to operate	Failure to deploy, loss of flight data, dangerous energy on ground	8	1	Use redundant deployment system	1	8
9	**Vehicle**	Telemetry fails	Loss of in-flight data	1	2	Careful inspection of installation and starting (fresh batteries, etc.)	2	4
							AVERAGE RPN	**36**

Table 43: FMEA - Failure Mode Effect Analysis

We have performed FMEA (Failure Mode Effect Analysis) both for the vehicle and AGSE. The FMEA sheet is also available online in Excel format at:

http://westrocketry.com/sli2016/FMEA_CDR_MadisonWest2016_Centennial.xlsx

Personal Hazards (RAC Safety Assessment)

Summary

This safety assesssment is an evaluation of the potential safety and health hazards associated with the operation of the Madison West Maxi-MAV AGSE and MAV launch vehicle. This assessment includes all operational aspects including the preparatory human interaction activities (loading the launch vehicle), autonomous operation, and post-autonomous procedures (vehicle launch and recovery).

Note that since this safety summary is integrated with the rest of the summary report, please refer elesewhere in this report to find separate sections describing theory of operation, operating procedures, block diagrams, and history of development.

Operating Environment

The Madison West Maxi-MAV is designed to operate for extended periods in typical office/laboratory environments (15-35ºC, controlled humidity, no environmental exposure), and for limited periods in a range of outdoor temperatures and environmental conditions. It has moderate levels of environmental hardening, considered roughly equivalent to IP55 (exposure to light rain and high humidity for limited periods of time).

The system is intended to be placed on a roughly flat surface such as carpet, concrete, or pebble gravel bed not exceeding approximately 2 inches of overall terrain height variation over a 3 foot by 8 foot area. Adjustable, threaded feet enable the unit to be leveled as needed. The autonomous robotic procedure is designed to operate in a controlled office environment. Erection, igniter insertion, and vehicle launch are design for outdoor operation under atmospheric and environmental conditions deemed safe for high-power rocketry as per NAS codes and rules.

Support Equipment

The AGSE is self-contained and has all aspects needed to load the payload and bring the rocket to a launch-ready state. This includes an integral control box as well as a remote control dongle.

To complete the payload insertion task, a payload is required to be placed outside the vehicle, and the launch vehicle must be present and configured and placed correctly on the launch rail.

In order to actually ignite the rocket motor and launch the vehicle, as separate set of igniter wires, associated clips or attachment means to the ignitors integral wires, and a low-voltage, high-current power source such as a lead-acid gel-cell battery. Note that having this be a separate system is an additional barrier/layer of safety to prevent accidental ignition of the launch vehicle.

Safety Engineering Considerations

To aid in the evaluation of identified hazards, potential incident and accident scenarios that have been defined are assigned a severity and probability of occurrence, which represents a Risk Assessment Code (RAC) when combined. Accident scenarios having a decision authority of high or medium require corrective action prior to operations (see Table 46). If resolutions do not lower the decision authority to Low, the accident scenarios with a high or medium decision authority must be formally accepted by the responsible authorities. The definitions of the hazard severities and hazard frequencies as well as the Risk Decision Authority Matrix are shown in Attachment 1.

Engineering Safeguards

The Maxi-MAV unit itself possesses a range of integrated safeguards to prevent mishap during installation, handling, and servicing of the unit.

Key engineered safety features:

- Low-voltage operation with moderate to low current in fully enclosed electronics and wiring harnesses
- Low mass of all moving and transportable parts
- Low moving speed of all lever arms
- Highly visible, high brightness safety beacon and audible horn
- Remote operation pendant capable of starting, pausing, and emergency stop of unit from at least 12 feet from unit
- Electrical motion stops built into stages to prevent going beyond defined range of travel

All of these safeguards must be reinforced by following all operating procedures correctly. Key aspects of this installation include blah.

The AGSE unit will be fully tested over a range of conditions and range of personnel.

The design of the above mechanical and system safeguards, the internal design of the electrical circuit architecture, and the firmware design are all extensively reviewed, challenged, revised, and tested during the development process. Issues revealed during the development process and that occur during prototyping are tracked and monitored to ensure the issues are fully resolved before moving to the next level of design maturity or revised assembly completion. Cross-project management and communication ensure that best practices and design techniques from other product developments or in-production processes are utilized across the company's product lines.

Dermal Hazards

It is unlikely that any personnel handling the Madison West Maxi-MAV or launch vehicle under normal situations will experience dermal hazards, or be otherwise sensitized. The potential exists for a small amount of the population to experience dermatitis or sensitization. Similar products have a history of safe use including but not limited to the rocket motors and solid chemical fuel contained within.

This results in a RAC of IV-D or Low.

Chemical Hazards

The AGSE is constructed primarily of aluminum, stainless steel, various plastic resins, and these materials comprise most of the human interaction/exposed areas of the structure.

All AGSE electronics are contained in an environmentally-sealed plastic housing. The launch vehicle contains electronic components in plastic and metal packaging fully contained within the launch vehicle itself. Lead-bearing solder is used in both the AGSE and launch vehicle electronics for high reliability and prevention of tin whisker growth.

The AGSE contains a single, fully-sealed lead-acid battery from a leading manufacturer. It is sealed with no vent holes and can operate safely in any orientation.

