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ODDISY Drone Dispatch System

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ODDISY
DRONE DISPATCH SYSTEM

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Abstract

Commercial applications that require autonomous air platforms are becoming more prevalent, however there is a lack of commercially available ground stations that enable remote takeoff and landing. This project served to design and fabricate a ground station and custom UAV interface to allow remote landing, storage, and takeoff of autonomous drones for commercial applications. This included hardware in the base station responsible for charging and protecting the drone with a weatherproof enclosure for storage. The drone was autonomously controlled using a high accuracy GNSS combined with custom control software to follow flight paths and land within the ground station. The drone is extendable and can mount various standard sensor suites to serve a wide range of commercial applications.

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1 Introduction

Autonomous Unmanned Aerial Vehicles (UAVs or drones) are becoming a widely adopted technology in various industries because of their ability to perform aerial tasks and provide precise data with low risk and cost compared to traditional methods (Uavia, 2018). Goldman Sachs Research predicts that by 2020, there will be a $100 billion market for drones, with the commercial sector spending over $13 billion over the next 2 years (Goldman Sachs Research, N.D.). Industries such as agriculture, surveying, infrastructure, utilities, and more all are using drones because of their quick, cheap, and safe inspection capabilities (Walker, 2017). With the growing operation of drones, companies need to adopt new systems to automate their use.

While many companies have already begun using drones to augment their operations, there are still many problems associated with such systems (Brodsky, 2017). Current technology requires companies to either have a skilled pilot on staff, or go through external companies for their drone needs. Both of these options can quickly increase their costs and limits the availability of these services. If a company ever needs to do an emergency inspection late at night, they are greatly limited by the schedule of the pilot. This cost and downtime is compounded by the current battery limitations for these drones, as pilots spend a large portion of their time landing, charging the battery, and then resuming their mission, rather than doing useful work.

Companies such as Uavia, Airobotics, and Drone Deploy are developing systems to allow pilotless operation of UAV’s for a variety of applications. These companies are using a combination of autonomous UAV’s and on-site base stations to control and maintain the drones, but these technologies are still emerging and have not fully matured. For example, Airobotics is currently using a base station the size of a minivan combined with a quadcopter to assist with a construction project (Airobotics, 2018). In May 2018, they partnered with Shapir-Ashtrom on the construction of a new seaport, Gulf Port as the first company to gain pilotless flight certification. As the regulations and technology develop, more competitors are expected to enter the commercial drone space. Autonomous drone systems reduce response time, increase consistency between surveys, increase operation safety, and decrease overall cost per use, making them an attractive solution to a variety of industries

Currently there is no widely accepted system for using drones. In its current form, drones have to be manually deployed by a trained operator with time spent developing the flight plan. Drone use in urban settings is almost nonexistent due to the safety concerns, setup and deploy time, and logistics required for the current regulations of the FAA (Uleski, 2018).

In this MQP, we designed and fabricated the ODDISY Drone Dispatch System, (ODDISY) consisting of a ground station and UAV interface platform that allows remote landing, storage, and takeoff of autonomous drones for commercial applications. This included hardware in the base station responsible for charging drone batteries, protecting the drone with a weather-resistant enclosure for storage, and a custom hexacopter capable of autonomous flight. These systems allowed complete autonomous takeoff, mission/navigation, and landing without any human intervention. The Base Station and drone were able to communicate to a remote human manager to provide flight statistics and logs. The base station was able to charge the drone automatically between flights, eliminating the need for manual intervention from a remote manager.

2 Background

In this chapter, we will begin by discussing the current regulations on commercial drone use and how they are expected to change. Next, several applications for drone use will be discussed. Finally, the metrics of drone use in each of these sectors will be rated and compared.

2.1 Regulations

Drones are a new technology and regulations have been slow to adapt to their uses. For the use of this project, the current and future regulations will be discussed to understand the directions of drone use in the US.

2.1.1 Current Regulations

Recently, the FAA is facing a new regulatory region for the commercial applications of drones. The FAA issued its first Unmanned Aircraft Systems (UAS) policies in 2007, in which the FAA stated it was hesitant to allow UAS uses for commercial purposes because of safety concerns (Speicher, 2016a). This policy prohibited non-recreational uses of UAS without an explicit Certificate of Waiver or Authorization (COA) with a public sponsor. These waivers were very difficult to obtain and often took large lengths of time to grant making them almost useless for commercial interest of drone development. This led to large entities like Amazon and Google lobbying congress to intervene in the FAA's policies. Politicians did not ignore these companies, and in 2012 they passed the FAA Modernization and Reform Act, in which congress gave the Secretary of Transportation the authority to allow certain commercial uses if seen fit, much like COAs. More importantly, the act required the FAA to "develop a comprehensive plan to safely accelerate the integration of civil unmanned aircraft systems into the national airspace" (Mica, 2012). This plan forced the FAA to address the rapidly growing need for regulatory changes by 2015 because the current regulations are stunting the growth and development of many companies. Every year the FAA delayed integrating UAS into the national airspace; approximately $10 billion is lost in potential economic growth (Dillow, 2013). The FAA's response to these concerns was the Small Unmanned Aircraft Rule, or Part 107, released in 2016. US Transportation Secretary Anthony Foxx stated:

> "We are part of a new era in aviation, and the potential for unmanned aircraft will make it safer and easier to do certain jobs, gather information, and deploy disaster relief. We look forward to working with the aviation community to support innovation, while maintaining our standards as the safest and most complex airspace in the world." (DOT; FAA, 2016)

This rule is estimated to generate over $82 billion for the US economy and 100,000 more jobs in the next 10 years. The rule allows small (<55lbs) commercial drone flights that follow a series of provisions designed to minimize risks (FAA, 2016a):

- Must keep drone within direct unaided line of sight.
- Operator cannot control more than one drone at a time.
- Only fly during daylight or in twilight (30 minutes after sunset or before sunrise).
- Maximum allowed altitude of 400 feet above ground, maximum speed of 100 mph, and maximum weight of 55 pounds.
- Cannot fly over anyone who is not participating in the operation, including moving vehicles.
- Operation only in Class G airspace without air traffic control permission.
- Pilot must have remote pilot airman certification for UAS.

These rules are in conjunction to a slightly modified waiver system, which still allows pilots to submit forms for flight exception to one or many of these provisions. However, the regulations themselves are the main barrier for commercial entities because the waivers are still exceedingly difficult to acquire and take six or more months to process. In order for the FAA to integrate commercial UAS into the National Airspace System, they first need to understand the commercial application and their roadblocks to develop regulations that are more adaptable.

The Part 107 regulations for commercial drones restrict most commercial applications in two ways: the need to maintain visual line of sight (VLOS), and only operating a single drone at a time. Using drones for agricultural monitoring, terrain surveying, delivery services, or disaster response are just a few of many applications that break one or both of the above rules during regular operation. Additionally, many commercial applications involve mass services with urban customers. This means that large, populated cities will likely become hubs for large commercial drone markets, which brings several additional safety concerns. Not only would drones be operating over populated areas, there would also be conflicting airspace for populated cities with airports. With current regulations, the FAA would need to approve waivers for each individual use in a case-by-case approval system for companies like Amazon Air or Google X to use their drone systems. This lengthy and arduous task is putting off large companies like DHL, Google X, and Amazon Air from developing UAS commercial applications inside the United States (Faggella, 2017). These companies are instead choosing to move their research centers overseas where approval processes for drone usage is much faster and more flexible. Countries like the United Kingdom, Germany, and Australia all offer much shorter application processes and more lenient approval decisions for developing and testing new UAS operations.

