Background

The team of nine students from the Virginia Military Institute collectively held their breath during the countdown. The result of their yearlong project, an 11-foot-tall, 60 lb. rocket, stood on the launch pad, holding an autonomous soil-collecting robot they designed. There was little doubt the engines would ignite, developing 450 lbf of thrust within 200 milliseconds; the worry was whether the robot would eject at apogee and survive the resulting 1,000-foot fall.

These were the opening minutes at the Battle of the Rockets Competition, hosted by the Federation of Galaxy Explorers, in Culpepper, Virginia in April 2019. The competition allows high school and college students to enter different contests of varying degrees of difficulty that test their skills in rocket and robot design. There are three different contests; in order of complexity they are the Target Altitude event, the Sounding Rocket event and the Mars Rover event. This paper describes the Virginia Military Institute's entry in the Mars Rover event, which involves designing an autonomous robot launched from a rocket. No teams have yet fully completed all facets of the Mars Rover challenge since the rules were made more stringent in 2015.

The rules governing the Mars Rover competition are simple to state but difficult to achieve: to design a robot and rocket system that launches in the air, deploys, lands on the ground, collects soil, and performs telemetry (transmits data). These parallel the tasks several American, Chinese, and European agencies are planning in Mars exploration missions. Specifically, teams must design a Mars Rover robot and a rocket to launch it to at least 1000 feet. The rover, weighing no more than 2 kg, must be enclosed within the rocket before launch and must safely return to the ground by "controlled descent," presumably by parachute. After the rover lands it must disconnect from its recovery device, travel at least three feet in any direction, and await a command to continue its mission. A handheld wireless device must be designed to issue this command with a single button press. Once given the command, the rover has 5 minutes to collect at least 5 grams of soil and place it in a detachable container. After the soil is collected, the team issues a second command from the wireless controller directing it to take a picture of the collection site and send it by wireless telemetry to be displayed on the handheld device.

Rocket

The rocket consists of four sections (Figure 1). From aft to fore these are: the booster, the avionics bay (AV bay), the payload bay, and the nose cone. The booster section houses the motor in the motor tube, the small drogue parachute that deploys at apogee (its point of highest altitude), and provides an attachment point for the fins to be mounted to the rocket. The AV bay joins the booster section to the payload section. It houses redundant flight computers that fire ejection charges to separate the booster section when the rocket reaches apogee and fire more ejection charges after the rocket falls to within several hundred feet of the ground. The payload section is located directly below the nose cone. It has two purposes: it houses the rocket's main parachute that deploys once the rocket falls from apogee to a point closer to ground level, and it houses the rover during the flight. The nose cone is the foremost section; besides providing a smooth aerodynamic shape, its forward weight helps stabilize the rocket's flight during ascent.

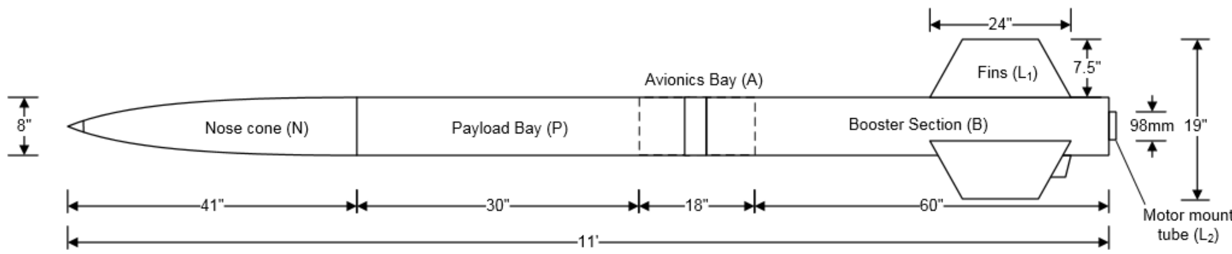

Figure 1. The rocket's major sections: a nose cone that separates from the payload bay by ejection charges triggered by flight computers in the avionics bay. A separate set of charges releases the booster section, which falls under its own parachute.

