Badger Ballistics
WSGC Collegiate Rocket Team 2015

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Abstract
This report provides an overview of the design features, construction and analysis of a high-powered rocket and payload. The rocket was designed and constructed to be a boosted dart that could be recovered in a flyable condition in accordance with the WSGC Collegiate Rocket Competition objectives. The boosted dart was comprised of an unpowered dart and a rocket booster. The two stages of the rocket were designed to separate as a result of drag after the boosted dart stopped providing thrust. After the drag separation, the unpowered dart was to continue coasting on a parabolic trajectory until an electronic deployment system released its parachute. The rocket booster also contained a parachute recovery system that was to release after separation. The payload of the unpowered dart was designed and constructed to collect on-board, nadir video and characterize the rotation of the rocket in the X, Y, and Z axes over time. Badger Ballistics achieved a successful flight with a successful launch, dart separation from booster, successful deployment of the booster recovery system, successful deployment of the dart recovery system, and the recovery of both stages in flyable condition. The predicted maximum apogee was 3248 ft. but the apogee recorded on flight day was 2059 ft. The approximately 57% error in this calculation is due to over simplification of the OpenRocket flight simulation software, launch alignment, and loss of energy due to pitching during flight. Additionally, overuse of construction materials, such as epoxy putty and paint, likely lowered the expected apogee because of their unaccounted weight.

[1]Badger Ballistics would like to thank WSGC for their generous financial and educational support throughout this competition.

1.0 Rocket Design and Construction

1.1 Airframe design Three primary design specifications were considered in the conceptualization of the team's rocket. These were: spatial accommodation of the required avionics, stability of at least 1 cal, and achieving maximum apogee. In accordance with these requirements, the overall rocket body dimensions were determined using a bottom-up design approach. The avionics system to be used was specified first. Then, using the dimensions of these components, it was found that a minimum dart diameter of 6.5 cm was required for spatial optimization. A booster tube with a diameter of 9.8 cm was then selected based on the sufficient drag it provided for stage separation.

The rocket design specifications also encompass the stability of the rocket before separation. Stability was accounted for in the design through ensuring that the center of pressure was a sufficient distance behind the center of gravity. This enabled the rocket to counteract any turbulence experienced during flight with restorative forces occurring behind the center of gravity.[2]

Achievement of the rocket's maximum possible apogee was also considered in the design. To accomplish this without adversely affecting the stability, the center of pressure was held constant with respect to the proportions of the rocket. The overall height of the rocket was scaled down significantly to a final value of 146 cm. This decrease in height greatly increased the maximum apogee from the original design by significantly decreasing the skin drag of the rocket. The final dimensions of the rocket ensured stability without sacrificing a great amount of apogee height.

1.2 Dart system The dart system consisted of the second stage of the rocket. This was the unpowered dart that was intended to reach maximum apogee. LOC tube was chosen as the material for this system because of its adequate structural stability and minimal weight. The length of the dart was 40 cm. It had an inner diameter of 6.5 cm and an outer diameter of 6.68 cm. The wall thickness of .18 cm provided sufficient strength to accommodate the dart's payload system.

1.3 Booster system The booster system consisted of the first stage of the rocket. This system was comprised of the engine mount and the booster recovery system. This system was integral in propelling the unpowered dart so that it could achieve maximum apogee. LOC tube was again chosen as the material for this system. The length of the booster tube was 50 cm. It had an inner diameter of 9.8 cm and an outer diameter of 10.16 cm. The wall thickness .36 cm provided sufficient strength to accommodate for the thrust of the engine that would be mounted in the engine mount. The 5.4 cm engine mount was attached to the rest of the booster system with 5.4 cm to 9.8 cm centering rings and glue. This apparatus ensured that the engine mount and