The main reason for the FAA's slow and ambiguous waiver system is that the FAA is much more cautious than their counterparts in other countries. The FAA was founded on the basis of aviation safety and they have kept that philosophy since their conception. They are unlikely to make hasty sweeping decisions when it comes to drone use in the National Airspace System. However, they are aware of the problem companies are having with the current system. The acting Administrator of the FAA, Daniel Elwell, stated in November 2017 that the current low-altitude (drone) authorization and notifications group receive between 500-600 requests and 100 waiver requests per week, which they can only process 300 of each week. This has led to a backlog of over 8,000 requests which Elwell has identified as unsustainable for both the FAA and operators. Backlogs like these will only stunt the growth of the industry which will not only decrease economic growth, but also encumber the FAA's integration efforts. This reinforces the need for change that would bring more commercial UAS operations to the US.

2.1.2 Current Actions

The FAA has put great effort into launching programs to safely accelerate technological system development for UAS integration into the National Airspace System. These programs range from risk management case studies and drone collision assessments to airport test centers for traffic management prototype testing. The notable programs are LAANC (Low Altitude Authorization and Notification Capability), UTM (UAS Traffic Management), COE (Center of Excellence), and the UAS Integration Pilot Program. Each of these programs is focused on an important aspect of UAS integration on both the policy and technological side of the issue.

The LAANC program, started in 2017, is a new system being tested at a select few airports in the US that allows drone operators to access and share low altitude air space with manned aircraft (FAA, 2018). This system allows drone operators to request digital airspace on live maps with manned air traffic, this request is than approved or denied by the air traffic controller. The NAS then updates this information, allowing all nearby air traffic to be aware of low-altitude traffic. This system shows promise to be a short-term solution to the issue of contested airspace for commercial drones. It does not, however, fully implement an automated control system as these requests are still reviewed by an air traffic controller.

The next program, the UAS Traffic Management system, does what the LAANC cannot, automatic flight assessment and safe flight coordination (Gipson, 2017). The FAA is teaming with NASA to design a platform to coordinate and analyze large numbers of Unmanned Aircraft Systems in local airspace environments to assess reliability and provide safe flying opportunities. This program has been tested in small-scale simulations at various testing sites and shows great promise as a platform to base future UAS operations on. "Industry will play a major role in the implementation, operation, and maintenance of UTM systems in the U.S. airspace," said Nasa coordinator, Arwa Aweiss. "The TCL2 test activities provide a glimpse into the roles of our many partners by connecting their system prototypes and components with NASA's UTM research platform." This system will be highly favorable for commercial uses as it can handle large numbers of drones and the potential for industries to collaborate and influence how drones will use the system.

The Center of Excellence is an alliance of 23 research institution partnered with industry and government to provide the FAA with research to quickly, safely, and efficiently integrate Unmanned Aerial Systems into the National Airspace System (Assure, 2018). This group of institutions conducts research towards various safety areas related to drone flight such as control, communication, DAA (Detect and Avoid), human factors, and training. This provides the FAA with vital information for risk management to assess potential damages than can be caused by drones and what can be done to prevent them. Unlike the LAANC and UTM, the COE is a source of knowledge, not technology. This makes them highly valuable for influencing policy framework by highlighting what risks of drone flight will be most important for integrating UAS into the NAS.

Last, the UAS Integration Pilot Program connects the policy makers with pilots, companies, and stakeholders to understand what issues are most important to each party. Applicants to the program are evaluated by the FAA and grouped together to create a dialog between the policy makers and the public. The Department of Transportation hopes to balance local and national interest with respect to UAS integration

Although the commercial use of our project does break the part 107 regulations without a waiver or pilot, we are developing our system in anticipation of FAA changes to the current regulations to allow fully autonomous planned flights in open airspace.

2.2 First Responders

First responders face some of the most difficult situations of any job and they are expected to respond quickly and adapt to the unique needs of every scenario. With so much variability in their daily activities, these professionals encounter a multitude of problems and are constantly looking for innovative ways to augment their existing response ability. As technology continues to advance, more departments are evaluating how they can integrate these new solutions into their daily workflow. This next section will investigate the responsibilities and current response methods of police, EMT and fire response teams and evaluate how technology could be used to augment their existing solutions.

2.2.1 Police

Police officers are responsible for a variety of daily activities ranging from patrolling areas to investigating accidents to apprehending suspects (Bureau of Labor Statistics, 2018). While many of their duties fall on the mundane side of the spectrum, it is the extreme emergency cases that make these figures known and garner respect from the general population. These extreme cases also present the most issues as they are often time critical and potentially dangerous to both the officers and the victims. Officers involved are expected to respond in minutes and make split second decisions using the information gathered once they arrive on scene. Before evaluating where technology can be used in these scenarios, it is important to understand their current response.

The first area to focus on is the response time of the officers. Response time is believed to be a key indicator of the performance of a police unit because of its close correlation to arrest rate and citizen satisfaction (Lee, Lee, & Hoover, 2016). By arriving on scene faster, officers are more likely to encounter the suspect on site and perform an immediate arrest. Having a faster response time has the added benefit of serving as a deterrent for future crimes. It is more difficult to rob a home or get away with violence if the police are likely to arrive in minutes. Despite the importance of arriving on a scene quickly, response times around the country vary widely, ranging from the usual case of 5-10 minutes to the extreme case of 60+ minutes (Auto Insurance Center, 2018, P, 2017). This is due in part to the many uncontrolled variables that affect how quickly an officer can respond. An officer's distance to the scene, their current activity, and their driving speed are all significant factors that may delay their response.

The second major component of police success rates are the availability of information about the incident and involved suspects. Officers spend time both on scene, and off scene gathering information about potential suspects and performing investigations in order to catch criminals. Issues arise however, when officers need to rely solely on the word of the victims in order to reconstruct what happened and who was involved. Boston criminal defense lawyer James M. Doyle states, "Memory is not like a videotape or photograph. It's very vulnerable to contamination, If you have physical evidence like blood, you can send it to the lab to see if it's been contaminated. With eyewitness evidence, you can't" (Opfer, 2013). Because of this eyewitness reports are often unreliable and can only construct a partial picture of what actually happened.

In an effort to better enable the information gathering of the police, over 900 agencies are turning to drones to gain an aerial perspective (Bergal, 2018). These agencies are using these drones at the scenes of car accidents to form a three dimensional model of the scene and reconstruct the crash. This helps them form a more accurate depiction of the accident in a much shorter amount of time, allowing roads to be reopened sooner. These drones have additionally been used to perform search and rescue missions because of their speed and efficiency in a wide area search (Dukowitz, 2018). By utilizing thermal imagery it becomes easy to identify people who may need help, even in dense smoke or foliage. As drone technology increases, emergency departments are increasingly using drones in a variety of other areas including traffic management, crime scene mapping, and hazardous material inspection. All of these drone uses however require a skilled pilot to be on the police force so country-wide adoption has been relatively slow.

2.2.2 Fire

Similar to the police, fire departments are increasingly using drones to increase the information they can gather on scene (PoliceOne, 2017). By using advanced imaging sensors, emergency responders can detect people inside of smoke-filled buildings and can analyze hot spots of the fire. This additional information ensures that firefighters know exactly what situation they are walking into which serves to keep both the victims and the rescuers safer. Jamie Moore from the public safety UAS response team stated, “It’s better information, and with better information comes better decisions. It’s the next best thing since a fire hose”. Flying near fires however complicates the pilots job as they need to take care to avoid high temperature areas and often need to fly in cluttered city environments.

2.3 Agriculture

Agriculture covers a wide spectrum of different tasks ranging from monitoring crops and cattle, to mapping farmland, to spraying crops. These tasks have traditionally been tedious or expensive, requiring specialized equipment or training. With emerging drone technologies, strategies utilizing cheap, easy-to-use drones have reduced time and cost for monitoring of farmland. With 33% of farmers stating that they use drones themselves and another 31% saying that they would consider using drones, the use of drone in agriculture is becoming more standard (Margaritoff, 2018). This section will cover the current state of agricultural monitoring and maintenance and will investigate the use of drones with accompanying new technologies.