The launch vehicle contains a fully-sealed lithium-polymer battery from a leading manufacturer.

No electrolytic capacitors are used.

The chemical hazards of the IRBA are only as they relate to proper disposal methods of the device at the end of product life, and are are no different than guidelines for any aerospace-grade electronic product or consumer battery. The HAZMAT requirements for lead-acid batteries, lithium-polymer batteries, and lead-containing electronics should be followed for disposal of the AGSE and launch vehicle during operating or at end of life.

The launch vehicle contains a chemical propellant from a leading and trusted manufacturer of high-power engines. The solid fuel itself is fully contained in the rocket engine and the only exposed aperture is the rocket nozzle itself. The chemical fuel used is highly stable and requires a one- or two-stage ignition system.

The hazard severity category for chemical hazards from the AGSE or launch vehicle is judged low because of the size of the engine (IV) (Could result in injury or illness not resulting in a lost workday). Because of the nature of rocket fuels as an explosive, we must assert a hazard probability of occasional (C).

This results in a RAC of IV-C, Low for the AGSE and vehicle combined.

Impact Injury and Musculoskeletal Trauma

Two areas of safety are believed to exist here. One related to transport of the AGSE and the other related to recovery the launch vehicle.

The AGSE itself weighs less than 100 pounds and is designed to be safely carried by two humans. This transport has been demonstrated safely over hundreds of feet with adult and teen humans performing the transport safely. Care must be taken to transport the unit safely. If dropped, the fall height would be limited to 1-2 feet of free fall. The unit has mostly blunt corners and no sharp edges or points that could result in puncture injuries if present.

The launch vehicle weighs less than 10 pounds and is not expected to be raised more than 4 feet above the ground, limiting both impact injury and musculoskeletal trauma.

The vehicle recovery aspects are extensively covered elsewhere and the use of dual-deployment recovery system ensures a high probability of safe, low-energy landing of the booster and payload sections below 75 foot-pounds.

This results in a RAC of IV-D or Low.

Pinch points or other mechanical safety risks

In addition to the engineered safety aspects described above, the AGSE will possess clear labelling of potential safety/caution area, such as pinch points near the erector pivot and robot arm. This labelling will be reinforced with the illuminated tower with beacon lights during the operation of the AGSE.

The launch vehicle has no moving parts; safety aspects of the vehicle are addressed elsewhere in this section.

This results in a RAC of IV-D or Low.

Conclusions and Recommendations

The Madison West Maxi-MAV and launch vehicle has been examined for all relevant safety considerations, most especially electromechanical safety and engineered controls to prevent mishap. All aspects of operational safety including dermal, chemical, impact injury, musculoskeletal trauma, and other mechanical safety risks have been examined and assessed a RAC of IV-D in all areas except chemical hazards of the launch vehicle which have been assessed an RAC of IV-C. Preliminary testing of the Maxi-MAV has been completed to support this safety assessment and risk assignments.

This safety assessment results in an overall low safety risk and supports the use of the Maxi-MAV for in all the capacities outlined in the NASA SLI statement of work.

Risk Matrices and Methodologies

The definitions of the hazard severities and hazard frequencies are listed in Tables 2 and 3, respectively, and the Risk Decision Authority Matrix is shown in Table 4. Accident scenarios that are of high or medium probability require corrective action prior to operations. If resolutions do not lower the scenario to low, accident scenarios with an unmitigated high or medium decision authority must be formally accepted by the responsible authorities. Table 4 outlines the decision authority matrix that will be used in accordance with AR 70-1, as required by MIL-STD-882D.

Catastrophic	I	Could result in death, permanent total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation.
Critical	II	Could result in permanent disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding $200k but less than $1M, or reversible environmental damage causing a violation of law or regulation.
Marginal	III	Could result in injury or occupational illness resulting in one or more lost workday(s), loss exceeding $10k but less than $200k, or mitigable environmental damage without violation of law or regulation where restoration activities can be accomplished.
Negligible	IV	Could result in injury or illness not resulting in a lost workday, loss exceeding $2k but less than $10k, or minimal environmental damage not violating law or regulation.

Table 44. Hazard Severity Categories

Frequent	A	Likely to occur often in the life of an item, with a probability of occurrence greater than 10^{-1} in that life.
Probable	B	Will occur several times in the life of an item, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} in that life.
Occasional	C	Likely to occur sometime in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life.
Remote	D	Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life.

Table 45. Hazard Probability Categories

	MISHAP SEVERITY CATEGORY			
MISHAP PROBABILITY	1 CATASTROPHIC	2 CRITICAL	3 MARGINAL	4 NEGLIGIBLE
A FREQUENT	HIGH RISK	HIGH RISK	SERIOUS RISK	MEDIUM RISK
B PROBABLE	HIGH RISK	HIGH RISK	SERIOUS RISK	MEDIUM RISK
C OCCASIONAL	HIGH RISK	SERIOUS RISK	MEDIUM RISK	LOW RISK
D REMOTE	SERIOUS RISK	MEDIUM RISK	MEDIUM RISK	LOW RISK
E IMPROBABLE	MEDIUM RISK	MEDIUM RISK	MEDIUM RISK	LOW RISK

Table 46. Risk Assessment Matrix