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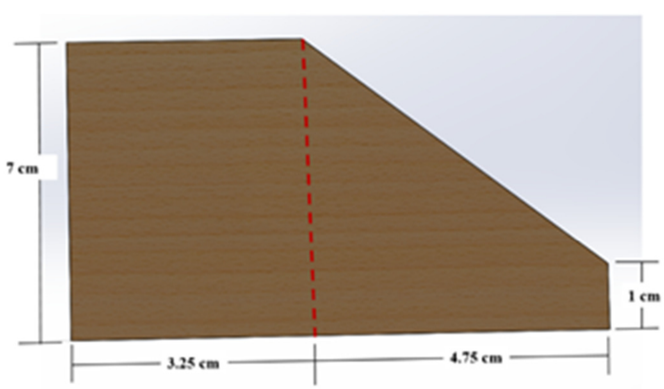
[2] "Rocket Stability." *NASA*. N.p., 12 June 2014. Web. <https://spaceflightsystems.grc.nasa.gov/education/rocket/rktstab.html>. (This excerpt from NASA describes the restoring and destabilizing forces present during rocket flight as well as how to align the CG and CP to achieve the desired forces.)

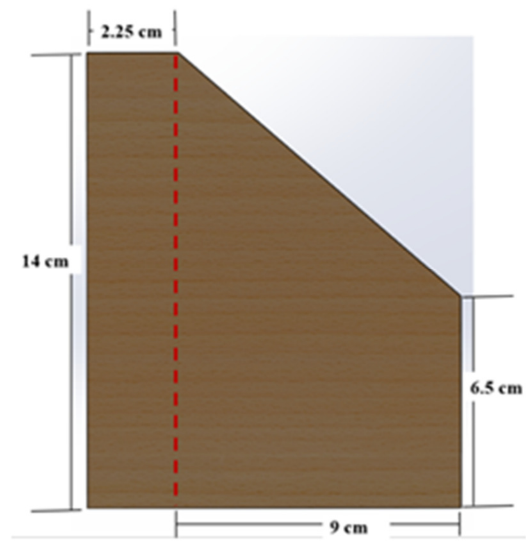
engine would remain straight during the flight. The aft end of the booster also included an aluminum boat tail retainer that both reduced drag at the end of the booster and acted to hold the engine and casing in place during flight.

1.4 Transition system The transition system was in place to allow for a smooth drag separation event. In order to achieve this, a 6.5 cm plastic nosecone was attached to the back of the dart. Next, a larger 9.8 cm nosecone was truncated on the fore end and attached to the booster at the aft end. This allowed the rear nosecone of the dart to nest in the larger, truncated nosecone of the booster. A 9.8 cm bulkhead was used to seal the aft end of the larger nosecone. This apparatus enabled a smooth drag separation while still ensuring the dart remained vertical during the rocket's ascent.

1.5 Fins The fins for both the booster and the dart were custom manufactured in-house using 1/8th in. 5-ply birch plywood. Plywood was chosen because of its maximum strength during launch as well as ease of fabrication. 5-ply was selected to ensure that the fins had sufficient stiffness to prevent deformation under turbulent conditions (i.e. high winds). A table saw, miter saw, and band saw were used for fabrication.

The fins for both the dart and booster were dimensioned with consideration to their effect on the overall stability and structural integrity of the rocket. Numerous simulations using different fin dimensions were run on OpenRocket. The final dimensions enabled a balance between the stability and maximum apogee of the rocket. The fins were also dimensioned to ensure that they remained fixed to the rocket during flight. The booster fins were attached to both the engine mount and the outside of the rocket to ensure structural integrity. The dart fins were attached both at the point where all the fins converged at the center of the rocket as well as the outside of the rocket. The final dimensions are shown below.





1.6 Recovery system The recovery system allowed both the dart and the booster to be recovered after the rocket's flight. For the booster, the ejection event was supplied by the motor used during flight. Because the aft end of the transition system was sealed, the transition would separate from the rest of the booster during the ejection event. This enabled the release of the 36 in parachute that was attached via shock cord to the transition and the motor mount centering ring. The dart recovery was supplied by black powder ejection canisters. The ejection canisters were connected to the StratoLoggerCF altimeter, which was to signal for detonation shortly after the dart's apogee. These caps were attached to the aft end of the electronics payload bay that separated the dart tube near the middle. This allowed a 24 in parachute to deploy.