2.3.1 Monitoring

Monitoring has traditionally required manned aircraft, fixed wing or helicopter, with a trained pilot and large sensor suites. More recent than the use of aircraft, satellite imaging has been used to give imaging of farmland. With advances in multispectral imaging and drone technology the same functionality and more can be fit onto a drone. This in term means that real-time analytics can be created to improve farm productivity and forecast crop yield. Drones equipped with multispectral and hyperspectral sensors can create a Normalized Difference Vegetation Index (NDVI). Figure 1 below shows the resolution of a conventional satellite NDVI compared to a drone imaging the same area.

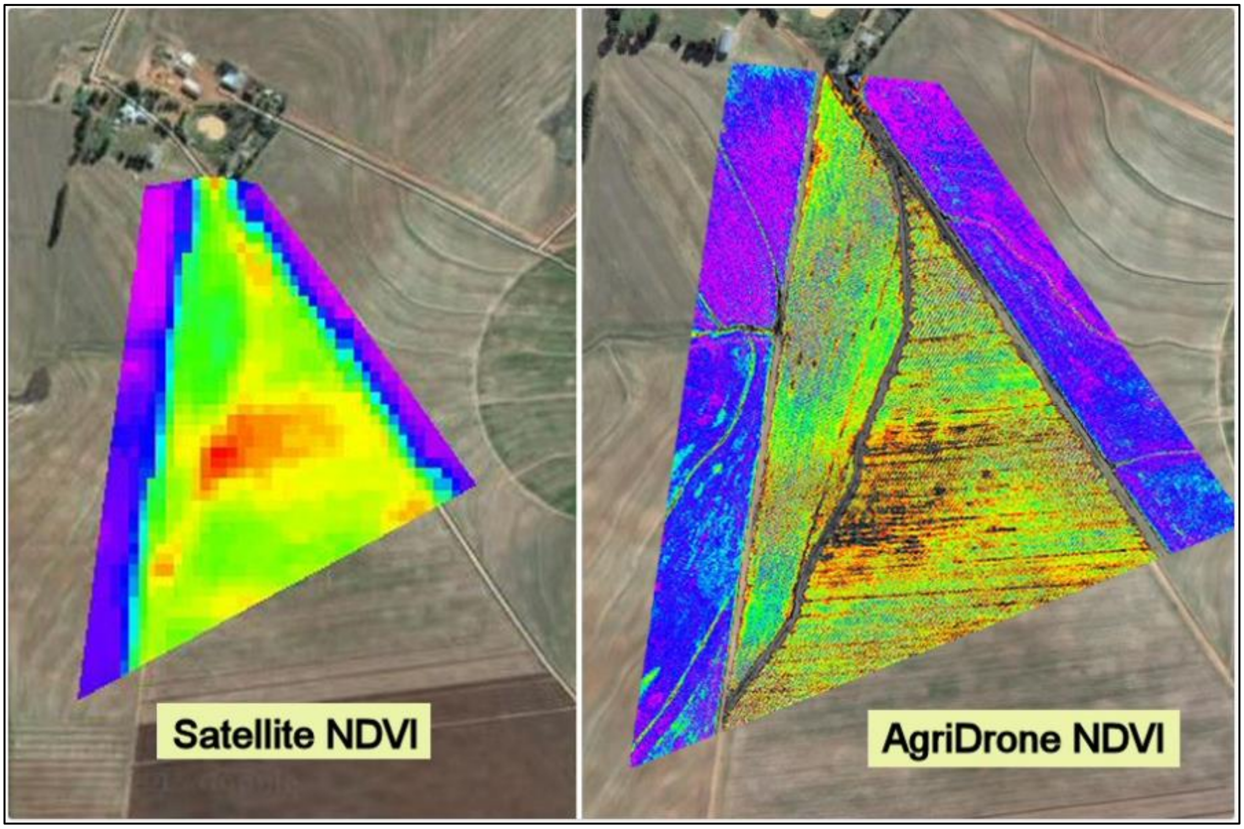

Figure 1: Evidence-Satellite NDVI (Agridrone, 2017)

NDVI has been shown to have strong correlation to crop yield estimations, making the availability of real time analytics crucial (Food and Agriculture Organization of the United Nations, 2018). While satellite imaging has the same sensor suite and drones, they are highly reliant on weather conditions to have clear line of sight from orbit to farmland. Additionally, they have to be ordered in advance are often less precise than imaging and spectrums created by drones and aircraft.

In addition to monitoring of crops, livestock monitoring requires an aerial view with specialized imaging sensors . This particular form on monitoring requires quick and up to date information, making satellite imaging to slow.

2.3.2 Spraying

Drones have also had new growth in crop spraying for crops that use fertilizers or pesticides (Baraniuk, 2018). Farmers are using large drones capable of carrying 20L tanks with spray nozzles to cover large areas; a single team could spray 100 acres in one morning. Not only do drones replace the need for planes or tractor spraying, they can also access fields that were previously difficult to reach. Farmers are still hesitant to adopt the new technology in some areas however. Baraniuk explains that “drones may be automated but they still require humans to pilot, program and service them, which raises the cost”.

2.4 Infrastructure Inspection

A promising field for UAV use is in infrastructure inspection locations. In particular large-scale projects that involve traditionally-difficult-to-reach areas show the most promise, include wind turbines, power lines, railroad tracks, solar panels, bridges, etc. As Han states, “camera-equipped UAVs provides an unprecedented mechanism for inexpensive, easy, and quick documentation,” of construction and operation of civil infrastructure (Han, 2016). With resulting reduction in cost UAVs could allow safety-critical inspections to be performed faster and more often (Panto, Thomas, 2015). This section briefly covers the current inspection methods of the mentioned industries, and lists some ways UAV’s are, or are expected to, assist.

2.4.1 Wind Turbines

Wind Turbines are becoming more prevalent as the world transitions to environmentally-friendly ways to generate electricity. However, with time, these turbines are subject to damage from the elements (rain, hail, birds, lighting, etc) and general wear, and need regular inspection to ensure they operate reliably (Murphy et al, 2012). Since wind turbines can reach heights of over 300 feet tall, manual inspection typically require a combination of a large crane and climbing-rigged technicians. This process is further complicated when the turbine is located offshore, further increasing cost and turbine down-time. With the rise of UAV technologies, some companies are already offering aerial inspections as an alternative to the labor-intensive manual process (Measure, n.d.)

2.4.2 Solar Panels

Similar to wind turbines, solar panels require regular inspection and maintenance to operate safely at peak efficiency. While solar panels are generally very tall, they require inspections from above with a thermal-camera or electroluminescence scan in most cases. Historically, this was achieved manually with a cherry-picker for small installations, or a manned-helicopter for larger solar farms. However with small helicopters costing upwards of $300 an hour to operate, this method can quickly become costly, in addition to the safety risk of hover-flight. These factors reduce the rate solar panels are inspected, increasing risk over time of a fire caused by a defective panel (Proline n.d). But with these same sensors attached to UAV solutions “working in difficult terrain and with non-standard designs becomes feasible,” and reduces cost of the operation (Koch et al, 2016).

