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Abstract

Food and agribusiness accounted for 3.5% of the $80 trillion global GDP in 2017[1]. Consumption is predicted to outpace crop production as farming continues as one of the least digitized sectors. Technologies in development to tackle this production issue include improved crop monitoring methods. Current monitoring methods in the landscape are comprised of drones and satellites. In our senior design project, we attempted to create a rocket based monitoring system equipped with an infrared camera to effectively determine crop health by measuring the normalized difference vegetation index at an altitude unreachable by drones and with higher image quality than satellites.

Project Background

By the year 2050, the global population is estimated to require 69% more food than current farms are producing. Currently, an estimated 20% to 40%[2] of crops grown by farmers die from preventable pests and disease. By using technological monitoring systems to investigate and treat those areas for issues such as disease, pests, dehydration and lack of fertilizer, farmers can mitigate these losses, increasing crop yields.

Business Analysis

Currently, there are two primary ways farmers monitor their crop health: drones and satellites. Unfortunately, current agricultural drones are limited by battery life. Even the most expensive models can only fly for about half an hour before needing to charge. Most multi-rotor drones can only cover an estimated 50 acres of farmland per charge.[3] Commercial satellite imaging provides only a very low resolution image of farms due to the large distance from the subject. In addition, satellites are unable to provide the Normalized Difference Vegetation Index (NDVI) images which drones use to reveal problem areas invisible to the naked eye. NDVI imaging is used in agriculture to determine if an area has live green plant life. NDVI uses a combination of green and near-infrared light to determine whether there is a presence of chlorophyll and water in the plants being imaged.

As an alternative to satellites and drones, a rocket could capture a far larger area than a drone as it can achieve heights an order of magnitude higher than a drone while still capturing high resolution imagery. Rockets would be faster than drones as the total flight time would be under a minute compared to 30 minutes of flight time per drone charge. A rocket is also far cheaper than a drone, manufacturable for only several hundred dollars including the camera whereas agricultural drones typically cost several thousand dollars. These benefits are well illustrated in Table 1. The team believes rockets would be far more practical for any farmer, especially those with farms over a thousand acres.

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[1] “Cornell Farms and Land in Farms 2017 Summary”

[2] Food and Agriculture Organization of the United Nations

[3] “Agriculture Drone Buyers Guide”

	Drones	Satellite	Rocket
Area Covered	Small	Global	Large
NDVI	Yes	No	Yes
Speed	Slow	Instant	Fast
Fixed Cost	$4000+	0	400
Pixel Resolution	V. High	V. Low	High

Table 1: A comparison of drones, satellites and rockets

The average farm size of the U.S.'s 2.1 million farms is 443 acres. 12% of farms average 2,068 acres in size and are in the top earning bracket with annual sales larger than $250,000. The team believes a rocket based solution could be an effective alternative to drones for this market.

Rockets equipped with NDVI lenses would be able to photograph entire farms well over 1000 acres and give valuable data about crop health, irrigation, and soil to the farmers that need it most. Our target market consists of farmers with over $250,000 in sales annually. These farmers almost all have farms of over 1000 acres with no current solutions for holistically monitoring their crop health with NDVI.

Current alternatives offer mixed results. Fixed wing drones (similar in design to a remote control airplane) can cover up to 10 times the acreage as multi-rotor drones but they fly over land at much higher speeds, leading to blurry images which are suboptimal for survey-grade 3D or topographical imaging. With a $10,000 price tag, they are fairly expensive. In addition, the commercial drone license required for their operation is a significant barrier to entry for farmers.

Drone charging stations offer a point for drones to land and recharge when reaching the end of their range. However, on very large farms, multiple stations must be installed (each costing several thousand dollars) and are often not weather-proof. Thus the farmer must set up this network of chargers each time he wishes to have his drone survey the farm. FAA regulations also require drones to remain within line of sight of the operator, requiring the farmer to move as they operate the drone.

We estimate that we can build and ship a reusable rocket for under $600 and sell it at cost. We would then sell the disposable rocket motors for $150 per charge plus shipping at a cost of roughly $50. Using this "razor and blade model" we believe we can entice farmers to try our product at a low cost ($600 compared to $1000+ for a drone) and eventually subscribe to monthly motor shipments. With a conservative customer churn rate of 15% annually, a 6 rocket motor per year subscription at $100 per month gives us a very strong customer LTV of $8000. If we are able to capture just 10% of our target market on a 6-motor plan, we would earn annual revenues of $15,120,000 in the US alone with a healthy 66% margin.