1.7 Engine The engine used in this launch was a Cessaroni I455-VMAX engine. The engine was mounted within the booster via the 5.4 cm engine mount and then retained using the aluminum boat tail retainer.

2.0 Payload System Design Features

2.1 Rotation sensor system The intent of the rotation sensor system was to capture rotational data in the X, Y, and Z axes as a function of time for use in post flight analysis. To accomplish this, Badger Ballistics considered the need for a user-friendly software platform with a large support community, compatibility of the sensor and microcontroller, and component size and weight. Ultimately an Arduino Uno microcontroller and a three-axis Grove gyro sensor were selected.

The Arduino Uno (ATmega328) was 2.7 in. by 2.1 in and weighed 25g. The Arduino possessed flash memory to store input data until it could be accessed by a computer via a USB cable. A 9V battery was required to power the microcontroller and included in the system.

Implementation of the gyro sensor took place in a two-phase process. In the first phase the gyro sensor and microcontroller were physically connected and open source code was used to write software for the implementation of the sensor. It is important to note that the sensor was intended to be manually actuated by the flight operator and record continuously for the estimated 65 second flight until manually shut down by the operator. This significantly simplified the software implementation by removing the need for the sensor to self-activate. In hindsight, the software could be written to self-activate in order to begin as soon as the rocket began to move.

After software implementation was complete, the hardware was tested to ensure correct functionality. To simulate flight conditions a simple jig of the nose cone was mocked up. The sensor was attached to the jig and rotated about its longitudinal axis. Data from the mock up was then compared to simple calculations performed by Badger Ballistics to ensure system operation. The functionality of the hardware was confirmed.

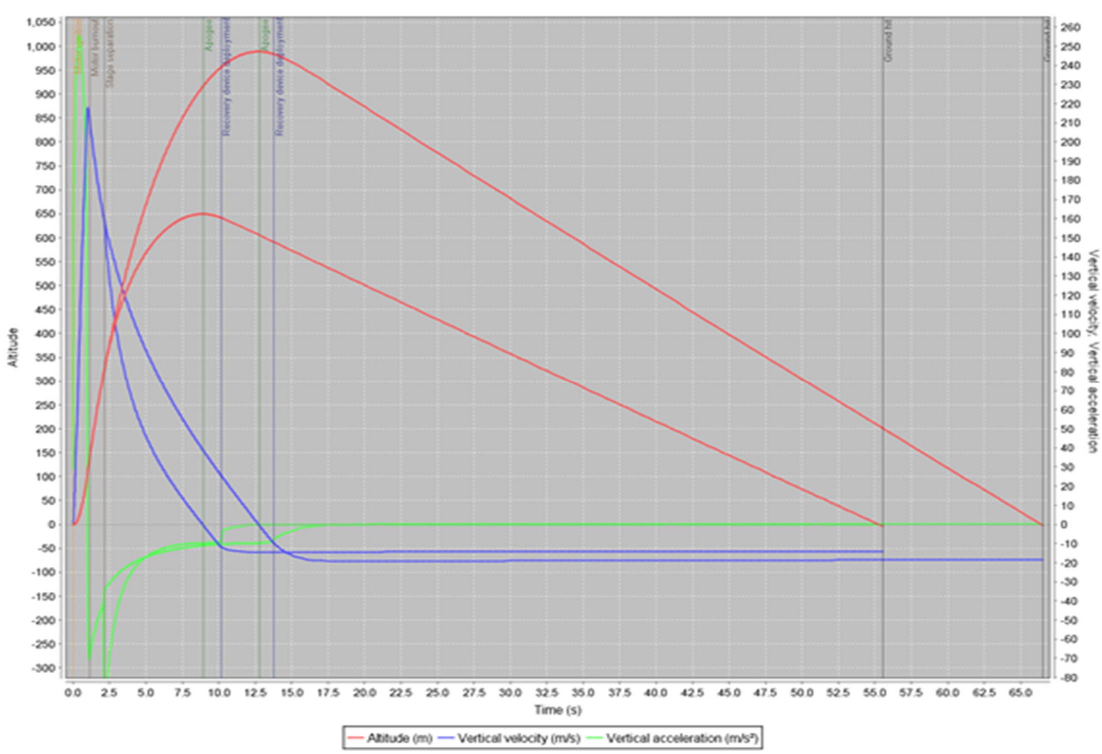
2.2 Video recording system The primary goal of the video recording system was to capture images of the drag separation of the rocket from the booster for post flight analysis. Cost effectiveness, low weight, small size, and electronic compatibility were the primary considerations in the selection of this system.

