MINI

Vanderbilt Aerospace Club

Mini MAV Post Launch Assessment Review

April 29 2015

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I. Introduction

The Vanderbilt Aerospace Club's rocket, named Mini-V, had an overall length of 58.4", with an outer body diameter of 4", and an assembled weight of 14.55 lbs. An off-the-shelf, reloadable Cesaroni J380 "Smoky Sam" was the chosen motor, propelling the rocket to an altitude of 2929 ft. above Bragg Farms. The recovery system flown at competition was a two-parachute system, with a rocket parachute deployed at apogee and a payload parachute deployed at 1000ft. Both of these 30" elliptical parachutes were connected to their respective sections via 15 ft. shock cords. The rocket parachute was housed and deployed at apogee from the tail and forward section of the rocket (just aft of the avionics bay), whereas, the payload parachute was housed and deployed at 1000 ft. from the forward section (just fore of the avionics bay).

For the vehicle design, the team initially proposed a 37.5 lb., 101.5" long, 5.5" diameter rocket. This choice was made in following with previous years' rocket designs, which had to include the space to house several scientific payload experiments. However, the subscale flights mandated by the NASA's Statement of Work influenced the design of Vanderbilt's final rocket to follow a different direction. After flying the first payload bay prototype in the second subscale launch, the team determined that a 5.5" rocket was no longer necessary for the purpose of the mission. In addition, by reducing the rocket's diameter and length as well, the design was able to be optimized for both volume and weight, allowing for a smaller motor choice, the Cesaroni J380 (as opposed to the L1030 to be used by the 5.5" rocket). The new full-scale design was validated by a test launch on March 15, 2015, and by the competition flight on April 11, 2015.

The payload containment mechanism is housed in the nose section of the rocket. The payload bay aims at securely storing the sample payload and then jettisoning via its own payload parachute at 1000 ft. on the way down from apogee. The payload bay design is driven by a lead screw, which acts as the method for linear actuation. By rotating against a lead nut, the motor-driven lead screw is able to securely open and close the payload bay by moving the nose cone in and out. The lead screw itself provides the force needed to secure the payload bay closed during flight—keeping the sample safely locked in place. The lead screw is non-backdrivable, meaning that axial forces, such as those experienced during launch, will not cause it to rotate against the lead nut. The payload bay contains custom aluminum bulkheads for structural support and a custom-molded carbon fiber tray and sabot system for payload retention. The payload bay houses its own electronics bay as well, providing the logic necessary for the payload bay to communicate with the AGSE during sample retrieval via a custom-made magnetic breakaway connector that attaches to the outside of the rocket.

The Autonomous Ground Support Equipment (AGSE) is a ground-based, robotic system that aims at autonomously picking up a sample payload and placing it within the rocket. Vanderbilt's AGSE includes the additional feature of camera-based vision, an enhancement allowing for a more adaptable, dynamic system. By having computer vision, the AGSE is able to find and retrieve a sample payload from anywhere within its workspace. The camera feed informs the AGSE on where to move next, a technique in robotics called visual servoing. The image seen by the camera is processed by an NVIDIA Jetson TK1 board located on the AGSE table. Filters are applied to the image to sort out non-sample objects. Once the sample—a known geometry and color—is found, a bounding box is drawn around it, allowing the center of mass to be found. It is this center that the AGSE uses to position the gripper over the object. In a similar way, the payload bay's position and orientation are found using two fiducial markers, similar to QR codes, in the payload tray. With both the sample and payload positions and orientations now known, the AGSE can pick up and place the sample in the payload bay and signal it to close. The AGSE radial and vertical movement is driven by two lead screws—influenced by the design of the payload bay. The AGSE rotates on its table base through use of a servomotor connected to its main shaft. The gripper is a custom design using a few parts from a Crust Crawler off-the-shelf gripper design. Using acrylic gear casing, metal linkages, 3D printed phalanges, and foam padding on the phalanges, the gripper has proven itself to be durable and robust not only in actuating but also in grabbing the sample. The gripper is actuated with a servomotor, as is its wrist movement.

Overall, Vanderbilt's team has focused on optimization, reliability, and adaptability in this year's design. The rocket and payload bay have focused on volume and mass efficiency, incorporating the smallest possible design that completes the sample recovery and launch mission. The AGSE's ability to use camera vision to locate the sample for retrieval allows great adaptability necessary for a fully autonomous system. These design philosophies fall directly in line with NASA's Space Launch System Mission; the competition this year is modeled after which. Volume and mass efficiency is imperative in any Space Mission, saving fuel use and therefore money with lighter payloads. Additionally, adaptability is a critical key to a Sample Recovery Mission such as the Mars one, where a variety of extraterrestrial factors could affect the ability of the system to perform its task.

Fig. 1: 3D schematic of the (i) Mini V Rocket (ii) Payload Containment System, (iii) Payload , (iv) Gripper, and (v) AGSE

II. Rocket Vehicle Summary

Design and Performance criteria for the NASA SL flight vehicle were laid out as follows:

(i) The rocket size will be optimally determined by the size of the payload, and the ease of payload placement in the rocket. The rocket weight will be as low as possible.
(ii) The rocket will be built of high-strength low-weight materials and that there shall be only three sections to minimize complexity and reduce overall launch weight.
(iii) The rocket should take-off perfectly following ignition and have a substantial speed (~70 fps) leaving the launch rail.
(iv) Rocket flight shall be stable (Static Stability Margin between 1.5 & 2.0), and be able to negotiate side winds and wind shear.
(v) The launch vehicle must attain an altitude of 3000ft AGL ±150ft.
(vi) The rocket parachute must deploy within 2.0 sec after apogee is reached.
(vii) The landing speed of the rocket from apogee shall be around 40 fps to minimize landing drift.
(viii) The payload compartment shall be deployed at 1000ft ±100 ft.
(ix) The landing drift of all rocket parts shall be less than 2500ft. under all launch conditions.
(x) The rocket parts shall not sustain any damage while landing.
(xi) The rocket parts shall not be affected by humidity conditions during flight, and ambient wet conditions at landing; that it be specifically protected against moisture damage.

Table 1: Mini-V NASA SL Flight Details

Rocket Total Height (in)	58.4	Rocket Parachute Diameter (in)	30” elliptical
Rocket Diameter (in)	4	Rocket Parachute C_D	1.5-1.6
Rocket Launch Weight (lb.)	14.55	Rocket Parachute Deployment Altitude (ft. AGL)	Apogee (backup +1”)
Rocket Static Stability Margin	1.85	Rocket Parachute Ejection Charge (gm.)	3.0 (backup 3.2)
Rocket Rail Exit Velocity (fps)	70	Shear Pins (4-40)	3
Rocket Average Acceleration (+G)	5.0	Tail Section Landing Mass (lb.)	4.15
Rocket Apogee Altitude (ft.)	2929 AGL	Landing Speed of forward & tail section (fps.)	31.8
Payload Parachute Diameter (in)	30” (elliptical)	Tail Section Landing Energy (lbf-ft)	65.2
Payload Parachute C_D	1.5-1.6	Payload Section Ejection Charge (gm.)	2.0 (backup 2.2)
Payload Compartment Landing Mass (lb.)	4.85	Motor	Cesaroni J380 SS
Payload Parachute Deployment Altitude (ft. AGL)	1000 (backup 900)	Motor Diameter (mm)	54
Payload section Landing Speed (fps)	23.0	Motor Length (cm)	32
Payload section landing energy (lbf-ft)	39.8	Motor Total Weight (g)	1293

III. AGSE Summary

We have developed the Autonomous Ground Support Equipment (AGSE) with the ability to operate on variable terrain as on Mars, and to capture the scientific sample, insert it into a rocket for delivery back to Earth. To meet this challenge, we developed a robotic crane-based system with a powerful control processor that can handle (i) detection of the sample and the rocket from camera video, (ii) robotic sensing and motor control, and (iii) path planning to maneuver the robotic gripper from its sensed position to the sample's and rocket's detected positions. Because this system was designed with the criteria of a (simulated) mission to Mars, we have designed the system such that it (iv) minimizes the AGSE size and mass while maximizing operational range, (v) minimizes power consumption while maximizing functionality, and is (vi) capable of detecting and mitigating different failure scenarios autonomously. These design considerations are important because in the real system (a) we must send the AGSE to Mars, so its size and weight affect the cost of the mission, (b) batteries are heavy and solar power on Mars must be taken into account, and (c) such expensive remote systems cannot be easily fixed or replaced, so any unrecoverable failure is wasted money and time which does not produce viable results. Finally, to keep the project manageable and decrease implementation complexity, we have designed the mechanical and software systems of the AGSE to be modular, which allows for individual system components to be worked on, tested, and upgraded independently of the rest of the system.