Initial Approach

Our initial proposal was to design a rocket motor that maximized the thrust of a rocket engine per cost of propellant for a 100 lb thrust rocket. However, this did not pose a useful business case as the least expensive fuels have a very low specific impulse, limiting their range of applications.

Accordingly, there was a pivot towards developing a rocket motor with an ALICE propellant - nanoporous aluminum and ice, aluminum acting as the fuel and ice (water) as the oxidizer. ALICE seemed like a feasible business case as aluminum is one of the most abundant chemicals on Mars's surface. If Mars's surface also has water, then developing an effective propellant that is manufacturable on the Martian crust would be useful for a number of aerospace applications such as rocket launches on Mars. However, we pivoted from this option when a Jet Propulsion Lab researcher cautioned us with their opinion that there was, in fact, very little water on Mars. In addition, the financial cost of manufacturing a nanoporous aluminum grain would have put our project quickly past budget. This led to the current objective - designing a rocket for data collection at altitude, specifically infrared photography to measure the NDVI of crops.

Project Approach

Designing and building a rocket for data collection employed a number of engineering disciplines. To begin, the structurally sound rocket was designed using mechanical engineering concepts learned in class, including finite element analysis and computational fluid dynamics. Next, a timely and economic manufacturing plan was developed and executed. Components were tested to ensure flight reliability. Camera functionality was also tested. With the rocket fully assembled, a launch took place on April 21, 2019.

Designing the Rocket

Designing the rocket took several stages, including a preliminary design review to define design criteria, a critical design review to outline how the design would meet its functionality goals and design criteria, and a final design review, to make certain that the rocket would function properly. Design goals for the rocket were to design a safe, durable rocket that could sustain many launches, equipped with a high quality camera that could generate useful data for farmers, at an affordable price for a profitable business case.

To design the nose cone, we tested several possible configurations for their structural integrity and aerodynamic performance, including: blunted cone, cone, parabolic, and ogive configurations. Blunted and cone configurations were the strongest configurations but, due to their natural shape, cause early flow separation which dramatically increases form drag and decreases aerodynamic stability. Ogive and parabolic configurations, on the other hand, have considerably more surface area, increasing skin drag. However, skin drag is negligible compared to form drag. After determining that we could manufacture a nose cone well past the structural requirements of the airframe flight, we decided to use the Von Karman Ogive configuration to minimize the coefficient of drag. In SolidWorks, we used an equation driven spline to define the geometry.

Designing the fins required more consideration. Similar to the nose cone, we were flying well within the structural limits of the three possible materials we considered: carbon fiber, medium-density fiberboard, and G10 fiberglass. Accordingly, instead of designing for strength, we could instead focus on drag reduction. In an effort to minimize the drag force, we choose an elliptical shape for the fins because elliptical fins generate the lowest induced drag of all configurations. To select the material, we calculated the center of pressure, and adjusted the required mass of the fins to move the center of gravity behind the center of pressure; the center of gravity must be aft of the center of pressure in order to achieve stable flight and prevent inversion should the airframe sustain lateral loads. By maximizing the mass of the fins, we were able to move the center of gravity to 10.51’’ from the tail, further behind the center of pressure at 10.89’’, making a for safe rocket, as seen in Figure 1. To maximize mass, we selected medium-density fiberboard as the material.

