Design, Construction, and Flight of a High Power Rocket Vehicle and Autonomous Payload

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The Battle of the Rockets Competition: Mars Rover event challenges students to simulate and autonomous payload and high-power rocket to transport said payload for deployment at altitude. The team representing The University of Alabama in Huntsville, Space Hardware Club, chose to tackle this challenge not as a problem to solve, but an opportunity to design and build a high-power rocket and rover system optimized for maximum efficiency. This involved students designing both systems from scratch and utilizing the necessary skills to manufacture and assemble every component. The rover utilizes components such as an infrared LED and sensor for measurement of its traveled path once landed. The rocket features unique airfoil fins, a composite payload fairing, and side recovery ejection for rocket inversion at apogee.

Nomenclature

SHC	=	Space Hardware Club
RBF	=	remove before flight
ABS	=	acrylonitrile butadiene styrene
RF	=	radio frequency
AM	=	additive manufacturing
CNC	=	computer numerical control
UAH	=	University of Alabama in Huntsville
FEA	=	finite element analysis
IMU	=	internal measurement unit
LED	=	light emitting diode
MCU	=	microcontroller
PCB	=	printed circuit board

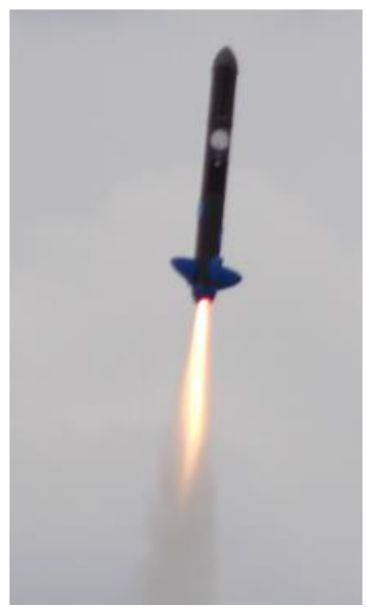

Figure 1. The Rover Rocket, Spitfire, during powered ascent

I. Introduction

THE Battle of the Rockets: Mars Rover event[1] requires students to design and build a payload that will autonomously maneuver a predefined course after

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descending from at least 1000ft. The rover must release bright markers to mark its course for judging. The rocket, which transports the rover to its required altitude must completely contain the rover until its deployment above 1000ft.

The Space Hardware Club (SHC) at The University of Alabama in Huntsville designs, builds, tests, and flies hardware including high-altitude balloon payloads, nanosatellites, and high-power rocket payloads, SHC creates many of its projects based on challenging design competitions such as The Battle of Rockets and CanSat.

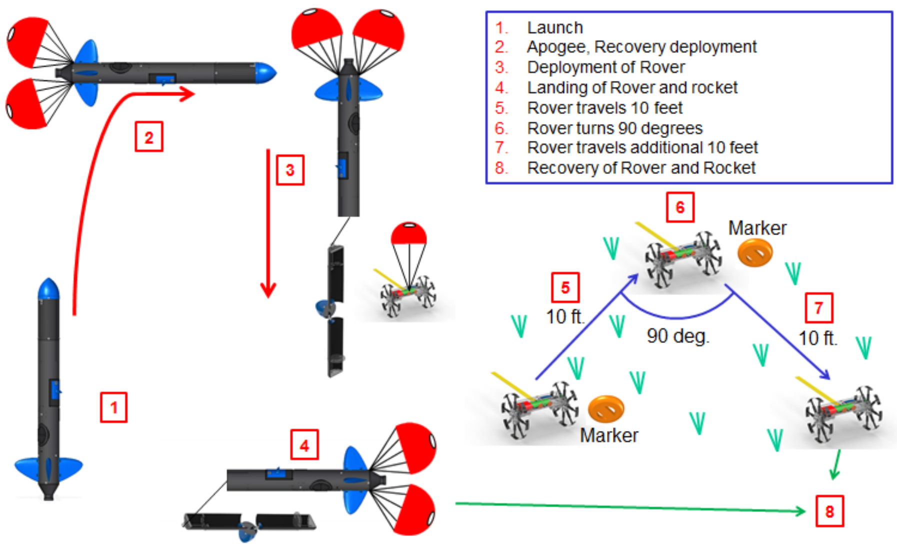

Figure 2. System Concept of Operations

II. Autonomous Payload Mechanical Design

The mechanics of the rover were designed to ensure that the rover completes the mission under all stresses from the rocket and landing, as well as being able to travel in various field conditions. The major considerations for design of the mechanics of the rover safety, structural survival, and maneuverability.