IV. Vehicle Preparation Summary

The launch pad was assembled at the launch site on the day of the competition. The prevailing ground winds at the time of the launch were around 9 mph, and were directed form NE to SW. The NAR officials had the rail tilted approximately 5 degrees, to launch the rocket away from the crowds and with the wind, as a safety precaution. The launch rail was greased with Vaseline to reduce the friction between the rail and the rail guides. The rocket went off the rail with no problems and the launch pad looked very sturdy during takeoff.

Shown below is a timing summary of our Launch Day activities. Each checklist was followed such that every system would work during flight. It should be noted that this timeline table represents the time stamps of the events that occurred rather than the actual time spent on the construction/setup of the rocket. The Vanderbilt team stopped construction activities several times and left the tent to watch each individual rocket launch; additionally, this is a recommended safety precaution. The cumulative time spent watching other team's launches were roughly about half an hour. This resulted in a ~1.5 hour time window for overall rocket and payload setup and preparation on launch day. As far the rocket activities: assembly to launch and recovery was accomplished in less than 2.5 hours.

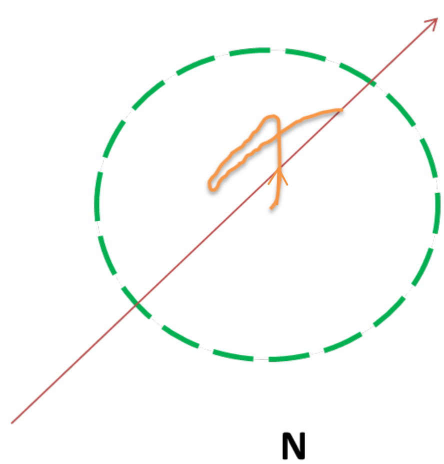


Figure 2: Wind pattern at launch site, and rocket flight path from take-off to landing.

Table 2: Launch Timeline

Task	Start	Finish	Total Time	6AM-7AM	7AM-8AM	8AM-9AM	9AM-10AM	10AM-11AM	11AM-Noon
Travel to Bragg Farm	6:45	7:15	30 min						
Setup	7:15	7:45	30 min						
Unload Vehicles	7:15	7:30	15 min						
Setup Tent and Work Stations	7:30	7:45	15 min						
Launch Pad Assembly	7:45	10:05	20 min						
Assembly Base and Rail at Launch Site	7:45	8:00	15 min						
Level to 5° away from crowd	9:55	10:00	5 min						
Recovery System Assembly	7:45	9:00	75 min						
Recovery Systems Preparation	7:45	8:15	30 min						
Electronics Verification	8:15	8:30	15 min						
Bay Assembly and Charge Placement Verification	8:30	8:40	10 min						
Parachute Inspection, Folding, and Verification	8:30	9:00	30 min						
Rocket Assembly	7:45	9:25	100 min						
Component and Tool Inspection	7:45	8:00	15 min						
Payload Bay Assembly and Initialization	8:00	8:10	10 min						
Mount Avionics Bay and Seal from Blasts	8:40	8:55	15 min						
Connect Parachutes, Mate Sections, and Insert Shear P	9:00	9:20	20 min						
Insert Motor	9:20	9:25	5 min						
Final Preparations	9:30	9:55	25 min						
RSO Inspection	9:30	9:45	15 min						
Transport to Pad	9:45	9:50	5 min						
Activate Altimeters	9:50	9:55	5 min						
Launch and Recovery	10:10	1:30	20 min						
Launch	10:10	10:15	5 min						
Wait for All Clear and Recovery	10:15	10:30	15 min						
Post Launch	10:40	11:15	35 min						
Test Payload Bay	10:40	10:45	5 min						
Disassemble Rocket	10:40	10:50	10 min						
Pack Up Work Area	10:50	11:15	25 min						

V. Vehicle Flight Results

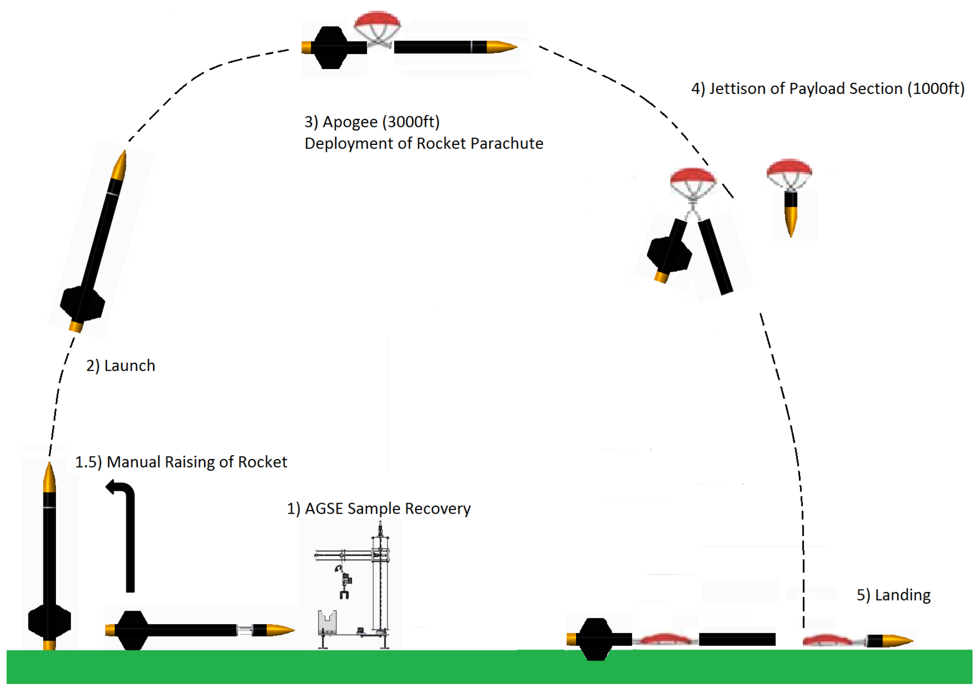


Figure 3: Vehicle Recovery Schematic

The Vanderbilt Aerospace Club's launch of the Mini-V rocket at the competition was extremely successful. The ground winds were ~9 mph and were directed from the NE-SW. The launch rail was tilted 5 deg with the wind. The rocket took-off straight up and reached an altitude of 2929 ft. against a target altitude of 3000ft. The rocket parachute deployed at apogee and the rocket could be spotted in the clear skies. The rocket descended to about 1000 feet under drogue, and the payload parachute charges fired with the parachute completely unfurling from the nosecone. The 30" elliptical parachute did an excellent job decelerating the rocket's descent and landed the rocket parts within 1200 ft. of the launch pad, and within the energy requirements laid down by NASA for the heaviest independent section of the rocket [<75 lbf-ft]. There was no damage to the rocket upon landing.