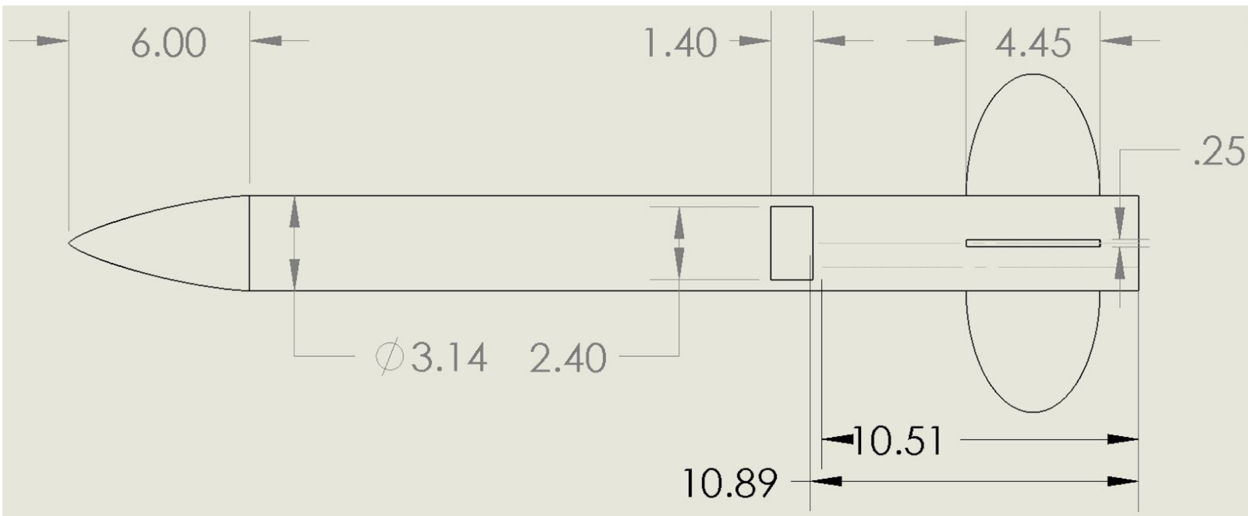

Figure 1: Dimensions of the rocket

In terms of the airframe, the aerodynamic forces were calculated at Mach 0.2 (the upper limit of our flight speed) and an average angle of attack of 2 degrees (typical of most rocket flight) using drag and pressure data from 2D and 3D computational fluid dynamic simulations, as seen in Figure 2. All forces were multiplied by a safety factor of 3 to ensure we were well within the rocket’s limits. The maximum axial force was calculated to be 2.34810^{2} Newtons. With this number in mind, we researched various materials and arrived at Acrylonitrile Butadiene Styrene plastic (ABS) which is well within the tensile modulus of the airframe, made of ABS plastic, which is tested to $4.64*10^{3}$ Newtons, and tensile strength to $2.29*10^{4}$ Newtons per square meter (ASTM D638). Lateral forces from the wind and pressure differences across the surface of the airframe were calculated to be 117 Newtons, well within the flexural strength of $6.03*10^{3}$ Newtons. To verify these results, normal forces were calculated using the surface integral of the aerodynamic pressure over the surface of the body tube in the direction normal to the rocket’s trajectory. In addition to the mechanical properties, ABS offers a number of advantageous chemical properties. ABS is an amorphous solid, meaning that at high temperatures (432˚ F) (such as those possibly sustained from the motor exotherming during flight), instead of melting, the solid transitions to a rubery substrate, maintaining most of its form. In addition, the material is fairly light, weighing 1.08 grams per cubic centimeter (ASTM D792), making it ideal for aerospace applications. ABS is also safe to machine as it does not generate microscopic carcinogenic particles.