Motor

The VMI team wanted plenty of space for the rover, which implied a large rocket diameter, and therefore a heavy rocket. The contest rules place no limit on the maximum rocket size or weight, but they do limit the total impulse (the integral of thrust over time) of the rocket motor to a maximum of 2560 Newton-seconds. Accordingly, the design of the rocket was driven by the contest's constraint on motor size. To ensure the rocket leaves the launch rail with sufficient speed to allow the fins to keep the rocket stable, general guidelines suggest the engines must develop at least five times more thrust than the mass of the rocket (i.e. it must have at least 5G's of acceleration). This implies that the rocket motor should develop a high thrust (greater than five times the rocket mass) for a short time to keep the total impulse under 2560 newton seconds, rather than develop a lower thrust for a longer time. A K1999N motor was selected whose 2540 Newton-seconds total impulse is the closest available to the maximum allowed and which burns very quickly in only 1.25 seconds, developing an average thrust of 1999 Newtons, or about 450 lbf. This sets an upper limit on the weight of the rocket at 90 lbs. A survey of available high-power rocket kits shows this translates into an 8" wide fiberglass rocket. Specifically, simulations of the Madcow DX-3 kit show it will reach 1,500' when carrying a 2 kg payload with a K1999N motor. This kit is comprised of only a nose cone, fiberglass tubing, cut fins and has no electronics, suggested motors, or even instructions. All design choices are left to the builder.

High power rocket motors such as the K1999N are composed of ammonium perchlorate propellant in a rubber binder, such as was used in the Space Shuttle boosters. This formulation has roughly eightfold higher energy density than the black powder composites used in smaller model rocket motors, although are considerably more difficult to ignite.

Stability

Wind and aerodynamic asymmetries push the rocket from a straight path upwards and create wobble during flight; in the extreme, an unstable rocket will follow a highly erratic trajectory that rocketeers call “skywriting”. The stability of the rocket is determined by the relative location of the rocket’s center of gravity (CG) and center of pressure (CP). When in flight, the rocket rotates around its CG, however the lift and drag forces act around the CP. While the drag force remains mostly vertical during small angle changes during flight, the lift force is parallel to the ground. If the CP is located below the CG, the lift and drag forces act in a restoring manner and cause the rocket to angle itself vertically again. If the CP is above the CG, the lift and drag forces will act in a destabilizing manner and cause the rocket to further deviate from the correct path of travel. This deviation quickly compounds and then the rocket begins to skywrite. The rocket described in this paper has a CG 8.9” higher than its CP as calculated by the RockSim simulation package, ensuring flight stability.

Recovery

We used a dual-deployment recovery system meaning that the rocket deploys different parachutes at two different times. While this system is complex, it increases the chance that the rocket will return safely to the ground without significant lateral drift. This system begins when the flight computer in the AV bay detects that the rocket has finished its ascent and has arced over at apogee. At this moment, the flight computer sends an electrical current through an igniter buried in 4.25 grams of black powder in the aft side of the AV bay, causing a sudden increase in pressure in the booster section that separates it from the rest of the rocket. The booster remains connected by a 40' shock cord, which has a small drogue parachute tied along its length. The drogue deploys and it, coupled with the non-smooth shape of the separated booster section and separated AV bay/payload/nose cone section, slows the rocket descent speed to about 72 feet per second (fps). This speed is fast enough that the rocket body will not drift much laterally, but slow enough that the main parachute will not rip apart when it deploys.

We programmed the flight computer in the AV bay to fire a second set of ejection charges, this time in the fore direction through the payload bay, when the rocket is 400' from ground. This pushes three things out of the payload section: the nose cone (which, unconnected from the rest of the rocket, flies freely away under its own small parachute), the rover (also unconnected, which also flies down under its own small parachute), and the rocket's main parachute, which is tethered to the rest of the rocket by another 40' shock cord. These three parachutes allow the two rocket parts and the rover to each descend gently to earth at about 20 fps. This process is entirely dependent on the flight computer. If it fails, the rocket and rover will have a catastrophic landing. To reduce this possibility, two electrically-independent flight computers are used, each of which are connected to redundant ejection charges.