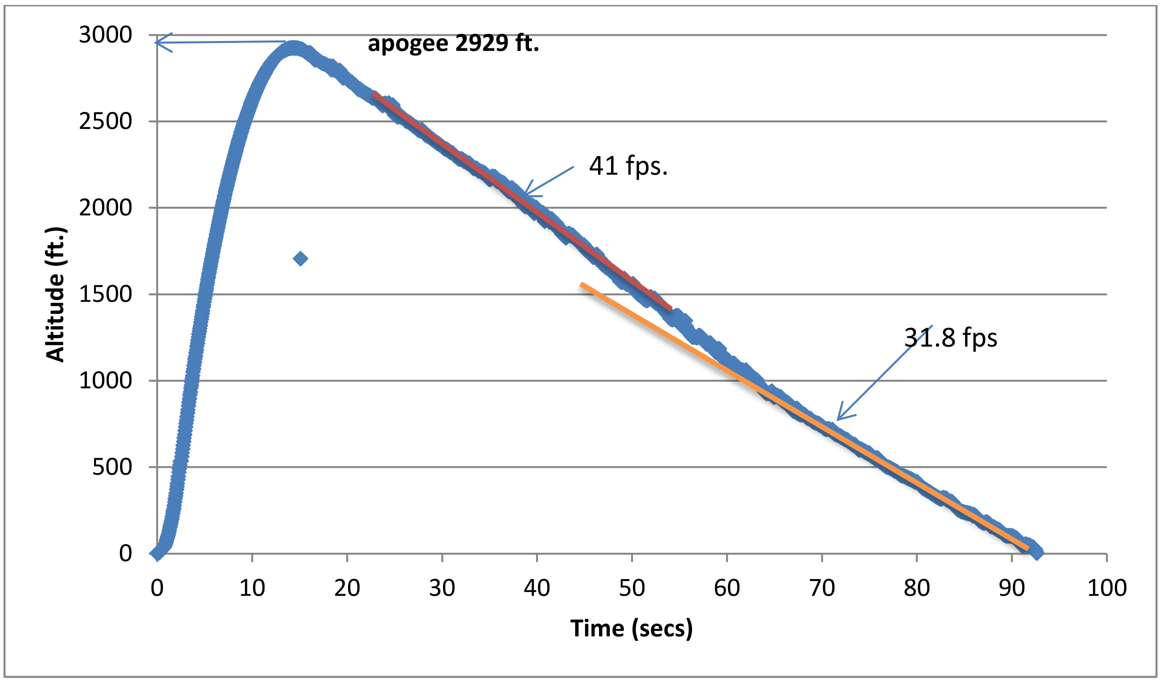


Figure 4: Flight altimeter data showing apogee of 2929 ft. and a landing speed of 41 fps. under rocket parachute, and 31.8 fps after payload jettison.

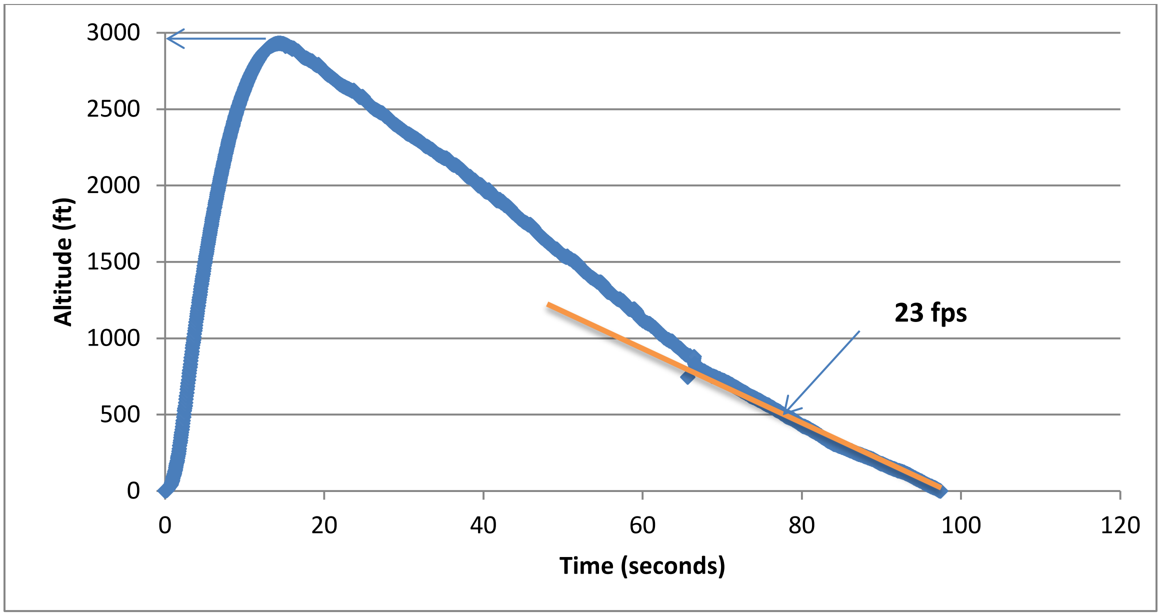


Fig. 5: Payload section altimeter data showing a landing speed of 23 fps following jettison

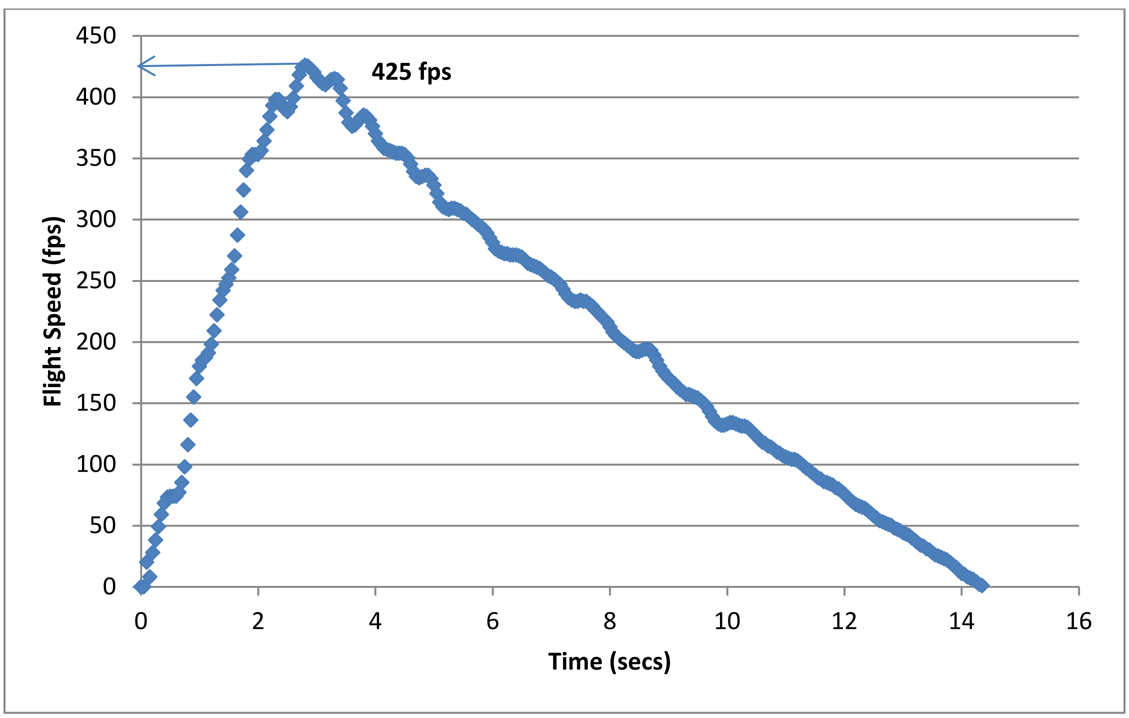


Figure 6: Rocket flight speed showing a maximum of 425 fps at 2.7" into flight.

Landing Energy of the tail section:

$$KE = \frac{1/2\, mV^2}{g} = \frac{0.5 * 4.15\ (lb) * 31.8(fps)^2}{32.2\ \left(\frac{ft}{s^2}\right)} = 65.2\ lbf - ft < 75\ lbf - ft$$

Landing energy of the payload section:

$$KE = \frac{1/2\, mV^2}{g} = \frac{0.5 * 4.85\ (lb) * 23(fps)^2}{32.2\ \left(\frac{ft}{s^2}\right)} = 39.8\ \ lbf - ft < 75\ lbf - ft$$

V.1. Flight Trajectory Analysis from Fast-Action Pictures

Figure 7 (a-e): High-resolution pictures with time-sequence showing a picture-perfect take-off and flight of the Mini-V rocket