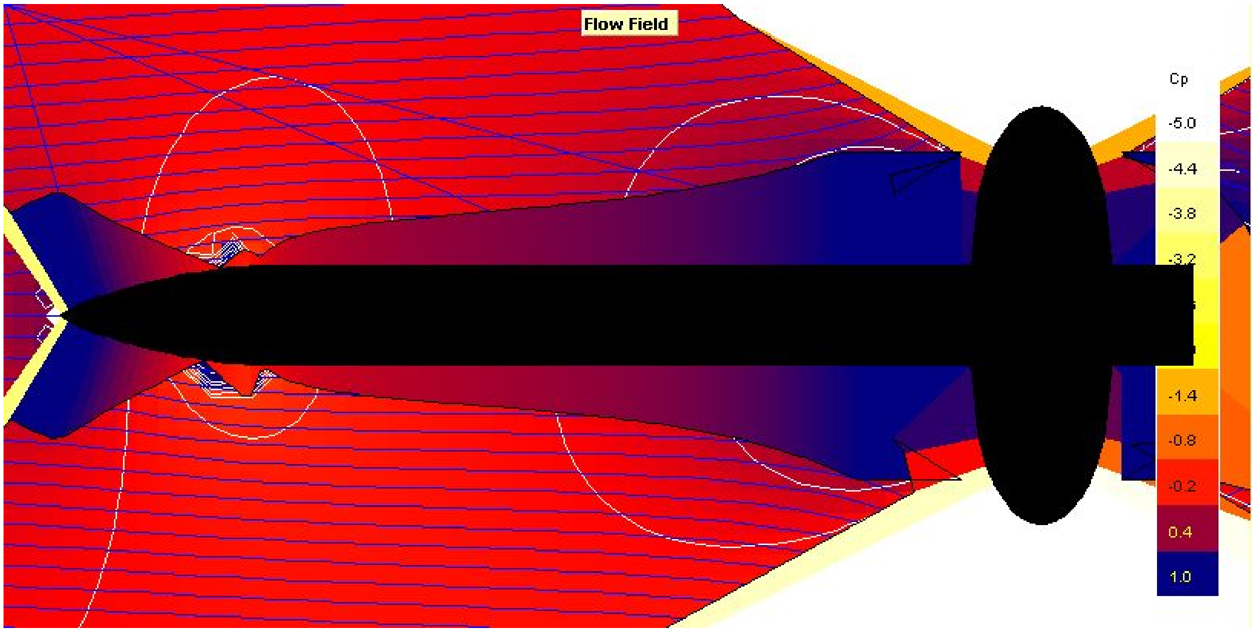

Figure 2: An example 2D simulation at 2 degrees Angle of Attack

For housing the camera, we designed a camera mount that would secure the camera facing outwards, perpendicular to the axis of the rocket so that the camera can effectively photograph a farm. As seen in Figure 3, we included ramps on either side of the mount to act as compression and expansion zones to deflect the hot gases that would be expelled from the ejection charge on the rocket motor. To ensure the camera would be facing downwards during the descent of the rocket, we employed a dual parachute system by mounting 2 parachutes to anchor points at the base and upper part of the airframe on the opposite side to the camera aperture. Figure 4 shows exactly how the rocket would be oriented during descent.