To accomplish this, a key chain camera was repurposed. The fully encased camera weighed 3.2 ounces, but the plastic housing was removed before installation to reduce overall system weight. This construction required that the rocket be recovered to acquire stored data, as it was saved on board the rocket.

To capture the drag separation, high attention to detail was placed on the positioning of the camera lens. It was mounted to the nosecone of the dart in the downward-facing (nadir) position. This created a counter-balance of weight in the nosecone. To counteract this imbalance, and ensure that the rocket dart flew straight, the opposite side of the nose was counterweighted with steel.

3.0 Analysis of Anticipated Performance

The anticipated flight of the rocket was predicted using OpenRocket, an open source model rocket simulator. Using this simulation, the altitude of the booster separation was predicted to be 1394.36 ft. (425 m), the apogee of the dart was predicted as approximately 3248 ft. (990 m), and the rocket peak acceleration was predicted as approximately 840 ft/s^2 (256 m/s^2). These results can be seen below. Note that some error is expected in this simulation as it is unable to account for the prevailing atmospheric conditions present during the true flight.



3.1 Flight and stability analysis Based on OpenRocket, the rocket had a center of pressure (CP) of approximately 39 in. (99.3cm) from the top of the rocket and a center of gravity (CG) of approximately 34 in. (87.2cm) from the top. This gave a stability of 1.19 cal which was above the benchmark of 1cal, and therefore inherently stable.

After separation, the booster and dart each had different centers of gravity and pressure. The dart had a CG located approximately 18 in. (46.2 cm) from the top and a CP approximately 21 in. (53.2 cm) from the top yielding an overall stability of 1.05 cal for the post-separation portion of the flight. This kept the pitching of the overall rocket and the dart to a minimum during the flight.

In contrast, the booster had a negative stability after separation that caused pitching. This was due to a CP of 17.5 in (44.6 cm) and a CG of 18 in (45.9 cm) from the top of the rocket. Because the separation occurred after motor burnout, and the incurred pitching is not considered to be a safety hazard, this was deemed allowable.

3.2 Recovery analysis To ensure recovery and reusability of the rocket, dual recovery systems were deployed to carry both the dart and booster safely to the ground. A fail safe recovery system was critical not only to retrieve data from the on board avionics but also to prevent property damage and injury.

The booster and dart were equipped with 36 in. and 24 in. chutes respectively. These were mounted via industrial hooks and kevlar cord. For their descents, the booster was expected to fall at a constant velocity of around 39 ft/s (12 m/s) and the dart was expected to fall at approximately 55ft/s (17 m/s).

3.3 Environmental conditions analysis Because the stability factor on the full rocket was above 1 cal, restorative forces on the aft end of the rocket should have mitigated any effect that the wind had on its flight. This would hold for light to moderate wind speeds (~10 m/s). If the wind speed was higher than that, it was possible for the rocket to tumble while the engine was burning, so launch was not recommended. The booster tumbled after separation, but this occured without hazard as it was unpowered at this point of the flight. The dart had similar flight characteristics as the full rocket, although it most likely faced higher wind speeds at higher altitudes. These speeds were of little concern as the dart was unpowered, and therefore posed little safety risk.