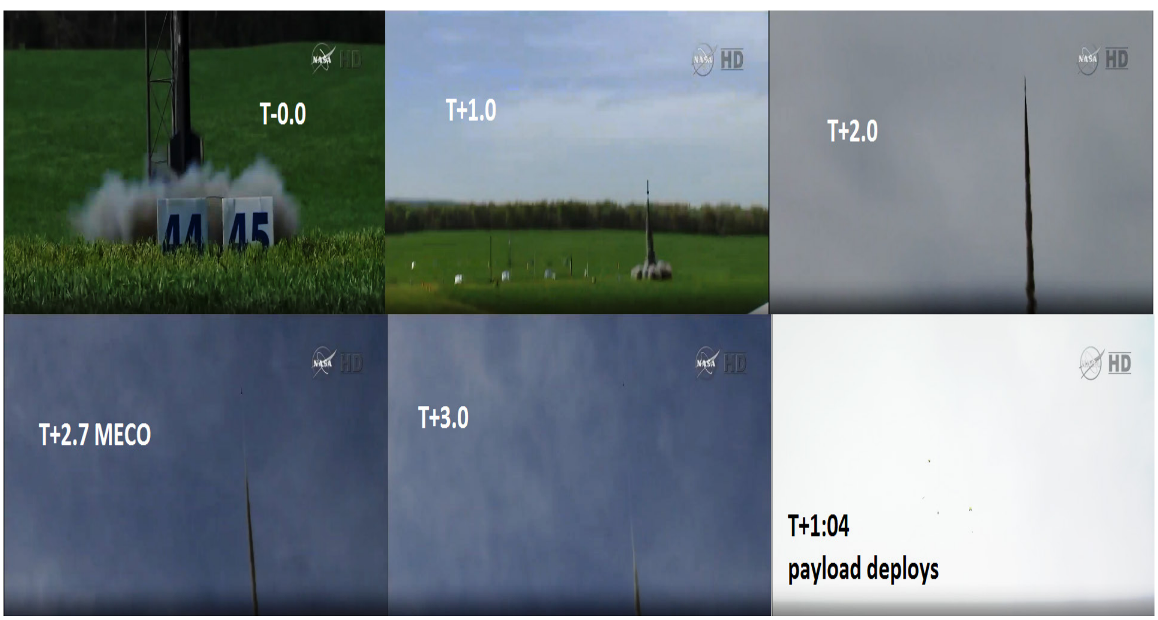


Figure 8: Video camera snippets of flight from take-off to t=3 secs, before the rocket becomes undetectable in the sky

T0: The all-fire signal has successfully ignited the rocket motor at T0 seconds. Ignition is preliminarily verified by a faint trace of smoke that exits the rocket for a few milliseconds.

T+ 0.3 Second: The rocket lurches into motion in a large puff of exhaust. This picture depicts the moment that the Mini-V rocket is just exiting the launch pad.

T+0.7 Second: The rocket has just exited the launch pad. At +5g thrust, it can be estimated that the launch rail exit velocity is around 70 fps at 0.5". Just exiting the launch pad, the rocket slightly windcocks, but is stable enough to correct itself.

T+1.0: The rocket continues straight-up with no hint of turning into the wind.

T+2.0: The contrail continues to show lack of strong winds throughout the thrusting phase. The rocket reaches maximum velocity of 425 fps at 2.7" into flight.

T+2.7: Rocket Motor cuts off. With the rocket being so small against a blue sky it becomes difficult to track it photographically after this time.

T: 2.7-15: Coasting Phase: During the coasting phase, it is clear to the eye that the rocket curves into the wind, with the upper level winds being higher. The rocket drifts into the wind during the coasting phase.

T+15: Apogee, Rocket Parachute Deployment

The rocket has reached apogee and the rocket parachute has deployed. The rocket will now begin its descent phase under the control of the rocket parachute until about 1000 feet at which point the payload will be jettisoned.

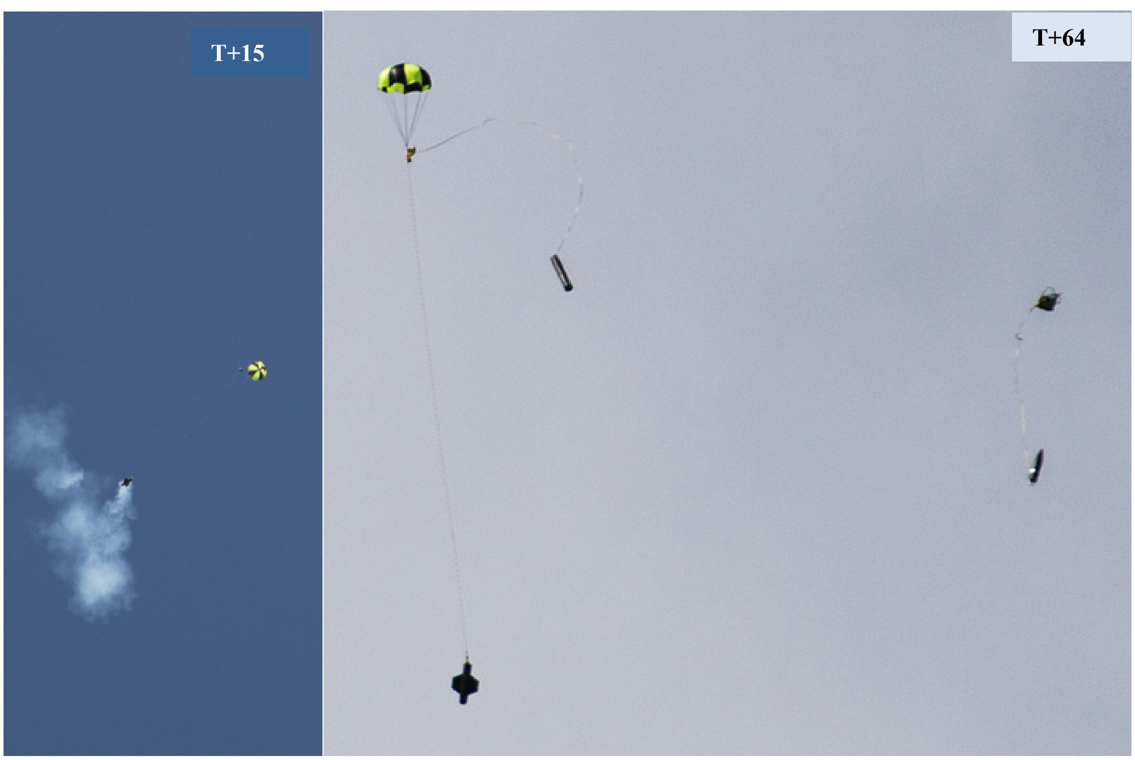


Figure 9: Rocket parachute deployment at apogee, and payload jettison at 1000 ft.

T+64: Payload Parachute Deployment & Jettison

The rocket has reached about a 1000' and the payload has been jettisoned. The rocket parts will now descend on two parachutes, one for the main body and the other for the payload section.

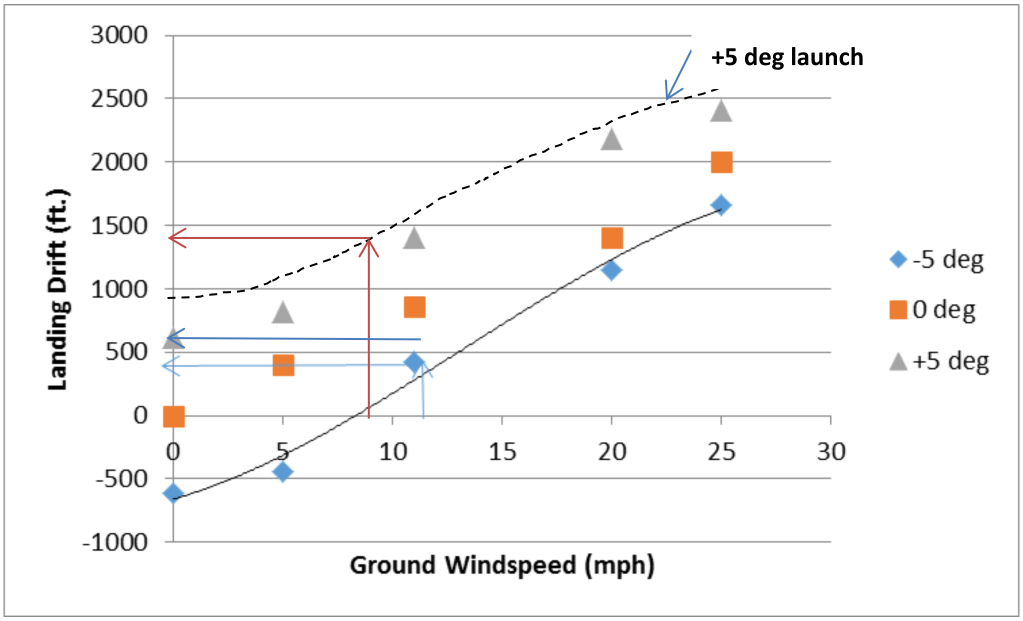
T+95: Landing

Both the rocket main body and the payload section landed very close to each other and about 1200 ft. from the launch pad. With picture-perfect deployment of the rocket and payload parachutes and successful recovery of the launch vehicle and payload, pursuant to the NASA SL 2014-2015 Handbook, the entire team could not contain their elation at the overall success of the launch.