A. Design Requirements

The requirements that relate to the mechanical design of the rover are as follows:

1) The rover cannot weigh more than to 2 Kg.
2) The rover must be contained completely inside the rocket during launch.
3) The rover must use two stages of recovery. The first stage must allow the rover to descend between 30 and 50 ft/s. The second stage, deployed at no less than 300 ft must reduce the rover descent rate to 15 ft/s.
4) After landing, the rover must travel 10 ft then drop a marker. The rover must then travel another 10 ft perpendicular to the first 10 ft.

B. Materials

The main considerations during the material selection process were yield strength, impact resistance, and weight. The rover must weigh less than 2 kg to meet the competition requirements; however, the goal was to make the rover as light as possible while maintaining structural rigidity and to ensure that the rover will never suffer from structural damage.

For the rover's chassis, materials such as aluminum, polycarbonate, and Acrylonitrile Butadiene Styrene (ABS) were considered. While ABS is an excellent material for rapid prototyping, it was ruled out due to poor yield strength and impact resistance. Polycarbonate was initially considered a favorable material due to its impact resistance. However,

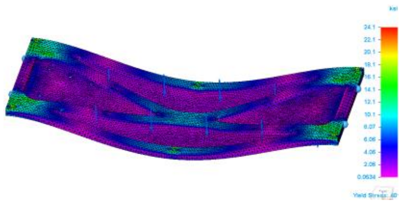

Figure 3. FEA of Rover Chassis

through finite element analysis (FEA) in Siemens Solid Edge ST8, the team determined aluminum to be a better choice. This was due to aluminum's high yield strength and the ability to make a light rover chassis that can still withstand an impact considering failure of the rover's main parachute.

The second major material selection for the rover was for composition of the wheels. One of the goals for the wheel was to have an extendable diameter. The materials considered for this were a lightweight foam or carbon fiber extension spokes with interior springs. Carbon fiber tubes were selected due to their rigidity and a greater possible wheel diameter. For the hub, aluminum and polycarbonate were both considered. Due to design restrictions on the spoked wheel concept, a polycarbonate hub was lighter with a sufficient factor of safety.

Figure 4. A rendering of rover integration with fairing

C. Descent Control

The descent control system was designed with the primary consideration being safety. The rover uses a two stage descent control system featuring a drogue parachute and a main parachute. One of the major concerns with the descent control system was entanglement with the rocket fairing and rover wheels. The solution to this issue is to have both parachutes contained in deployment bags. With the drogue deployment bag tied to the fairing, the drogue parachute is passively deployed when the rover falls away to ensure there is always a safe descent. The drogue parachute is attached to the main parachute with relieved tension during initial descent. Above 300ft, a hot nichrome wire burns the tension release line allowing the drogue to pull the main parachute out of the main deployment bag. Upon landing, a second hot nichrome wire will release the descent control system from the rover.

D. Rover Mechanics

One of the major challenges for the rover is to travel through a field with crops in any weather condition. To solve this problem, the maximum ground clearance for the rover must be attained while maintaining traction. Two major wheel designs were considered. Square foam wheels were considered, as they compress easily and expand and the edges allow the rover to gain traction. However, travel when square wheels is difficult to predict. For this reason, an extendable carbon spoke wheel design was chosen. The carbon spoked wheel had a similar ground clearance to the foam wheel and each spoke allows the wheel to gain traction. The major advantage to this wheel is that the rover's travel is much smoother and it allows the infrared sensor to detect each wheel rotation.

A second issue with the rovers travel is ensuring the two wheeled rover can move forward. The rover uses a tail to torque off the ground and allow the wheels to pull the rover forward instead of simply rotating the chassis. However, this tail must be deployable. For that reason, a measuring tape was used to allow the tail to roll up during flight, but stay rigid for the rover's travel.

E. Rocket Integration

The integration of the rover into the rocket fairing is crucial for mission success. The telescopic wheels compress to a 6 in diameter and the stability tail curls around the rover to allow the rover to easily be placed in the fairing. The drogue parachute must be packed into the deployment bag that is attached to the fairing. A remove before flight pin is be placed in the rover and accessible through the fairing on the flight line.

III. Rocket Design

The rocket was designed with the primary purpose of reliably deploying an autonomous rover at a specified altitude; the rover descends under its own control to autonomously execute preprogrammed commands upon landing. This controlled payload deployment is achieved through use of a clamshell payload fairing. Although this rocket was designed with the autonomous rover in mind, the payload fairing has the ability to transport other payloads, making it a very flexible launch system that will aid in future SHC projects.