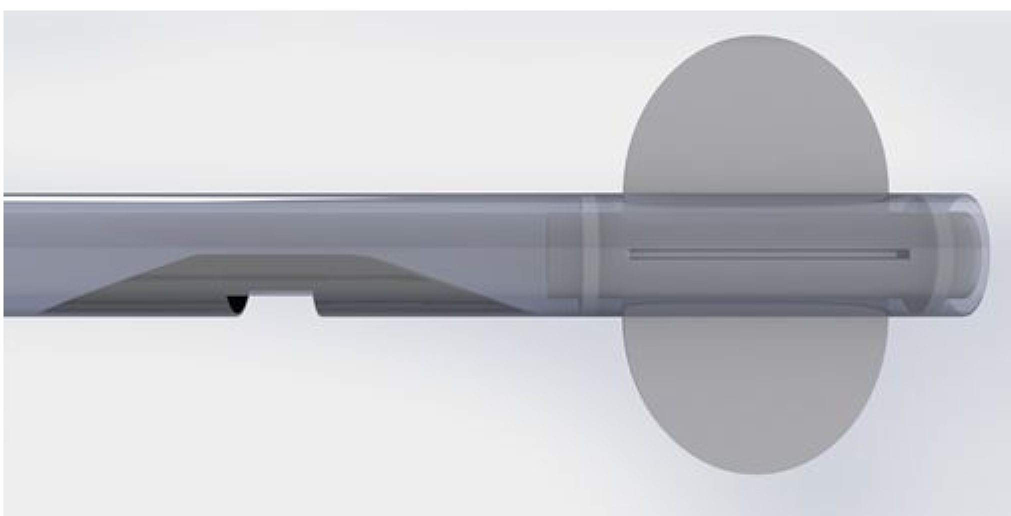

Figure 3: Cross-sectional view of camera mount in rocket

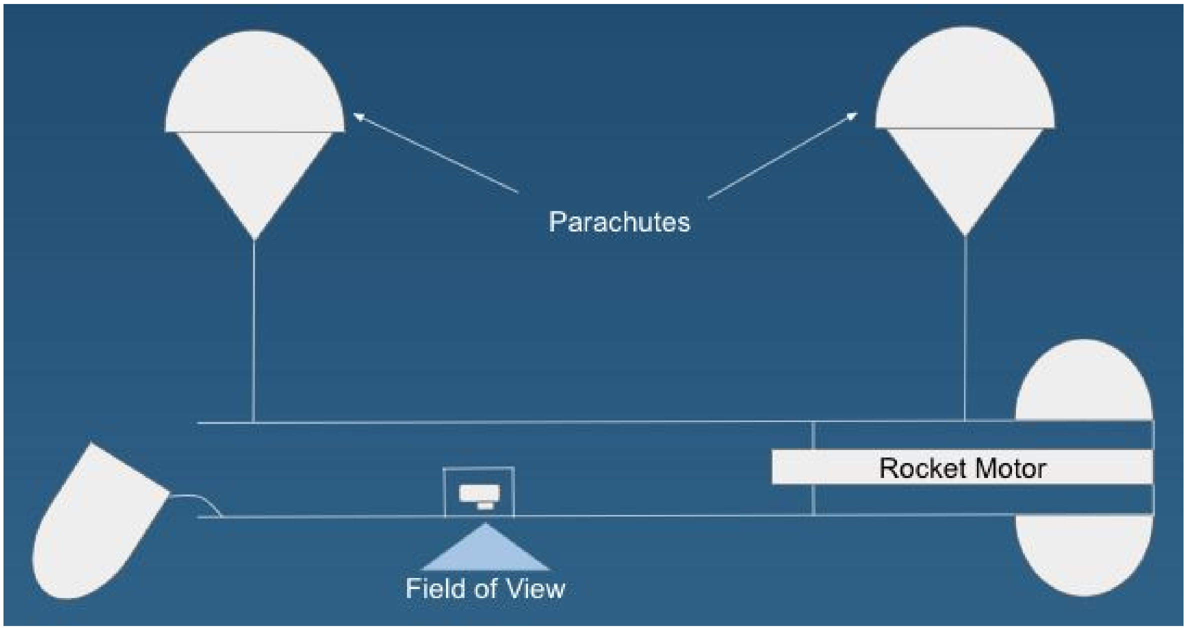

Figure 4: Descent configuration of the rocket

Manufacturing the Rocket

Manufacturing the rocket took a number of pivots. Initially, potential sponsors were contacted to inquire about their willingness to donate parts, labor, tools, or material in support of our project. Unfortunately, none were able to commit to the opportunity. Thus, using an industry standard mandrill spinner to roll the airframe and contracting a nose cone were no longer options.

Accordingly, AddLab was contracted to 3D print the camera mount and a tool for the nose cone, seen in Figure 5. After the mold was sanded and primed, a wet layup was performed using PT2712 epoxy resin. Subsequently, the two halves were bonded together using Loctite EA 9309NA, potting compound; potting compound is an airtight adhesive with flexible bonds, optimal for use in aerospace applications that experience serious vibrations. The finished nose cone, seen in Figure 5, was trimmed, sanded, and polished to improve aerodynamic performance during flight.

Figure 5: Nose cone tool and nose cone

For the airframe, a 3'' diameter x 3' length tube was purchased. Milling took place on a ProtoTrak 3-axis CNC in the Precision Machining Lab. MDF jigs were used to hold the tube in the vice during all milling operations, as seen in Figure 6.

