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Car-Snow Clearing Drone

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Car-Snow Clearing Drone

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Preface

This project was affected by the coronavirus (COVID-19) global pandemic for the entirety of D-term. The pandemic caused academic buildings to be closed and MQP projects to be worked on remotely. Although the team was able to remove the project from academic buildings at the conclusion of C-term and make limited progress with the physical build in D-term, the pandemic greatly decreased the project potential and disrupted the work schedule.

List of Accompanying Submissions

Submitted with this paper as a part of the eCDR to fulfil the Worcester Polytechnic Institute Major Qualifying Project for graduating students are a number of additional files that are of use to this project. They are:

- Final Presentation - Slides
- Project Presentation - Poster
- Project Presentation Video - ME
- Project Presentation Video - RBE
- Pack & Go CAD files
- IR camera guide

Acknowledgements

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Chapter 1: Introduction

In the wintertime, snowfall can cause dangerous conditions across the world. Among these dangerous conditions, snow on roads, car roofs, and windshields proves to be a hazard for all drivers. Snow on windshields can impair visibility, and snow on car roofs can fall off and hit other drivers or create obstacles on the road. Laws regarding snow on vehicles vary across the United States. In the state of Massachusetts, there are no laws that prevent motor vehicle operators from driving with snow on their vehicles (Massachusetts Registry of Motor Vehicles, 2019). However, while there is no law that directly states that drivers must remove snow from their vehicle prior to operation, there are other laws that hold drivers accountable for accidents due to snow falling off their car. One Massachusetts law in particular, Chapter 85, Section 36, covers unsecured loads on cars. Another Massachusetts law, Chapter 90, Section 24, covers the reckless or negligent operation of a motor vehicle. Police officers can issue a $40 fine for a driver with obstructed windows and a $200 fine for driving with an unsecured load on the roof (Glaun, 2016). According to the Federal Highway Administration, weather-related vehicle crashes average nearly 1,235,000 each year, with 18% of these crashes caused by snow and sleet (Federal Highway Administration, 2016).

Removing snow from cars is an unappealing, time-consuming, and potentially dangerous task for even the average person. For people with disabilities or limited physical ability, removing snow from cars can be a nightmare. Staying outside for an extended period of time in cold weather conditions, as is often required when clearing snow from cars, increases the risk of frostbite and hypothermia. Frostbite can set in quickly, depending on temperature and wind chill. In -10°F conditions with no wind, frostbite symptoms begin appearing in less than thirty minutes. With the same temperature and wind speeds of 25 mph or higher, symptoms start appearing in less than 10 minutes (National Oceanic and Atmospheric Administration, 2019). Walking in icy conditions carries a risk of dangerous falls. Any methods to reduce or eliminate exposure to the cold and ice while providing the same effective safety of proper clearing of car snow are worth investigating.

Many solutions have previously been created in an attempt to address this problem, but none are safe, highly effective, and practical. Most people who live in cold climates use a plastic scraper and brush to remove snow and ice from their car. Some companies use an adjustable stationary scraper for their fleet of trucks. There are multiple consumer sprays and online recipes for homemade solutions that are manually sprayed on the windshield of a car to remove snow and ice. None of these solutions eliminate the need for a human to go outside and be exposed to the elements, nor are they convenient.

Most solutions to clearing cars and other road vehicles are conventionally manual efforts. Research conducted about drones' role in replacing manual labor tasks find wide-ranging examples of drones completing tasks otherwise dangerous to humans, such as clearing ice from tall wind turbines or removing moss from residential home's roofs. As the popularity of consumer drones rises, there is a distinct gap in this space for a drone solution that homeowners can use to clear their car of snow to save time, while remaining safe from the cold weather. A drone solution to clearing the ice and snow off cars is in many ways an extension of these previous solutions, as they have similar components and tasks. However, each solution must be tailor-made to the problem at hand, and a snow-clearing drone is no exception.

While many agriculture and cleaning drone platforms allow users to spray liquids, they are not specifically designed to spray deicing fluid on cars in cold conditions. This snow-drone unmanned aerial vehicle is specifically designed to spray deicing fluids on cars in cold conditions. There are a number of unique challenges that this task presents that existing commercial drones are not currently designed to accomplish, including carrying a large liquid payload and operating in colder weather where the electronics must be protected and operating temperatures are a concern. The goal of this project was to design, manufacture, and implement a drone solution to aid consumers in the removal of snow off of cars. The project focused on collecting case study data of different drone design and applications; designing the mechanical, electrical and computer systems of the unmanned aerial system; testing and evaluating the accuracy, repeatability and precision of the removal process; and presenting a comprehensive design summary with a compelling vision for the future of drones aiding society, specifically in the consumer space.

Chapter 2: Background

2.1 Drone Design

A drone is a form of Unmanned Aerial Vehicle (UAV), and a UAV together with all the related peripheral systems not physically contained on the UAV forms an Unmanned Aerial System (UAS).. Generally, small UAVs all share similar, high level designs and all have the same basic controllers. Most UAVs have three to eight rotors, with propellers that have two or more blades. The most common configuration for small UAV is four rotors with two-bladed propellers. Almost all small UAVs are flown using brushless motors. Brushless motors are powered by direct current (DC) from a battery and controlled with an electronic speed controller (ESC), which provides pulses of current to the motor coils, controlling the speed and torque of the motor. Without friction between the stator and the rotor, the efficiency of a brushless motor improves significantly. Heat and friction are reduced, optimizing the energy of the battery. This increases the power of the motor by 20-60 percent, depending on the battery. The brushless motors work similar to three-phase alternating current (AC) motors, they have three electromagnets that constantly turn on and off causing the magnets to spin the rotor. Because of the three-phases, each motor needs an ESC that regulates the speed of the motor. The ESC takes the throttle input and varies the switching rate of a network of field effect transistors. Changing the duty cycle, or frequency, of the transistor changes the speed of the motor. Another essential part of a small UAV is the flight controller of the drone. The flight controller determines the revolutions per minute (RPM) of each of the motors in response to an input. A command is sent to the flight controller from either a radio (manual control) or a pre-planned path, which determines how the flight controller manipulates the motors to complete the task. Common flight controllers have sensors inside, such as an inertial measurement unit (IMU), that helps the drone achieve stable flight. An IMU consists of multiple sensors that are important for autonomous flight, such as accelerometers and gyroscopes. Lastly, receivers (Rx) and transmitters (Tx) are used to control drones with a radio. Today, there are transmitters and receivers that can transmit and receive commands from miles apart, meaning someone could fly a small UAV that is not within line of sight.

2.2 Drone Flight Control (Navigation)

Drones use a variety of sensors for control and navigation. Inertial navigation is one of the most common techniques that drones use to navigate. To accomplish this task, sensors onboard the drone, such as an inertial measurement unit (IMU), measure acceleration and rotation to determine metrics like current orientation, speed, and position. This information is used in a feedback loop to help control and guide the drone. However, inertial sensors can be responsible for a large portion of noise in the data, which greatly affects the accuracy of the data. Another common sensor used on drones is a global positioning system (GPS) receiver. GPS relies on a satellite network in orbit to determine the latitude and longitude of the receiver. The system works worldwide but is generally only accurate to a distance of about three meters, making its usefulness limited in the context of precise navigation and control work, such as for this project.

Many drones have an onboard camera that can be used to aid in controlling and guiding the aircraft. The camera can have a live feed sent back to a person manually flying the drone, or the image can be processed automatically to provide feedback for flight control. While more complex to design using existing resources, computer vision allows for potentially more accurate data to be used when flying the drone.

The most effective way to accomplish controlled flight of a drone is through sensor fusion. Sensor fusion is the combination of sensory data from different sources such that the resulting information has less uncertainty than when the data was processed individually. Most modern aircraft today navigate using a combination of GPS and inertial navigation, as neither is highly effective on its own. Adding in visual sensing from an imaging device will further allow for improved navigation as well as increased ability for other tasks.

One of the most common ways to more precisely control an automated system is to use a Proportional Integral Derivative (PID) controller to manage motion and sensor feedback. PID loops calculate the difference between the desired value (setpoint) and the actual value and perform operations on the input data to reduce the overall error in the system. The three parts of PID control can be used as is or can be split up and used in a variety of combinations including P, PI, and PD, just to name a few examples. Proportional control multiplies the error by a set constant proportional gain, allowing a smaller response from the system as it approaches the setpoint. Integral control sums all previous states up to the current point to look at the past behavior of the system in order to apply an appropriate correction. Derivative control uses the current rate of change in the system to anticipate upcoming error and correct it accordingly. By leveraging a PID controller, a drone can fly steady, straight, and to its destination regardless of sensor noise and other environmental factors that could cause it to become unsteady.

2.3 Custom Drone Part Materials

As drone flying and building becomes more accessible to non-engineers, more and more people are designing and fabricating their own custom drone components. There have been numerous solutions that hobbyists utilize at home to manufacture their own drone elements, such as 3D printing and easily machined parts on manual machine shop tools.

3D printing has become one of the most prevalent rapid prototyping tools for engineers to design and iterate their designs. Unlike other manufacturing methods, such as CNC milling or turning, 3D printing technology can produce more complex geometries in parts due to the addition of support material during the printing process. 3D printing also provides a cost saving solution and doesn’t require a technician to be present in order to operate the machine while the part is being manufactured. The aforementioned advantages of 3D printing led hobbyist drone builders to utilize this technology when designing and making their drones. However, critical drone flight components must be fabricated to a high level of precision to protect the mechanical integrity of the drone, and unfortunately, most consumer grade 3D printers do not lend themselves to the level of precision required for designing a commercial drone. These inaccuracies often occur during printing. Parts often delaminate during the printing process, causing separation in the layers of the part and causing inaccuracies in geometry. Additionally, the resolution of the print needs to be adjusted by the design engineer to optimize nominal dimensions during printing (Kujawa, 2017).

To resolve some of these issues, an easy solution to delaminated layers that have lifted during the print process is inserting a layer of a carbon fiber sheet to bolster the print surface (3D Printed Racing Drone - Will It Survive?, 2017). In addition to carbon fiber sheets under flat print surfaces, carbon fiber rods are also beneficial for elements that need to maintain an internal rigidity (Sandoval, Sanchez, & Sandoval, 2016). These rods reinforce the internal infill of 3D printed parts by combining the strength of the hexcomb plastic infill and lightweight, strong carbon fiber.

The reason that carbon fiber is often used in conjunction with the 3D printed material is because of its resilient material properties. Carbon fiber has a very strong strength to weight ratio and a stiffness to weight ratio. These properties allow for carbon fiber elements to be very strong and not fracture under a high load, while also not deforming under high loads as well. Applying even a carbon fiber sheet to 3D printed material as mentioned above, gives the more brittle 3D printing material, often PLA or ABS plastic, a more rigid backbone as long as it is fixtured properly along the printed feature. Additionally, carbon fiber can be purchased in sheets that are incredibly flat, which is beneficial for mounting components like electronics and motors that need to be level. Carbon fiber is also used on its own in drone designs due to its lightweight properties, while being difficult to fracture from its high tensile strength. A number of drone components are commonly built from carbon fiber materials, including the center frame, landing gear, and rotor arms.

The other commonly used material for custom drone elements is aluminum alloy, and most commonly aluminum 6061 alloy. While aluminum is heavier and has a lower yield strength than carbon fiber, it is far more machinable. Carbon fiber is a composite material, meaning you have to shape it when you make the original shape, which often is a tube or a sheet. Aluminum, however, is easily machinable, allowing someone to purchase a billet or tube of the stock machine it to whatever shape they desire on a mill or lathe.

2.4 Drones in Weather Conditions (Snow)

As with all aircraft, weather can have a significant impact on the ability of a drone to fly. Operating a drone in snow and cold temperatures presents a particular set of challenges. Flying in below-freezing weather will have a significant impact on the life of a battery, which typically is designed for optimal performance around 20º C (68º F) ambient temperature. A number of drone manufacturers have looked to solve this problem through battery insulators or heaters onboard the drone (Martinez, 2019). The cold can also impact other equipment like cameras and electronics that do not operate well in low temperatures due to condensation on lenses and other components.

Another challenge weather can create when attempting to fly a drone in the winter is wind. In order to maximize payload capacity and minimize costs, most drones have been designed to be as light as possible. As a result, the drone is affected by wind speeds and is unable to be safely flown with precise control in even moderately windy conditions. One study involving a drone found that it couldn't be reliably flown in winds any faster than an average of 8 km/h (Weber & Knaus, 2017). Any drone that is going to be operated in the winter needs to either compensate for the wind, or only be used during favorable conditions.

Icing on the drone itself can be a serious hazard in the winter. Ice on the frame or propellers can significantly change the aerodynamics of the system or make it completely unable to fly. In order to combat icing, a drone should be stored indoors when not in use. The drone also needs to be visually inspected before and intermittently during flight, to ensure that no ice is building up (Dorr & Duquette, 2015). Choosing weather resistant materials will help prevent icing and generally help it hold up against harsh weather conditions.

2.5 Fluid Spraying

Drones have already been proven useful for spraying applications, most commonly for agricultural purposes. Tasks such as spraying of pesticide and fertilizer, are completed quickly and efficiently by drones, while limiting the exposure of humans to potentially harmful chemicals. Most applications for spraying drones other than agriculture are far more small scale or precise in nature. With a similar focus on human safety as agriculture, Hercules drones from DroneVolt are designed for spraying residential house roofs and other hard-to-reach or dangerous areas that need washing or some form of liquid treatment (Hercules 20, n.d.). The use of drones for painting 3D surfaces has also been explored, as has the deicing of wind turbines.

A variety of spraying strategies have already been employed for various different applications and industries. Many agricultural drones use multiple nozzles angled down, often attached below rotors. By attaching nozzles to the existing rotor arms, this configuration allows for more distributed spraying, while requiring less additional frame structure. The accuracy lost due to rotor wash interference is unimportant in agricultural applications due to the wide area coverage required in their efforts. Applications that require more accurate spraying, such as a painting drone, may favor a design with a fixture to extend the nozzle or nozzles outside of rotor wash to limit interference with accuracy.

Any drone which plans to spray liquid must compensate for the thrust generated during spraying, either by factoring the force into the control model, or with a robust control system design that can more generally compensate for such errors.

2.6 Spray Nozzle Design

The application of sprayed fluid is largely dependent on the geometry of the spray nozzle that the fluid is applied from. Each different shaped nozzle will produce a different pattern on the sprayed surface and optimizing this pattern can reduce time required for spraying (Sumner, n.d). These geometries can also affect the uniformity of the spray pattern, which if uneven may require reapplication. This factor, the "misting" of the sprayed fluid and particles spreading out past the intended nozzle geometry, is known as drift. Drift is a factor also influenced by the fluidics pump for the system. Reduction in drift can be achieved by ensuring the fluid pressure at the nozzle is what the nozzle is rated for, as pressures above or below can impact the drift of the fluid after exiting the nozzle.

The three typical nozzle varieties for commercial agriculture applications are flat-fan, even flat-fan, and cone (Sumner, n.d). For flat-fan nozzles, the recommended pressure is 20-30psi to reduce fluid particle drift, as the coarse particles begin to drift more at high or low pressures. Cone nozzles are more commonly used when particle drift is not an issue, or where the environment does not induce drift. These nozzles operate at higher pressures, compared to that of the flat-fans, at pressures of 40-80psi. Unlike the flat-fans, the particles tend to penetrate through layers of foliage or other non-rigid boundaries due to the smaller particle size (Sumner, n.d). Even flat-fans are similar in shape to the aforementioned flat-fan nozzles, however they provide an even distribution of application across the fan. The width of this band is determined by the nozzle height, and the advised pressures are between 20 and 30 psi to reduce drift. Cone nozzles do not necessarily guarantee spray uniformity so there are two different varieties: solid-cone and hollow-cone. Solid-cone nozzles will produce a uniform spray throughout the cone's distribution, while hollow-cone will concentrate on the perimeter of the cone's spray (Sumner, n.d). To ensure uniform spray pattern, regardless of the nozzle geometry, overlapping the outer edges of the individual nozzle sprays will result in better uniformity (Dorn, n.d).

2.7 Deicing

The most common application of commercial deicing is aircraft deicing, which is regulated by the Federal Aviation Administration (FAA). For this project, the drone needs to be able to remove snow, ice, and prevent further solidification of ice on car windshields, which is a problem the FAA deals with on aircraft. The FAA has regulated deicing and anti-icing fluids into four different categories depending on the chemical quality of the fluid: Types I to IV (Federal Aviation Administration, 2008). For most aircraft, removing ice is performed as a two-step process. The first step is deicing, which is the process of removing ice from a surface, followed by anti-icing, which is done to prevent more ice from forming. Anti-icing is generally the same chemical substance as deicing but has a higher active chemical concentration in the mixture. Deicing is accomplished by combining heated fluid and hydraulic force to remove a layer of ice off of surfaces (Wadel, 2016). In the case of aircrafts, separate deicing fluid and water tanks are used in order to vary the mixture concentration depending on the weather conditions with a valve. The deicing fluid and water tank lines are in direct contact to make the mixture.

There are a variety of solutions used for different methods in de-icing car's windshields. The substance used for deicing and anti-icing varies greatly between different industries and consumer-grade products. A mixture of glycol and water (either propylene or ethylene glycol) is used on airplanes in accordance with FAA regulations. A commercial solution sold by many automobile retailers is made up of a solution of methanol and water. A variety of different homemade solutions exist including vinegar and water, which is often used for anti-icing, and isopropyl (rubbing) alcohol and water used for deicing. Thickening agents are often added to the mixture to increase the viscosity to prevent shearing forces from the wind blowing the substance off the surface. Dish soap is often used as a thickening agent in homemade solutions. Homemade pretreatment solutions also exist, which are generally made of a solution of white vinegar and water, which helps prevent ice from forming in the first place (AAA Automotive, n.d.).

Some substances are superior in ice removal but could potentially be damaging to consumer's cars by weakening the protective layers and leaving the paint exposed. Thus, there are several additional considerations to consider when choosing the deicing medium. Hot water, or heating a homemade solution to too high of a temperature can potentially damage car windshields by cracking it from thermal shock. Pretreatments made up of vinegar, alcohol-based deicing solutions, and dishwashing soap can remove car wax and will leave the finish exposed to the environment, which could potentially damage the car.

2.7.1 Environmental Impacts of Deicing Fluids

The most well-studied, similar deicing solutions to analyze for environmental impact are aircraft deicing solutions. As with any unnatural mixture, most deicing solutions are relatively harmful to the environment, either by entering soil, mixing with water drainage, or evaporating into the atmosphere. That being said the glycol-based mixtures used on airplanes are by far the most harmful to the environment. Glycol based deicing fluids reduce dissolved oxygen levels in water, contaminate groundwater and surface drinking water, and can reduce, or completely eliminate, entire aquatic communities. Thus, areas with airports have a high concentration of these fluids in their stormwater drainage, and tend to send this drainage to wastewater treatment plants for processing due to the otherwise adverse effects these fluids would have on the surrounding environment (Environmental Protection Agency, 2012). Vinegar, methanol, and isopropyl alcohol are all solvents, and generally solvents are harmful to introduce to the environment. All three however, are considered to be among the more environmentally friendly solvents, with vinegar in particular being considered one of the least environmentally harmful of all solvents (Tobiszewski et al, 2017).

Chapter 3: Approach

The mission of this project is to design, manufacture, and implement a drone to aid in the removal of snow and ice off of cars. The project objectives are:

1. Analyze existing drones and applications, as well as conduct research on the operation and regulation of drones and snow removal methods.
2. Design the mechanical, electrical, and computer systems for a drone that is able to fly in mild winter weather conditions with a liquid payload of 4kg for removing snow and ice off of cars.
3. Test and evaluate the accuracy, repeatability, and precision of autonomously/teleoperated cleaning the two windshields of a car in a real environment.
4. Present a comprehensive design summary with a compelling vision for the future of drones aiding society, specifically focused on individual applications.
5. Suggest future Major Qualifying Projects, or iterations for this project.

3.1 Project Approach

The idea for this project came from a video of a drone deicing wind turbines, because they are generally difficult to clean. The team, along with the project advisors, believed that the application of using a drone to deice could be used for many other applications, including cleaning snow off of cars. The project has a positive societal impact by helping humans avoid potentially hazardous cold weather conditions, where oftentimes the everyday person could be putting themselves at risk of frostbite, hypothermia, and even cold- or stress-induced heart attacks. Driving with snow on a vehicle can be dangerous for other cars and will also result in fines for the driver. The project presents an opportunity for automation of an everyday, potentially dangerous task and can improve the lives of vehicle drivers during the winter by saving time, saving money, and reducing the risk of injury. This would especially be helpful for elderly people, people with injuries, and for those with impaired motor skills or other physical disabilities. It is also important to consider the approach towards other applications of this drone beyond just an individual's single car. Other applications for this project on a larger scale include car dealerships, rental car services, shipping truck fleets, and airlines. Investing in an autonomous system to clean these complex spaces would have significant economic benefits. The project could also be applied to clean snow off of houses (gutters, windows, roofs), schools, roads, and parks.