2.4.3 Bridges

While bridges are usually in more urban areas compared to wind turbines and solar farms, they are often more difficult and tedious to inspect. Much like offshore wind turbines, many bridges can be difficult to reach with crane solutions. However, since bridges are more intricately shaped than wind turbines, and are usually continuously populated with traffic, helicopters cannot be used for inspection. This leaves inspections to be performed entirely manually by a combination team of climbing-rigged inspectors and specially designed “snooper” trucks (Zink, Holdhusen, Lovelace 2015). The costly process can cost upwards of $10000 for small to medium sized bridges (Zulfiqar et. al., 2016). Unlike previous applications, UAVs are not currently being used for bridge inspection, since several critical problems have yet to be solved, such as stability and accuracy of control, and safety to the public (Chan, Guan, Jo, & Blumenstein, 2015). However, with the US infrastructure such as bridges rapidly deteriorating, many anticipate UAV inspection could provide significant benefit to public safety.

3 Methods

In order to create a more functional drone, we first developed a set of metrics to decide on a specific application to focus on. This gave us a specific task that has basic flight requirements which can later be adjusted to fit other needs if the project is expanded. As detailed in the next section, we decided to approach the agricultural inspection sector. The design requirements for this application were then broken up into six categories: user interaction, drone design, maintenance, storage, landing/takeoff, and batteries. Each of these has a set of requirements that is tailored to meet the metrics specified below. The user discussed in the following sections will be defined as an end user who does not have vast experience operating drones. Some requirements, however, will be tailored to the nature of this being an MQP to allow us to test, debug, and minimize the chance of failures during development.

3.1 Metrics

Based on the applications described in section 2, we have established a set of metrics to evaluate what each industry would need from a drone system. These metrics include:

Payload - The weight measured in kilograms that a drone would need to carry

Flight Time - The time measured in minutes a drone would need to fly

Usage Frequency - number of potential drone usages per day

Response Time - The time measured in minutes the drone needs to respond to a flight request

Environment Motion - A rating from 1 to 5 describing how much movement is there in the environment, where 1 would be a static farm with little to no creatures, and 5 would be a busy city with many moving obstacles.

1. Entirely stationary
2. Small/occasional movement, slight wind
3. Predictable movement, moderate wind
4. Unpredictable movement, heavy wind
5. Unpredictable, frequent movement, severe weather conditions

Environment Clutter - A rating from 1 to 5 on potential drone obstacles

1. No obstacles above ground level
2. Occasional trees / powerlines
3. Forest/ small buildings
4. Small City/town
5. Skyscrapers / very tall structures

Environmental Complexity - The rating from 1 to 5 on drone flight difficulty. 1 is the easiest and 5 is the most difficult. Derived from the average of environment motion and environment clutter.

The payload for the majority of these applications consists of one or two cameras mounted on a gimbal which have weights ranging from 0.2 to 0.5 kg. The exception to this is the agricultural spraying which requires a much larger payload for the actual pesticides and spraying equipment. Data on the required flight time for each of these applications was not readily available so these numbers are estimated based on each usage. From an average police and fire response time of 15 minutes and an average incident length of 15 minutes the drone would need to remain on scene for about 30 minutes to gather relevant information. For each of these applications, longer flight time is always better to have a better response even in longer situations. For the agriculture and inspection sectors, flight time is not as important as the drone would have many opportunities to charge and then resume its flight. For usage frequency of police and fire, the uses/day was estimated using the number of calls per year and the number of police or fire departments around the U.S which resulted in about 45 emergency responses per day for police, and 1 response per day for fire departments. Based on current satellite monitoring of agriculture data we estimate that farms will still want at least 1 inspection per day. Spraying and inspection however happen infrequently enough that they would need less than 1 drone use per day. The environmental complexity was estimated using our intuition about common scenarios and environments for each sector. For most of these applications, if severe conditions were present, the flight could be delayed. This does not apply to police and fire situations as they will always need an immediate response. These metrics are summarized in table 1.

Application	Payload (kg)[0]	Flight time (min)	Usage Frequency (uses/day)	Response Time (Min)	Motion (1-5)	Clutter (1-5)	Complexity (1-5)
Police	0.2- 0.5	30	45[2]	< 5	5	5	5
Fire	0.2 -0.5	30	<1	< 5	5	5	5
Agr. Monitor	0.2-0.3	15[1]	1	< 60	2	2	2
Agr. Spray	10-20	15[1]	<1	< 60	2	2	2
Turbine Insp.	0.2 - 0.5	15[1]	<1	< 60	3	3	3
Solar Insp.	0.2 - 0.4	15[1]	<1	< 60	1	2	1.5
Bridge Insp.	0.2 - 0.4	15[1]	<1	< 60	3	5	4

[0] values estimated based on current market sensors/gimbals/payloads
[1] Flight time may require repeated flights for task completion
[2] Assuming 240 million calls per year and 15,000 police departments and 100% need drones (Greenberg, 2016, NENA, 2017)

Table 1: Autonomous Drone Application Metrics

From the above table we can see that some applications are much simpler to design for and allow for more relaxed design considerations for an initial system prototype. Combining these difficulty metrics along with the current FAA regulations we narrowed our development to focus on the agricultural monitoring application. We started by eliminating the police, fire, bridge inspection, and solar inspection applications from our design scope because of the navigational complexity. While these would still be viable for future development, the autonomous navigation requirement was too complex for the scope of this project. We then eliminated the agricultural spraying application because of its large payload requirements. In order to lift enough pesticide a much larger drone would be required which was outside of our desired budget. Additionally having pesticide onboard the drone would require another system to refuel this resource. We finally eliminated the solar inspection in favor of agriculture inspection because solar arrays need much less inspection than farms and there are far more crop yielding farms than solar farms. The agriculture inspection provided a simple, known environment to fly over while still being highly beneficial to many farmers.

3.2 User Interaction

Creating a way to control our drone system and access information that is collected is vitally important to the success of any drone mission. What the drone is doing, where it is going, and when it is going there needs to be conveyed before the system can do anything.

The user must be able to make simple flight plans using waypoints to mark areas to monitor. The user must also have control over the payload that it is carrying. The gimbal mounted sensor will be specified by the user, but the system will control it during operation.

Since this drone would be equipped with a monitoring device such as an NDVI camera, the drone will need to transmit the data recorded throughout a mission to the user. For agricultural use this data can be transmitted at the completion of the mission and does not need to be streamed live as the response time in this case is much longer. Typical NDVI systems do image analysis on board and present the result to the user, however for this project we will only be required to transmit the raw data.

The system also must stay compliant with FAA regulations for the duration that they are in effect. The most important regulation to consider for agricultural use is that the person in command of the drone or a participating observer is within visual line of sight of the drone. This means that someone must be able to view the drone; and someone must have the capability to command the drone to take immediate actions should the need arise. For this reason, the user interface must include manual override commands. Additionally, for the development stage of this project a full manual override command will be included such that an operator can take joystick control over the drone. This improves both the safety of the observers and the drone in the event of problems occurring during testing.

3.3 Basic Drone Design

The drone design requirements for agricultural monitoring are determined by the payload size and weight, the flight time required, payload safety, and the complexity of the required flights. As previously discussed, for agricultural monitoring, the drone must be capable of 15+ min flights with a payload of ~300g. Additionally, since the drone will be carrying an expensive sensor as the payload, there must be flight redundancy and protective measures to prevent damage to the sensor. Since the complexity of the environment for farms is low as there are a low number of elevated obstacles, the drone will not be required to sense and avoid objects during flight.

3.4 Maintenance

Keeping the drone at operational status or notifying the user in the event of problems is an important aspect of any system both during development and after deployment. In order to keep the drone operation, the battery is the most important system to maintain.

Since the drone is carrying a large capacity Lithium Polymer battery (LiPo) (see section 3.7), special precautions must be made to keep the battery from degrading or reaching a potentially dangerous state. LiPo's can degrade from overvolting, undervolting, extreme temperatures, or nonuse. In order to prevent over or undervolting, each cell of the battery needs to be measured to prevent going above 4.2v or below 3.0v. If either of these happen, the cells can catch fire and cause catastrophic damage to other systems. The battery must also only be used at temperatures ranging between 32F and 140F to prevent cell damage during charging or discharging. For long term storage, the battery must be cycled at least once per month to prevent capacity degradation.