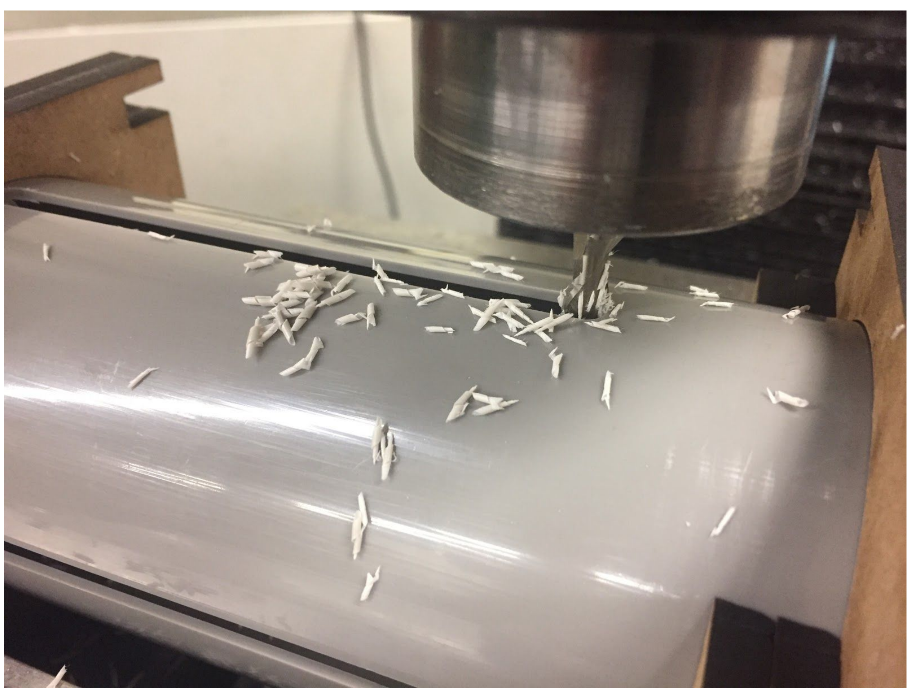

Figure 6: Tube in vice with ProtoTrak

Once all components were manufactured, the rocket had to be assembled. To hold together the components, we used an aerospace grade adhesive, 3M DP420 Epoxy Adhesive. Tested up to 1.4 $*10^5$ Newtons per square meter, we were confident in the adhesive strength. Prior to bonding, all surfaces were sanded with 80 grit sandpaper to maximize contact area and cleaned with acetone to remove impurities. Sufficient time was allowed for each adhesive to cure before additional layers were applied.

Camera & Lens

Normalized Difference Vegetation Index (NDVI) imaging is used in agriculture to determine whether an area has live green plant life. NDVI uses a combination of green and near-infrared light to determine if there is a presence of chlorophyll and water in the plants being imaged. NDVI is calculated using the following equation:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \qquad 1.1$$

Using the near infrared and red light indices, an NDVI index can be calculated to generate a colormap image. NDVI is currently used in drone photography of farms to understand what areas of the farm need more attention, whether it be water or fertilizer, to improve overall crop health on the farm. In order to compete with drones as the most effective means of monitoring crops in large farms, our rocket needed to be equipped with a NDVI camera.

Our team decided to use a GoPro Hero 4 equipped with an infrared lens and a blue NDVI filter. Combining the effect of the lens and filter produces an NDVI color map of the farm. When descending on the parachutes, this camera will take photographs of the farm, generating the NDVI image. Subsequent analysis of the NDVI images will identify the areas of the farm that need additional attention. As a result of NDVI imaging's focus on green vegetation, wheat farms will not be imaged using this camera.

The goal of the rocket camera is that the image captures as much area a farm as possible. Our camera has a vertical field of view of 94.4° and a horizontal field of view of 122.6°. At the target height of 5000 feet, the rectangular area captured by the image would be 4660 acres, large enough to capture the entirety of most farms with a single launch.

Computing and Image Analysis

A python photo transformation script was coded for this project. Near infrared photographs are transformed into colormap photos denoting pixel NDVI index. In the script, NDVI is calculated using the following equation:

$$NDVI = \frac{(red - blue)}{(red + blue)} \qquad 1.2$$

In the above equation, red corresponds to the red value of the pixel red-blue-green (RGB) value; red corresponds to near-infrared light. Blue corresponds to the blue value of the pixel RGB value; blue corresponds to blue light. Blue light normalizes for visible light from the plants. Regardless of the health of a given plant, blue light tends to be reflected at the same level. This gives an accurate NDVI index regardless of the incident sunlight in the photo.

Launching the Rocket
On April 21, 2019 at Fairmount Park in Philadelphia, PA, the rocket was launched. In terms of the rocket leaving the launch pad, the launch was successful. In terms of collecting useful data, the launch was not successful. This is due in large to that the NDVI camera was damaged during the launch. As a result of a failure with the igniter, there was a contained explosion within the rocket that propelled the rocket body approximately 10 feet into the air. Figure 7 shows the rocket on the launch pad just before the launch.

Figure 7: Rocket Pre-Launch

In the aftermath of the failed launch, the rocket motor, the portion of the rocket body surrounding the explosion, the camera mount, and the camera itself experienced significant damage. Further analysis of what exactly caused this critical failure during can be found in the failure analysis section of the report.

Failure Analysis
Having examined the damage to the rocket and the pieces left behind, we have reached the conclusion that failure resulted from the igniter. During our first launch attempt, the igniter included with the rocket failed to ignite the motor. Accordingly, we used a backup igniter, designed for a motor with slightly wider nozzle. This igniter was successful in lighting the fuel but failed to be ejected; this was a failure of a store bought component. Instead, it likely plugged the nozzle causing the fuel to burn in a confined environment, building in pressure until the entire nozzle ripped off, shearing the motor casing; this was another failure of a store bought component. This is shown in more detail in Figure 8. The nozzle became a projectile that was launched downwards denting the metal launch plate. The motor casing launched upwards, ripping through the camera mount and ramp as seen in Figure 9, ultimately denting the camera.