Simulations

RockSim simulations, including a mass representing the rover, show the rocket leaves a 12' launch rail at 57 fps, which is sufficient for stable flight. It maintains stability through the powered phase of flight, developing up to 6.5G of acceleration for 1.24 seconds, at which time it is traveling at 326 fps, or about 225 mph. It then commences its unpowered, coasting phase of 0G flight for 11.4 seconds before arcing over at an apogee of 1,495 feet, well in excess of the required 1,000-foot floor. The simulated rocket deploys its drogue parachute at that time, and 26.4 seconds later it will reach 400 feet from ground, at which time it will deploy its main parachute. This will slow it down to a 24 fps landing, 72 seconds after launch.

Avionics Bay

The avionics bay is a two-foot-long tube mounted between the payload bay and the booster. It is capped by bulkheads on both sides connected by threaded rods, so the inside is pneumatically isolated from ejection charge pressures in the adjoining lower booster section and upper payload section. The outward-pointing faces of the upper and lower bulkheads each have two black powder charge holders and two U-bolts. A fire-resistant Kevlar shock cord connects the fore side U-bolts to the main parachute. A second Kevlar cord connects the AV bay's aft side U-bolts to the rocket's booster section and the drogue parachute. A hole called a static port is drilled through the exterior of the AV bay to ensure the outside air pressure equalizes with the interior, which enables barometric pressure sensors on the flight controllers to calculate the altitude of the rocket. The placement of the static port was given careful consideration since small projections above it could influence the surrounding air pressure.

The primary and redundant flight controllers are housed inside the AV bay. These are connected by wires, which run through the fore and aft AV bay bulkheads to the black powder charge holders. The aft ejection charge fires when the rocket reaches apogee, separating the booster section from the rest of the rocket and releasing the drogue parachute. The fore ejection charge fires when the rocket falls to about 400 feet above ground level, separating the nose cone (which falls under its own parachute), ejecting the robot (which falls under its own parachute), and also ejecting the main parachute attached to the rest of the rocket.

As the rocket ascends, decreasing external air pressure will tend to cause air trapped in the lower rocket to separate at its junction with the AV bay, and similarly tends to cause separation at the payload bay/nose cone junction. These events should only be initiated when the flight controller causes an ejection charge to fire. To prevent this we connected these junctions with small plastic screws called shear pins. These pins are designed to shear under the pressure difference caused by the ejection charge, but not under the smaller pressure differences caused by rocket ascent. To further discourage premature separation, small vent holes are placed in the payload and booster sections, large enough to reduce altitude-induced pressure differentials, but small enough to allow the ejection charge to create a pressure differential large enough to shear the pins. Much larger diameter screws are used at the junction between the AV bay and payload section to prevent separation under any flight conditions.

Two additional holes placed through the AV bay wall allow external access to two safety switches that ensure the ejection charges cannot be fired before the rocket is safely on the launch rails. These disconnect safety switches are a contest requirement.