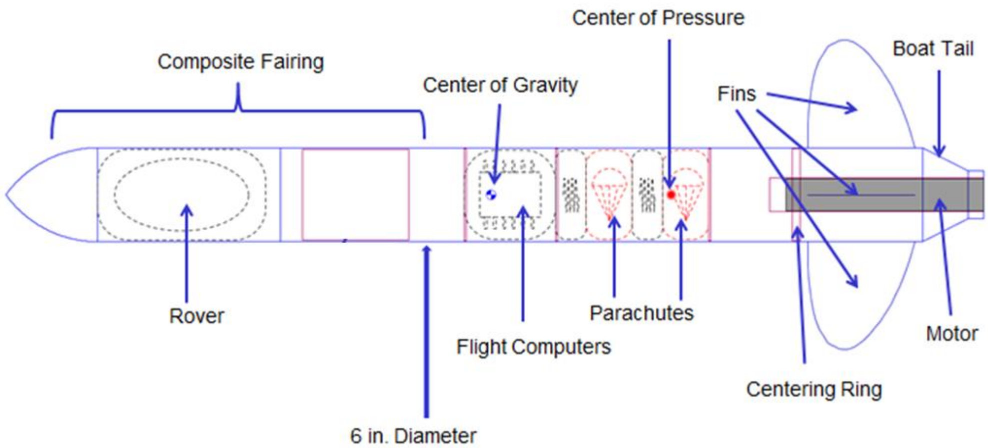

Figure 5. The layout of major rocket components

A. Optimization vs. Problem Solving

The Battle of the Rockets: Mars Rover competition requires the rocket to reach an altitude of at least 1000ft. on a K class motor or smaller. This means that the total impulse must be less than or equal to 2,560 N·s. However, the team's goals in designing the system were to meet and surpass the requirements by optimizing the system. This resulted in flying on a J class motor with a total impulse of 1092 N·s, 43% of the allowable impulse while maintaining a large factor of safety for altitude.

B. Materials

The main considerations during the material selection process were the materials' strengths vs. their weight, the goal being to make the rocket as light as possible while ensuring that it will never suffer structural damage. However, considerations such as RF transparency and feasibility must also be taken into account. The only time that heavier alternatives were used is all fasteners and load bearing joints, which were made from steel.

For the rocket's airframe, materials such as cardboard, fiberglass, and carbon fiber were considered. Cardboard was immediately ruled out because of its structural weakness. G12 fiberglass was also ruled out as the team did not have the ability to manufacture it, it is prohibitively expensive, and it is unnecessarily heavy. Additionally, the team has the knowledge to hand layup body tubes and wanted to pass that knowledge to the younger generation of team members through experience. Having decided on an in-house layup, the team chose carbon fiber rather than fiber glass because it is significantly lighter. Furthermore, because the competition mandated no communication with the payload, the RF shielding characteristic of the carbon fiber was not a problem.

Although the rocket had an apogee around 2000ft. and was clearly visible throughout flight, a tracking system was added to ensure it cannot be lost. To accommodate this communication, the fairing's nose cone was constructed from fiberglass.

For the rocket's internal components, such as bulkheads, centering rings, and the fairing's structural components, hand layups were again considered in addition to machined polycarbonate. Because they are lighter, composite layups were used where possible, i.e. bulkheads. However, all structural components, such as the centering ring and fairing pieces were made from polycarbonate.

If not composite or polycarbonate, components were additively manufactured from ABS. This was used in places where the part had geometries prohibitively difficult or expensive to machine from stock material. However, when any component took a significant load, the ABS was reinforced with either epoxy resin or duct tape to avoid cracking and layer separation. This process was used to make the fins, boat tail, electronics bay, and parachute deployment pods.

Finally, ¼ in. diameter Kevlar shock cord was used to connect the parachutes to the body tube. And, the parachutes were composed of rip-stop Nylon, protected from the ejection charges by large pieces of Nomex.

C. Payload Fairing

Initially, to accommodate the diameter of the rover's wheels, the fairing had a diameter greater than that of the body tube. However, by changing the wheels to a telescopic spoke, the diameter of the fairing was reduced to be flush with the body tube.

Additionally, to better constrain the rover, which provided a constant outward push on the fairing, the design was changed from separating the fairing halves completely to hinging the halves, providing much better constraint to the rover and reducing the chances of the fairing opening mid-flight. This also allowed the fairing to include a small bay above the hinges to accommodate a tracking system that.