Fig. 10: Mini-V Rocket landing in separate sections and full recovery with no damage

V.2. Flight Comparisons with Simulations

Flight simulations which were done before launch were compared with the NASA SL field-day launch conditions of +5 deg launch pad inclination and flight with the wind, and for ground windspeed of 9 mph. Figures 11a, b show that there is perfect correlation between the predicted and the actual landing drift, however, the predicted peak altitude and the actual peak altitude differ by about 250 ft.



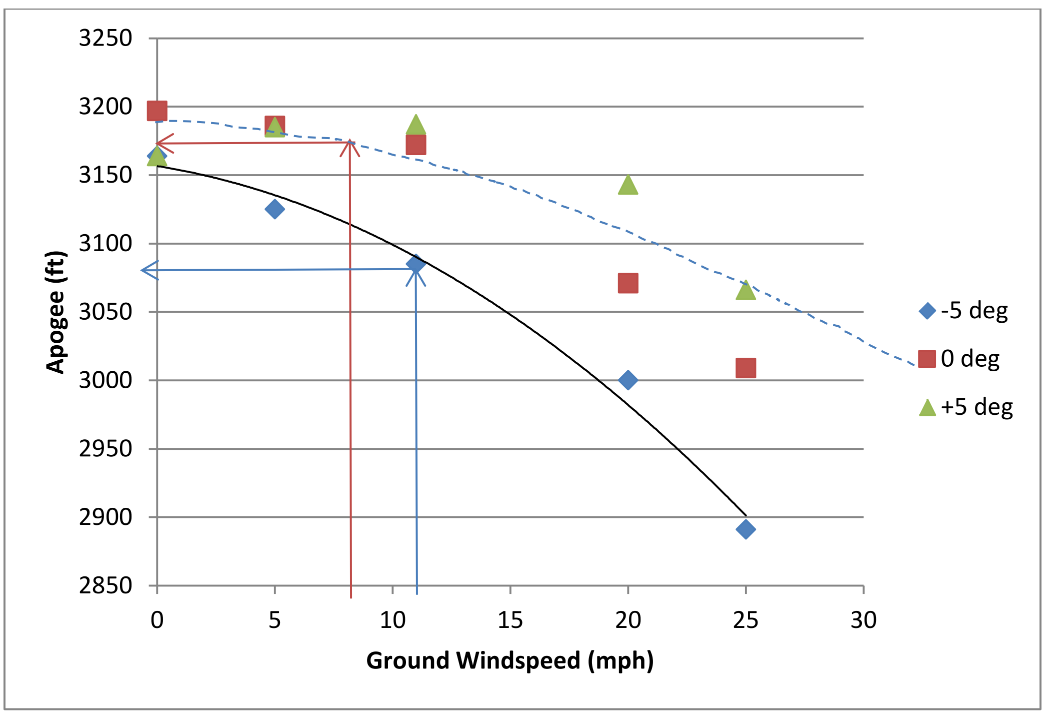


Figure 11: (a) Predicted landing drift, and (b) predicted apogee for the NASA SL flight conditions

The predicted altitude for a perfect flight, with the wind, would be around 3175 ft. But the actual altitude reached was 2929 ft. Reasons for the anomaly can be found either in the flight pattern and the resultant drag, or in the thrust delivered by the motor. First we look at the motor thrust; the predicted maximum speed of the rocket is 450 fps per simulation. The actual maximum speed of the rocket during NASA SL is 425 fps (fig. 6). Simplistic analysis says that the altitude reached will be lowered by $(450^2-425^2)/2g = 200$ ft. during the coasting phase of the rocket flight. Since the rocket took off vertically during the thrusting phase, the only two possibilities for this scenario are (i) the rocket is underpowered with a thrust that is lower by 5%, or (ii) the rocket has a drag that is higher by about 40%. Vehicle drag does not play a major role during the thrusting phase, it is more likely that the rocket motor is under-powering the rocket. The evidence for this can be found in figure 12, where the maximum flight speed attained by the rocket during full scale launch in March 2015 is about 35 fps higher, and that the coasting phases overlap, implying that vehicular drags match up. The case can be further strengthened by noting in figure 13, how the simulated variation of vehicular drag has a weak impact on maximum flight speed attained during the thrusting phase, compared to the apogee attained after the longer duration coasting.

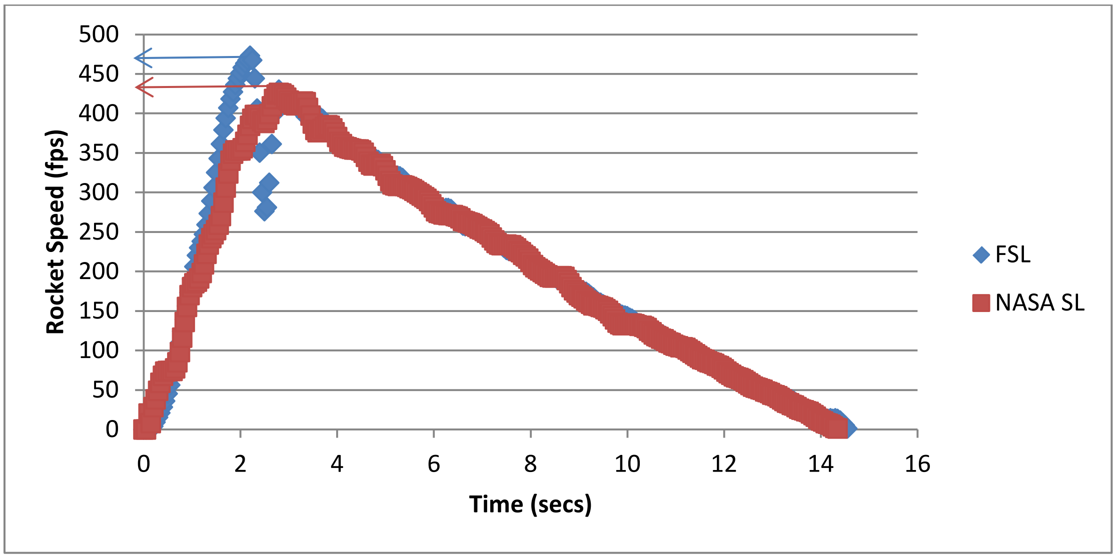


Figure 12: Comparison between the maximum speeds attained by the rocket at Full Scale Launch and at NASA SL for the same J380SS motor.

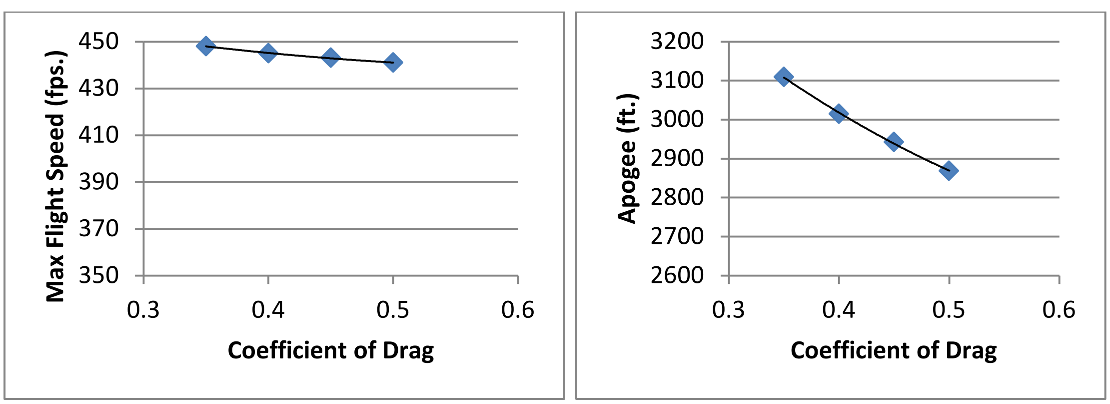


Figure 13: (a) Simulated data showing weak impact of vehicle C_D on maximum flight speed, and its stronger impact on apogee attained.