The general approach for this project was based on research on existing agriculture drones. Drones that spray pesticides for large fields of crops is a similar concept to a drone to clean snow off of cars, so the team based the overall look and design of this drone off agriculture drones. An aerial system was decided on over other types of vehicles due to the versatility that a drone provides. In the winter, a rover would have to maneuver over different levels of snow and ice, which could prove difficult. Conversely, an aerial drone is free to move around without restraint, provided that wind and other weather conditions have subsided. An aerial vehicle also does not require contact between itself and the car, preventing potential damage to the car. The drone also has six degrees of freedom, which allows for much more mobility compared to that of a ground robot with three.

The team has set concrete milestones to create a functional drone by the end of the project timeline. Varying performance metrics were developed as well as design specifications for electrical, mechanical, and software, in order to determine a successful project. In addition to metrics, the team created goals that were to be accomplished through the design. These goals can later be adjusted as the project is developed. The first goal was to, at minimum, clean ice and snow from the car's front windshield. The team decided on this task because the front windshield is the most important for drivers and the most time-consuming window to clear, and the team wanted this to be the primary focus to accomplish precisely before moving on to other sections of the car. Another design goal was to have the drone be relatively portable. Due to possible size and storage constraints for a consumer, the team wanted the drone to have a modular structure that could be more compact when stored. The team's final goal is focused on modular components. The intent was to design the drone assuming the maximum weight of the fluid tank and power supply.

The team developed a design process to follow for the development of the drone system for the purposes of this project. First, the team defines the problem: developing an easier way to automate cleaning snow and ice off of a car. After that, the team performs background research by conducting a literature review to learn more about how drones fly, what solutions currently exist for deicing, spraying mechanisms, drone regulations, and materials that can be used to make a drone. After the background research is completed, the team defines project specifications and requirements for a successful car-snow clearing drone, found in the later sections of this chapter. After the project criteria is decided, the team begins brainstorming and evaluating solutions for the core project problem. Based on the solutions, the team constantly iterates the design until it is feasible. From there, the team chooses a solution, develops a prototype, and tests the prototype. Based on the testing, necessary design changes are made, which leads to more testing. From there, the tested solution becomes the final product and the team communicates results via a presentation and written report. **Figure 1** below shows a visual of the approach.

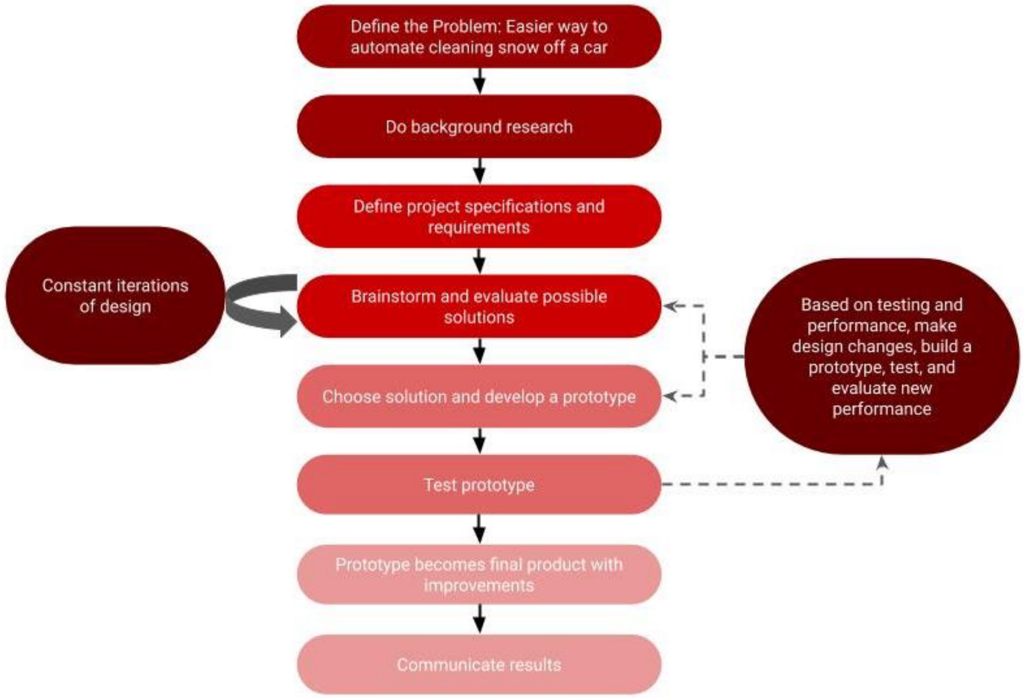


Figure 1. Approach Visual

A project deliverable schedule, in the form of a Gantt Chart, was created to keep the team on track to complete the project. At the conclusion of the first project term, the team performed and annotated background research, defined project specifications and requirements, wrote a project proposal for acceptance and developed an initial design as a solution to the defined project. By the end of B term, the team wanted to enter a functional prototyping stage where they chose a solution, wanted to develop a prototype, and tested it, and wanted to test spraying and flying in snow conditions. By the end of C term, the team finalized testing and turned the working prototype into the final design. In D term, the team finalized the drone assembly and testing, finished the written report, and presented the results.

3.2 Metrics

In order to assess the ability of the system to meet its stated goals, the team plans to measure the performance of the project with established metrics. These performance metrics will determine the success of the project overall, while the engineering design metrics will evaluate the actual design and construction of the system.

3.2.1 Performance Metrics

The most important performance metrics will be determining if the drone can perform operations as intended with consistency and accuracy. The performance metrics that have been determined are:

- Capable of fully clearing a minimum of two inches of snow and de-icing the front windshield of an average-sized sedan
- Drone is able to autonomously/semi-autonomously clear a car's front windshield
- Drone is able to operate in temperatures at and above -10°C (approximately 15°F)
- Drone is able to fly in wind speeds of up to 10m/s
- Drone is capable of carrying at least five liters (four kilograms) of spraying fluid as the payload
- Drone is able to fly for at least 15 minutes while carrying the full payload

3.2.2 Engineering Design Metrics

The team plans to use a set of pre-defined engineering design metrics to measure the robustness and effectiveness of the design. The engineering design metrics are as follows:

- No leaks in the fluid components
- No short-circuiting of electronic components, or overloading of ESCs/Motors, due to weather conditions
- Drone frame is structurally sound and does not deform when fully loaded, due to motor lift, or does not break, due to Von Mises stress
- Drone is able to hover in one position without drifting
- Drone is able to maneuver smoothly with a payload
- Ability to manually define the car's windshield using a four-point identification method

3.2.3 Project Requirements

This project is bound by both logistic and technical constraints from WPI that affect its design and fabrication components. This drone must be designed by the project team and fabricated using resources at WPI, such as 3D printers, laser cutters, and CNC machining. Constrained by time and money, the project has limited funding and must be completed by the end of the academic year. All design decisions made in this project must be backed by research through a literature review of existing technology. Additionally, to finalize the design of each drone component, significant prototyping must verify the design's feasibility.

3.3 Drone Design Process

In order to ensure that all the parts for the drone were compatible, a process was carried out to make sure all requirements for a drone that sprays are covered. When designing the drone, the main consideration was the payload or the amount of extra weight the drone had to carry. Therefore, the drone was designed around the idea of carrying a maximum of five kilograms, one of the team's metrics.

3.3.1 Mechanical Structure

In order to design and build a drone, criteria must be met to ensure that the drone performs the task effectively. When using a drone to spray deicing fluid on cars, the drone must be capable of lifting up a heavy payload. The payload consists of the deicing liquid, along with all the peripherals, required to fly, navigate, and spray deicing fluid. There are two options that can be used in order to lift a heavyweight with a drone: adding more rotors and motors onto the drone or increasing the size of the drone's propellers. Both of these options come with advantages and disadvantages. The advantage of having six or eight rotors is the presence of redundancy in the system, meaning the aircraft can successfully land in the case that one of the motors fails. In addition, drones designed to have more rotors allow for the propellers on each arm to be smaller in comparison and allow the user to have less powerful motors. The main disadvantages of a six or eight rotor drone, as compared to a four-rotor drone, are increased overall energy consumption and a greater number of parts that can fail. An X4 configuration drone would offer reduced energy consumption and fewer points of failure, but would require larger propellers, and more powerful motors, than a configuration with more rotors in order to create more thrust for lifting heavy objects. The system is more stable and reliable in an X4 configuration, but in the case that a rotor fails, the drone would also not be able to safely land. Therefore, flight dependent components are soldered together extremely well, and the primary components are inspected thoroughly prior to every flight. In addition, the team will ensure the drone will hover slightly above ground at the beginning of every flight to make sure all motors are operating properly before takeoff. The team wanted to design propeller guards but did not have the resources for such a large drone. After examining the advantages and disadvantages, an X4 configuration drone was chosen, not only because the snow-drone will not be lifting more than 20 pounds and will only be performing short missions within close proximity of the user, but also because it is most cost-effective based on the amount of funding available for this project. As seen in **Figure 2**, the basic frame design will be composed of a top and bottom center plate with four arms that will clamp into the center of the frame between the two plates. These plates also hold all the electronics of the drone. A third plate sits below the bottom plate, housing both the batteries. In order for the drone to carry the spraying gear and be able to take off and land, the landing gear is attached to the center frame, which creates an open space for the spraying gear to occupy between the landing gear. A plastic cover, vacuum formed out of ABS, will protect all the electronics and battery from the natural elements and will ensure the drone is professional and reusable. ABS has safe operating temperatures from -20°C to 80°C, which is lower than the -10°C that the drone is intended to operate in.

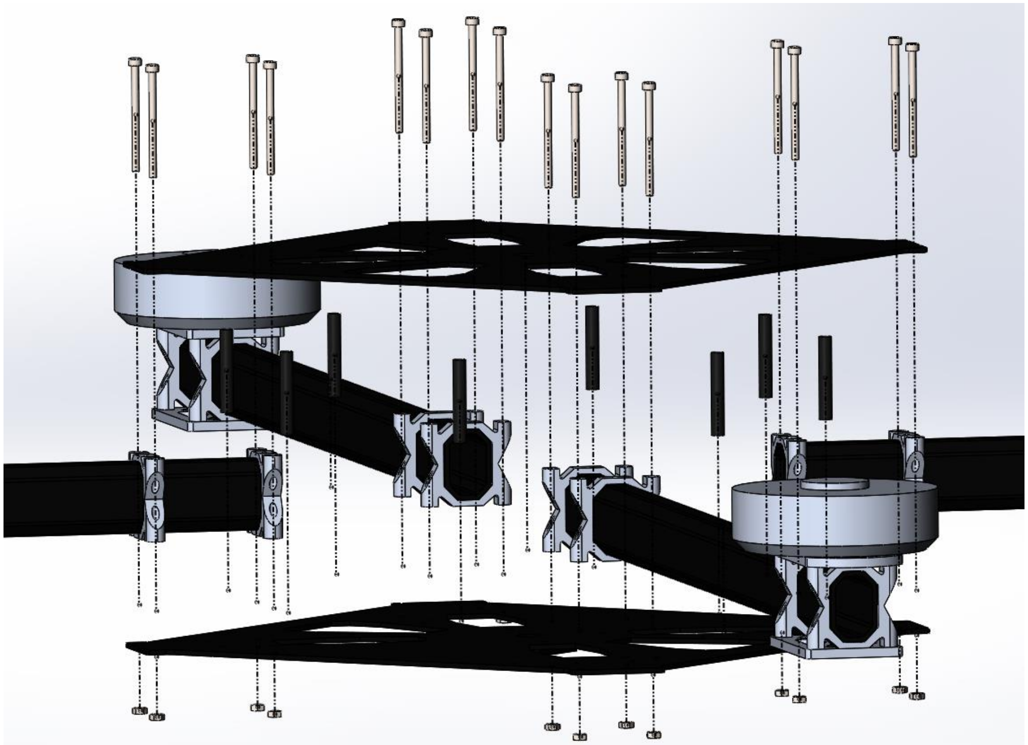


Figure 2. Exploded view of the center frame assembly and hardware

3.3.2 Part Selection

Drones must be designed to be as lightweight and durable as possible. To maximize both conditions, part and material selection becomes a crucial element of drone design. In order to lift a payload of 5000g with an X4 configuration, the team estimated the MTOW (maximum takeoff weight) of the aircraft by adding all the weights of all major parts of the drone, shown in figure two. Dividing the MTOW by four gives the amount of weight that each motor will need to lift at around 50% power. By focusing on each motor only using 50% power, a greater than 2:1 power to weight ratio is ensured to prioritize efficiency and add a factor of safety. After calculating the thrust each motor must produce, motor spec sheets are reviewed to find what motor will produce the desired thrust. Most drone motor manufacturers release test bench specifications of each of the motors they sell combined with different size propellers. To properly operate the motors on the drone simultaneously, an on-board flight controller is necessary. The flight controller should enable the drone to hover in place using a combination of sensors and GPS. Other peripherals found on the drone include an IR camera for detecting the snow/ice on the car and a sensor to detect deicing fluid levels.

3.3.2.1 Materials

The drone is mainly constructed out of carbon fiber and aluminum. The frame, which is composed of the three plates, the rotor arms, and the landing gear, are all 3D printed or stock carbon fiber that have been waterjet cut. Carbon fiber enables the aircraft to be lighter and more energy-efficient, while still being very strong and durable. 3D printed parts are fairly lightweight and are able to be rapidly manufactured. The hardware on the drone is all made of 6061 and 7075 aluminum, which also contributes to the drone being lightweight. 7075 aluminum has a density of 2.810 g/cm³, compared to steel, which has a density of 8.05 g/cm³, making it a lightweight structural metal. The fasteners, in particular, were specially ordered to be 7075 aluminum alloy in order for the drone to be as lightweight as possible. Fasteners are used throughout the assembly, so choosing aluminum screws, which are not commonly used, greatly helped reduce the overall weight. Having lightweight hardware allows the drone to cut weight from components that are necessary to have on the drone, while aluminum is still metal, steel is much heavier. The cover of the drone is made of vacuum-formed ABS plastic, which is waterproof and lightweight.

3.3.3 Fluid Selection

Based on background research performed by the team on the widely used fluids for de-icing applications and their environmental impacts (refer to **2.7 Deicing**), the team is using a mixture of isopropyl alcohol and water in the final drone solution. Based on research, isopropyl alcohol is an easy at-home solution that is recommended by AAA to be effective at cleaning snow and ice off of car's windshields and has a relatively low environmental impact. Although this is the solution the team is using, alternative solutions should be explored with extensive testing.

3.3.4 Software Functionality and Architecture

Software on the drone will provide four main functionalities to support its mechanical and electrical features: controls, spray & fluid management, navigation, and computer vision. The below categories can be implemented as classes, with key functionalities as functions or sets of functions for each class. They can be combined together into a state machine that methodically and automatically controls the drone in its snow-clearing efforts from start-up and take-off to landing and shut-down. In **3.3.4.5 High-Level Workflow**, architecture and functionality are visually represented.

3.3.4.1 Controls

Controls will allow the drone to adjust for outside forces through the management of how the drone moves. The controls functionality will focus on two main aspects: maintaining constant position and the ability to move at constant speeds along any or all axes. These control algorithms will allow the drone to reliably move in predictable patterns and adapt to changing conditions to ensure proper coverage when spraying.

3.3.4.2 Spray & Fluid Management

Key functionalities necessary for the drone to properly spray a car and manage its fluid reserves are digital control of both on and off functionality, as well as spraying pressure will allow for efficient snow and ice removal by spraying. Additionally, monitoring of fluid reserves will allow the drone operator to be notified when the drone requires a refill, therefore, ensuring that the drone does not attempt an operation that it cannot complete due to lack of fluid.

3.3.4.3 Navigation

While motion is directly determined by controls, navigation feeds instructions to the control system, and together, they move the drone to where it needs to go. Navigation is responsible for two main functionalities: location and pathing. The drone must be able to keep track of its location relative to important landmarks such as its initial takeoff point, the target car, and any relevant obstacles to avoid. Additionally, the drone must be able to generate efficient paths that get the drone between destinations and provide comprehensive spraying coverage of the target car, all while maximizing the precision of drone motion.

3.3.4.4 Computer Vision

Just as controls account for variation in motion, computer vision allows the drone to account for variation in the environment. Computer vision will provide three main functionalities: snow detection, car location verification, and obstacle detection. Snow detection, using infrared images, will inform the drone of its progress, as well as parts of the car it needs to return to in order to complete its snow-clearing operation. Car location verification checks that corners of the target car are where the drone expects them to be, updating navigation with both the car's orientation as well as confirmation or adjustment of the car's stored location.

3.3.4.5 High-Level Workflow

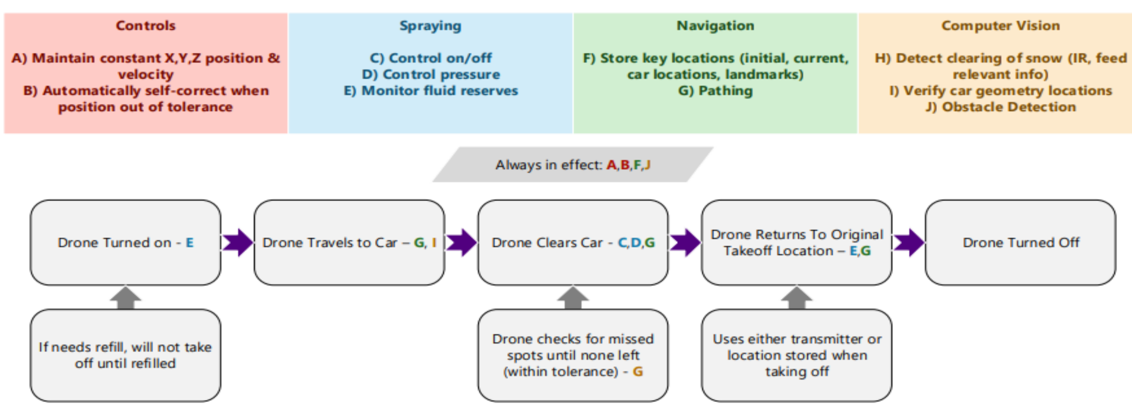


Figure 3. High-Level Workflow

Chapter 4: Design

Throughout B term, the team focused their efforts on designing the mechanical, electrical, and software components of a drone to de-ice and clear snow off of cars. The overall design can be viewed in **Figure 4** below. In the rest of this section, each of the individual components will be explored in more detail and explained how they contribute to the overall assembly.

Figure 4. Overall Drone Design

4.1 Design Specifications

Based on the team's background research, project mission, objectives, and approach, the team decided to build an X-4 configuration drone. The X-4 configuration was chosen because having only 4 motors simplifies the design/build process, is cheaper to build and consumes less energy than hexa/octocopters leading to longer flight times. Approximate weight calculations were performed on parts selected in order to determine the necessary motor and propeller size. The team determined a 28-inch propeller, and thus a 1200mm size drone (diagonal motor to motor distance), is required based on the weight calculations affected by the mechanical and electrical components. The team assumed a 5000g payload, equating to approximately 5 liters of de-icing fluid based on the weight of water, and designed the drone, based on this weight.

4.1.1 Drone Weight Specifications and Motor/Propeller Selection

It is vital to pick out the correct motor and propeller combination when building a drone to ensure the drone will safely hover, navigate, and perform its desired tasks with a payload. An important measure to follow when picking out the correct motor and propeller combination is to make sure the drone has a 2:1 power to weight ratio. This factor of safety will ensure that the drone can safely operate in situations where the drone is not using maximum power. **Table 1** below contains all the parts of the drone and their respective weights in grams.

Table 1. Component Weight and MTOW Calculation

Component	Weight (grams)	Weight (lb)		
Battery (22,000 mAh)	2696	5.944		
Motors (x4)	1108	2.443		
ESC (x4)	292	0.644		
Propeller (x4)	240	0.529		
Flight Controller + Cables	100	0.220		
FPV Gear	50	0.110		
RC Receiver	20	0.044		
Frame	2000	4.409		
Tank	670	1.477	**Payload (grams)**	4317.96
Fluid (1 gallon, 5 L)	3782.96	8.340	**Total (without battery) (grams)**	3810
Pump	285	0.628	**Total (grams)**	11493.96
Nozzles + Beam + Tubes	250	0.551	**Total (lb)**	25.34

Since the Maximum Takeoff Weight (MTOW) of the drone is 11494g (25.34 lb), the drone should be able to lift that amount at ~50% power, ensuring a 2:1 power to weight factor of safety. To get the amount of thrust each motor is responsible for, the MTOW is divided by four. Therefore, each one of the four motors of the drone is responsible for carrying 2873.5g (6.34 lb). From this, the team looked at specification sheets to identify what motor would produce around 2800g of thrust at 50% power. The team selected the T-Motor UII 190KV brushless motor with a T-Motor carbon fiber 711.2mm x 233.68mm (28in x 9.2in) propeller. This motor and propeller combination has an upward thrust of ~2800g at around 55% throttle at an efficiency of 11.5 g/W.