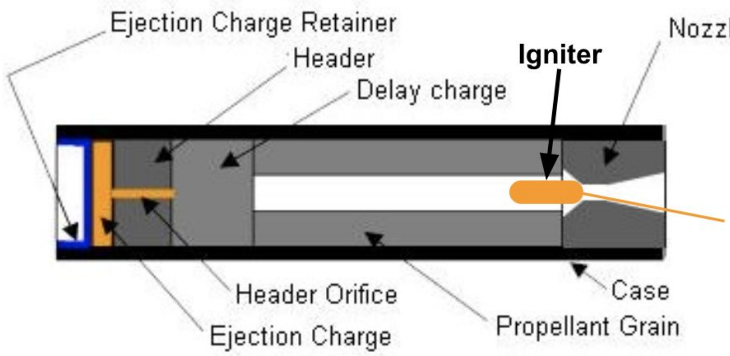

Figure 8: Cross section of the rocket motor with failure


Figure 9: Launch Aftermath

Data/Results

Although the planned launch was unsuccessful, data was collected using our NDVI camera prior to launch. Photos were taken from the top floor of the high rise buildings on the University of Pennsylvania campus, approximately three hundred feet high. Though this is only a fraction of the height we intended to reach with the rocket launch, the height serves as a proof of concept for our NDVI camera. The color map NDVI image shown in Figure 11 shows analysis of plants in the image to extreme accuracy. It is clearly visible in the image where people are standing and blocking plant life from the lens. At the height of 5000 feet, individual plants will be difficult to see, but areas of the large farm that contain large amounts of stressed or dead plants will be easily identifiable. Figure 10 shows the NDVI image before the transformation to color map by the python script, and Figure 11 shows the image after transformation.