4.0 Competition Flight

The flight took place on May 2, 2015 at the Richard Bong State Recreation Area just outside of Milwaukee, WI. During the competition day the only adjustment made to the rocket was rerouting the arming wires for the altimeter to allow greater control of the firing of the rocket. The rocket was launched with a stable trajectory, and dart separation occurred before apogee. Upon recovery deployment at dart apogee, the dart tailcone came out of the dart, and the electronics package fell out with it. Both items were easily recovered. Booster recovery also deployed and the booster was recovered.

5.0 Post Flight Analysis

The predicted apogee for the flight was 3248 ft, however the rocket actually only reached an apogee of 2059 ft. This means our results had an error of 57%, which is quite high. It is likely that multiple factors contributed to the lower than theoretical apogee. Among possible causes are: overuse of construction materials and adhesives, energy loss due to unexpected pitching, and inadequate or oversimplified modeling. The flight performance was predicted using OpenRocket's open source simulation software. The software, while very helpful to the design of the rocket, was not sufficient to account for all aspects and variables of the actual rocket launch. For example, the simulation software assumed a perfectly vertical launch, but on the launch day the rocket was not launched entirely perpendicular to the ground. The software was also unable to account for pitching in the rocket's flight path. The pitching of the rocket during its flight, while minimal, almost certainly decreased its maximum apogee.

Upon dart recovery deployment, it appeared from the ground that the dart tailcone fell out of the dart body, and our electronics with it. After further inspection, we believe that the tailcone was actually ejected from the rocket due to the recovery event. Because we had to modify the rocket on launch day, the electronics bay had a hole running through its length. This hole should have been filled, acting as a bulkhead. Since it wasn't, when the black powder charge detonated, the exhaust gasses were forced through the electronics bay. This caused both ends of the rocket to separate, and allowed some of the electronics to fall out.

The electronics were recovered in operating condition, but unfortunately with no relevant data. Despite our previous successful testing of the electronics system, we had unforeseen issues on launch day that adversely affected our data. There were last second problems with lining the dart up with the booster at the launch pad which caused a time delay from when we activated the electronics to when the rocket was actually launched. By the time the rocket was launched, we had run ten minutes of sampling on the launch pad, and did not receive data from the actual flight.

6.0 Conclusion

We approached the competition with the desire to gain experience in rocketry while honing our skills developed at UW-Madison. Our design was meant to be a simple one. We sacrificed performance for safety, and took a traditional design approach to our rocket in terms of materials and structure.

The flight did not go exactly as expected, but it was considered successful. The rocket flew lower than we thought by a 57% margin, and we did not collect the data we had hoped to collect. However, our flight was stable, our dart separated before apogee, our parachute deployed for

both the booster and the dart, and all of the pieces were recovered in flyable condition. Thus, the flight itself was successful by meeting these parameters.
This competition was an incredible learning tool. Not only did it allow our team to put engineering principles into practice, but we also received a wealth of experience in designing a system from the ground up. We also gained experience in meeting and presenting, writing technical papers, and dealing with firm deadlines. These are experiences that are difficult to recreate in a classroom setting, but are vital for a career in engineering. If future competitions were to be attempted, we would take what we've learned from this rocket build and try to implement unique design elements. Specifically, we learned of the pitfalls of using only an open source simulation software to simulate the flight of the rocket. In future competitions, more simulation sources would be used and checked against one another. We also learned of the problems and unintended consequences of modifying the rocket on launch day. In future competitions, more testing would be done prior to launch to ensure that the rocket would not need to be modified on launch day.

In conclusion, the design was considered successful. The flight on launch day was safe and successful and the simple design of the rocket enabled its construction to come in about 20% under budget. Much was learned through this opportunity and Badger Ballistics is grateful for the knowledge and experience gained.