4.1.2 Drone Flight Data

Using eCalc's online electric motor calculator, the team calculated predictive flight data based on the drone's motors, propellers, ESCs, battery, and weight. In order to calculate these predictive numbers, a user must input all major components of the desired drone into the calculator for it to calculate the flight data. The table below shows some metrics from the four conditions analyzed. One measure that is calculated on eCalc is estimated flight time, **Table 2** shows that at MTOW (Drone & five liters of Fluid) the drone will fly a total of 16 minutes. When carrying only half a tank of fluid the drone gets an additional four minutes of flight time. Once the team begins testing the amount of fluid actually needed to clean a minimum of two inches of snow off of a car, the team will determine the actual flight time based on this actual data. Additionally, these flight times will change depending on the weight of the fluid being carried, and as the drone sprays the fluid, there will be less weight onboard thus increasing possible flight time.

Table 2. Estimated Flight Data Gathered Using eCalc

	No Payload	Empty Tank	2.5 Liter of Fluid (Half Tank)	5 Liter of Fluid (MTOW)
Flight Time (min)	39	25	20	16
Electric Power (W)	1057	1057.9	1057.9	1,057.90
Case Temperature (^{0}C)	85	85	85	85
Thrust-Weight Ratio (N/N)	3.5	2.6	2.2	1.9

4.2 Mechanical Design

A structurally sound mechanical design is imperative for the success of this project. If any mechanical component fails, the drone will fail at performing the project objective. It was important to take a number of considerations into account when designing the drone, including the operating temperature, mechanical stress and strain, forces caused from lift, and vibrations, among many other considerations. This section will explore the mechanical design and part selection of the key components.

4.2.1 Frame

The drone consists of a central control system compartment, four rotor arms, and two main landing gear legs. The center compartment contains two areas to mount the control system electronics, such as the flight controller. Electronics that are sensitive to vibration will sit on standoffs with rubber feet in order to dampen vibration. There are two main plates in the center, each holding key electronics for the function of the drone. These two plates are protected by a cover that will be vacuum formed from the negative of the center frame. Under the two plates is a battery plate, which supports the heavy battery of the drone, which is attached via two carbon fiber rods and rubber washers so that it is easy to remove if needed.

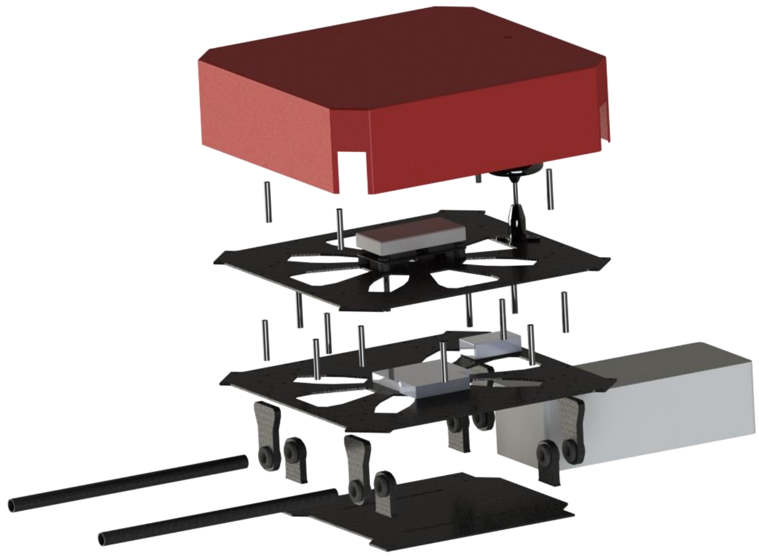


Figure 5. SolidWorks model of drone's center frame assembly

The drone's landing gear is made of four carbon fiber circular rods that are attached in pairs at the base by a horizontal beam and attached to the center plate of the drone. The connecting brackets are 3D printed from ABS plastic in halves to fit around the rods and tightened by using a set of screws and bolts. The legs are angled outward at 100 degrees relative to the horizontal and have a wider base. This wide base helps centralize the center of mass and assists when the done is not perfectly balanced when coming down for landing. A wider base increases the probability that the drone will not tip when landing by offering greater stability and strength to support the drone.

Figure 6. SolidWorks model of drone's landing gear assembly

4.2.2 Spray System

In order to melt the snow and ice off of the windshield of the car, a deicing fluid is sprayed from the drone onto the car. There are a variety of different chemical mixtures, discussed earlier in the report, that can be used for this purpose. All potential options involve mixing a different chemical with water to lower the mixture's freezing point. For this application, the system uses isopropyl alcohol and water mixture for removing snow and de-icing.

The system used on the drone is largely modeled after similar systems used on agriculture drones that are used to spray fields. The drone holds a tank made of lightweight high-density polyethylene mounted underneath the center compartment that stores all of the fluid needed for de-icing. The tank has a 5-Liter capacity, as this is the smallest volume tank of this type that is commercially available. While large, the tank will never need to be filled with more than one four liters (80% capacity) in order to complete a task. The tank features an upward-facing inlet and downward-facing outlet so that it can be easily refilled without disassembly of the system.

Fluid is gravity-fed to the bottom of the tank where it is pumped into the spray line with an onboard 24V brushless motor diaphragm pump. The pump will be fastened to the bottom of the tank and will push liquid through the spray line. The spray line consists of 8mm soft PVC tubing that runs to three separate nozzles mounted along a spray bar. This spray bar is actuated by servo-driven poly-cord pulleys that drive the spray bar. Both the rotating spray bar and multiple nozzle features were selected to allow for maximum coverage of the car windshield to be achieved without needing extreme precision in-flight control of the drone. A servo was chosen because the rotating spray bar does not need to rotate across an angle of more than approximately 60 degrees. The spraying mechanism can rotate on the pitch axis of the drone, while the drone itself can rotate in the yaw direction, which allows the spray bar to have two degrees of freedom.

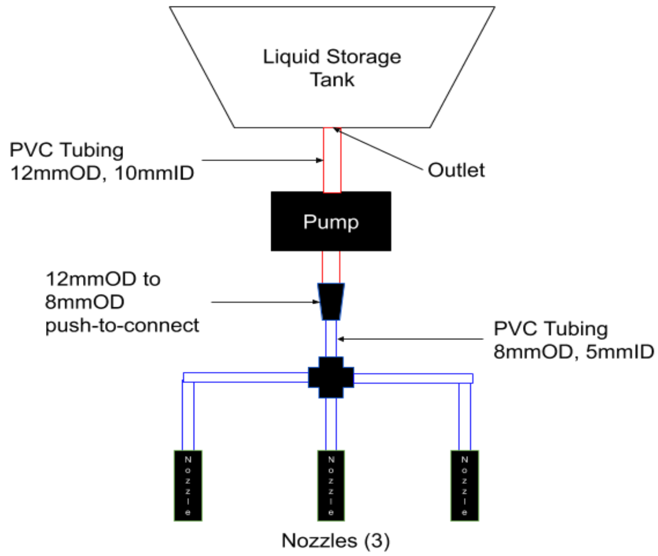


Figure 7. Fluidics Diagram

The fluidic tank, pump, nozzles, and connectors purchased for this project were specifically designed for agricultural drones that spray a high volume of fluid. The pump has a flow rate of 5.5 liters per minute at a pressure of 276 psi within the tubing. Each individual nozzle has a flow rate of 0.6 liters per minute over a flat-fan (110 degrees) spray pattern. The fan pattern will allow the liquid to be prayed across a width of 2.1 meters. This will provide adequate coverage as the average width of a car windshield is just under 2 meters. The following diagram in **Figure 7** depicts how the fluidic components interact in the system, and **Figure 8** shows a detailed view of the system flow in CAD. The latter diagram below, **Figure 9**, shows the two degrees of freedom that the spraying mechanism has: pitch, from the spray-bar servo actuation, and yaw, from the drone's orientation rotating about its center axis.

Figure 8. SolidWorks view of the spray-bar system

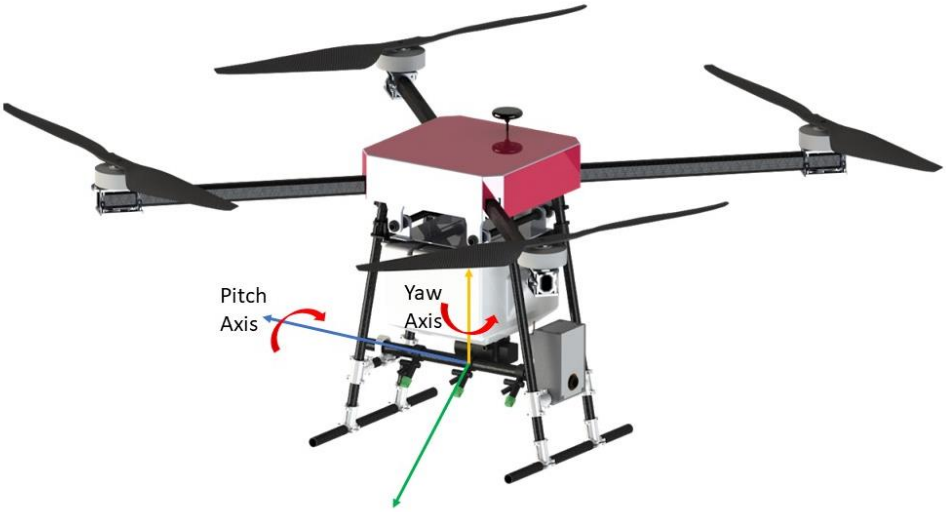


Figure 9. Degrees of Freedom for the Spraying Mechanism

4.2.3 Rotor Arms

The length of the rotor arm is dependent on the swept diameter of the propellers. Due to the larger 28” (711mm) overall diameter of this drone propellers, each rotor arm is approximately 400mm long, with 50mm of this length constrained to the center frame assembly in order to prevent deflection from the thrust force. These arms are designed using commercially available, rectangular carbon fiber tubes. Carbon fiber was chosen so that the rotor arms were lightweight yet rigid and strong. To ensure that the chosen materials and the design of the collars fixturing the arms to the center frame would perform as intended, the project team utilized SolidWorks Simulations to perform static analyses as well as simplified hand calculations. With a force of 67N of thrust from the rotor at the end of the arm, the SolidWorks simulation demonstrates that the maximum deformation, shown in green, is 0.45mm (shown in **Figure 10**). A force of 67 Newtons was chosen because each motor and propeller combination produce a maximum thrust of 6761 grams, which is equivalent to 67 Newtons. The team used a simple free body diagram (FBD) model to check if the SolidWorks simulation was valid, and this model is shown in **Figure 11**. The results of this model tell the project team that while the numeric value for the deflection is not identical to the value from the FEA, the magnitude is the same. The team recognizes that the FBD model is not perfect; the thrust force from the propellers is not a point load, but a distributed force through the motor mount plates, and the FBD neglects to account for the rotor assembly with the motors, propellers, and motor mounts. However, the simplified model from the FBD yields a deflection value that has the same magnitude of the deformation, which is sufficient as a check to the simulation. This amount of deformation from both calculations is minimal, thus removing concerns on the rotor arms being deformation limited.

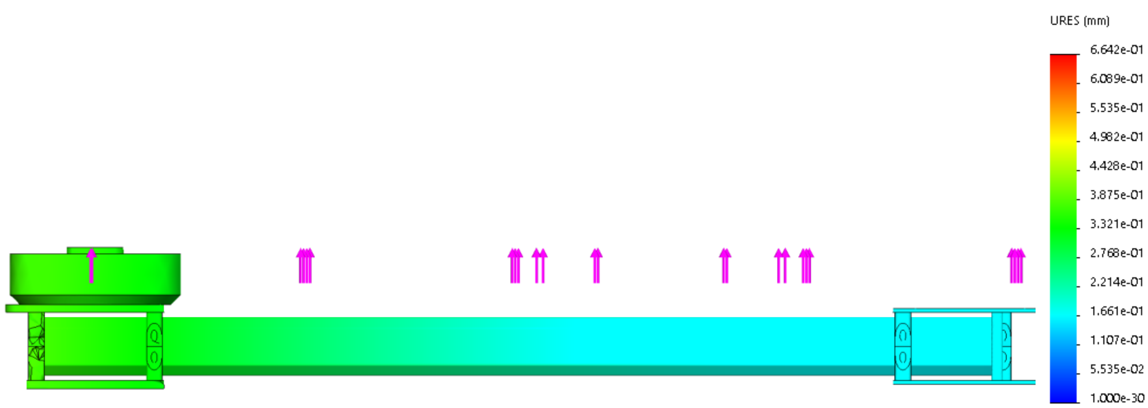


Figure 10. SolidWorks deformation analysis of a rotor arm [left] unit scale [right]

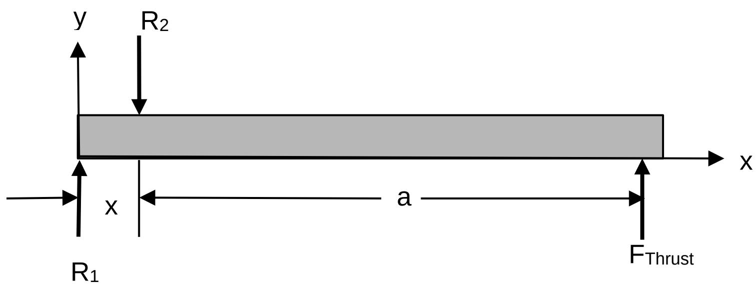


Figure 11. FBD model of the rotor arm

Equation 1. Deflection calculation for a rotor arm

$$F = 66N$$

$$a = 0.462m$$

$$E = 228GPa$$

$$I = 2*10^{-5}kg.m^2$$

$$\delta = \frac{Fa^3}{3EI} = \frac{(66N)(0.462m)^3}{3(228GPa)(2e-5kg.m^2)} = 0.475mm$$

Similarly, examining the results of the simulation checking for stress on the system, the maximum von Mises stress level does not surpass approximately 5MPa, shown in **Figure 12** in green/yellow, meaning the carbon fiber bar will not fracture due to the reaction force from the rotor. The carbon fiber chosen has an approximate ultimate strength of 3.5 GPa, a level of strength magnitudes higher than the stresses the arms will ever endure during normal operation.

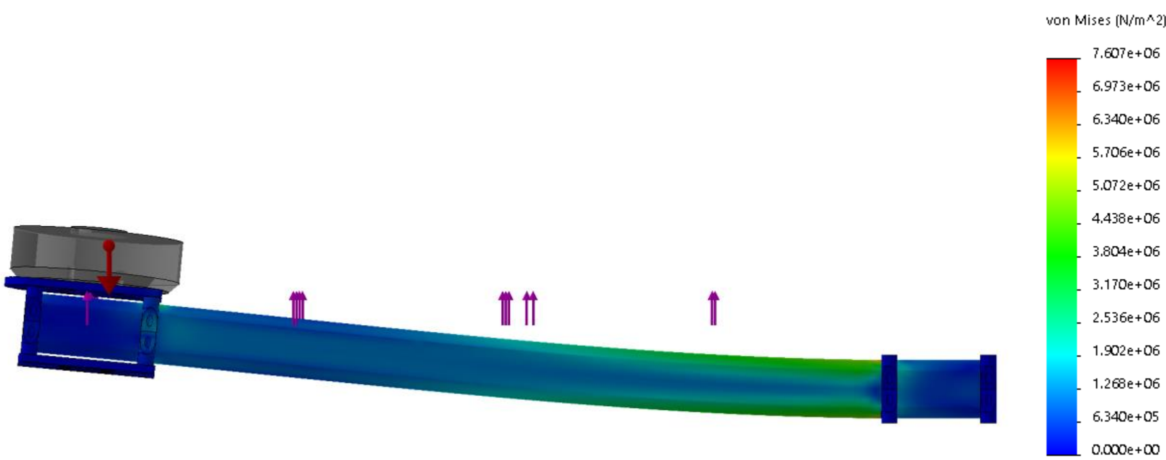


Figure 12. SolidWorks stress analysis of a rotor arm [left] unit scale [right]

The results of both SolidWorks simulations confirmed to the project team that the proposed design for the rotor arms, along with the design of the fixturing collars and the spacing between them was suitable for this application. Additionally, the team expanded this simulation of the rotor arm, to examine the center frame assembly of the drone with all four rotor arms attached with the same thrust force applied from all four propellers. This simulation allowed the team to examine the stresses and strains on the brackets used to mount the rotor arms to the two center frame plates, as the failure of these brackets would be disastrous to continual use of the drone system. However, even with a factor of safety of 1.5 or 2, based on most commercial standards, the simulated stress is far below the threshold for component failure. The results shown in **Figure 13** and **Figure 14** demonstrate that in the benchtop SolidWorks simulation, the brackets do not show questionable stresses and strains, and are within reason for the selected aluminum alloy they are machined from.

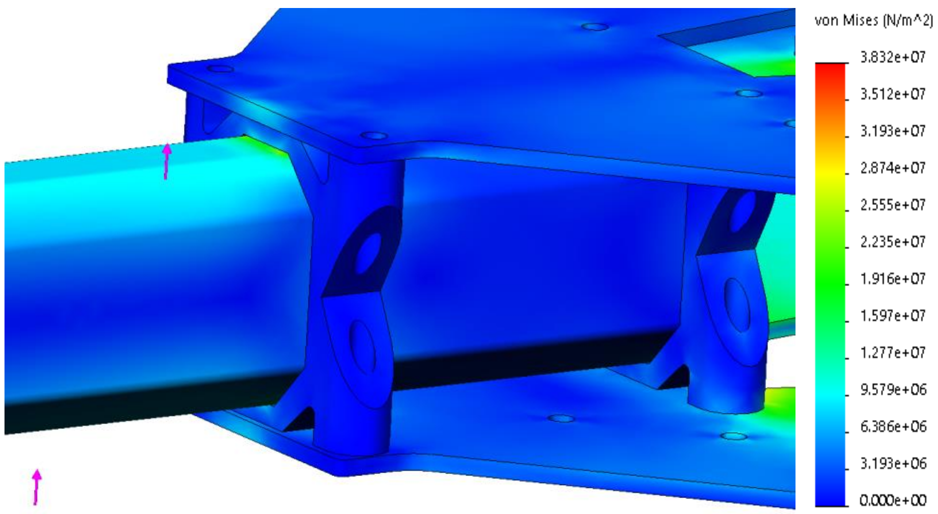


Figure 13. SolidWorks stress analysis of the center frame brackets [left] unit scale [right]

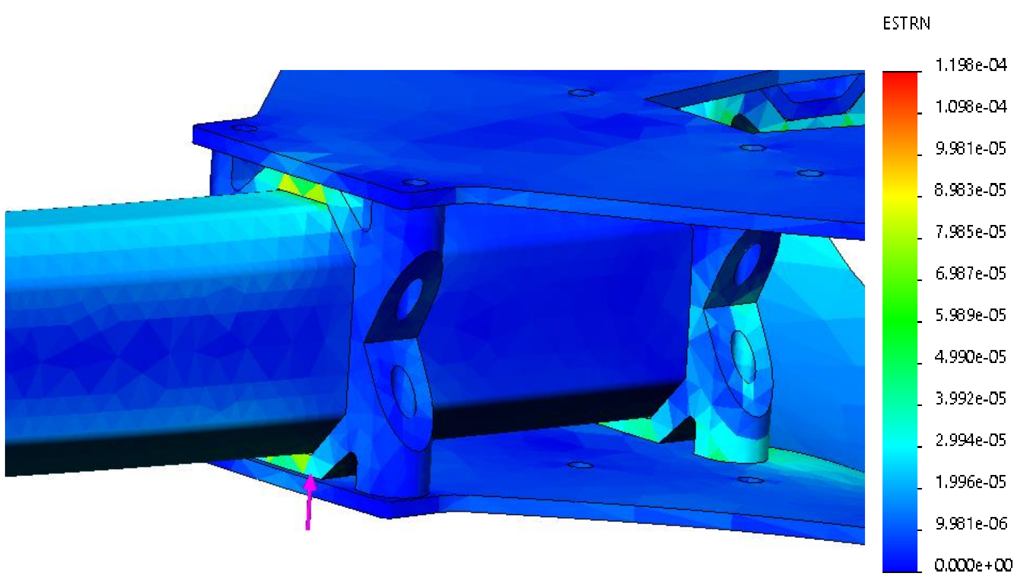
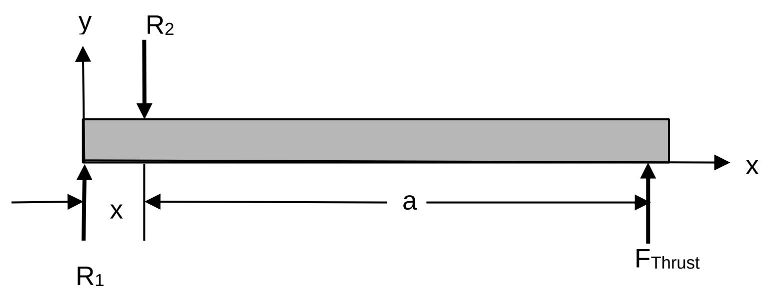


Figure 14. SolidWorks strain analysis of the center frame brackets [left] unit scale [right]

Similarly to the deflection calculations the team performed to verify the FEA simulation, the project team made a simple model and calculated the resultant forces that each of the rotor arm brackets should be experiencing due to the external thrust force from the propeller at the end of the arm. This model was shown in **Figure 11** and restated below, as well as the calculations used to analyze the resultant forces R_1 and R_2 in **Equation 2**.