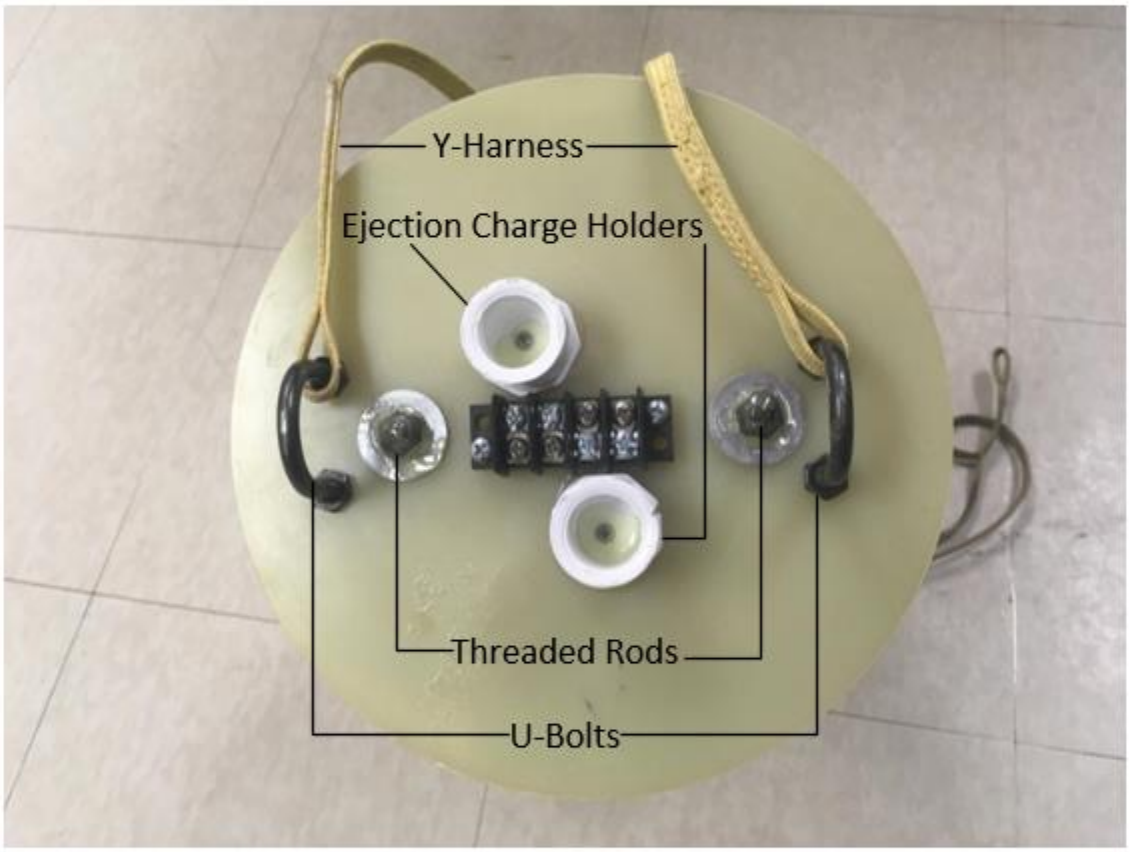

Figure 2. Bottom of AV Bay showing the white wells that will hold black powder ejection charges, the electrical bus that will be connected to e-matches to ignite the ejection charges, and the epoxied ends of the all-thread rods that join the caps of the AV bay together.

Two separate flight controller redundantly monitors the attitude (angle) of the rocket and its altitude to determine the optimal time to deploy the fore and aft ejection charges. The primary flight controller is the Eggtimer TRS, a kit built from surface mount components that requires soldering. The backup flight controller is the Telemetrum Easymini. Both controllers are powered by batteries that are secured by aluminum brackets and redundantly secured with zip ties to reduce chances that the 6.5G of flight acceleration will dislodge them.

The amount of black powder used for each ejection charge is critical. If there isn't enough the rocket will not separate and the corresponding parachute will not deploy. If there is too much the booster or payload section will rupture. We experimentally determined that 4.25 grams for the fore side and 2.75 grams for the aft side, proportional to the volume of free space in each section, worked well.

Typically, flight computers are secured onto a plywood sled, and are connected to the batteries, mechanical safety switches, and ejection charges through wire harnesses. A common failure mechanism for such designs is for wires to disconnect under the heavy rocket acceleration, resulting in a "lawn dart"; a rocket whose ejection charges do not deploy and that lands at high velocity, nose-downwards. To mitigate this cause of failure we designed a printed circuit board (PCB) on relatively thick 1/8" fiberglass to mount the primary and backup flight computers, their batteries, and the disconnect switches, thus eliminating both the wiring harness and the sled as a separate structural component (Figure 3). Like the more typical plywood sleds, the PCB is attached to two threaded rods that are epoxied into the AV bay's endcaps. The placement of the antenna for the Eggtimer TRS that provides GPS telemetry was given special attention to avoid attenuation by being electromagnetically shadowed by the threaded rods.