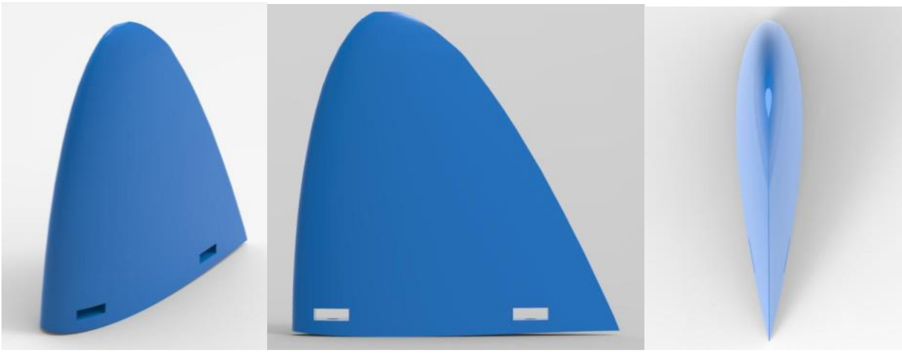

Figure 7. Fin shape from different angles

D. Fins

The optimal design for any fin or wing uses both an airfoil cross section as well as an airfoil profile, similar to that of the Supermarine Spitfire wing. This design is effective until the vehicle reaches speeds where the airflow becomes compressible. However, the rocket will be reaching a maximum velocity of 359 ft/s or Mach 0.32, so compressibility was not a problem.

The reason this fin design is seldom used, even at low speeds, is that it is nearly impossible to produce using subtractive manufacturing, such a cutting or milling. However, using additive manufacturing (AM), the shape is simple to construct. So, by designing the fins to use a minimal amount of material and reinforcing the printed ABS with epoxy resin, the team was able to optimize the drag produced by the fins.

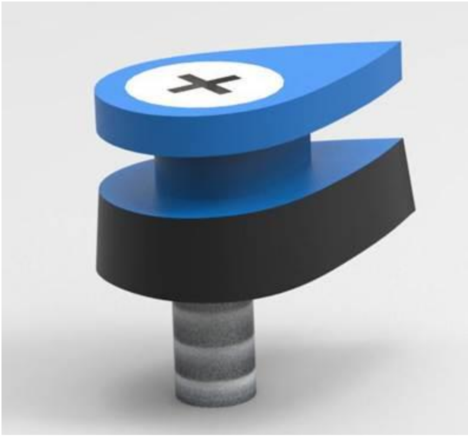

Figure 8. Rail button design

E. Rail Buttons

Although they provide nearly negligible drag, the rail buttons were designed to be as aerodynamically efficient as possible without compromising their strength. This was accomplished by using AM processes to 3D print airfoil shaped rail buttons using ABS filament. Steel bolts were used as a structural core and for attachment to the airframe. However, the design ensures that only ABS comes in contact with the rail to avoid the rocket locking on the rail upon ignition, as happens with metal rail buttons. Having metal in contact with the rail upon ignition is also detrimental to the health of the rail.

F. Recovery System

The recovery system was comprised of two parachutes each capable of reducing the rocket's descent rate to a speed considered safe by the competition's standards (20ft/s) individually. This redundancy allows for the deployment of one parachute to fail without compromising the safety of the flight.

Figure 9. Descent under both parachutes during January test flight

The recovery system was designed to invert the rocket upon parachute deployment at apogee. This inversion places the rocket in a "nose down" state and allows for the rover to be deployed beneath the rocket. A side deployment technique was used to accomplish this. Deploying the parachutes out of the side of the rocket while anchoring the shock cords aft of the post motor burnout center of mass produced the inverted recovery desired. Side pods were designed to house the parachutes within the rocket and were manufactured using AM processes due to their large, thin-walled shape, which would waste large amounts of stock material if subtractively manufactured. Since the body diameter of the rocket determines how deep the pods could be, the pods were made an oval shape instead of circular to maximize the volume of the pod while maintaining a strong round structure. A secondary benefit of using a side deployment system was that when using common parachute deployment techniques with a complicated payload deployment system such as the one presented in this paper, the risk of parachute tangling is increased. The side deployment system reduces this risk by ejecting both parachutes away from each other and from the rocket.

A second form of redundancy was implemented by use of redundant PerfectFlite StrattologgerSL100 altitude based deployment altimeters. These altimeters are used to deploy the parachutes by igniting black powder charges. They are also used to blow a black powder charge with redundant igniters for payload deployment.