In order to debug the system to uncover problems, the drone needs to be able to log data that can be inspected later. These problems could consist of communication issues, motor loss, power loss, or a wide variety of other reason. It is impossible to predict what will go wrong, but periodically logging actions and various sensor data will give the best chance of being able to locate and solve the problem.

3.5 Storage

Given the nature of the overall task the drone must be stored in a separate structure that can dock and charge it, known as the "base station" in this paper. One of the major aspects of having a base station is that it must be outdoor, and thus must be weatherproof against sources of water precipitation, namely rain and snow. The base station must have an actuated mechanism that can allow the drone to take off and land, but protect against the weather when the drone is being stored. The structure must satisfy IP32 standards, which specify that it is protected against all solid particles >2.5mm and falling water at a 15° angle. This will give protection against common storms and prevent animals or unauthorized humans from being able to access the inside of the structure while closed. The Base station will also be responsible for housing all electronics and components for take-off and landing that are not attached to the drone. In effect, it serves as the "origin" of any mission performed by the drone.

3.6 Landing and Takeoff

A major aspect of the function of the drone is in the takeoff and landing capabilities. The drone must be able to autonomously take off from and land on a fixed position inside the base station when the user specifies. Since the drone must be able to do these actions on its own with sensors, a passive docking system will be assumed which will give a 130mm diametrical landing circle as tolerance. This passive system is based on the overall diameter of the drone and estimated diameter of the payload to give proper clearance. The drone will require its own localization sensors to detect where the station is and how to properly land in it. This means the drone needs to stabilize and control its own flight during operation.

In order to satisfy the mission requirement of 15 minute flights, minimizing the time required for takeoff and landing is critical. Because of this, we established time-limit goals for takeoff and landing as 15 and 45 seconds respectively in order to keep the remaining time for the mission largely unaffected (7% reduced).

3.7 Battery

Since drones need to remain powered throughout all flights, properly selecting batteries and chargers, as well as managing their usage is an important aspect of this project. Based on preliminary testing, we determined that the power required for a similarly sized airframe to be 414 watts without any additional payload. This means the battery must be able to supply a constant 450-550 watts during flight. Additionally, since farmers want frequent inspections of the farm, we needed to develop a charging system that could allow the drone to perform another mission after 30 minutes of downtime. This charging system would be responsible for safely and quickly charging a lithium polymer battery. In tandem with the charger we needed to develop a battery management/power distribution system to ensure the safety and longevity of the battery. This system is responsible for the following battery solutions:

1. Cell Balancing: The system must be able to keep each cell of the battery within 1 millivolt of the other batteries. This ensures the lifetime of the battery and increases the safety of the battery system.
2. Safety Monitoring: The system must be able to read and report battery temperatures and voltages and have the ability to disconnect motor power in the event of a motor problem.
3. State of Charge Estimation: In order to estimate remaining flight time and ensure the aircraft always has the ability to return to the station, the system must continuously monitor how much charge is left in the battery.
4. Power Distribution: This system must be able to pass power from the battery to the motors while simultaneously powering any other peripherals. This system should also be able to shut off power to noncritical subsystems while docked in the station to reduce passive power draw.

3.8 Design Approach

For each of the above sections we followed a similar design approach. We started by identifying the problems that each of these requirements created and performed preliminary research to identify the pros and cons of each possible solution. Each solution was explored until we reached a consensus on which idea would be most beneficial to this project. From there we repeated this process until our preliminary research did not yield any additional issues to address. Once the rough outline of problems and solution pairs was created, we developed initial prototypes to gain a better understanding of the solution and further identify any additional problems that arose. These prototypes were then redesigned and recreated until we were satisfied with their performance and were ready for integration into the entire system. The results of this process are reviewed in section 4.

4 Design

In this section we detail the final product we constructed as part of this project. Using the design requirements we described in section 3, we created a prototype and proof-of-concept drone, base station, and supporting infrastructure. Each aspect of the design is summarized below, organized around the design requirements. The full prototype design, including mechanical CAD files, Electrical PCB designs and schematics, and software for all devices can be found in the archive provided with this paper.

As an important note, when presented with an unconstrained design choice, we often decided on solutions that reduced cost and increased the ease of manufacturing. For example, if a part could be made of sheet-metal, or CNC billet machined, the latter was chosen because WPI has an extensive CNC lab but few sheet metal facilities. As another example, if a motor driver cost $450 but could be constructed ourselves for $30, we often chose the latter because, while more work, it saved money on the project. If this design were to be mass-produced, or became less budget and more time constrained, many of these choices would change.

4.1 Flight Safety

Due to the dangerous nature of flying aircrafts, safety was a very important consideration in the development of our communication and control systems. The main player in the safety system is the Flight Safety Handler, or FSH. The FSH is responsible for receiving data streams from sensors and sending them to the drone computer, a Raspberry Pi (Pi). This custom electronics board also receives both the manual radio control (RC) commands from the controller as well as the RC commands sent from the autonomous controller and sends a single stream of RC commands to the flight controller. During the development stages of this project, it was important that the manual operator was able to easily take control of the drone at any time to correct flight path problems or code bugs. Figure 2 shows the fully assembled FSH with power indication LEDs at the top and connectors around the center of the board for connecting peripherals.

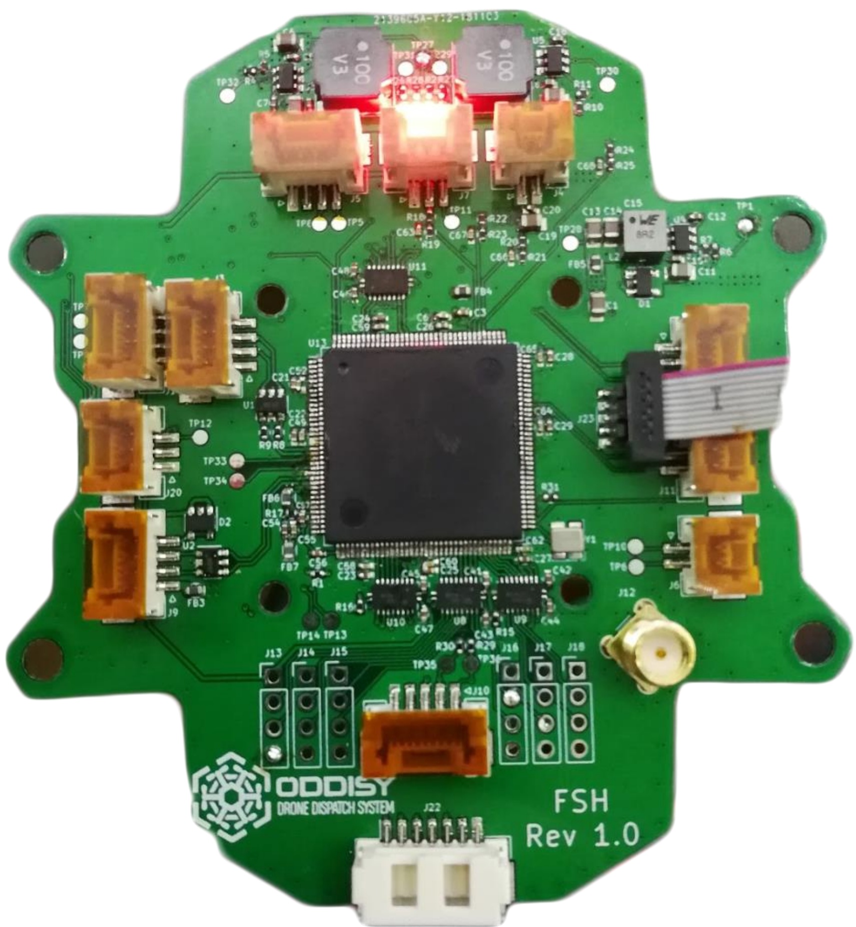

Figure 2: Top view of fully assembled FSH

The FSH, in addition to maintaining the safety of the drone and people nearby, was responsible for taking data input from sensors and packaging them into a form which was easy for the Pi to parse. The FSH was also responsible for providing different power levels to other sensors and modules including the power supply for the Raspberry Pi. As shown in figure 3, 25V from the PDB is stepped down to 12V where that is then stepped down to 3.3V and two separate 5V supplies. One 5V supply is used for powering the Pi whereas the other is used for all other 5V peripherals. Power indication LEDs were added for debugging on each power level.