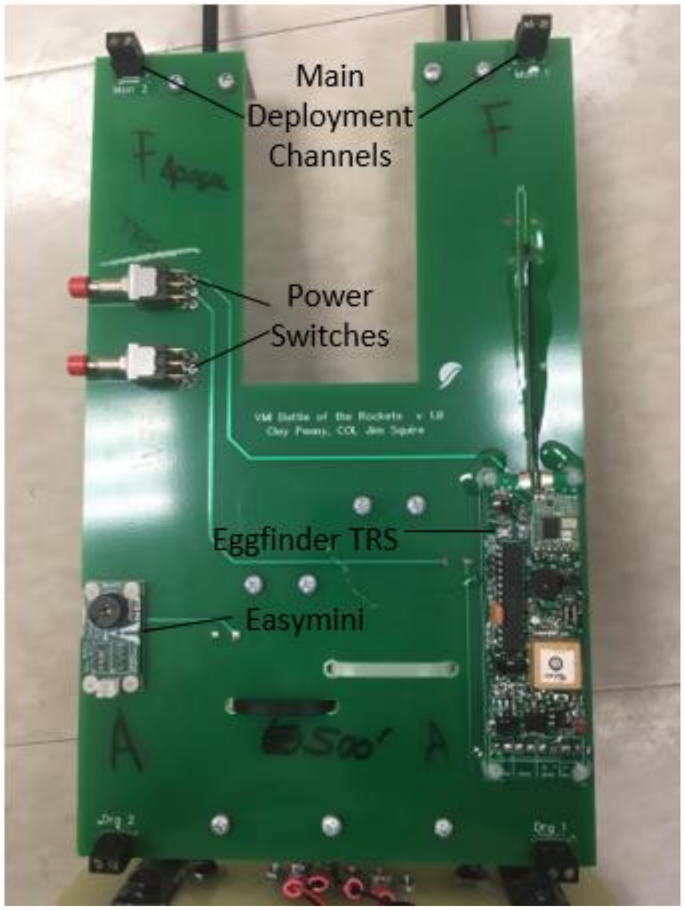

Figure 3. Completed printed circuit board with the two flight computers, electrical connections for the e-match ejection charge ignitors, and separate disconnect switches labeled.

The rocket's flight is filmed using two video cameras. These are mounted just aft of the AV bay on the outside of the booster section on opposing sides of the rocket to prevent asymmetry. They are attached to the external rocket body using a 3D printed mount that permits access to the video recording switch.

Mars Rover

The Mars Rover design has a number of strict constraints. One is physical size: although the rocket is 8” in diameter, the rover must fit into the narrower 7.75” coupler tube joining the nose cone and payload bay. Second, contest rules require the rover to weigh less than 2 kg. These quantitative constraints are joined by qualitative requirements of durability since the rover is exposed to 6.5 Gs of launch acceleration, approximately 15G acceleration from the ejection charge at apogee, and significant landing forces.

Once the rover lands safely it must detach itself from the recovery system and travel three feet autonomously. Contest rules discourage the use of wheels or tracks, so the rover uses a combination of wheels and legs called a wheg. These spindle-like projections from the hub, like a wagon wheel without the rim, traverse rough terrain better than standard wheels or tracks. They are capable of traversing obstacles almost twice their height, which is helpful when navigating a harvested cornfield such as the competition uses (Figure 4). The whegs were designed to rotate in the same direction to move the required three feet. Then they counter-rotate, causing bottle-top “nails” to scoop dirt, which as the wheg rotates, is then deposited into a channel in the wheg that directs it to a collection tray on top of the rover.

Figure 4. Mars Rover staged in a cornfield for a full systems test. The whegs rotate together for horizontal movement and then counter-rotate, causing the bottle-tops to scoop dirt into angled channels in the whegs that ultimately deposit it into the red top-mounted trays. The system is vertically symmetric; should the rover land upside-down it will work in the same manner. The camera is visible at the front and the parachute-detachment mechanism in the rear.

Competition Day

The morning was cool and damp on the day of the Battle of the Rockets competition. Weather forecasts predicted two hours of calm weather before the wind would pick up, but we were not concerned; countless system tests in our lab had taught us how to prep the subsystems in minutes. Four people re-tested the Mars Rover while the rest of the team started to assemble the rocket. We secured the motor tube retention strap to the AV Bay while the ejection charges were packed. Once the flight computer verified charge ignitor continuity we loaded the parachutes and verified that all the harnesses were attached correctly.