VI. AGSE Results

The functionality of the AGSE was demonstrated to the NASA SL judges on the 9th of April, 2015. The high-level software running on the AGSE followed the design principles of a *Search and Rescue Robot.* This means that the AGSE made no assumptions on the position of a target sample or the position of rocket payload bay. Therefore, the software on the AGSE was written in such a way that a fully initialized system would execute a deterministic and bounded state machine. The following are the high-level states that are traversed by an initialized AGSE:

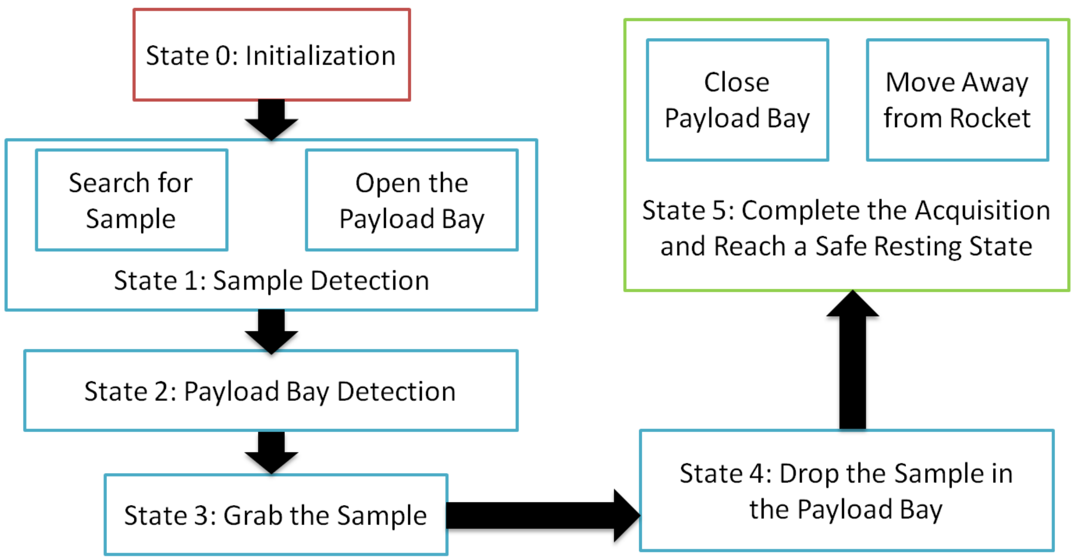


Figure 14: Flow chart detailing the functional sequence of the AGSE

As the above figure shows, there are 5 high-level states for the AGSE. In State 0, the system performs a series of initialization tasks. This includes reaching the maximum height, the minimum radial reach and a closed gripper state. The base rotation servo angle is set to 0^0. When all of the initialization goals are met, the AGSE safely traverses to State 1: Sample Detection. During sample detection, the AGSE instructs the payload bay of the rocket to "open" using our quick disconnect USB cable. It must be noted here that although we are using this cable to interact with the payload bay, the AGSE makes no assumptions about the position or relative orientation of the payload bay. During sample detection, the AGSE first reaches a vertical height $\mathbf{H_v} = \frac{1}{2}\,(\mathbf{H_{vmax}})$, half of the maximum vertical height and a radial height $\mathbf{H_r} = \frac{1}{2}\,(\mathbf{H_{r\,max}})$, half the maximum radial height. This ensures that the camera mounted to the gripper is sufficiently close to the ground and still high enough to not run into the electrical components on the base of the AGSE. Upon reaching a base rotation angle of 0^0, the arm starts to sweep the length of the radial arc. Due to the wide viewing angles of the Logitech C920 camera, the AGSE is able to cover the entire radial span when the camera is mounted at $\mathbf{H_r}$. Using sweeps of 20^0- 40^0 resolution; the AGSE is able to find a sample within its operating range in less than 1.5 minutes. Once a sample is found, the AGSE refines its observations by making sure that the sample, as seen by the camera, is in the center of the image. The error in this refinement is as low as a circle of radius = 100 pixels. This is important because the camera mounting point is offset from the gripper both radially and vertically. This offset is accounted for when the AGSE gripper grabs the sample. Once sample detection is complete, the AGSE searches for the payload bay. QR-style markers on the payload bay make bay detection easier. The AGSE performs a similar sweep to identify the payload bay of the rocket, this time at a slightly higher height so as to allow the camera's auto focus to be able to see the markers without blur. Once the payload bay is found, the AGSE transitions into the final phase of the acquisition process. The AGSE travels to the sample and orients the gripper to align with the angle of the sample. Once the vertical height is low enough, the gripper is closed to secure the sample. Then, the AGSE travels upward till it reaches a safe height, before rotating to the payload bay position.

VI.1. Demonstration & Observations:

The AGSE operation was presented three times on the day of the demonstration. We learned several lessons during these demonstrations. The exercise showed us that we needed to level the base platform of the AGSE relative to the floor so that the vertical actuation to the floor is not skewed on either side of the AGSE. This is important so that the gripper reaches an optimal height above the floor to retrieve a sample securely. If this calibration is off, the gripper could be too high or too low relative to the ground to correctly grip a resting sample. It was also evident that our image processing algorithms were “robust-enough” for the lighting conditions of a well-lit hotel conference room. On all three accounts, both sample and payload bay detection methods succeeded without failure.

During the final run of the night, we allowed one of the judges to place the sample at a random location within the reach of the AGSE. The AGSE identified the sample and the payload bay. When attempting to grab the sample, the radial actuation was not sufficient for the gripper to be *perfectly* aligned above the sample. However, due to the curved nature of the gripper, the gripper managed to grip most of the sample despite the slight misalignment. Even with sub-optimal gripping, and reasonably fast base rotation, the gripper held on to the sample and placed it correctly in the payload bay. **To summarize, on all three demonstrations, the AGSE successfully performed the 5 high-level states previously described without software or mechanical failure.**

Table 3: Summary of the timing results observed during the NASA SL Demonstration.

State	Description	Time Taken
State 0	Initializing the AGSE – Reach safe height & rotation	0 – 30 s
State 1	Open Payload Bay & Detect target sample	30 – 90 s
State 2	Find the Payload Bay	90 – 150 s
State 3	Grab the sample	150 – 180 s
State 4	Place retrieved sample in payload bay	180 – 240 s
State 5	Close Payload Bay & rotate to safe region	240 – 280 s

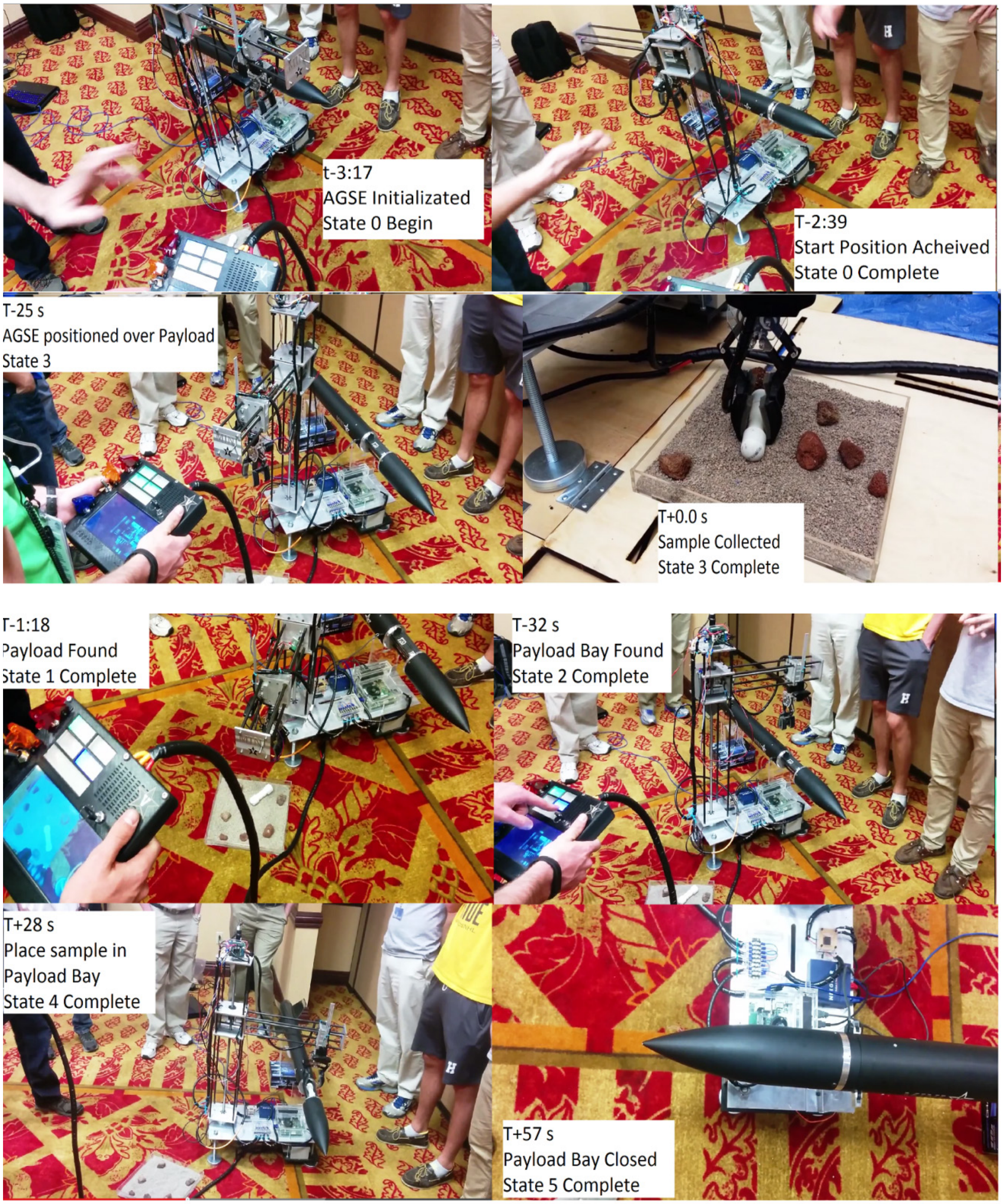


Figure 15: Picture sequence with action time markers from the NASA SL Demonstration