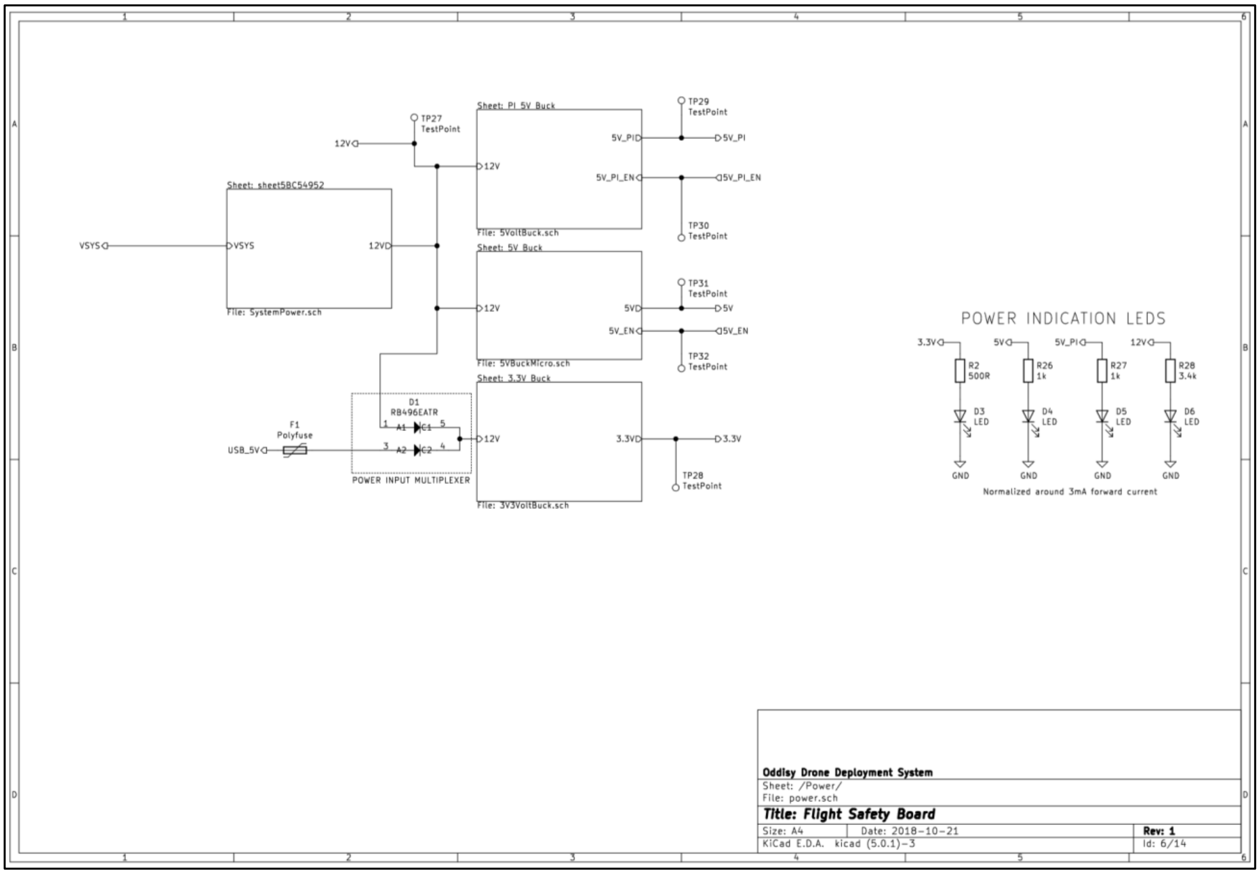

Figure 3: Overview of different power supplies

Multiple Universal Asynchronous Receiver/Transmitters (UART) peripherals on the FSH were used to read sensors. GNSS packets were parsed and then relayed to the Pi, keeping only the crucial data to save transmission time and CPU resources on the FSH. RC control from manual operator input was received as an inverted serial stream at 100,000 bits/s. Using a serial based RC stream instead of PWM enabled the use of only four wires from the receiver and only one interrupt service routine. Additionally, up to 16 channels were supported at 55Hz with a dedicated byte for failsafe from the manual control transmitter. This ensured the FSH knew the link status of the RC receiver and transmitter.

Communication to the flight controller was separated into two different links, a pulse position modulated (PPM) signal and a full duplex UART running at 1Mbit/s. PPM was used to transmit throttle/roll/pitch/yaw values to the flight controller. This signal was generated using a timer configured to interrupt at varying rates based on desired RC values. UART was used to poll raw IMU data off of the flight controller and command individual motors for debugging purposes.

The flight controller we are using also has its own isolated backup failsafe mode in case the FSH itself becomes inoperable during flight. This failsafe is triggered when a certain number of RC messages are missed over a 10ms period which we configured to then set a descent throttle for 10 seconds or until the craft stops moving. This is the last safety measure to ensure the drone does not continue flying if our custom boards stop functioning.

A 433MHz wireless transceiver was used to enable telemetry messages and bi-directional commands between the Base Station and drone. A packet structure was defined to enable any device with the same hardware to listen and transmit common packages. The packet consisted of an address to, address from, message length, message id, data, and a Cyclic Redundancy Check (CRC) byte.

4.2 Drone Design

In this section we will detail the design choices for selecting the frame, power systems, and basic control structure for the drone. We chose to manufacture a custom drone instead of buying a pre-assembled similar drone frame because of cost and customizability. There is a large market of available drone parts with varying quality and costs that allowed us to choose what fit our goals best. We aimed to design a mid-sized drone with enough thrust to carry large payloads while still using cheaper parts. These cost saving measures resulted in a flight worthy drone with a cost of

~$500 compared to a commercially available drone of ~$1,800. Additionally, most drones on the market do not offer the customizability to allow us to mount additional sensors, computers, or communication systems for our control system.

As described in section 3.3, the drone needed to be capable of greater than 15 minutes of continuous flight with a 150g payload. First, in order to select a frame, the size and shape configuration needed to be decided. Carrying payloads of that size require a large frame to maximize the efficiency of the propeller/motor combination. Additionally, when carrying expensive payloads, having motor redundancy is important to reduce the risk of crashing due to single motor or power failures. For these reasons, we chose a hex frame shape that uses 6 motors and focused on frames in the 600mm+ range which would be capable of carrying such payloads. The Tarot 690S frame was the cheapest on the market that allowed for easy customization and met both these requirements. The frame is lightweight and sturdy with carbon fiber plates and tubes with glass reinforced nylon hardware. The frame also uses common M2.5 hardware and has sufficient room for mounting additional components. Figure 4 below shows the frame without its case.