Unfortunately, the rover testing team reported back with problems. The Mars Rover, which was thoroughly tested the night before, was now refusing to turn its rear whegs, although its front pair worked normally. After 45 minutes of troubleshooting we located an intermittent open in the motor wires. We re-soldered all the motor wires onto a duplicate PCB to avoid the chance of a second wire failing. Using a cooler as a flat surface, we had to kneel in the dirt to get close enough to a car's cigarette adapter, our power source for the soldering iron. Imagine trying to quickly re-solder small, critical connections in an increasingly windy and dusty environment while keeping aware of the flight paths of other rockets being flown. It was not easy.

Once we replaced the PCB we tested the rover again. It still did not work. Another 20 minutes of troubleshooting revealed that the voltage regulators in the spare PCB were -5V instead of 5V. Amongst all the subsystem testing we had done, we forgot to test the spare PCB. The only correct regulator we had was in the original PCB. I had to carefully desolder it and then resolder it into the new PCB without breaking its delicate legs or overheating it. Thankfully, I was successful but it was one of the most nerve-wracking soldering experiences of my life. Once that was completed all the rover systems tested perfectly; we quickly loaded it into the rocket. It was finally time to fly.

We carried the rocket to the remote launch pad and turned on the flight computers. Everything came up smoothly until an error message about charge continuity appeared on our LCD receiver, although we double-checked continuity during assembly. Power-cycling yielded the same error message. We needed to take the rocket back down and open up the AV Bay to investigate, which was complicated by the fact that we were now out at the remote launch pad, away from our rocket stand and tools, and with the wind picking up. Three people balanced the rocket on their knees while two people pulled the pieces apart very carefully so we didn't disrupt the payload bay or ejection charges. We were able to get everything opened up with just enough room for me to get my hands inside the AV Bay. I was able to move two sets of ejection charge wires to a redundant flight computer, all while smaller rockets continued to launch behind us and the wind blew dust everywhere. We reassembled the rocket and had it back on the launch rail in about ten minutes.

We were finally ready for launch! The countdown began and the launch button was pressed. Silence, nothing happened. The process was repeated; nothing again. Because the flight computers were armed, only the Range Safety Officer and I were permitted to approach the rocket. I hoped that replacing the motor igniter would fix the problem. Although the original igniter looked perfect, it had internally opened when electrical current was applied. We replaced it quickly and returned to the firing line and the countdown began again. By now, the wind had picked up considerably and was gusting at 15 mph.

Launch! The K-class motor took one second to build up its full 450 lbs thrust, a time that seemed like forever; then there was a thunderous roar and the rocket spat off the launch rail in a smoky rush. It looked so beautiful going up. The rocket reached apogee and everything ejected correctly. The nose cone's parachute deployed fully and it landed safely in a nearby field. But the high winds whipped the ten-foot diameter main parachute around, and like a thrown bola, swept into the rover's parachute. The two entangled, and continued to wrap around each other while descending, with shroud lines immobilizing two of the rover's whegs. The two entwined parts landed in a cow field, where ground wind blew the main parachute and rocket/rover into an electric fence. Wind gusts caused the main parachute to rotate, repeatedly pummeling the attached rover against the ground.

Once we determined that the rover could not free itself, we carefully crawled through the electric fence and untangled everything. We decided to run the rover just to see what would happen. It worked flawlessly! However, it was disappointing to see it work so well since the failure to detach from the recovery system disqualified the entire attempt.

The tangling was unfortunate and not the ending that I envisioned. Yet, I was proud of the way the team performed under pressure and that every subsystem we designed worked independently. My team accomplished a successful launch, nothing broke, and the rover worked. The experience taught me more about project management and engineering than any class-based course I have taken. I could not be more grateful to my outstanding teammates, my family members, advisor, and department.

Figure 5. Team with the VMI Mark 1-9 rocket on competition day. The author is in the front row second from the left.

About the Authors

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