VI. 2. Scientific Value of AGSE:

Following principles of model-driven development, we developed a modeling language and a graphical user interface (GUI) called ROSMOD to design and rapid prototype the software for the AGSE. We created design-time code generators that generate useful deployment code that runs the actual system. This is also evidenced by the fact that although the AGSE software compiles and runs logic spanning 10,000+ lines of code, almost 6,000 lines of C++ code was automatically generated from the design model of the AGSE. It must be noted here that this tool is not specific to the AGSE but a more generic design-time tool for Cyber Physical Systems (CPS) that represents a class of systems where hardware and software closely interact with the physical environment. This greatly simplified our software development process so we could more easily focus on the image processing and mechanical robustness of the system. In order to build a robust AGSE, we also developed various feature classification, image segmentation and object detection algorithms based on the parameters of the target object of interest.

We developed an autonomous, modular, extensible platform for extra-terrestrial sample acquisition. We showed how the AGSE can detect multiple samples of interest and not just one sample at a fixed location. This ensures that our AGSE transcends from being a simple pick-and-place robot to a more sophisticated, smart sample retrieval robot. Secondly, the filters used in the AGSE for detecting the sample can be easily modified and replaced to detect, track and locate a heterogeneous variety of samples, based on physical and visual features. This allows the sample software and hardware to be used repeatedly for differing objectives at different points of the mission plan. Such flexibility and robustness truly represents the value of this AGSE.

VII. Budget Summary

The team started with a budget of $15,000 generously provided by the Vanderbilt University Mechanical Engineering Department. In addition, we received a $2,000 grant from Boeing as well as the $600 stipend from NASA, bringing the total budget to $17,600. Meticulous tabulation of all expenditures allowed the team to track its budget throughout the year and ensured that we remained in the black. A detailed breakdown of the expenditures for the team over the year is shown in figure 16. Briefly, all AGSE-related purchases came to about $6000, all rocketry-related purchases came to about $4100, and expenses towards outreach and launches came to about $5500.

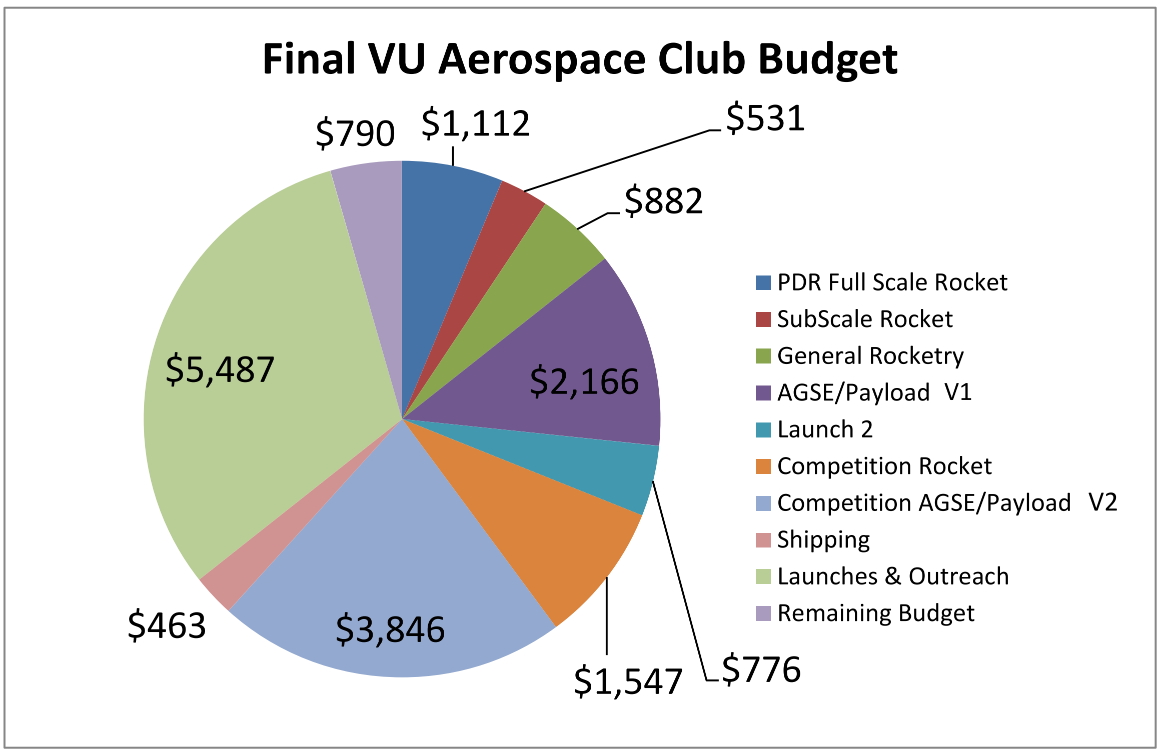


Figure 16: Breakdown of expenditures docked into various categories

The team was left with $790 at the end of the year, which they plan to spend on a celebratory dinner. However, at FRR, the leftover amount was a little over $2000. This discrepancy came about in a series of last-minute expenditures that were unforeseen: (i) some AGSE electrical issues made it necessary to replace several controllers and servos, and (ii) it was decided to step up the power of the horizontal carriage motor. These last-minute purchases increased our cost by $993. In addition, our treasurer had forgotten to account for the team dinner in Huntsville, which accounted for another $350. However, because we were diligent in keeping on top of our budget and refraining from unnecessary purchases, we were still able to remain within our budget.

Figure 17 details the as-flown costs of the entire system which includes the AGSE and the Mini-V Rocket. A more detailed listing of the individual parts is listed in the FRR. As can be seen, the final launch vehicle, payload bay, and AGSE were well under the $5,000 limit imposed by NASA, coming out to $3,232. Again, this is due to the team's emphasis on using the most efficient design and refraining from purchasing overpowered or unnecessary parts for our system.