Figure 11. FBD model of the rotor arm



Equation 2. Resultant forces calculations for rotor arm mounting brackets

$$F_T = 66N$$

$$a = 0.462m$$

$$x = 0.051m$$

$$[1]\ \Sigma F_y = F_T - R_1 - R_2 = 0$$

$$[2]\ \Sigma M_y = R_2(x) + F_T(a) = 0$$

$$from\ [2] \rightarrow R_2(0.051m) + 66N(0.462m) = 0 \rightarrow \boldsymbol{R_2 = -597.9N}$$

$$from\ [1] \rightarrow 66N - R_1 + 597.9N \rightarrow \boldsymbol{R_1 = 531.9N}$$

The team additionally needed to confirm that these resultant forces were not excessive and would not be beyond the ultimate strength of the bolts chosen to hold the rotor arms onto the center frame. The team took the 16.69mm^2 surface area that one bolt has on the carbon fiber center frame plates, and divided it by each resultant force to calculate the distributed force along that surface area and compared it to the ultimate strength of the zinc-plated steel the bolts were comprised of, these calculations are seen in **Equation 3** below. The steel has an ultimate strength of 1172Mpa or 1172N/mm^2, which is far above the resultant distributed force of 31.86 N/mm^2 and 35.82N/mm^2 respectively for R_1 and R_2 confirming that the bolts will not become uncompromised during flight. These values give an additional safety factor of 2.0 as well, seeing as the simplified model in **Equation 2** is symmetric, and all values are calculated for one side, and these values would be split across both screws in each location.

Equation 3. Calculations for distributed force on center frame bolts

$$A = \pi r^2$$

$$A = \pi(2.75^2 - 1.5^2)$$

$$A = 16.69\ mm^2$$

$$R1 = \frac{531.9\ N}{16.69\ mm^2}\ ; R1 = 31.86\ N/mm^2$$

$$R2 = \frac{597.9\ N}{16.69\ mm^2}\ ; R2 = 35.82\ N/mm^2$$

$$U_T = 1172\ MPa = 1172\ N/mm^2$$

One of the byproducts of this rectangular arm geometry is the need for custom designed and manufactured motor mounts. Using the technical specifications for the selected motors, the team decided to utilize a compression driven design for the motor mount assembly. The motor mount assembly, as seen in **Figure 15**, is reducible to two machined plates that have reliefs that fit onto the top and bottom of the carbon fiber extrusion. The top plate has countersunk holes to mount the motor onto, and the bottom has another set of countersunk holes to thread the two pieces together. The benefit of this design is that it is easy to both manufacture and assemble.

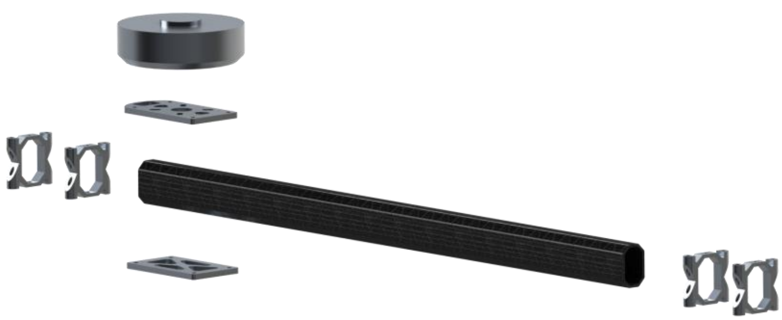


Figure 15. SolidWorks model of the rotor arm assembly

4.2.4 Custom Part Fabrication

Although there are a number of parts that will be purchased for this project, there is still a large number of custom-engineered parts that will need to be fabricated at WPI. The table below, **Table 3**, outlines each of the components that will be fabricated. A bill of materials for the physical parts in the assembly can be viewed in **Appendix B. Drone Component Bill of Materials** and a bill of materials for all electronic components purchased by the team can be viewed in **Appendix C. Assembly Bill of Materials**.

Table 3. Parts and Manufacturing Method

Subtractive Manufacturing	Additive Manufacturing	Other
Motor Mounts (from Aluminum 6061)	Landing Gear Brackets and Tank Mounts	Electronics Cover (vacuum formed)
Carbon Fiber Center Frame, Anti-Vibration Mounts (waterjet)	Spray Bar Servo Assembly	

An isometric view of the final mechanical assembly of the drone without the cover is presented in **Figure 16** below. In summary, the drone has an approximate motor-to-motor diagonal distance of 45" (1150mm) with a square top-down side length of 32" (814mm) as seen in **Figure 17** below.

Figure 16. Isometric Top View (without cover)

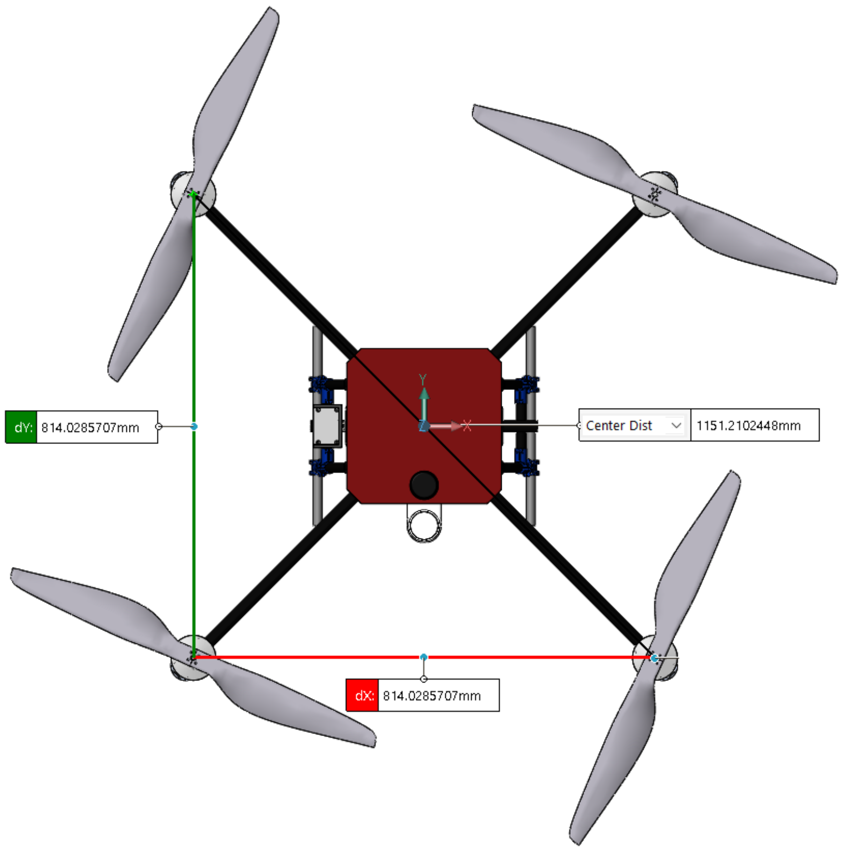


Figure 17. Drone dimensions from a top-down view

4.3 Electrical Design

The drone will carry a number of sensors on board that will help it autonomously navigate to and clear snow and ice from vehicles.

4.3.1 Flight Controller Sensors

The primary sensor used for navigation is a GPS receiver that will be able to determine the drone's latitude and longitude. The Holybro Pixhawk GPS module uses a Ublox Neo-m8n which has accuracy of approximately 2.5m (Kikutis et al., 2017). The drone's location can be compared to the known location of the car found on the map plug in on QGroundControl to inform the control system about which direction it should be headed in, or if it has arrived at the desired location. Additionally, the flight controller is equipped with multiple accelerometers and gyroscopes, enabling determination of the drone's orientation throughout flight.

4.3.2 Peripheral Sensors

One sensor used onboard the drone will be an infrared (IR) camera to detect thermal differences between the spraying fluid, the car, and snow. This camera is capable of detecting temperatures from as low as -40°C to as high as 300°C. The MLX90640 thermal Camera breakout is calibrated by the manufacturer to be precise enough to detect a temperature difference of as little as 1°C. Combining a thermal camera with computer vision capabilities will allow the drone to detect where it has been sprayed and where it has not, as the liquid coming from the drone will be warmer than the snow and ice around that it is trying to move. The car windshield will remain at a temperature above freezing for a longer period of time if clear of snow, allowing for verification of how clear of snow the windshield is.

A stereo camera mounted with servo control to rotate about the pitch will provide depth information. Using this depth information, cars can be differentiated from the surrounding environment through their unique contours, even with snow on them, and the drone can be localized relative to its target car on a more precise level than GPS can provide. This information can further be used to provide locational context to readings from the above-mentioned IR camera to allow for the determination of locations where snow patches still remain.

4.3.3 Electronics Parts and Wiring

To drive all four motors the drone is equipped with four [HOBBYWING XRotor PRO 50A ESCs] rated for six cell batteries. The drone has a [HolyBro Pixhawk 4] flight controller, which enables the drone to hover in place using GPS and fly semi-autonomously (waypoint coordinate navigation). The entire drone is powered by a 22.2V 25C 6S 22000mAh battery which provides power to not only the propulsion and flight control system but the spraying mechanism as well. When flown manually the drone is controlled by FrSky's Taranis x9d Plus which communicates with the onboard FrSky L9R receiver.

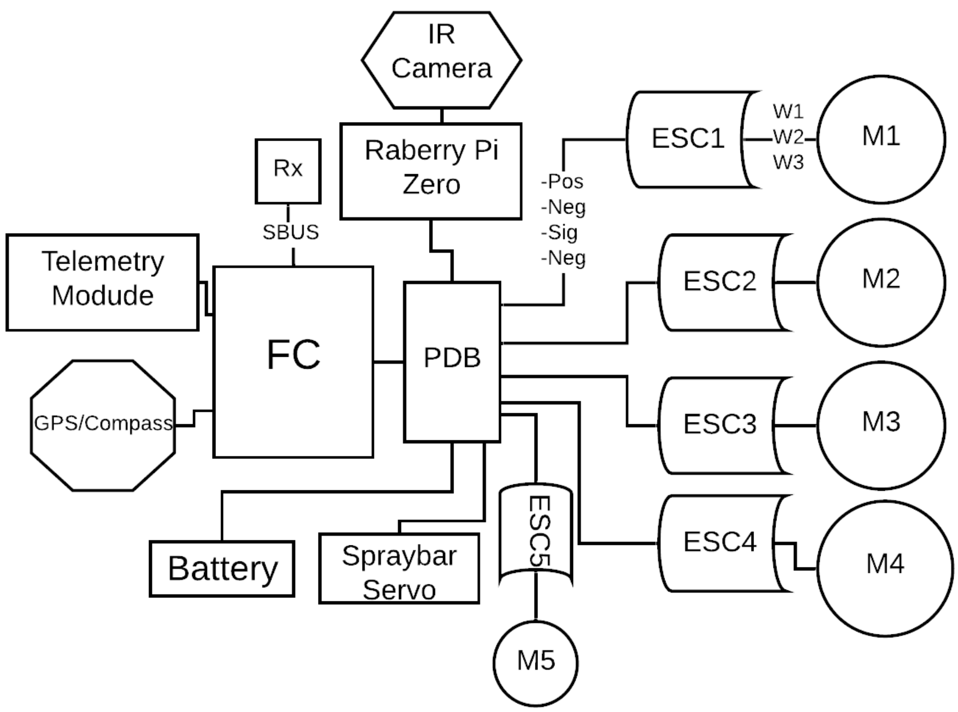


Figure 18. Drone Wiring Diagram

4.4 Software Design

With all of the sensors and electronics onboard, controlling a drone can be complicated. However, the selected Pixhawk flight controller was designed specifically to support an open-source autopilot software created by ArduPilot called ArduCopter. ArduCopter particularly specializes in controlled flight when given spatial positioning instructions, including both controls of specific destination locations and flight speeds. ArduPilot's Mission Planner simplifies flight plan creation, with an interface designed for selecting GPS-based waypoints and altitudes. ArduPilot's "Software In The Loop Simulator" enabled realistic testing, simulating parameters including wind conditions, drone battery state, and GPS positioning.

4.4.1 Precision Localization

While the aforementioned software packages enable larger-scale navigation, GPS does not provide the detailed and relative localization necessary for accurately spraying a car. As mentioned above in section 4.3.2, the mounted stereo camera compensates for GPS inaccuracy when fine-tuning the drone's current location. Frame transforms and known drone geometries enable conversion of depth readings to useful relative positioning for both the drone in general and specific cameras on the drone, allowing the drone to more precisely spray only remaining snow on its target car.

4.4.2 Computer Vision

Computer vision is the digital analysis of images and their patterns to extract useful information from said images and patterns. Often used to detect objects or features, determine information from detected objects or features, or filter out unimportant portions of images, computer vision provides invaluable information that allows the drone to compensate for differences between an expected environment and reality. Some of the computer vision techniques employed to localize the drone include edge detection and feature matching, examples of which can be seen in **Figure 19** and **Figure 20** respectively.

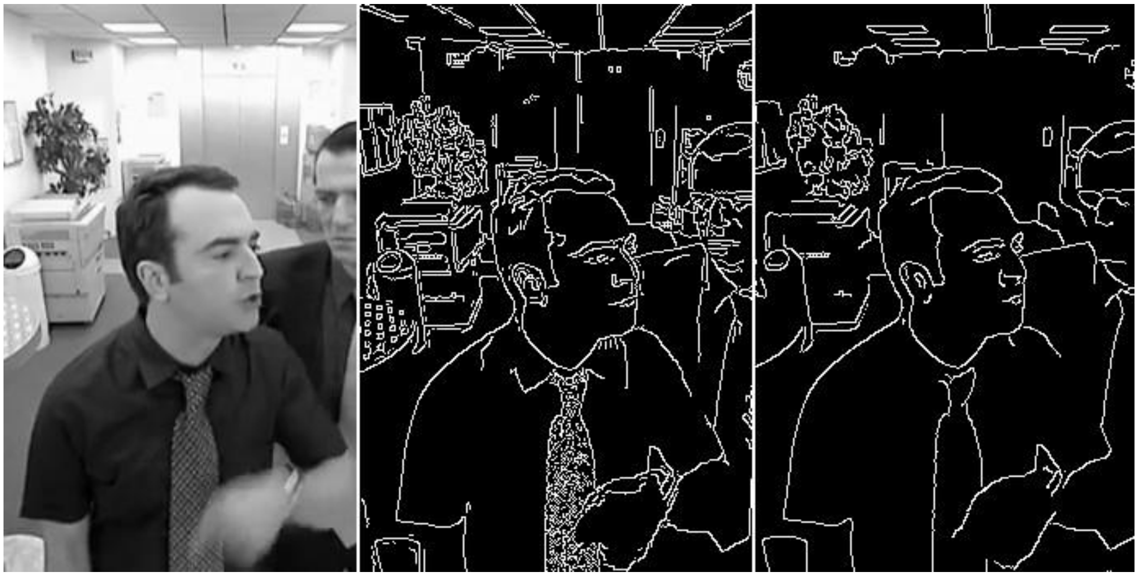


Figure 19. Edge detection example (left) from "Edge Detection in Opencv 4.0, A 15 Minutes Tutorial",
https://www.sicara.ai/blog/2019-03-12-edge-detection-in-opencv.

Edge detection will allow for identifying different regions in IR images, in order to provide the drone with information about regions of the car that are significantly warmer than other regions, denoting regions that have been cleared of snow.

Figure 20. Feature matching example (right) from "OpenCV: Feature Matching",
https://docs.opencv.org/3.4/dc/dc3/tutorial_py_matcher.html

Feature matching allows for recognizing data patterns such as shapes of a car wheel or the angle of a windshield, which can be combined together to enable car identification and orientation.

Images and video captured by the IR camera are analyzed using OpenCV to detect where snow is on the windshield. Images are first thresholded by temperature to create a binarized image that highlights a region of interest. The binarized images are then modified through processes called opening and closing. Opening is a process in which the whites region of a binary image is shrunk then expanded, and is often used to remove noise in an image. Closing is a process in which the white regions of a binary image are expanded then shrunk, and is often used to fill small gaps in the white regions of a binary image. Once cleaned of noise and gaps in objects, the centroid (center of mass) associated with each distinct shape in the binarized image is identified to enable identification of every distinct remaining patch of snow. These centroids are then classified as either in range to be sprayed by the drone or out of range, thus requiring the drone to move either forward or backward to clear them.

Chapter 5: Results

This section of the report details the results the project team has demonstrated through the academic D-term in April 2020. It covers the roadblocks faced by the team in regard to part acquisition and faulty electronics, as well as the mechanical, electrical, and software testing and functionality exhibited by the drone.

5.1 Preliminary Roadblocks

5.1.1 COVID-19 Pandemic

Nearly every engineering project encounters unexpected difficulties, and many of these projects must adjust to compensate for these unforeseen circumstances. The largest challenge this project faced as it neared its conclusion was a global pandemic. Coronavirus disease, often abbreviated as COVID-19, is a highly infectious respiratory disease whose outbreak began in Wuhan, China in December 2019 (Kolifarhood et al, 2020). The outbreak spread to become a global pandemic in the following months, causing the closing of all except for the most essential businesses in most regions worldwide. Most or all United States colleges and universities, including WPI, changed all in-person classes to be online and mandated that, barring extenuating circumstances, all students, faculty, and staff must leave campus.

The main effects of the COVID-19 pandemic on this project manifested as limitation or prevention of part acquisition, facility access, and team centralization. Even before the United States government and WPI administration began to take preventative measures, the team was beginning to feel the effects of COVID-19. Necessary parts sourced from China were delayed due to temporary and indefinite business closings that resulted in halting of manufacturing and shipping operations. The team had prepared to spend the first few weeks of D-term on finishing drone assembly and testing. Instead, the team barely had enough time and opportunity to remove the partially assembled drone and all relevant parts from the MQP lab before all WPI facilities were closed. With the team scattered across the country, only one member able to work on the physical drone, and no access to manufacturing or testing facilities for the remainder of the project, the team was forced to reassess project goals and pivot their focus. Extensive testing of the drone was no longer feasible, and the team redirected much of their focus towards analysis, simulation, ideation for future work, and getting the drone off the ground for its maiden flight. The rest of this paper (starting in **Chapter 5: Results**) is a reflection of the effects of the coronavirus and the work the team was able to accomplish with the extenuating circumstances.

5.1.2 Part Acquisition

One of the most substantial challenges that the team encountered was part acquisition. Due to a limited budget and the desire to make the drone as lightweight as possible, the team made critical design decisions to purchase a number of the components from suppliers in China.

While items from these suppliers overseas were often less expensive than local suppliers, a number of the parts had long lead times of approximately two weeks to one month. As mentioned, the team chose to purchase as many parts in carbon fiber as possible to minimize the drone's weight, and all of these carbon fiber parts had to be shipped internationally. Namely, the carbon fiber rotor arms, propellers, center frame plates, and landing gear rods in addition to aluminum screws and nuts, had large lead times that prevented the team from moving forward quickly with assembly. Long lead times and part acquisition often put the team behind schedule when assembling the drone components in C-term.