Figure 4: Picture of Drone Airframe

Selecting the motors, electronic speed controllers (ESCs), and power system is a complex task and does not have an easy solution. The three main variables we focused on for selecting these components were power, efficiency, and cost. In order to find the range of usable motors, we used ecalc.ch, an online multirotor thrust calculator, with an approximated final drone weight to calculate the required overall thrust. This allowed us to test different motors, props, and battery combinations to approximate a final flight time and thrust to weight ratio. For a drone to fly well and be as efficient as possible, a thrust:weight ratio of ~2:1 is desired. After testing various combinations, we decided on 600 rpm per volt (Kv) motors with 12x4” propellers. This combination of motors and props can draw 3 kilowatts at 6s (25v), producing nearly 31 pounds of thrust for short periods of time. After finding an affordable motor with the power and voltage specs required, 51A Multistar ESCs were selected to drive the motor due to their high amp rating, cheap cost, configurability to adjust motor timings, and telemetry capabilities.

For all our power systems, we decided on running 6s (22.2v nominal) lithium polymer (LiPo) batteries because the higher voltages reduce the amperage requirement which reduces overall weight for wiring and most components while still being supported by most cheaper drone suppliers. In order to maximize our flight time while maintaining a ~2:1 thrust ratio, we tested different combinations of ESC motor timings, battery capacities, and propellers using a low altitude hover. We tested 12x4” vs 13x5.5” props, and 6000mAh vs 9000mAh batteries.

Duration (sec)	mAh	Efficiency (min/Ah)	Description
1104	6166	2.9841	Default motor timing, no mag comp, 13x5.5” props
1074	5810	3.0809	High de-mag comp, 11 deg esc timing, 13x5.5”
1218	5783	3.5103	High de-mag comp, 11 deg timing, 12x4”
1490	9120	*2.7230	New 9000mAh batteries, RTK, FSH, all antennas

*test done with all additional flight sensors, increasing drone weight

Table 2: Drone Power Systems Efficiency Testing

After completing these tests, we determined the best combination was 9000mAh batteries with 12x4” props while using de-mag compensation and the correct ESC motor timing for our 600Kv motors. This combination results in 24 mins of continuous flight for the full 9000mAh with the control suite on board. This greatly exceeds our 15 minute flight time requirement, but since we performed our testing without any payloads, the approximated flight time with a payload would be reduced to approximately 20 minutes.

The last important part of any drone is the flight controller. This controls the motors and received RC input commands in order to fly. There are several autonomous flight controllers on the market, such as Ardupilot, Eagle Vector, or the Pixhawk, but all these controllers can only use certain sensors, do not have complex safety/testing abilities, and cannot be easily modified with custom software/firmware. We instead choose a simple 32bit controller that only stabilizes the drone based on RC input. This allows us to build our own sensor suites and control algorithms and input these to the controller to fly.

After receiving the drone frame and accompanying parts, we created a full CAD model of all components in order to have a reference model when making circuit board outlines and mounts for electronics in the future. This was done using various measuring devices including calipers, tape measures, and pictures to verify shapes and alignments. A CAD model of this frame is shown below in figure 5, with proper material and mass properties.

Figure 5: CAD of Drone Airframe

4.3 Battery Charging and Maintenance

An important design consideration for reliable and sustained operation throughout charging cycles required a robust battery charging and management system. A Power Distribution Board (PDB) and Lithium charger were designed to meet the charging time requirements given the selected battery capacity. The PDB was designed to distribute power to ESCs, enable charging, and provide power to the FSH.

The PDB was designed to fit in the void space inside the drone frame. Wire pads were placed around the perimeter of the board to enable easy connections. The PDB used a 32bit microcontroller that ran a balancing algorithm and State of Charge estimation (SOC) algorithm. An analog front end used I2C for communication and allowed the PDB to measure per cell voltages, temperature of battery, and the current through the battery. This enabled SOC estimation for calculating the remaining battery capacity. The front end also had balancing circuitry that connected a low valued resistor across a single cell. A high side MOSFET driver was used to enable the control of power to ESCs, FSH, and charging. The PDB used UART to communicate with the FSH to enable motor power and receive battery cell voltages. Figure 6 below shows the PDB before it was assembled in the drone.

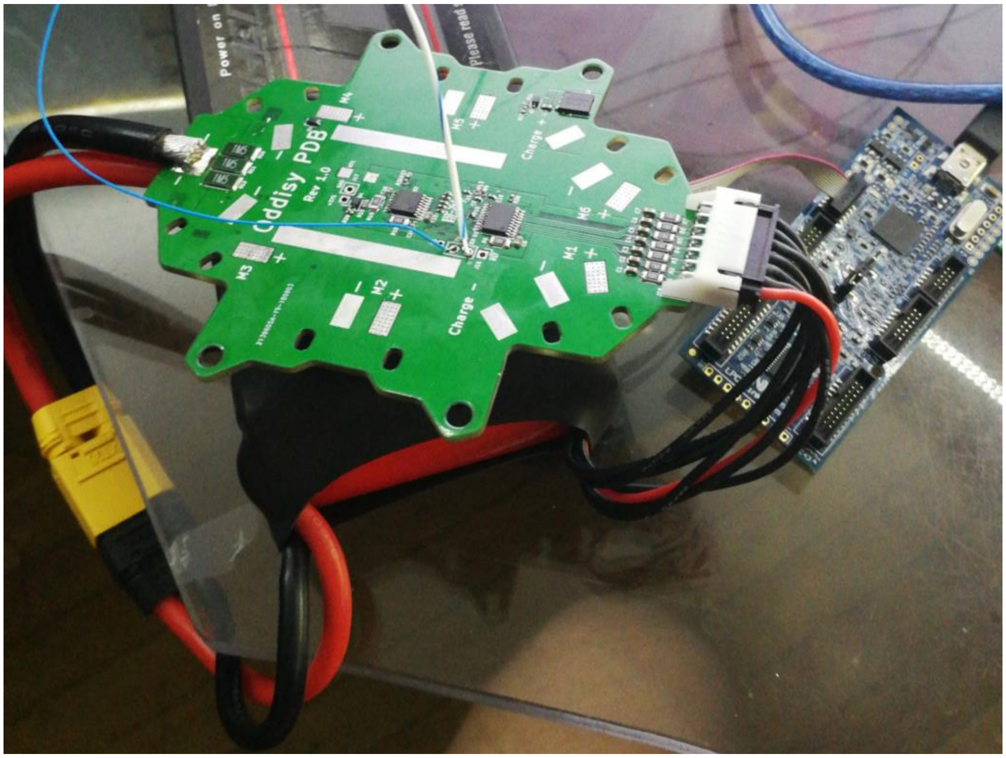

Figure 6: PDB Connected to 6 Cell Lithium Polymer Battery

The Lithium charger design was based on the set of charge time requirements of 30-45 minutes and output voltage requirements of 25V. Due to the use of a 28V power supply for input, the charger used a step down (Buck) topology. This design requires two MOSFETs in a half bridge with an inductor in series with the output. Two P channel MOSFETs are wired back to back to disallow the battery to back-drive the power supply in the case where the power supply is off but the charger is connected. Two shunt resistors are used to regulate current draw from the adapter and the actual battery charge current. Due to the fact that buck converters are current amplifiers, adapter and battery current are not always the same. Shown in figure 7 is the fully assembled charger board with input power on the top left and output to the battery on the top right. Two fans were used to cool the charger when charging currents above 5 amps were set. Status LEDs where added on the bottom of the board next to the UART connector.