IV. System Manufacturing

The Space Hardware Club challenges its teams to manufacture every part of the system. This provides valuable experience to students in activities ranging from hand-soldering printed circuit boards to laying up composites by hand and CNC operations. The UAH machine shop, managed by Stephen Collins, provides the facilities required for the more difficult manufacturing challenges, such as high quality AM and CNC machining and means of composite manufacturing.

A. CNC Machining

In addition to the ability to produce unusual 2-dimensional geometries, one advantage of having access to and the experience to use CNC mills is the ability to precisely manufacture parts. This came into play when designing the rocket by allowing the team to completely forgo a motor tube by machining a centering ring to exactly 54.00mm.

CNC mills were also used for construction of all of the structural components of the rover. By machining all of these pieces out of uniform stock material from custom designs, the rover's body was extremely durable while also being incredibly light for its size.

B. Additive Manufacturing

As stated earlier, the rocket's unique fin design was made possible due to the advanced AM capabilities available in the UAH machine shop. Additionally, an electronics bay was printed in order to make the switches for arming ejection charges easily accessible. This was done to minimize the danger to the flyer when arming the charges and motor just before flight. Although they could be stronger if machined out of stock material, the parachute deployment canisters were also printed from ABS. This made fitting them into the body tube securely a trivial task and minimized the amount of wasted material during fabrication. Finally, the boat tail was also additively manufactured after performing FEA to ensure a large factor of safety when transferring the thrust produced by the motor to the rest of the rocket.

Figure 10. Body tube preparing for cure on the mandrel

C. Composites

Through the UAH machine shop, the Space Hardware Club has access to composites that were generously donated by local companies. The main composites used in the rocket were for the body tube and cylindrical fairing pieces. All of these were hand laid up on a 6in. mandrel with a custom heating system. The heating system, also constructed by SHC, circulated heated water through the mandrel in order to cure the carbon fiber.

The carbon fiber used for body tube and fairing layups was pre-impregnated with TLM45-EL epoxy, meaning that it already had the correct amount of epoxy and was as light as possible. However, to layup the nose cone, the team did a “wet” layup, meaning they soaked cloth in epoxy resin before applying it to the mold. Throughout the process of curing, which was done at room temperature, due to the different epoxy resin, a vacuum was applied to the layup, and “bleeder” material was used to soak up as much excess epoxy as possible.

V. Testing

A. Ground Testing

Prior to the maiden flight of the system, the potential failure points of the system were thoroughly tested on the ground. The tests for the rocket included parachute ejection testing, fin load testing, fairing deployment testing, and crush testing of the body tube. Parachute ejection tests were used to determine the correct sizing for the black powder charges required for successful parachute deployment. The attachment method used to secure the fins to the body tube was tested in order to prove that the fins would remain secured to the body tube under a load similar to what would be experienced during flight due to aerodynamic drag.

For the rover, there were two major ground tests of mechanics. The first test was to structurally load the chassis of the rover and confirm the conclusions made through FEA. And the second test was a ground test to calibrate the infrared sensor and ensure the rover travels accurately through the whole ground mission reliably.

Figure 11. Parachute deployment testing

Figure 12. Ignition during a full system flight test

B. Flight Testing

Beginning in December, 2015, the team started flight testing components of the system’s final design. Initially, the team tested the airframe, electronics bay, parachute deployment, and flight software. On the first launch, the redundancy of the recovery system was also tested when a faulty altimeter didn’t deploy one of the parachutes, and the rocket came down under a single parachute. However, the rocket remained unscathed, meaning that the test was successful.

On the second flight test, the rocket came down under both parachutes, and the new fins were proven to be sufficiently strong both during flight and upon landing. By the third flight test, in February, 2016, the system’s components were sufficiently ground or flight tested, and the team performed a full system test of the rocket with a simulated payload.

The rover's first flight test will occur in March, 2016. As such, there is no information on it. It will be tested again in April prior to competition so that it will have two tests before competing.

VI. Conclusion

The rocket design is unique in that it is optimized for performance at the Battle of the Rockets: Mars Rover event. However, many of the features are applicable to higher powered and larger rockets. Additionally, the skills learned by team members for this project will be very useful later in life in the aerospace industry. After fully testing every component and the full system, the team will be competing in April, 2016 and hopes to once again take first place for the Space Hardware Club and the University of Alabama in Huntsville.

Figure 13. Kyle Renfroe, Davis Hunter, Will Hill, and Bradley Henderson ready for a full system test

Acknowledgments

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