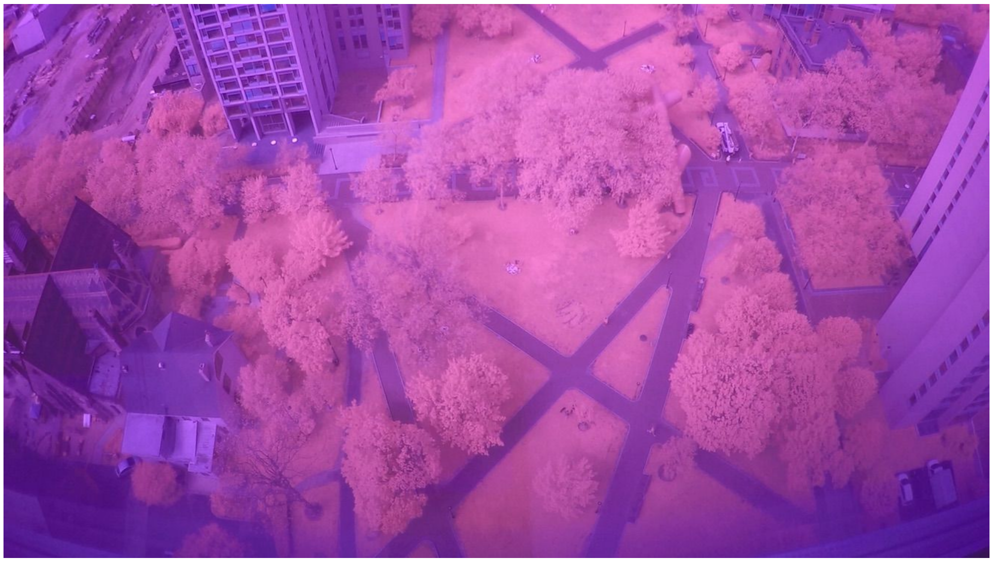

Figure 10: NDVI Image Before Transformation

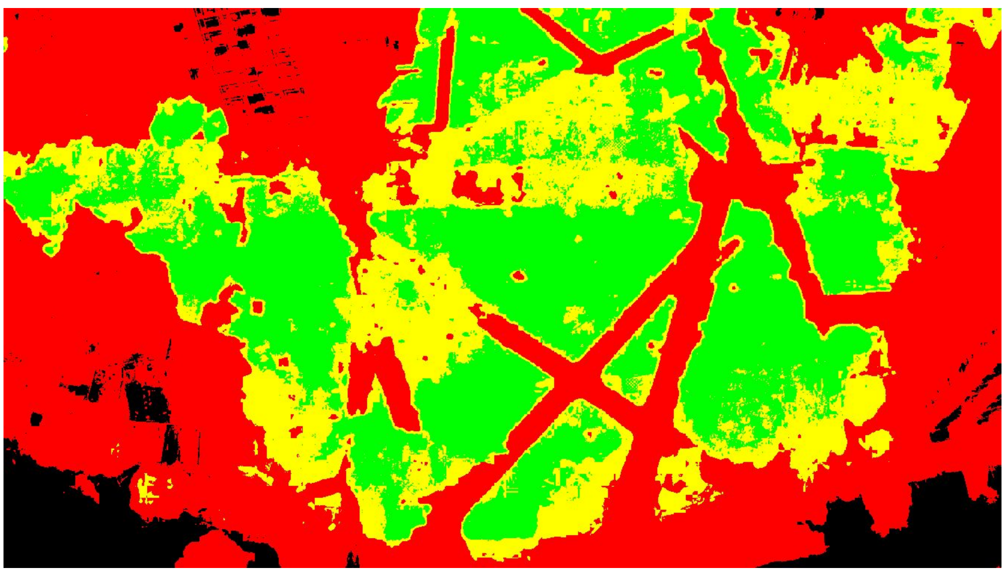

Figure 11: Transformed NDVI Color Map Image

As can be seen from Figure 11**,** after the transformation, all non-organic matter appears in either black or red, and any organic matter appears in either green, yellow, or red, consistent with what the colormap should be showing. Yellow and red are shown around paths which indicated areas where plants are walked on, while green areas are almost entirely on the interior of grass areas, further demonstrating the camera's ability to display variances in plant health. Using similar images of a farm, farmers would be able to easily identify areas of their farm that contain large amounts of stressed and/or dead plants and take the necessary steps to improve yield in those areas.

Conclusions and Future Work

Evidently, the rocket failed as a proof of concept. However, the team is confident that with a larger budget and more time, a second launch could be prepared based on the work we have done. We are also highly confident that if the igniter had not plugged the motor, the camera would have been able to reach the desired altitude and photograph the surrounding area. Nonetheless, there are several improvements that could be made. First, we could design an online website where raw footage could be uploaded and automatically processed and overlaid onto satellite imaging. Second, we could build a custom camera as a less expensive option than GoPro, operable by buttons on the side of the rocket frame. Third, to improve image quality, we could develop stabilization mechanisms including computer controlled parachute reefers, a gimbal mount for the camera, and a stabilizing mechanism to center the camera during descent. As seen through the course of the project, our work serves as an initial proof of concept applicable to the farming industry at large.

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References

"Acrylic", Build It Solar, https://www.builditsolar.com/References/Glazing/physicalpropertiesAcrylic.pdf .

"Acrylonitrile Butadiene Styrene", Prospector, https://plastics.ulprospector.com/generics/1/c/t/acrylonitrile-butadiene-styrene-abs-properties-processing .

"Agriculture, Forestry, and Fishing, Value Added (Current US$)", US World Bank, https://data.worldbank.org/indicator/NV.AGR.TOTL.CD?page=2 .

"Agriculture Drone Buyers Guide", Best Drone For the Job, https://bestdroneforthejob.com/drone-buying-guides/agriculture-drone-buyers-guide/ .

"Aluminum-Bearing Site on Mars Draws NASA Visitor", JPL, https://www.jpl.nasa.gov/news/news.php?release=2014-201

"Astralis Rocketry Corp", Astralis Rocketry Corp, http://www.astralisrocketry.com/ .

Cantwell, Brian,. *Aircraft and Rocket Propulsion*, Stanford University.

Conversations with the following: Professor Vanessa Chan, Professor Eric Detsi, Professor John Crocker, Professor Sangeeta Vohra

"Cornell Farms and Land in Farms 2017 Summary", US Dept. of Agriculture, https://usda.library.cornell.edu/ .

"Data for Public Land Management", US Department of the Interior, Bureau of Land Management, https://www.blm.gov/about/how-we-manage/data-for-public-land-management .

"Everything You Need to Know About Acrylic (PMMA)", Creative Mechanisms, https://www.creativemechanisms.com/blog/injection-mold-3d-print-cnc-acrylic-plastic-pmma .

"FAQS", FAA, last modified August 29, 2018, https://www.faa.gov/uas/faqs/ .

PML Airframes FAQ, Public Missiles, https://publicmissiles.com/images/pmlairframesfaq.pdf .

Sutton, G., Biblarz, O., *Rocket Propulsion Elements Eighth Edition*, John Wiley & Sons, Inc., 2010.

Westerfield, Mike, *Make: High-Power Rockets*, Maker Media, Inc., 2017.