Once the carbon fiber stock for the center frame and battery plate had arrived, the team encountered another roadblock: figuring out how to cut it to shape with all the holes for mounting. At the time of assembly, there were no resources available at WPI accessible to students that could be used to cut carbon fiber sheets. The team was able to outsource the cutting to HydroCutter, a waterjet cutting facility in North Oxford, MA. The president and owner of HydroCutter, Tom Gravel, worked with the team to cut the carbon fiber plate stock on his waterjets. However, a problem occurred when one of the water-jet clamps snapped mid-operation, snapping one of the carbon fiber plates. Due to this error, the team had to order a new piece of stock, which took approximately two weeks to arrive, putting the team behind schedule again.

5.1.3 Improper Fittings

Another oversight by the team was realizing that not all of the components purchased have the same size connectors. Namely, the pump has a 10mm barbed output for a 10mm inner diameter (ID) tube, while the sprayers have a 8mm outer diameter (OD) input. Thus, the team could not use the same tubing for all components, so the tubing had to be changed between parts. Connectors exist to step-down tubing from 12mm OD to 8mm OD, however, most tubing sold in the United States have a minimum of 14mm OD, and there are no connectors to go from 14mm OD to 8mm OD. Therefore, the team designed a 3D printed barbed fitting for 10mm ID tubing to 5mm ID tubing to go from the pump to the spray nozzles. The team ordered a 10mm ID x 12mm OD tubing from a supplier in China to use the step-down connector and were only able to install this component at the beginning of D-term. This, latest fluidics component, improves the reliability of the fluidics system.

5.1.4 Issues Encountered

The final iteration of the drone has five ESCs, four of them for the four motors which the propellers are attached to and one to drive the spraying system diaphragm pump. The team decided to first test the sprayer system since it would take them less time to wire the pump compared to the four ESC/motors of the propulsion system. The team first soldered the ends of the ESC to both the pump leads and the power distribution board (PDB). Next the team plugged in the signal wire of the ESC to the radio receiver and then connected the test battery (1300mah 6 cell) into the XT60 connector of the PDB. The team had already paired the receiver to the radio before beginning the pump testing. As the team increased the throttle of the radio, the motor on the diaphragm started twitching, but did not spin. Therefore, the team identified the faulty component to be either the ESC or the diaphragm pump's brushless motor. The casing of the pump was opened to inspect the diaphragm pump, however, after visual inspection, the team decided the brushless motor looked to be in a reliable working condition. Since it is very difficult to determine if an ESC is faulty based on visual inspection, the team tested the pump with the rotor ESCs, which successfully identified the ESC as the faulty part. After replacing the ESC, the team tested the pump again and the pump started spinning and successfully pumped water through the lines. The team determined that the ESC arrived faulty from the manufacturer, and therefore purchased another ESC from a different manufacturer. As soon as the new ESC arrived, the team connected it to the pump and tested the pump, which worked flawlessly.

Another unexpected roadblock occupied the change in rotor arm tube geometry that is discussed in **5.2.4 Rotor Arm Iterations**. The tube stock material for the rotor arms does not have a 45° chamfer on the corners, which was an important geometric feature used when the motor mounts were designed.

5.2 Drone Assembly

5.2.1 Initial Part Configuration

The project team assembled the drone landing gear, spray-bar assembly, and laid out all of the flight and power electronics over the course of C-term. By the end of the term, the team had all components assembled except for the redesigned motor mounts, but they were able to verify that all components worked in synchronization. To accomplish the assembly, the team fabricated all of the components required to assemble the frame and sub-assemblies of the drone.

5.2.2 Landing Gear Assembly

The team was able to successfully fabricate all of the components for the drone landing gear. The carbon fiber tubes that comprise the landing gear struts were cut to length and assembled with all the 3D printed connectors and brackets to hold them together. These landing gear brackets were printed in PLA from the 3D printers available in WPI's Foisie Innovation Studio Prototyping Lab. Additionally, the project team began to reprint the tank mounts and center frame mounts using a chopped carbon fiber Onyx filament used to print on the Markforged 3D printer available in the WPI Robotics Engineering offices and labs. These carbon fiber mounts were iterated with a new material so that the mount will be stronger than the PLA plastic, and far more lightweight.

Figure 21. Fully assembled landing gear mounted to the drone center frame

5.2.3 Spray-bar Iterations

The spray-bar used to mount the fluid sprayers underwent several different iterations since the project team began to fabricate parts for the drone assembly. The design was initially derived from a SolidWorks sketch to ensure that the transmission angle would be close to 90°. The center-to-center distance between the grounded points at the center of the servo and the spray-bar was chosen to ensure that the driving links did not collide, seeing as the crank link and bar cannot collide. **Figure 22** shows the range of motion the spray-bar rocker moves through when the crank sweeps through a 90° motion, the resulting range is about 80°, which is an acceptable range of motion because the spray-bar will never need to move outside of a 90° range to spray an element of a car.

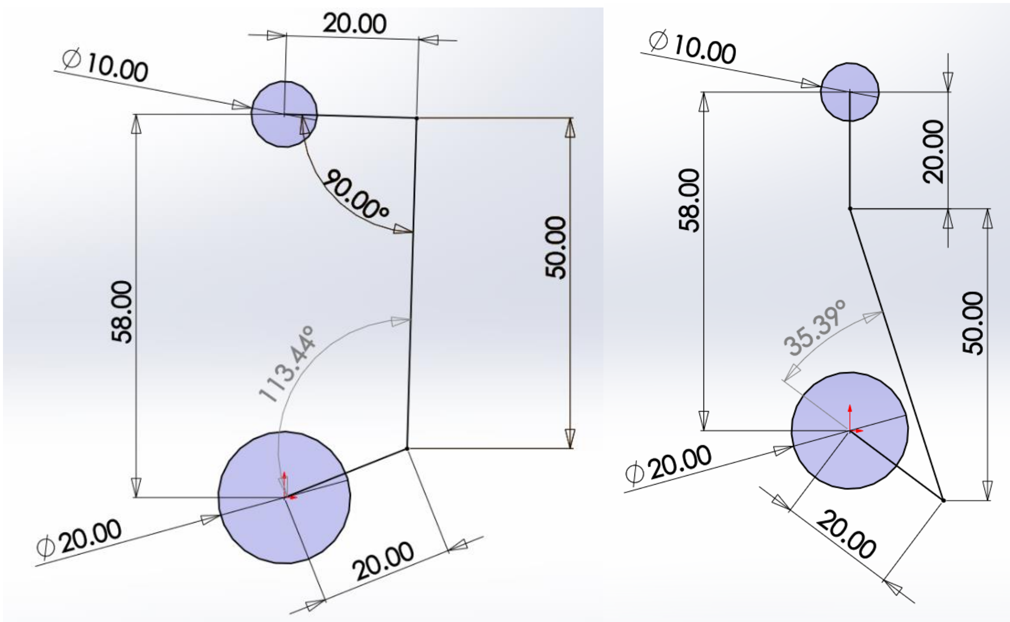
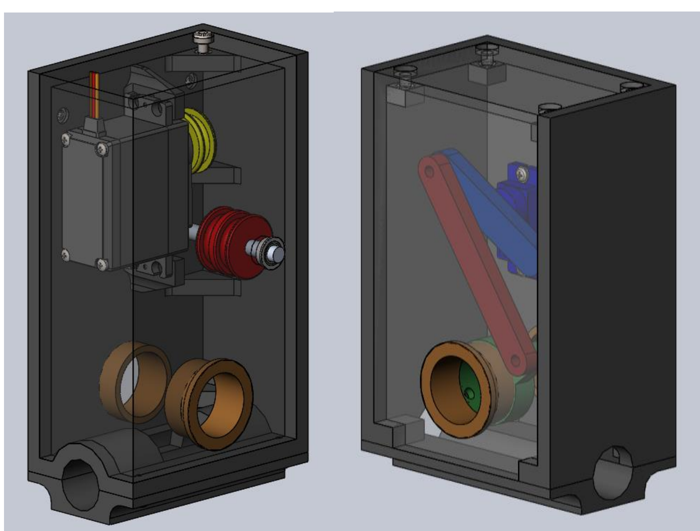


Figure 22. SolidWorks sketch of linkage mechanism rotating through 90°

Including the initial design for the actuation mechanism for the spray-bar, the team produced four iterations of the actuating mechanism (shown in **Figure 23**). The project team originally chose to use a small 25g servo motor but found that it did not supply the torque required to rotate the spray-bar. The subsequent iterations used different motors or servos, including a Pololu 35T motor, however this option was not lightweight, and served to be troublesome to control and required more voltage than the Pixhawk 4 flight controller was able to give it. The final iteration of this actuation mechanism uses a commonly found 95g servo and rotates a four-bar linkage that rotates a collar-link epoxied to the spray-bar. This servo was easily controlled using PWM signals and was tested using an Arduino UNO.



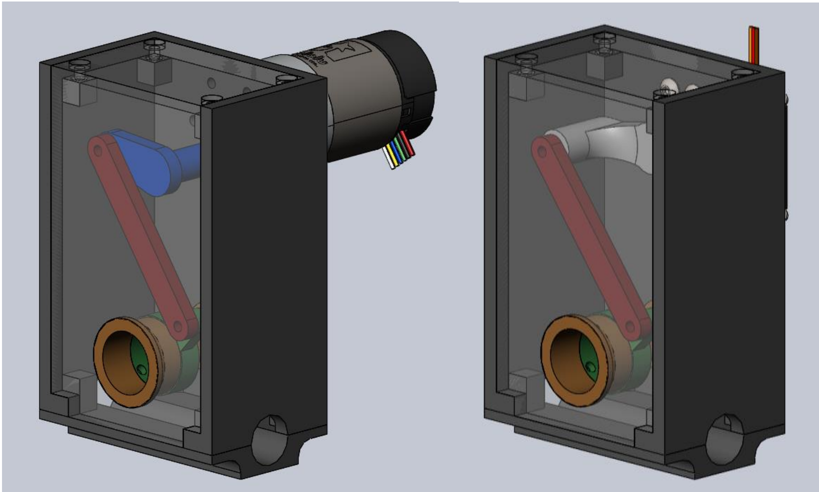


Figure 23. CAD models of the four iterations prepared for the spray-bar actuation mechanism

Figure 24 below shows a close-up of the spray bar mechanism, with the fluid components connected with the pump and the spray nozzles.

Figure 24. Close-up of spray-bar on the built drone

5.2.4 Rotor Arm Iterations

Apart from the spray-bar actuation mechanism, the only elements of the drone assembly that have changed over the course of the project were the components on the rotor arms. Originally, the team had a carbon fiber stock set aside for the arms, and all CAD models were based on the cross-section geometry of that stock. However, because of cost savings and stock availability, the team purchased and implemented a different selection of carbon fiber stock to be used as the rotor arms (**Figure 25**). Changing the geometry of the stock saw the project team iterating the motor mounts and center frame mounted to conform with this new tube stock. To conform to this new geometry, the team redesigned the geometry on the motor mount blocks that fixture to the rotor arm tube, as well as mount onto each rotor motor.

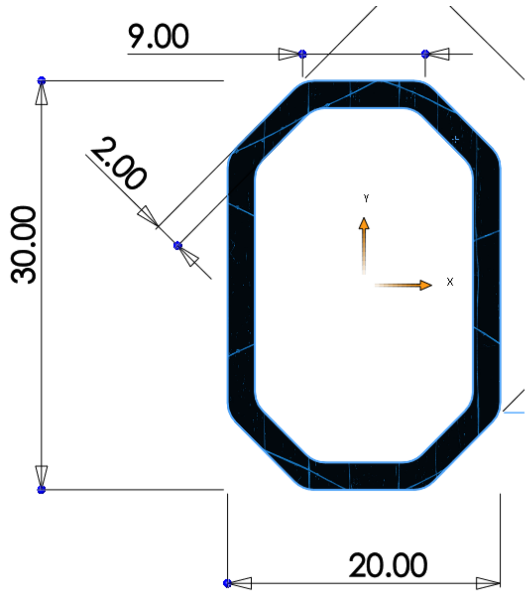


Figure 25. Cross-section of the carbon fiber tube stock used as rotor arms

5.2.5 Electrical Components

The team was able to assemble all the electronics components of the drone. The electronics components were broken into three parts: the flight management unit, the thermal imaging unit, and the spraying unit. For the flight management unit, the team soldered wires to the PDB where the ESCs connect to and soldered bullet leads connected to the end of the wires. This creates a reliable connection between the PDB and ESCs but makes it easy for the leads to be disconnected quickly if needed. Bullet connectors were also soldered to the motors in order to connect them easily to the ESCs. After the power unit was soldered, it was attached to the bottom plate of the center frame with nylon screws. The flight controller was then secured to the anti-vibration plate with double sided foam tape. Once those two units were put in place, sensors and peripheries like the GPS puck and receiver were able to be connected. For the spraying unit, the team soldered the diaphragm pump motor to a designated ESC which was soldered to the PDB. The last unit to be assembled was the thermal imaging unit. For this unit the team soldered the thermal camera to a Raspberry Pi Zero W, and soldered pigtails to the Pi where it will be powered from. After all the components were soldered and mounted, the team flashed the flight controller with PX4, set up the radio controller, and calibrated all the onboard sensors.

5.3 Individual Component Testing

5.3.1 Spray Testing

In addition to flying the drone, the other critical task was to spray and remove snow off of a car. At the early stages of C-term, the team wired the pump and ran it to test it with bottles of water. With limited documentation on the pump, the team discovered that they could adjust the flow rate by rotating a single screw attached to a spring on the inside. With the pump set to the maximum flow rate, the team could adjust the pump effectiveness with the hand-held flight controller. Then, the team mounted the pump to the tank with a custom carbon fiber mount and rubber anti-vibration stand-offs. The team first tested a single sprayer with the pump, and then connected all three sprayers together, the latter test is shown in **Figure 26**.

Figure 26. Remote test of three sprayers operating simultaneously

The team was able to effectively run the sprayers remotely outside with the on-board battery and hand-held flight controller. The current nozzles create a misting effect, and the team planned to experiment with different nozzle opening sizes, which is a recommendation for future years (refer to **7.1 Mechanical Recommendations**).

5.3.2 Motor Testing and ESC Calibration

To simplify soldering and wire management, the Pixhawk 4 comes with a PDB that all the motor ESCs can be connected to. The team soldered all the power leads of the ESCs to the PDB and then soldered the bullet connectors to the three motor wires on both the ESCs and the brushless motors. The bullet connectors make it easy to change the direction of the brushless motors, since the only thing that would have to be done is unplug two wires and reconnect them to the wire they were not originally connected to. After all the soldering of the wires to the PDB and to the bullet connectors, the team calibrated and tested all four main motors (motors used for propulsion). Additionally, the ESCs were all independently calibrated. First, one team member turned on the radio and put the throttle stick to the top position. After, the second team member plugged in the PDB test battery, once the motor made two beeps the first team member lowered the throttle stick to the bottom position. This procedure was then done on the remaining 6 parts, three ESCs and three motors. Calibrating an ESC involves teaching the ESC what range of throttle inputs the ESC should respond to. The ESC needs to know what PWM value on the throttle channel corresponds with which of the motors being off, and what PWM value corresponds with a full throttle.

5.4 Initial Software Functionality

5.4.1 Flight Control and Navigation

The team was able to set up and upload the firmware to be used on the onboard flight controller. The Pixhawk was set up and able to read data from its integrated gyroscope, barometer, magnetometer, and accelerometers. Readings were also able to be taken from the GPS module attached to the Pixhawk. Testing accuracy of the GPS would be difficult, so the team assumed that the GPS was accurate to within 3 feet as per the manufacturer specifications. All of this data is utilized by the autopilot for stable and controlled flight.

5.4.2 Thermal Camera

The IR thermal camera was attached to the Raspberry Pi using communication over I^2C. The camera was shown to display the temperature difference between sprayed fluid, snow, and the surrounding area. The images captured on the camera were set up to be recorded automatically on each flight so that the video could be reviewed afterwards for the purposes of debugging and demonstration. The camera is mounted onto the drone using its custom 3D printed case (seen in **Figure 27**). Examples of images captured by the camera can be found in **Figure 28**.

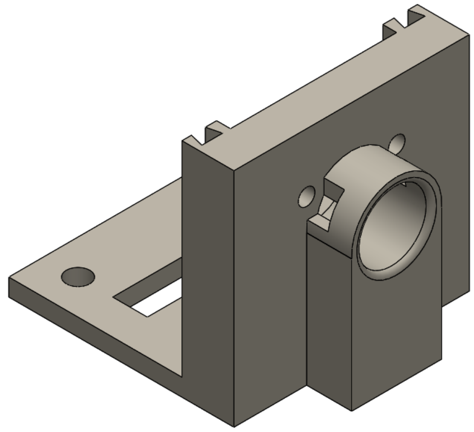


Figure 27. Thermal camera case

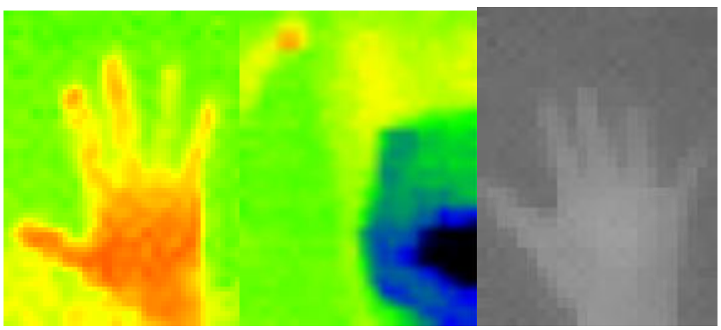


Figure 28. False colored & grayscale images from the thermal camera of a hand (left & right) and snow (center)

Figure 29 is the result of processing a generic thermal image of a teapot pouring tea into a cup using OpenCV, with darker, cool colors indicating lower temperatures and lighter, warm colors indicating higher temperatures. The image processing identified the tea remaining in the pot, the stream of tea from the pot to the cup, and the tea within the cup as three distinct entities with their own identifying centroid.

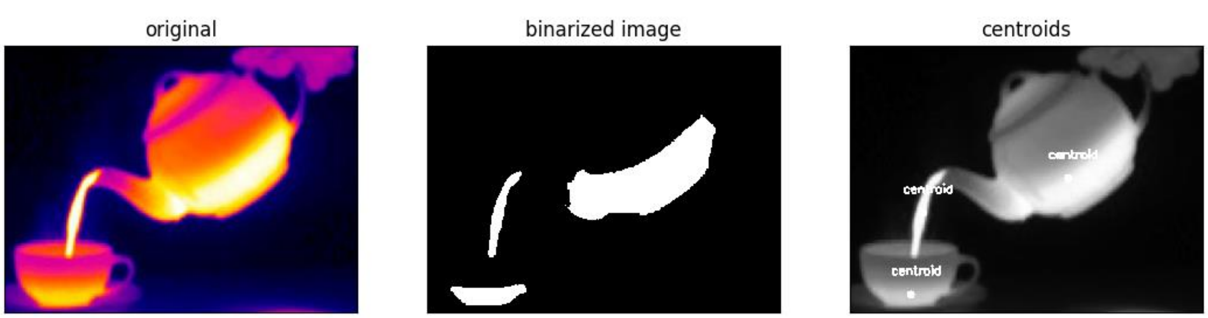


Figure 29. Thermal image of teapot, thresholded binarization, & grayscale image with overlaid centroids. Original image retrieved from https://cdn.static-economist.com/sites/default/files/images/2014/08/blogs/babbage/20140816_stp503.jpg

Figure 30 is the result of processing a grayscale image of a hand and a grayscale image of a car captured by the drone's IR camera, with darker grays representing lower temperatures and lighter grays representing higher temperatures. In the hand's case, only one object is identified in the image. The binarized hand image shows one of the limitations of lower resolution infrared cameras, which have a harder time accurately representing the temperature of narrower objects. In order to capture the pinky of the hand, a lower threshold was used, which caused some noise between the middle three fingers to be considered part of the hand. The car image was captured by the same 24x32 camera but was scaled up afterwards. Even with scaling up, details are similarly difficult to determine in originally low-resolution images, but the car itself is identified effectively, nonetheless.

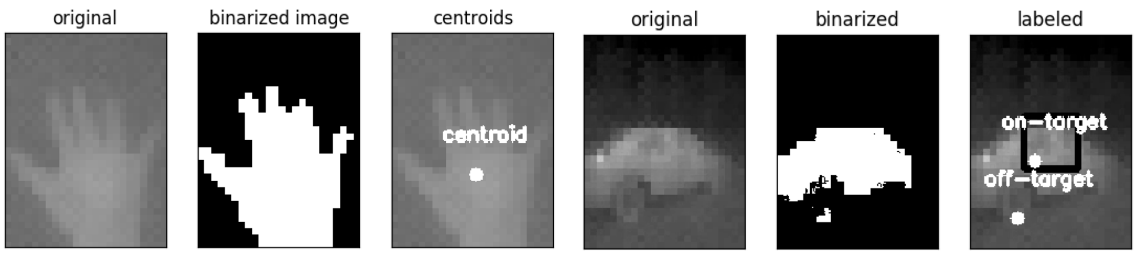


Figure 30. Image of hand from IR camera and image of car from IR camera, thresholded binarization of each, & grayscale image with overlaid centroid(s) of each

5.5 Drone Set-Up

Once the drone was fully built including the center frame, rotor arms, landing gear, spray-bar, and tank, it was necessary to perform some additional set-up steps in order to fly. It was important to assemble the drone to make sure the landing gear was angled correctly to the center frame. From there, the center frame was removed from the landing gear to connect the necessary electronics, and the top plate could be removed to access the PDB. Additionally, it was necessary to leave the propellers off of the drone until after all of the set-up steps and just before it was going to fly in order to calibrate the motor ESCs.