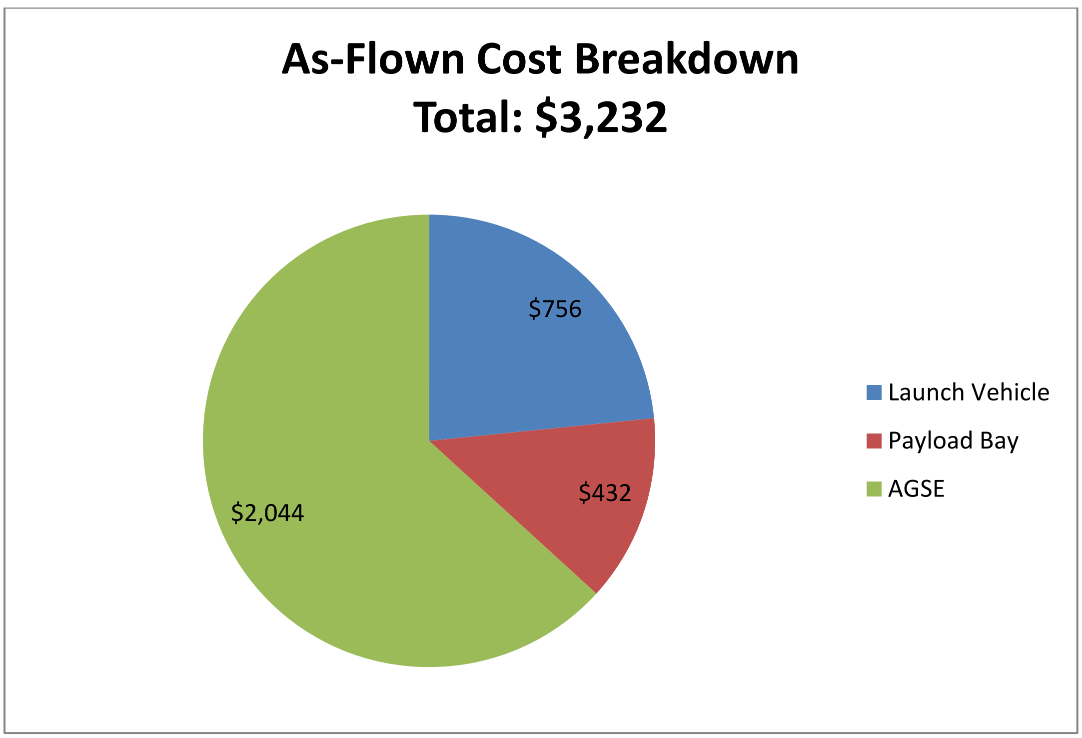


Figure 17: As-flown cost of AGSE and the Mini-V Rocket

VIII. Educational Engagement Summary

Figure 18: Vanderbilt Outreach to Middle Tennessee Schools

Each year, the Vanderbilt Aerospace Club performs outreach events as a part of the Student Launch competition, but also out of a genuine desire to promote enthusiasm for STEM within the State of Tennessee. The study of science and engineering is a strong path toward improving quality of life; this is both for an individual and the quality of life of those who benefit from their inventions and discoveries. The club believes very strongly, that introducing rural and underfunded areas to opportunities in STEM is the greatest long-term gift we can bestow. Children who may have otherwise never even known they had an interest in or aptitude for engineering may now go on to make significant contributions to their community, or even mankind. For this reason, the team's early events were centered on rural schools, which do not have access to the materials or even just encouragement and support structure of larger urban or suburban schools.

Lessons at these schools are typically a combination of experiments meant to help the students better understand Newton's Laws and demonstrations intended to increase enthusiasm for STEM courses and careers. Students separated into teams and performed a series of experiments using "frictionless" cart and track setups. Each experiment asks students to predict the results, record the actual data, and then explain what happened in terms of one of Newton's three laws. These experiments, along with brief lectures and longer discussion periods allowed team members to teach students the 3 Laws, and also demonstrate how to apply a classroom idea to a physical design. This disconnect between classroom and application is often what makes it difficult for young students to grasp scientific concepts. To get students excited, the team also brought along bottle rockets made from soda bottles and launched from a pressurized PVC pipe.

Interestingly, some of the State's top performers at the high school level are presented with a wide variety of career options, but engineering isn't typically one of them. The team feels that it is important that these students be encouraged to consider engineering as well. For this reason, some of our later outreach events were focused around showing students in Nashville and nearby Franklin some of the exciting projects and tools engineers get to work with, and encouraging them to consider it as a field of study.

For these events, the priority was to get students interested in engineering as a career path, rather than to impart specific scientific knowledge. Because students were older, this also required a slightly more advanced demonstration than the earlier events. The team would typically bring in parts of the rocket and AGSE and demonstrate how they work and the kinds of analysis and construction that went into making them work. After giving the students an idea of what mechanical and aerospace engineering projects look like, the team would answer questions about everything from studying engineering and career trajectories after college to college admissions processes and advice for transitioning into college. The team identified advice from college students, rather than books or teachers, as an important mechanism to get high school students excited about studying engineering or even just attending college at all.

Table 4: Educational Engagement Locations and Timeline

Event Name	Location	Date
Cannon County High School Visit	Woodbury, TN	10/10/2014
Adventure Science Center "Spooky Science Day"	Nashville, TN	10/25/2014
Linden Middle School Visit	Linden, TN	11/21/2014
Hunters Bend Elementary School Visit	Franklin, TN	1/23/2015
Winfree Bryan Middle School Visit	Lebanon, TN	2/6/2015
Montgomery Bell Academy Visit and Demonstration	Nashville, TN	3/9/2015
Page High School Visit	Franklin, TN	3/13/2015
NASA SLS Presentation	Nashville, TN	3/20/2015

Above is a table of all of the team's outreach events from this year. Members of the Vanderbilt Aerospace Club visited 6 schools and a museum, and hosted an event on our campus as well. Through this process we reached numerous students and educators across the state of Tennessee. Beyond just quantity, however, we feel that these events have genuinely educated and engaged the students we have reached. Through the use of both qualitative and quantitative analyses, the team ensures that we are doing everything we can to benefit the students.

IX. Overall Experience and Lessons Learned

The NASA Student Launch competition provides a unique outlet for young engineers to develop their professional skills in an exciting, team-oriented environment. This year, through the collaborative efforts of undergraduate and graduate engineering students, the Vanderbilt Aerospace Club has worked to produce a fully autonomous robotic system to support launch operations. This Autonomous Ground Support Equipment, or AGSE, combines complex elements from mechanical engineering, electrical engineering, computer science, and several other fields to produce a fully integrated system. Because of the multi-faceted requirements of such a system, this project has allowed members of the design team to work closely with each other, as well as with graduate and faculty advisors throughout the year. This collaboration across disciplines of engineering has not only broadened the scope of knowledge of each participant, but has also allowed each team member a chance to showcase their own strengths and interests. Of all the challenges the team faced this year, technical or otherwise, each has brought the team closer together in a collective attempt to produce the best quality work possible.

Perhaps the most daunting of the challenges we faced were technical in nature. Although the interdisciplinary nature of the project brings a lot of opportunity to the table, it also means that team members did not have all the prior knowledge necessary at the beginning of the project. In spite of this obstacle, we researched and reviewed literature relevant to our project, including issues related to computer vision, linear actuation, instrumentation, and a host of other technical topics. After an initial phase of research, team members organized into several focus groups according to their strengths and areas of interest. This approach allowed us to make a coordinated attempt at developing each part of our AGSE system semi-independently. One of the most complicated sub systems in our project is the onboard image processing system, which was designed and built in-house by students on the team. This system utilizes GPU accelerated image processing that supports computation on 200 cores simultaneously. This parallel processing allows image data to be collected and processed in real time, both decreasing the time needed to find the sample and enabling full autonomy from sample identification to insertion into the launch vehicle.

Another critical subsystem of our project is our payload bay, which is integrated into the forward section of the flight vehicle. Although the basic design tenants of such a system are straightforward, the payload bay had to be rugged enough to survive ejection and landing without compromising containment of the sample. To ensure these requirements were met, the team flew a prototype payload bay in a subscale launch in December, and used the lessons learned from this attempt to refine the final payload bay design. Once constructed, the finalized design was thoroughly tested for impacts significantly larger than those expected during launch in order to ensure an adequate factor of safety for structural integrity.

In addition to the initial design and testing the team did, we also thoroughly tested and evaluated our system as we integrated individual subsystems. Among these tests were simple functionality and repeatability tests, as well as the evaluation of hysteresis and quantification of uncertainty throughout the system. These evaluations gave us valuable information with regards to the precision requirements of the AGSE for reliable sample acquisition. After evaluating the results of these tests, several changes to both the AGSE and the payload bay were made so that they could work together more reliably. These changes included adding a taper to the payload bay tray, allowing a small amount of positional error when placing the sample into the launch vehicle. Through confronting these challenges, as well as countless others, the team has developed a sense of the importance of project organization and design methodology.

Perhaps the most rewarding aspect of our efforts in the Aerospace Club this year has been the lifelong friendships and memories we have formed. Throughout the entire process team members were unfailingly supportive and encouraging towards each other. At the early stages of design, the team collectively brainstormed ideas, and in the following weeks constructively critiqued each other's designs while remaining positive and respectful. Even in the face of the most difficult challenges, where success was not guaranteed and when there was no easy path to take, the team remained united in our efforts. Although many team members are moving on to the next stage of their professional or academic careers, the memories made and lessons learned throughout the year will last a lifetime.

- Careers: Fred Folz- *Space*-X, Jacob Moore- *UT Austin*, Cameron Ridgewell- *Virginia Tech*, Chris Lyne- *Vanderbilt University*, Connor Caldwell- *Deloitte Federal Technology Consulting*, Alex Goodman- *DISH Analytics*