Initially, to connect the electrical components as per the diagram in **4.3.3 Electronics Parts and Wiring**, each of the motor ESCs signal wires (white) were soldered to the PDB in each of the respective motor solder pads labeled M1-M4. The ground wire (black) was soldered to a ground connection on the PDB near the motor solder pads. Bullet connectors were used to create longer wires to connect the ESCs to the respective motors through the rotor arms.

The 3D printed onyx carbon fiber flight controller plate was attached to the top plate with the anti-vibration ring stand-offs. The FC was then attached to the plate using foam pads. The GPS puck was mounted to the GPS stand using the foam sticky pads. The GPS stand was then attached to the top frame using foam pads pointing in the same direction as the FC. The PDB could then be wired to the FC and all of the peripherals could be wired to the FC. The diagram for the Pixhawk 4 FC with all of the necessary connections is labeled below in **Figure 31**. **Figure 32** below shows the corresponding FC connections on the PDB in addition to the motor ESC signal wires and the pump ESC connection. The pump ESC signal wire is wired directly to the receiver.

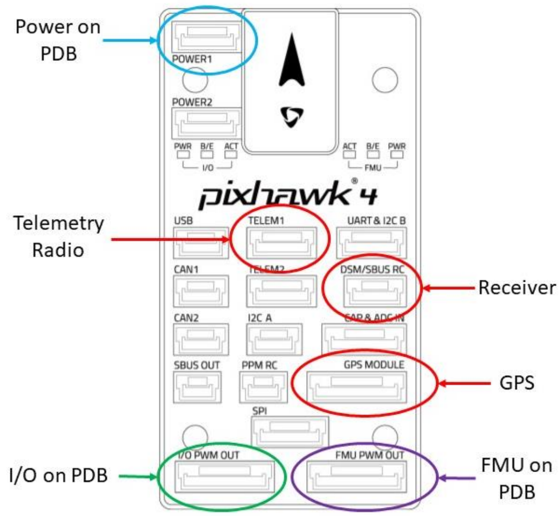


Figure 31. Flight Controller Electrical Connections

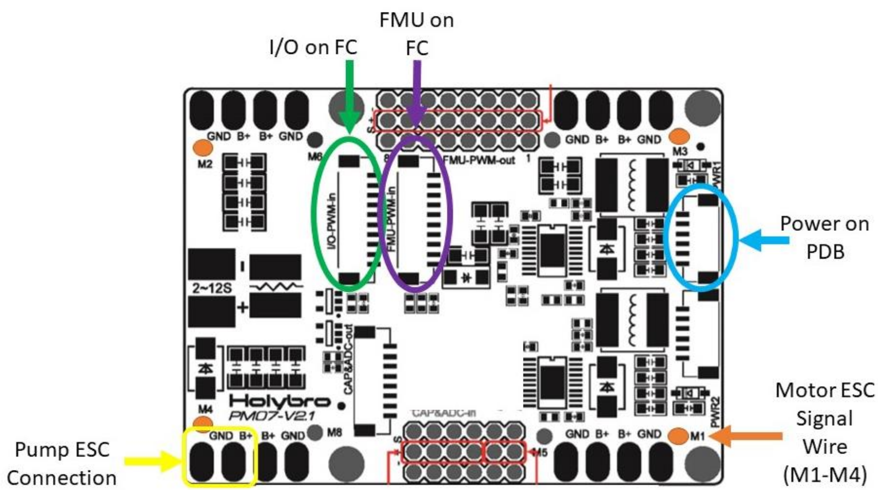


Figure 32. Power Distribution Board Electrical Connections

After all of the multi-pin connections were made between the FC, PDB, and peripherals such as the receiver, telemetry radio, and GPS the wires needed to be covered with a nylon sleeve. Since the carbon fiber plates were waterjet, they are extremely sharp and could cut the low gage wires, so they needed to be protected with nylon sleeves.

Once the drone was completely wired and all peripherals were mounted to the center frame using the foam sticky tape, the center frame was re-assembled with the rotor arms as well. It was then necessary to balance the motors and center frame as seen in **Figure 33** below. Leveling all the motors and center frame is crucial for the drone to stay stable during flight. Even objects were placed at the end of each rotor arm, and in the middle of each rotor arm, and then a level was placed on the center frame and spun around the top of each motor to measure if they were level. If they were not level, the center frame screws were adjusted until both the center frame and motors were level.

Figure 33. Leveling the Drone

When the drone was eventually leveled, calibration could begin. First, the Taranis radio channels needed to be adjusted to be in AETR mode, meaning that CH1 is set to Ail, CH2 Ele, CH3 Thr, and CH4 Rud. Then the latest PX4 firmware update was installed on the Pixhawk4 FC. In order to do this, the QGroundControl software was installed on a PC. One telemetry radio was connected via USB to the computer, while the other was wired to the drone for wireless communication. From there, the drone flight preparations began.

In the QGroundControl program, the vehicle needed to first be specified and set-up. Under the airframe tab, “quadrotor x” was chosen with the “generic quadcopter” option selected in the drop down as shown in **Figure 34**. This specified that the configuration of the team’s drone was X4 and custom built.

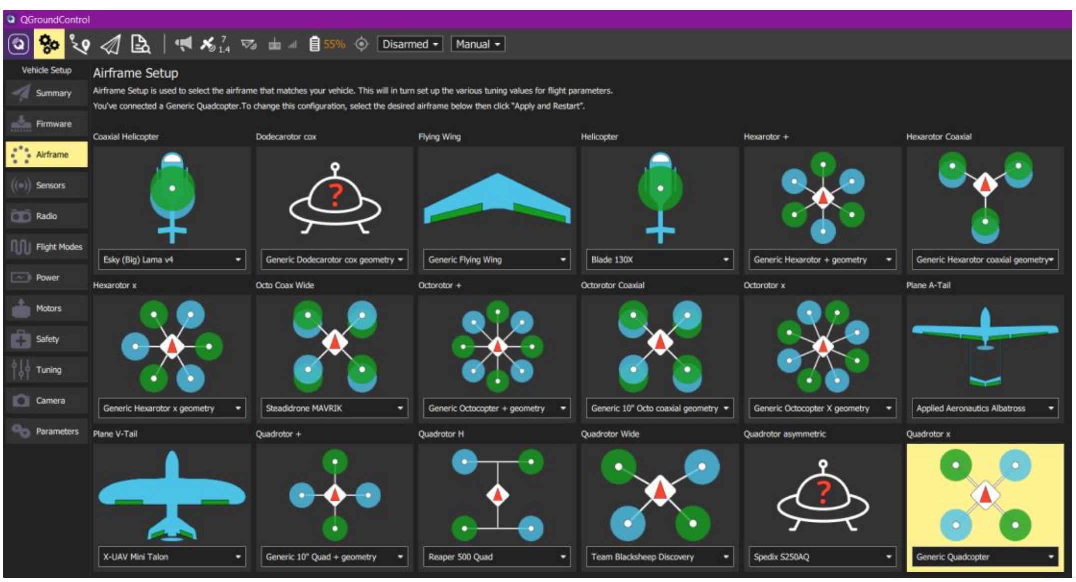


Figure 34. QGroundControl, Airframe Tab

After the airframe was specified, the sensors needed to be calibrated. With the drone still resting level on the block (not yet mounted to the landing gear and rest of the assembly), the “sensors” tab was selected in QGroundControl. There, calibration of the Pixhawk 4’s compass, gyroscope, accelerometer, and level horizon were performed by rotating and orienting the FC and frame. The menu for this tab can be viewed in **Figure 35** below.

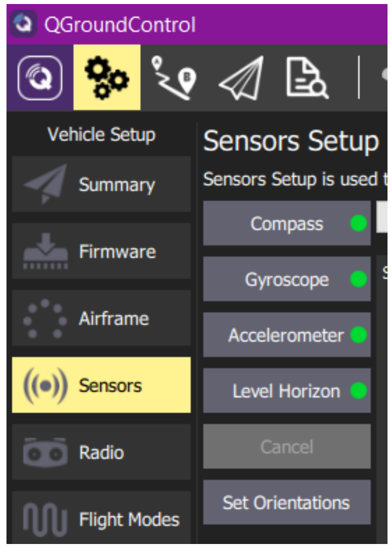


Figure 35. QGroundControl, Sensors Tab

The next tab is radio setup. With the Taranis radio connected to the receiver, the QGroundControl program required the team to move the controller sticks so that the program could map movement to the throttle and angular adjustment in the roll, pitch, and yaw directions. **Figure 36** below shows the radio calibration tab.

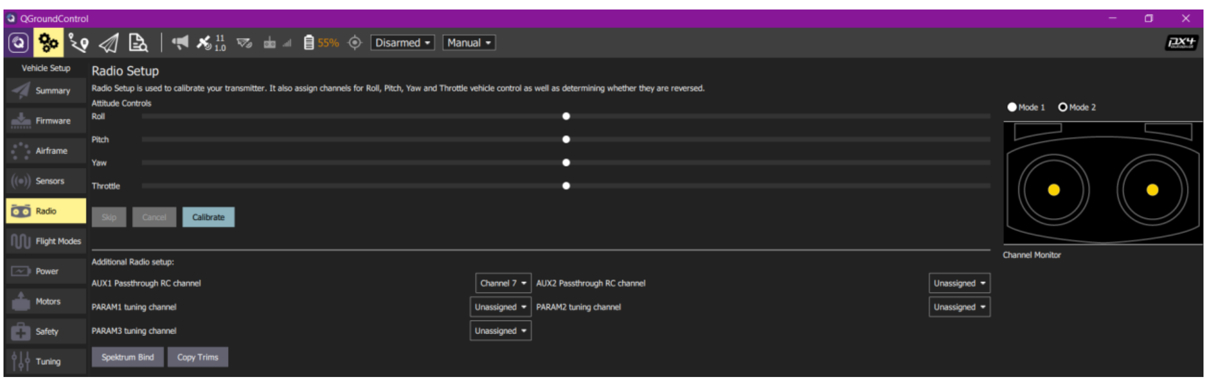


Figure 36. QGroundControl, Radio Tab

The next requirement to setting up the drone for flight was located in the flight mode tab. Six flight modes were established in order for the drone to take-off, perform the navigation and spraying requirement, and then land. The flight modes programmed can be viewed in **Figure 37** below. Channel 5 on the Taranis radio is used to switch between the flight modes. In addition, channel 6 is used to arm the drone prior to take-off. This is essentially an “enable” switch.

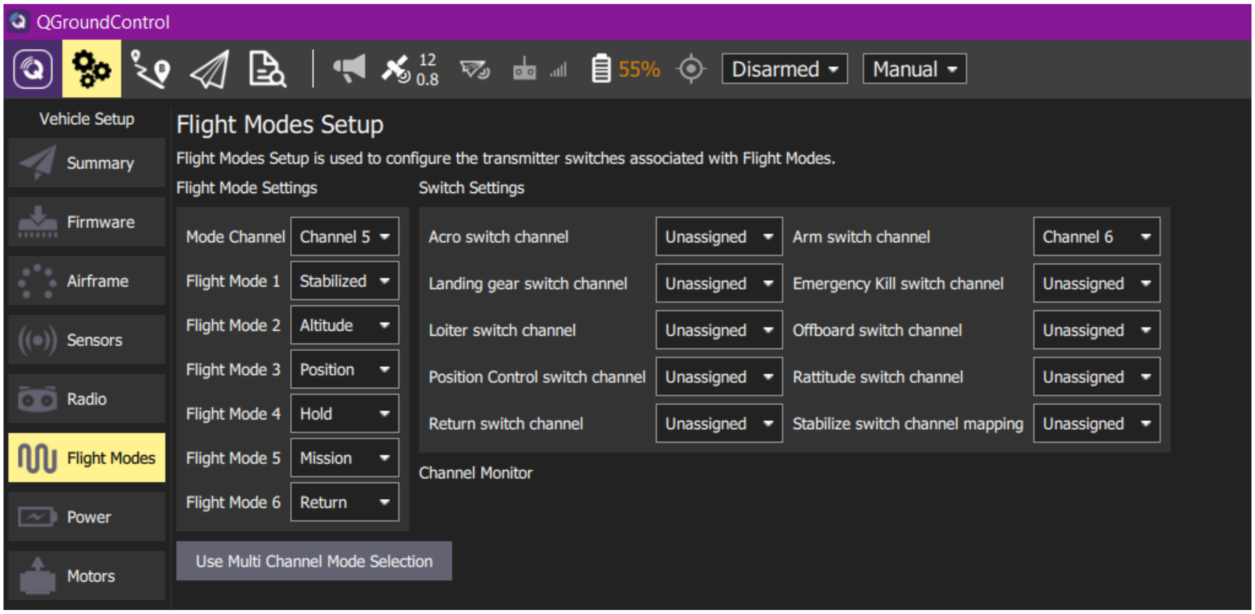


Figure 37. QGroundControl, Flight Modes Tab

The last calibration requirement prior to flying was calibrating the power. In the "power" tab, the user specified the number of cells in the LIPO battery used, the maximum voltage, and the minimum voltage. In addition, the user calibrated the motor ESCs through this power tab by pressing the "calibrate" button as shown in **Figure 38** below.

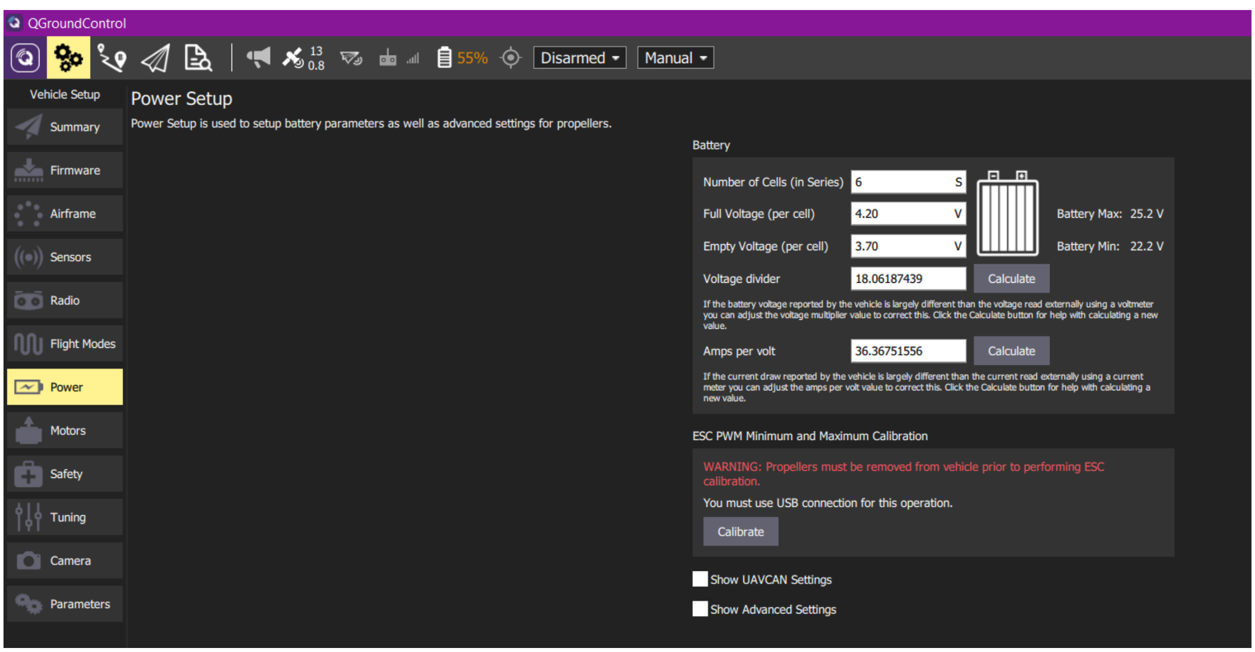


Figure 38. QGroundControl, Power Tab

After all of this calibration was performed, the motors could be tested by arming the drone using the Taranis radio, and then varying the throttle on the left stick. The direction of the motors was analyzed and changed on the ESCs so that motors diagonally across from each other were rotating in the same direction, CW, and the other pair of motors diagonal were rotating in the opposite direction, CCW. Refer to **A.2 Drone Physics and Flight** for an explanation of how drones operate with respect to the direction of propellers. Then, the propellers could be mounted to the motors in preparation for flight.

5.6 Flying

One of the most important results to touch upon is the operation and flight of the drone. Due to the COVID-19 pandemic as discussed earlier, the team was displaced with only one team member having access to the drone. By the last week of D-term, the drone flight was tested on campus. The drone successfully flew to the six feet height that the team estimated it would be operating at for a majority of the time, due to this being the typical height of the top of a car's windshield. However, when the drone reached the six feet height, the drone began to get unstable and oscillate. As a result, the team landed the drone and decided to evaluate what could have caused the issues encountered. Some reasons that the team came up for unstable flight included calibration errors, structural issues, an unlevel center frame, or requiring a control loop to be implemented. The team believes that if there were not extenuating circumstances in D-term, they would be able to solve the stability issues encountered.

Another important thing to note is that all of the drone systems could be operated with the Taranis radio. This includes the roll, pitch, and yaw of the motors, controlling the speed of the motors (and thus, the thrust), and the pump and sprayer unit. The team was able to successfully spray remotely mid-flight with just the radio and the drone.

Chapter 6: Conclusion

Snowfall creates many challenges and dangers every winter for those living in the colder regions of the world. Removing snow from a car can be a time-consuming, labor intensive, and dangerous task. For those of limited physical ability, clearing snow and ice from a car can be difficult, if not impossible. For some businesses, the labor spent clearing snow off of a fleet of cars adds up to be a significant cost. Everyone who drives has to get the snow off of their vehicle in order to safely operate it and not risk the safety of others.

Fortunately, as this project has demonstrated, advances in UAV technology has allowed for the vehicle snow clearing process to be automated. Due to its efficient but effective design, the drone is capable of taking off and spraying a car with deicing fluid. The fluid is able to be stored onboard the drone and pumped through multiple nozzles that allow for optimal windshield coverage. Additionally, other sensing components such as a GPS receiver and an IR camera give the drone potential autonomous flight and additional car identification capabilities.

This drone meets the majority of the criteria outlined in **3.2 Metrics**, including being designed to operate in cold temperatures, carry a five liter (approximately one gallon) liquid payload, and is structurally sound, leak free. The team was able to test the flight and spraying capabilities and get the drone off the ground to a height of approximately six feet.

In addition, the drone is designed in such a way that could allow for it to be easily used for a variety of other applications separate from the goals of this project, including, but not limited to:

- Clearing snow from the roofs of buildings
- Washing vehicles
- Disinfecting a dangerous area
- Small-scale firefighting
- Spraying for mosquitoes or other disease carrying insects

Additionally, the team intended to design the drone to be a standalone unit that had all necessary flight and operation capabilities on board. This project, with the same frame and design, could be expanded to allow for tethered power and spraying with a ground unit in order to lessen the weight of the drone and allow for greatly increased flight time.

This car-snow clearing drone was successfully able to fly and spray deicing fluid in a way that could be used to clear the snow and ice from a car windshield. Despite technical, fiscal, and weather limitations, the project was clearly able to demonstrate the feasibility of using a drone to help people clear the snow from their car in order to improve their quality of life and reduce the risks associated with such an activity. **Figure 39** below shows the fully assembled drone the team was able to accomplish after four terms of work.

Figure 39. Finalized drone build

Chapter 7: Recommendations for Future Iterations

Due to the complexity of this project and factors outside of the team's control, such as COVID-19,long part lead times, and insufficient funding, there were a number of goals that the project team had that they were unable to achieve. Both the team and the advisors began this project with the intent for this to be a multi-year project, with initial goals set for the first iteration. The ideas we had for the future included a number of mechanical, electrical, and software recommendations.

7.1 Mechanical Recommendations

With the truncation of the term of this project, the team compiled a series of recommendations to improve the mechanical structure of the drone and its sub-assemblies. These recommendations will cover components that require further testing for validity, as well as components that need further design iterations. The first recommendation for future work would be to re-manufacture the spray-bar actuation mechanism. The team developed the CAD models for a fourth iteration of this component to allow for a servo, as opposed to a motor, but were not able to finish reprinting it due to the cancellation of D-term on campus. These models can serve as reference to a future team to decide if a linkage system would be preferable to move the spray-bar. Additionally, a future iteration of this component would include a smoother bearing surface that the bar would rotate inside, as the current iteration uses bronze bushings that are slightly undersized compared to the carbon fiber tubing, requiring that the inner diameters be reamed to fit adequately. Secondly, the project team recommends that an electronics housing component be manufactured to cover the sensitive electrical components mounted on the center frame. This electronics housing has been modeled by the team, and the CAD model can be found in the CAD repository compiled by the project team. The project team recommends that this component be made of a durable plastic material that is weather-proof to allow for flight in snowy weather. One solution that could be explored for this component would be to vacuum-form a sheet of ABS plastic to the desired shape to sufficiently cover the center frame. In order to manufacture this component with vacuum-forming, the negative of the cover will first need to be manufactured.

The project team has additional recommendations for future iterations of the project that would require design challenges that this initial iteration was not able to solve. The team recognizes the design challenge that accompanies protecting the car from the drone in the case of failure in the flight controls. The team offers the task of a mechanical solution to future project iterations to design components to protect the car from the propellers colliding with the windshields or body of the car, as the team was not able to come up with a viable solution with the funding and materials provided, as the team was not able to come up with a viable solution with the funding and materials provided. With increased ability to test the drone in future versions, a subsequent team will be able to formulate safety measures to protect both the drone and the car. Lastly, the project team had made the design decision to build the drone to be operated detached from a ground station, making the system more mobile for autonomous flight.

However, the team acknowledges that the drone has the potential to be tethered to a ground station, giving the drone more flight time (refer to the idea for this project in **3.1 Project Approach**, a tethered drone cleaning a windmill blade). A tethered solution could include a mobile ground station that gives the drone the ability to have a larger deicing fluid reservoir, as well as an external power supply. Both these additional capabilities would allow the drone system to spray more deicing fluid and fly for a longer period of time if the system was powered from a continuous power supply. However, implementing these tethered solutions would require further design considerations to alter how the spraying system works, as well as the electrical engineering task of incorporating an external power supply. While future iterations of this project could have other mechanical focused changes made to the structure of the drone, these recommendations are all tasks that the project team determined to be the most logical iterations of the current design.

7.2 Electrical Recommendations

Some of the improvements that can be made to the electronics include upgrading to a real time kinematics (RTK) system, adding a stereo camera, and adding a companion computer. First, upgrading the current GPS sensor with an RTK system will increase the accuracy of the drone from its current accuracy of three feet to being accurate to the centimeter. With this in place, the drone will more accurately spray de-icing fluid where programmed to, and the drone operator can more accurately determine the position of the drone. Another electronic component that the drone would benefit from would be a stereo camera and a companion computer. These systems would allow the drone to autonomously map out the object it wants to de-ice and be able to create paths and targets for where it needs to spray the fluid. With this system on board, the drone will also benefit from the anti-collision systems that could also be implemented, as noted in Section 7.2. A good choice for a companion computer is the NVIDIA Jetson, which is lightweight, but powerful. The addition of these systems creates a drone that, when programmed correctly, can take-off, de-ice and land fully autonomously. The vision for this project going forward is transitioning from a manual operator to autonomous flight that only requires an operator to start the drone.

7.3 Software Recommendations

Due to timing, budget, and drone-access limitations and roadblocks, most software plans were cut or low-priority in comparison to work on the physical drone systems or other aspects of the project. Opportunities for software improvements include two major categories: computer vision, and autonomation.

While some research and work on thermal imaging was accomplished with this project, timing and non-snow weather conditions restricted how much useful data could be collected for actual tuning of this software. By the time the IR camera was secured, most opportunities for recording snowy conditions similar to what the drone would experience had passed, and the winter the team experienced had very minimal snowfall. With access to the camera during snowy months and a fully built drone, plenty of meaningful data can be gathered to refine the thermal imaging software, particularly for identifying what parts of a windshield have been cleared and what parts still have snow covering them.

The other primary intended computer vision functionality for this project, depth sensing, had to be cut due to budget and time restrictions. While GPS can get the drone close to the car and thermal imaging can distinguish the car from its surroundings if its temperature is significantly different from these surroundings, not all cars have remote starting features or similar that would cause such a temperature difference. However, using either a stereo camera ((mentioned above in **7.3 Software Recommendations**) or two cameras mounted on different places on the drone, one would be able to sense depth, and thus object shapes, independent of temperature. Using artificial intelligence techniques such as Feature Matching (discussed in **4.4.2 Computer Vision**), the stereo images can be analyzed to identify the car and its position and orientation relative to the drone. With this information, the drone can properly be oriented relative to the car and combined with the snow-clearing progress information from the IR camera, the car can be accurately and efficiently cleared.

Due to the team's primary focus being on getting the drone and its peripherals assembled and functioning, there is plenty of opportunity for automation. With teleoperated flight test data and improved car identification and localization, the automated flight plan outlined in **3.3.4.5 High-Level Workflow** can be realized. This automation has multiple components, including flight path plans for clearing snow, spray pattern management, reorientation routines when the drone is off-course, and on-board resource (i.e. power and deicing fluid) contingency routines.

7.4 General Recommendations

Aside from specific recommendations that fit under the three categories (mechanical, electrical, and software) the team came up with additional recommendations. Two general recommendations that the current team recommends future teams look into are: a variety of de-icing fluids and their efficiency in cleaning a car, and the environmental impacts of these fluids. Background **2.7 Deicing** outlines research performed on existing mixtures for de-icing used widely across different industries. Due to the drone not being operational in the winter and the team not receiving a significant amount of snow in 2020, the team was only able to test one solution, isopropyl alcohol and water, manually. Further solutions should be investigated to determine their efficiency and environmental impact. Another general recommendation the team has was connecting the Raspberry Pi to the flight controller via an on-screen display, in order to be able to fly the drone via first person view.

Two more general recommendations that the team came up with relate to the spraying mechanism. The team had intended to test various nozzles and their effectiveness at clearing snow and ice off of cars, but, due to the coronavirus, shipping from China was slowed and the team was displaced, as noted earlier. The team recommends that different nozzle shapes be tested (as discussed in **2.6 Spray Nozzle Design**) in addition to nozzles that allow different flow rates.

The flow rate that is best for de-icing the car should be determined. In addition, the team recommends using a step-down voltage regulator to power the Arduino directly from the flight controller. The Arduino powers the spray bar servo using the PWM outputs.

Chapter 8: References

3D Printed Racing Drone - Will It Survive? (2017, October 17). 3D Printed Racing Drone - Will It Survive?. Retrieved from https://www.youtube.com/watch?v=vjvlB7RjnYI.

AAA Automotive. (n.d.). How To Deice Your Cars Windshield. Retrieved October 8, 2019, from https://www.aaa.com/autorepair/articles/how-to-deice-your-cars-windshield.

Allain, R. (2017, June 3). How Do Drones Fly? Physics, of Course! Retrieved from https://www.wired.com/2017/05/the-physics-of-drones/.

Buckley, J. (1999). Air power in the age of total war. London: UCL Press.

Dorn, T. (n.d.). Sprayer Nozzle Tip Selection. Retrieved from https://www.spraysmarter.com/content/sprayer-nozzle-tip-selection.

Dorr, L., & Duquette, A. (2014, September 19). Fact Sheet – Flying In Icing Conditions. Retrieved from https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=10398.

Environmental Protection Agency, Department of Water. (2012, April). Environmental Impact and Benefit Assessment for the Final Effluent Limitation Guidelines and Standards for the Airport Deicing Category. Retrieved from https://www.epa.gov/sites/production/files/2015-06/documents/airport-deicing_environmental-impact-and-benefit-assessment-final-2012.pdf

Federal Aviation Administration. (2019, August 20). Certificated Remote Pilots including Commercial Operators. Retrieved from https://www.faa.gov/uas/commercial_operators/.

Federal Aviation Administration. (2019, August 13). Recreational Flyers & Modeler Community-Based Organizations. Retrieved October 8, 2019, from https://www.faa.gov/uas/recreational_fliers/.

Federal Aviation Administration. (2008, August). FAA 121 Carriers International Manual Forward - International De/Anti-Icing Chapter. Retrieved from https://www.faa.gov/other_visit/aviation_industry/airline_operators/airline_safety/deicing/media/standardized_international_ground_deice_program.pdf.

Federal Highway Administration. (2018, September 17). How Do Weather Events Impact Roads? Retrieved October 10, 2019, from https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm.

Glaun, D. (2016, December 12). Clear snow from your car or get pulled over, state police warn drivers. Retrieved October 10, 2019, from https://www.masslive.com/news/2016/12/clear_snow_from_your_car_or_ge.html.

The History Of Drones (Drone History Timeline From 1849 To 2019). (2018). Retrieved September 24, 2019, from https://www.dronethusiast.com/history-of-drones/.

Hercules 20. (n.d.). Retrieved from https://www.dronevolt.com/en/expert-solutions/hercules-20/.

Kikutis, R., Stankūnas, J., Rudinskas, D., & Masiulionis, T. (2017). Adaptation of Dubins Paths for UAV Ground Obstacle Avoidance When Using a Low Cost On-Board GNSS Sensor. Sensors, 17(10), 2223. doi: 10.3390/s17102223

Kolifarhood, G., Aghaali, M., Mozafar Saadati, H., Taherpour, N., Rahimi, S., Izadi, N., & Hashemi Nazari, S. S. (2020). Epidemiological and Clinical Aspects of COVID-19; a Narrative Review. Archives of academic emergency medicine, 8(1), e41.

Kujawa, M. (2017, September). Research Gate. Retrieved from https://www.researchgate.net/publication/320197696_Assessment_of_3D_printing_as_a_Manufacturing_technology_for_drones'_wings.

Leishman, J. G. (2006). Principles of helicopter aerodynamics. Cambridge: Cambridge University Press.

Massachusetts Registration of Motor Vehicles . (2019). Driver's manuals. Retrieved October 10, 2019, from https://www.mass.gov/lists/drivers-manuals.

Munson, K. (1968). Helicopters And Other Rotorcraft Since 1907. Retrieved September 25, 2019, from http://www.aviastar.org/helicopters_eng/oemichen.php.

National Oceanic and Atmospheric Administration, National Weather Service, & US. Dept of Commerce. (2019, August 1). Wind Chill Chart. Retrieved from https://www.weather.gov/safety/cold-wind-chill-chart.

Object Identified With Feature Matching. (n.d.). Retrieved from https://docs.opencv.org/3.4/dc/dc3/tutorial_py_matcher.html

Office Worker With Detected Edges. (n.d.). Retrieved from https://www.sicara.ai/blog/2019-03-12-edge-detection-in-opencv

Policies. (n.d.). Retrieved from https://www.wpi.edu/about/policies.

Pullen, J. P. (2015, April 3). This is How Drones Work. Retrieved from https://time.com/3769831/this-is-how-drones-work/.

Sandoval, E. P., Sanchez, I., & Sandoval, S. C. (2016, April). WPI Gordon Library. Retrieved from https://digitalcommons.wpi.edu/mqp-all/3262/.

Sikorsky Helicopters. (1997). Retrieved October 3, 2019, from https://www.helis.com/timeline/sikorsky.php.

Sumner, P. E. (n.d.). Sprayer Nozzle Selection. Retrieved from https://www.spraysmarter.com/content/sprayer-nozzle-selection.

Tobiszewski, M., Namieśnik, J., & Pena-Pereira, F. (2017). Environmental risk-based ranking of solvents using the combination of a multimedia model and multi-criteria decision analysis. Green Chemistry, 19(4), 1034-1042.

Wadel, M. (2016, September 27). Which Fluid is Right for Your Aircraft? Retrieved October 8, 2019, from https://aircrafticing.grc.nasa.gov/2_3_3_1.html.

Weber, S & Knaus, F. (2017). Using drones as a monitoring tool to detect evidence of winter sports activities in a protected mountain area. Eco.mont - Journal on Protected Mountain Areas Research and Management, 9(1), 30–34. https://doi.org/10.1553/eco.mont-9-1s30.

Appendix A. Additional Background

A.1 Introduction to Drones

The Introduction to Drones section provides a basic overview of what a drone is and when it was invented. The key element of the background is to understand how drones were invented and how they've evolved over time. For the purpose of this paper, a drone will be defined as a multi-rotor remote-controlled pilotless aircraft.

A.1.1 History of Rotary Aircrafts

Rotor Aerial Vehicles, also known as UAVs have been in existence for hundreds of years. As Igor Sikorsky, a Russian-American aviation pioneer known as the father of the helicopter described, "The idea of a vehicle that could lift itself vertically from the ground and hover motionless in the air was probably born at the same time that man first dreamed of flying" (Sikorsky Helicopters, 1997). The first type of flying "rotor" vehicles were Chinese tops, a toy children would play with made out of a bamboo stick and a propeller made of feathers (Leishman, 2006). This toy has been being played with since 400 B.C.E. The toy is spun manually to produce lift and propel itself into free flight when released. Other examples of early rotorcrafts designs and concepts can date to Leonardo Da Vinci's Helicopter drawings but have only been around 100 years since there have been big advances in rotary aircraft (Leishman, 2006). The pioneers of rotorcraft, Stanley Hiller and Igor Sikorsky, are known as the fathers of helicopters because of their work with rotary vehicles, which have become a major part of modern aviation due to their ability to take-off and land vertically.

The first progress with quadcopters came in the early 20th century with Etienne Oemichen, a French engineer and helicopter designer. His research started with an aircraft he built in 1920 called the Oemichen No.1. This aircraft was powered by a 25 hp engine that spun two rotors. Sadly, this aircraft failed to produce the necessary thrust to lift the vehicle off the ground. Therefore, Oemichen built the Oemichen No. 2 aircraft with 4 rotors and 8 propellers, driven by a 120 horsepower engine, which was later swapped for a 180 horsepower engine. This aircraft is now recognized as a famous multirotor aircraft advancement, first flying unassisted in 1922, and flying for several minutes in 1923. The following year this aircraft set the first-ever Federation Aeronautique Internationale distance record for helicopters. In the 1920's Oemichen was able to fly the vehicle more than 1,000 times, where he was able to improve stability and control of the vehicle. Even with his success, Oemichen thought the machine was not practical, and abandoned the design to start working on single rotor aircrafts (Munson, 1968).

In the same time period, the Army Air Corps contracted Dr. George de Bothezat and Ivan Jerome to create an aircraft capable of flying vertically. They created a vehicle that was only able to get 1.8 meters off the ground and fly a maximum of 1 minute and 42 seconds. Just as Oemichen was discouraged and abandoned his ideas, the Army Air Corps did not continue with the project. From the 1920's through the early 2000s, minimal research into multi-rotor vehicles occurred, especially ones capable of lifting passengers or heavy payloads, with the only exception being tiltrotor-style crafts, such as the Osprey. More recently, companies have been looking into quadrotors and researching their use for passenger chartering, or as cargo vehicles. One example is the Bell Boeing Quad Tiltrotor project, which is a part of the U.S. Army's Joint Heavy Lift program.

A.1.2 History of Drones

Unmanned Aerial Vehicles were first created 170 years ago (Buckley, 1999). These "drones" were used in 1839 when Australian soldiers attacked the city of Venice with unmanned balloons filled with explosives. These "drones", or unmanned balloons, were unsuccessful and therefore not widely adopted. The first pilotless winged aircraft was built in 1916 by Great Britain, called the Ruston Proctor Aerial Target (Dronethusiast, 2018). This aircraft was based on a design by Nikola Tesla and was controlled via radio like many modern day drones. American Engineers observed this advancement in the British technology and later created an alternative, the Hewitt-Sperry Automatic Airplane. The plane was upgraded and mass produced under the name Kettering Bug. During World War II and the Cold War, UAV technologies were being researched and developed. However, these new mechanisms were still seen as unreliable and expensive (Dronethusiast, 2018). Although drones were previously associated with military operations because of their initial uses, drones today are used for a wide variety of tasks. Some of today's drone functions include: delivery, surveillance, mapping, agriculture, natural disaster relief and even autonomous transportation vehicles.

A.2 Drone Physics and Flight

Understanding the science behind how drones operate is essential to determine the design specifications and parts required to design a functional drone. There are a number of factors that contribute to drones being able to lift off the ground and fly, especially with a payload. Drone flight is often compared to that of remote control (RC) helicopters, but in reality, they have significant functional differences. While RC helicopters can fly with one main rotor, drones require multiple rotors in order to achieve the control necessary to be self-reliant. Michael Perry, a public relations manager at the popular consumer drone company DJI, said that "having more than one propeller gives drones more fail-safes. For instance, if one of the motors fails, the aircraft can still stay aloft with the remaining motors working in concert to compensate" (Pullen, 2015). The controls, navigation systems, and sensors (discussed further in section 2.4) allow drones to have a level of autonomy, where the systems on-board can communicate with each other to overcome any difficulties or failure during flight. This autonomy allows them to stay steady when a strong gust of wind passes, for example. Drones are capable of flying, hovering, or navigating without pilot input, making drones unique compared to other aircraft.

There are two main factors to consider about how drones fly: physics, and the relation of one rotor with another in order to navigate. Drones use rotors for propulsion and navigation control. The spinning blades push air down, which creates an opposite force from air pushing back on the rotors. This creates lift and pushes the drone off the ground. In order for a drone to lift off the ground, the force of lift needs to overcome the weight of the drone. Ultimately, drones need to control the upward and downward forces from the rotors in order to control flight. The faster these rotors spin, the greater the force of lift is and the faster the acceleration off the ground. The more rotors on a drone, the more lift a drone will generate, which allows it to carry a heavier payload. Drones can do three main functions: hover, climb, and descend. In hovering, the upward lifting force from the rotors equals the downward force from gravity acting on the drone. When climbing, there is a non-zero upward force that is greater than the downward force. In order to descend, the downward force from weight must be greater than the upward force of lift (Allain, 2017).

The other main factor is how rotors rotate in relation to the other rotors. In the most common drone configuration, X4 (four rotors), the rotors diagonally opposite from each other rotate in the same direction. In Figure 1a, rotors 1 and 3 are both spinning clockwise while rotors 2 and 4 spin counterclockwise. In the hovering state of the drone, the net angular momentum is zero, which means that all rotors have the same net rotational velocity. Some rotors may have different velocity, but the net rotational velocity would add up to be zero. Rotation about the vertical center axis can be caused by decreasing (or increasing) the angular velocity of a rotor so that the drone has a net angular momentum. However, when changing the angular velocity of one rotor, you also need to change the angular velocity of the opposite pair of rotors, with the same, but opposite, magnitude, in order to compensate for the change so the drone doesn't tip or descend. For the drone to move in a direction, a forward component of thrust from the rotors is needed. As seen in Figure 1b, in order to move in a linear direction while still hovering, the drone decreases the angular velocity of the front rotors (2 and 3 in **Figure 40**) and increases the angular velocity of the rear rotors (1 and 4 in **Figure 41**). Since the rotors in each pair spin opposite directions, the angular momentum is still zero (Allain, 2017).

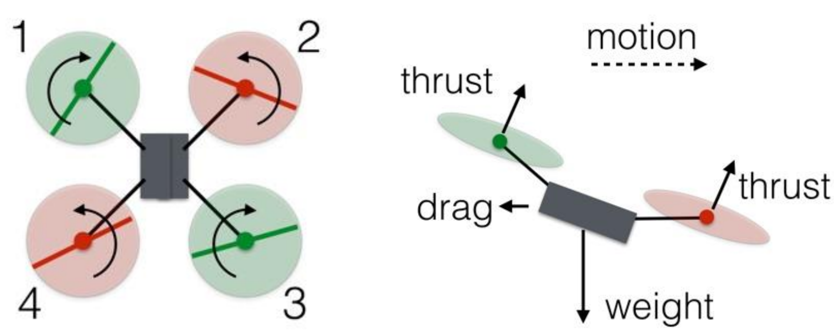


Figure 40. Rotations of Drone Rotors in Hovering State (Allain, 2017)
Figure 41. Rotations of Drone Rotors in a Forward Motion State (Allain, 2017)

A.3 Regulations

Drone law and regulation in the United States is primarily federal mandated. Federal law requires registration of drones as well as compliance with FAA guidelines for model aircraft. Within Massachusetts, Boston is the only city that has additional laws, requiring that recreational drones are flown in city parks.

FAA guidelines are similar in their restriction of both recreational and commercial drones. Additionally, while the FAA only requires that commercial drone pilots receive a Remote Pilot Certificate from them, they have indicated plans to implement a pilot certification requirement for recreational drones in the future. FAA guidelines for flying a drone for recreational purposes are as follows (Federal Aviation Administration, 2019):

1. Register your drone, mark it on the outside with the registration number (PDF), and carry proof of registration with you.
2. Fly only for recreational purposes.
3. Follow the safety guidelines of a community based organization.
4. Fly your drone at or below 400 feet when in uncontrolled or "Class G" airspace. This is airspace where the FAA is not controlling manned air traffic. To determine what type of airspace you are in, refer to the mobile application that operates your drone (if so equipped) and/or use other drone-related mobile applications. Knowing your location and what airspace you're in will also help you avoid interfering with other aircraft.
5. Do NOT fly in controlled airspace (around and above many airports) unless you receive an airspace authorization for operations in controlled airspace through LAANC (Low Altitude Authorization and Notification Capability), before you fly.
6. You are flying at a recreational flyer fixed site that has a written agreement with the FAA. The FAA has posted a list of approved sites and has depicted them as blue dots on a map. Each fixed site is limited to the altitude shown on this map, which varies by location.
7. Keep your drone within your line of sight, or within the visual line-of-sight(VLOS) of a visual observer who is co-located and in direct communication with you.
8. Do NOT fly in airspace where flight is prohibited. Airspace restrictions can be found on our interactive map, and temporary flight restrictions can be found here. Drone operators are responsible for ensuring they comply with all airspace restrictions.
9. Never fly near other aircraft, especially near airports.
10. Never fly over groups of people, public events, or stadiums full of people.
11. Never fly near emergencies such as any type of accident response, law enforcement activities, firefighting, or hurricane recovery efforts.

12. Never fly under the influence of drugs or alcohol.

Additional guidelines for commercial drones that are not being used for payload delivery are as follows (Federal Aviation Administration, 2019):

1. Drone must weigh less than 55 lb (25000 g)
2. Drone cannot fly under a covered structure or inside a covered stationary vehicle
3. Drone must be flown during daylight or civil-twilight (30 min before official sunrise to 30 min after official sunset)
4. Drone cannot be flown above 100 mph
5. No person may act as a remote pilot in command or as a visual observer for more than one drone operation at a time
6. Maximum altitude of 400 feet above ground level (AGL) or, if higher than 400 feet AGL, remain within 400 feet of a structure.
7. May operate from a moving non-aerial vehicle if operating over a sparsely populated area
8. Cannot carry hazardous materials
9. Preflight inspection by remote pilot in command is required
10. A person may not operate a small unmanned aircraft if they know or has reason to know of any physical or mental condition that would interfere with the safe operation of a small UAS.

WPI has drone-specific policy restricting their operation by WPI students or faculty as part of WPI academic research in addition to FAA guidelines outlined above. WPI policy states that that any WPI employee or student wishing to operate a drone as part of WPI academic research must notify the Office of Public Safety. Additionally, if operating said drone outdoors, the WPI employee or student must do so as a 14 CFR Part 107 Pilot in Command for drones weighing less than 55 lb or obtain a Certificate of Waiver or Authorization issued by the FAA (Policies, n.d.).

Out of all of these restrictions and mandates, one of the most notably restrictive is the requirement for a drone to be operated within line of sight of the operator or a visual observer. This requirement restricts the ability of a drone to legally operate autonomously in a legal manner, even on private property. Any drone that would need to travel somewhere to operate would be significantly limited in its range of operation, especially if the operator is using the drone to prevent exposure to weather conditions and thus plans to remain indoors. Furthermore, a drone operating autonomously would still need to be monitored in person the entire time, partially negating the value provided by automating the drone's operation.

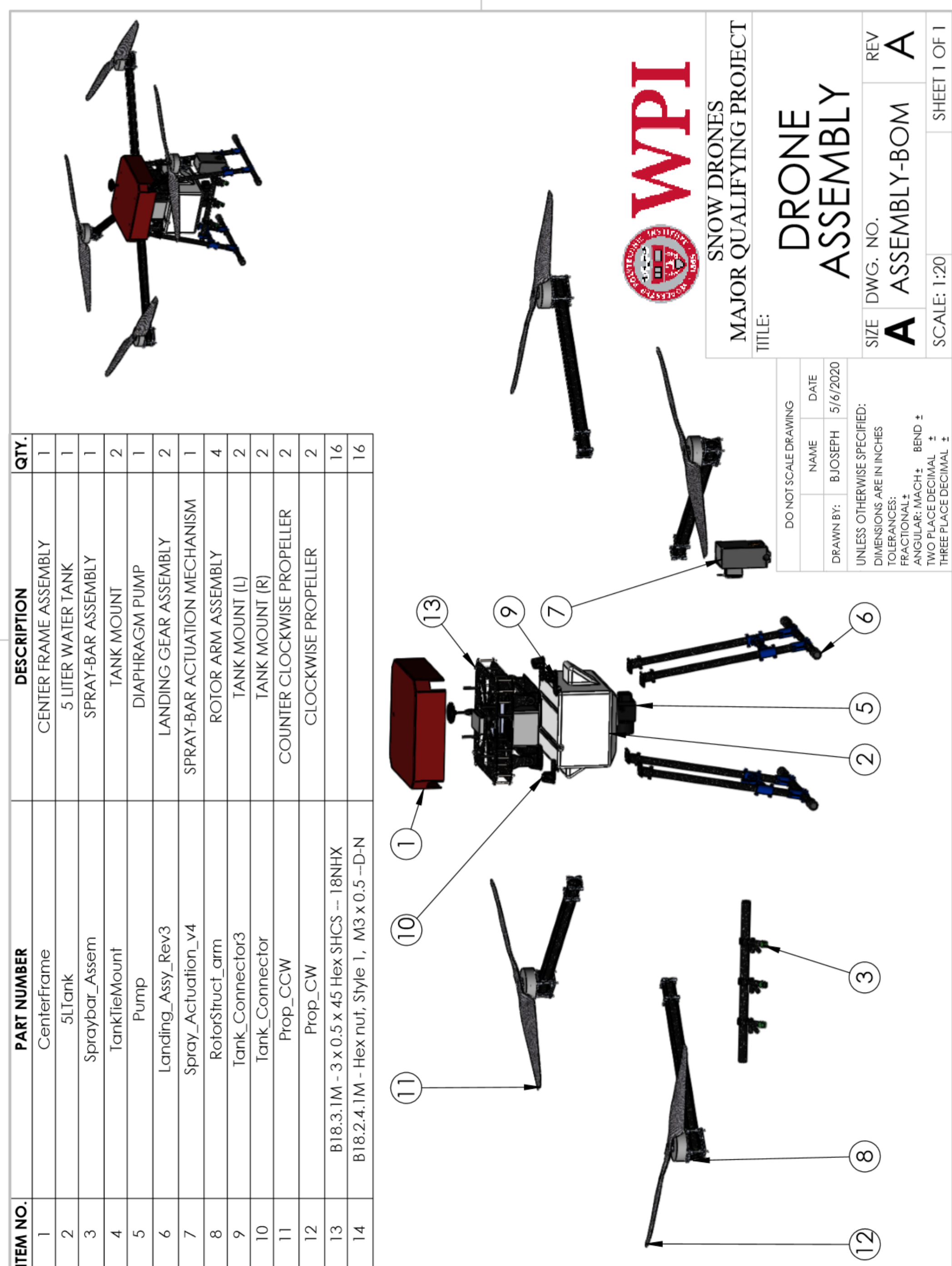
Appendix B. Drone Component Bill of Materials

Table 4. Part Bill of Materials

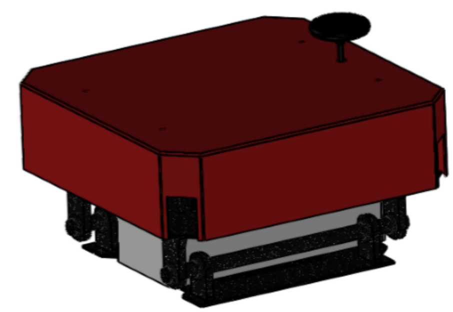
Part	Link	Description
Flight Controller	Link	Pixhawk 4 Flight Controller
Receiver	Link	FrSky L9R Long Range Receiver (9/12ch Non-Telemetry)
Telemetry Radio	Link	Holybro 100mW Transceiver Telemetry Radio Set
Spray Nozzle	Link	Agricultural Spray Nozzle (8mm)
Tank	Link	5L Agricultural Drone Tank
Pump	Link	Eaglepower Brushless Diaphragm Water Pump
Camera	Link	PIM365 IR Camera
Motor	Link	Lumenier LU8 II 190kv Professional Motor
Propeller	Link	28” Folding Propellers
Motor ESC	Link	HOBBYWING XRotor Pro 50A ESC
Pump ESC	Link	HOBBYWING XRotor 40A ESC COB
Battery	Link	Tattu Lipo 22.2V 25C 6S 22000mAh
Cross Connector Quick Fittings	Link	Cross Connector Quick Fittings Connector (8mm OD hose)
PVC Plastic Tubing	Link	8mm OD x 5mm IDSoft PVC Plastic Tubing
PVC Plastic Tubing	Link	12mm OD x 10mm ID PVC Plastic Tubing

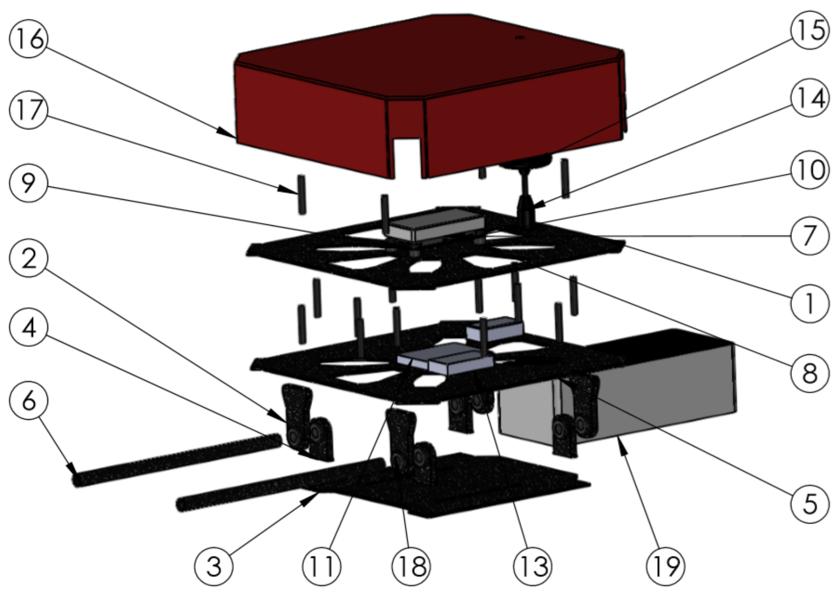
Appendix C. Assembly Bill of Materials

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	CenterFrame	CENTER FRAME ASSEMBLY	1
2	5LTank	5 LITER WATER TANK	1
3	Spraybar_Assem	SPRAY-BAR ASSEMBLY	1
4	TankTieMount	TANK MOUNT	2
5	Pump	DIAPHRAGM PUMP	1
6	Landing_Assy_Rev3	LANDING GEAR ASSEMBLY	2
7	Spray_Actuation_v4	SPRAY-BAR ACTUATION MECHANISM	1
8	RotorStruct_arm	ROTOR ARM ASSEMBLY	4
9	Tank_Connector3	TANK MOUNT (L)	2
10	Tank_Connector	TANK MOUNT (R)	2
11	Prop_CCW	COUNTER CLOCKWISE PROPELLER	2
12	Prop_CW	CLOCKWISE PROPELLER	2
13	B18.3.1M - 3 x 0.5 x 45 Hex SHCS -- 18NHX		16
14	B18.2.4.1M - Hex nut, Style 1, M3 x 0.5 --D-N		16



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TOPPLATE	CARBON FIBER TOP PLATE	1
2	BATTERYPLATESTANDOFF	BATTERY PLATE UPPER MOUNT	4
3	BATTERYPLATE	CARBON FIBER BATTERY PLATE	1
4	BATTERYPLATESTANDOFF2	BATTERY PLATE LOWER MOUNT	4
5	BOTTOMPLATE	CARBON FIBER BOTTOM PLATE	1
6	BATTERYPLATETUBE	CARBON FIBER BATTERY MOUNT TUBE	2
7	PIXHAWK4FC	PIXHAWK 4 FLIGHT CONTROLLER	1
8	ANTI-VIBARATIONRUBBERDAMPENER	ANTI-VIBRATION DAMPENING STAND-OFF	4
9	FLIGHTCONTROLLERANTIVIBPLATE	CARBON FIBER FLIGHT CONTROLLER PLATE	1
10	PIXHAWKFOAMSPACER	FLIGHT CONTROLLER FOAM SPACER	4
11	PIXHAWK4POWERMANAGEMENTBOARD	FLIGHT CONTROLLER POWER DISTRIBUTION BOARD	1
12	FRSKYL9R	FRSKYL9R RECEIVER	1
13	PIXHAWKTELEMETRYRADIO	PIXHAWK 4 TELEMETRY RADIO	1
14	GPSSTAND	GPS STAND	1
15	PIXHAWKGPSMODULE	PIXHAWK 4 GPS MODULE	1
16	TOPCOVER	ELECTRONICS HOUSING	1
17	CENTERFRAMESTANDOFFS	CENTER FRAME STAND-OFF	16
18	TRUWASHER	BATTERY PLATE RUBBER WASHER	8
19	BATTERY	TATTU 22.2V LIPO BATTERY	1





SNOW DRONES
MAJOR QUALIFYING PROJECT

TITLE:
CENTER FRAME ASSEMBLY

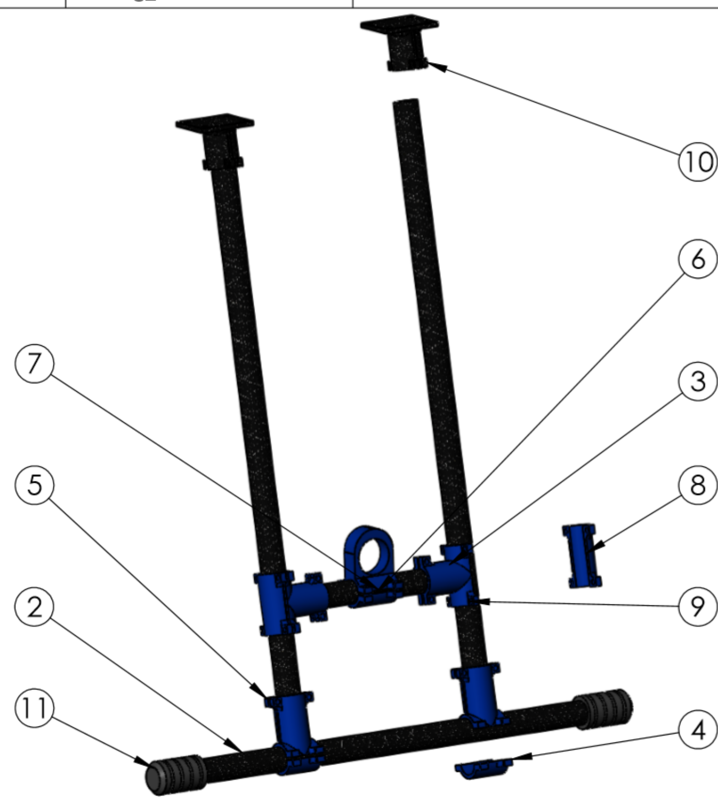
DO NOT SCALE DRAWING		
	NAME	DATE
DRAWN BY:	BJOSEPH	4/27/2020

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

SIZE	DWG. NO.	REV
A	CENTERFRAME-BOM	A
SCALE: 1:10	SHEET 1 OF 1	

SOLIDWORKS Educational Product. For Instructional Use Only.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Landing_Rod_Longer	400MM LONG CARBON FIBER TUBE	2
2	Landing_Rod_Base	350MM LONG CARBON FIBER TUBE	1
3	Landing_Rod_Center	125MM CARBON FIBER TUBE	1
4	Landing_Bottom_Split_Base	ABS PLASTIC BASE JOINT BOTTOM	2
5	Landing_Top_Split_Base	ABS PLASTIC BASE JOINT TOP	2
6	Landing_Cross_Beam_Bottom	ABS PLASTIC CROSS BEAM JOINT BOTTOM	1
7	Landing_Cross_Beam_Top	ABS PLASTIC CROSS BEAM JOINT TOP	1
8	Connector_Bottom	ABS PLASTIC CONNECTOR JOINT BOTTOM	2
9	Connector_Top	ABS PLASTIC CONNECTOR JOINT TOP	2
10	Landing_Bracket_Rev2	CARBON FIBER LANDING BRACKET	2
11	Landing_Feet	RUBBER LANDING GEAR FEET	2



SNOW DRONES
MAJOR QUALIFYING PROJECT

TITLE:
LANDING GEAR ASSEMBLY

DO NOT SCALE DRAWING

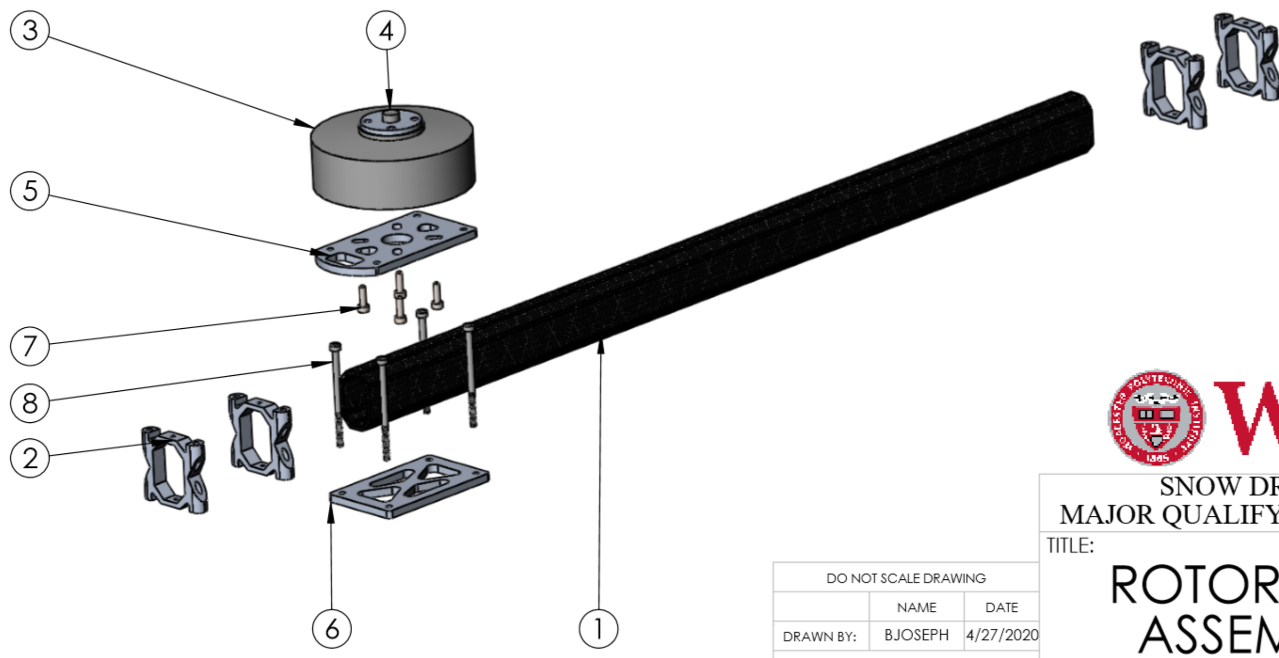
	NAME	DATE
DRAWN BY:	BJOSEPH	4/27/2020

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

SIZE	DWG. NO.	REV
A	LANDINGGEAR-BOM	A

SCALE: 1:10 SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	RotorStruct_arm	CARBON FIBER ROTOR ARM	1
2	RotorStruct_clamp	ROTOR ARM ALUMINUM COLLAR	4
3	MN701S	LUMENIER 190KV MOTOR	1
4	FoldProp_bottomspacer	MOTOR SPACER	1
5	Top_CNC	MOTOR MOUNT TOP PLATE	1
6	Bottom_CNC	MOTOR MOUNT BOTTOM PLATE	1
7	B18.3.1M - 3 x 0.5 x 10 Hex SHCS -- 10NHX		4
8	91292A026		4



SNOW DRONES
MAJOR QUALIFYING PROJECT

TITLE: ROTOR ARM ASSEMBLY

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN BY:	BJOSEPH	4/27/2020

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

SIZE A | DWG. NO. ROTORARM-BOM | REV A

SCALE: 1:10 | SHEET 1 OF 1