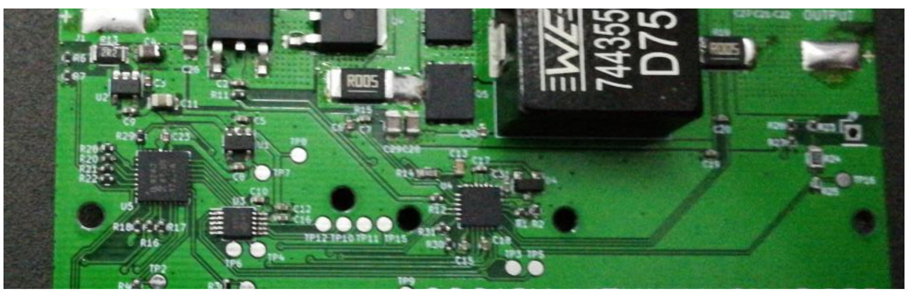

Figure 7: Fully Populated Lithium Charger Board

4.4 Storage

A significant part of this project was the drone storage structure, or Base Station. As detailed in section 3.5, the Base Station was responsible for shielding the drone, docking system, and supporting components from weather elements in accordance with IP32 standards. It must also autonomously open to provide clear space for the drone to take off and land. In this section we detail the base station’s overall shape, frame construction, door and actuation mechanisms, weather sealing, and supporting component storage.

The overall shape of the Base Station was dictated by the shape of the drone, and the desired ability to naturally clear water and snow from the top. From a top perspective the base station takes the shape of a hexagon. This matches the shape of the drone and provides ample space inside for landing, while having a smaller overall footprint than a square equivalent. While a circular profile ultimately would have been the most space-efficient shape, it would have proposed significant manufacturing challenges since the curved frame components would have been difficult to construct. Figure 8 show a top-down view of the Base Station, with square and circular equivalent perimeters drawn.

Figure 8: Base Station Profile Render with Circle and Square Comparisons

Additionally, we decided against making the top of the Base Station flat. While simple and easy to construct, it would have had a tendency to collect water and snow. Instead we opted for a slanted roof design, similar to that of a house. A side view of the Base Station is provided in figure 9, with the right door showing the profile of the slanted roof.

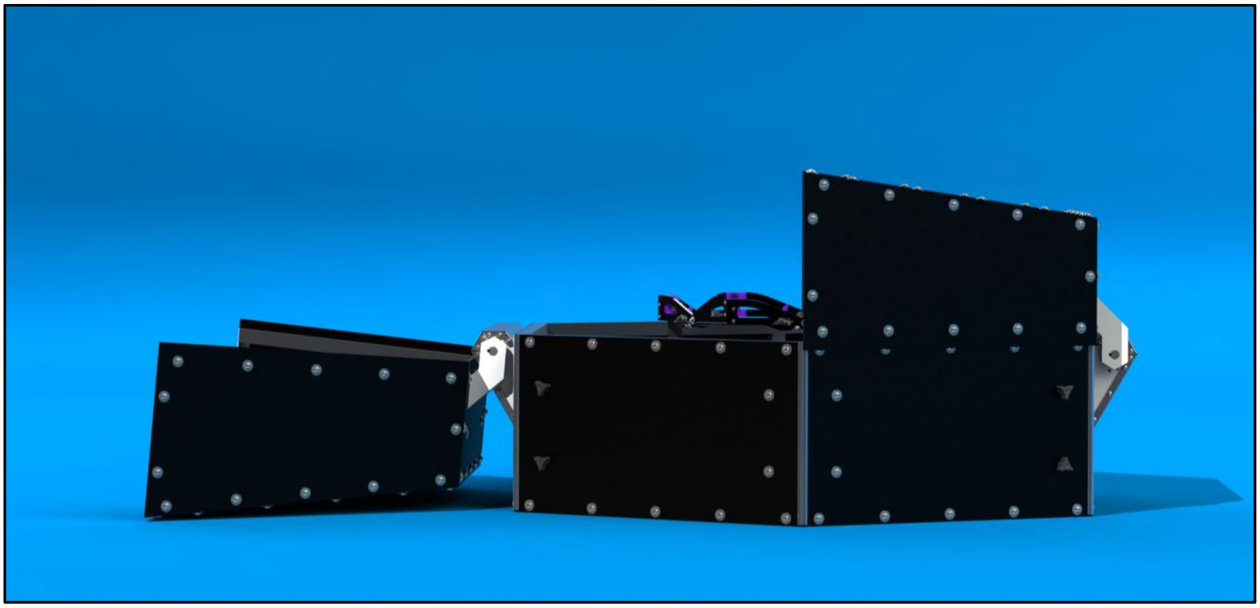

Figure 9: Base Station Side View Render

When the drone is flying in close proximity of the base station, special care needed to be taken into consideration to minimize ground effect and turbulence. Ground effect occurs when the downward propeller wash creates a cushion of air that momentarily increases lift. This can be beneficial in some cases, however near the Base Station it can create turbulences that make landing more difficult. In order to minimize this effect, we made a mock landing ring and cardboard cutout of the perimeter of the station to test how much air needed to be evacuated before a stable flight was reached, shown in figure 10.

Figure 10: Elevated Base Station airflow testing

After testing several configurations including: no walls, only walls, walls with side exhausts, and finally raising the station; it was determined that the only way to remove the ground effect was to raise the station ~6-10” which allowed for air to pass under the walls and increased the overall distance between the ground and the drone when landing.

The frame of the base station was constructed out of 6061, 1/16” wall square aluminum tubing and extruded angled aluminum. We chose this material for its high corrosion resistance, light weight, high machinability/weldability, and low cost. The lower frame was constructed solely out of square tubing, while the upper sections were made primarily out of angled extrusions to reduce weight. Reducing the weight of the rooves was necessary to decrease the required torque for opening and closing. Figure 11 shows the some aluminum components before final welding (left), and the final frame (right) and figure 12 shows the strength of the base station frame.

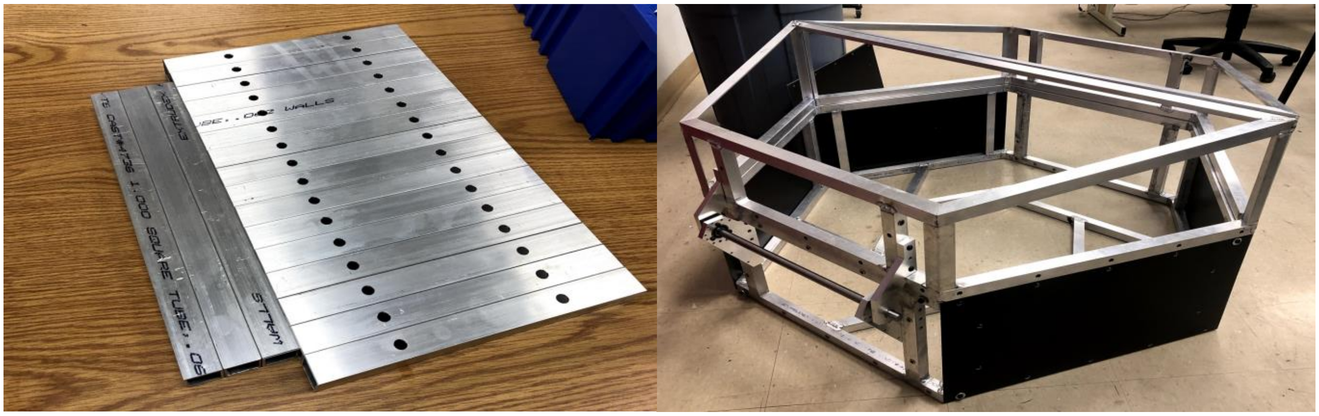

Figure 11: Aluminum Components Before and After Assembly

Figure 12: Aluminum Frame Supporting ~170lbs

The doors of the Base Station are what converts it from being weather sealed, to open for take-off and landing. While the mechanism and overall design is simple, the actuation mechanism needed to be especially robust. Since the base station would be deployed remotely, if the doors malfunctioned the drone would not be able to take off, or worse not be able to land. The doors are each attached to the base station via ½” aluminum plates, ball bearings, and a hardened ⅝” steel shaft. These components are all both readily available and highly robust. Figure 13 shows a top-down render of these components on the base station.

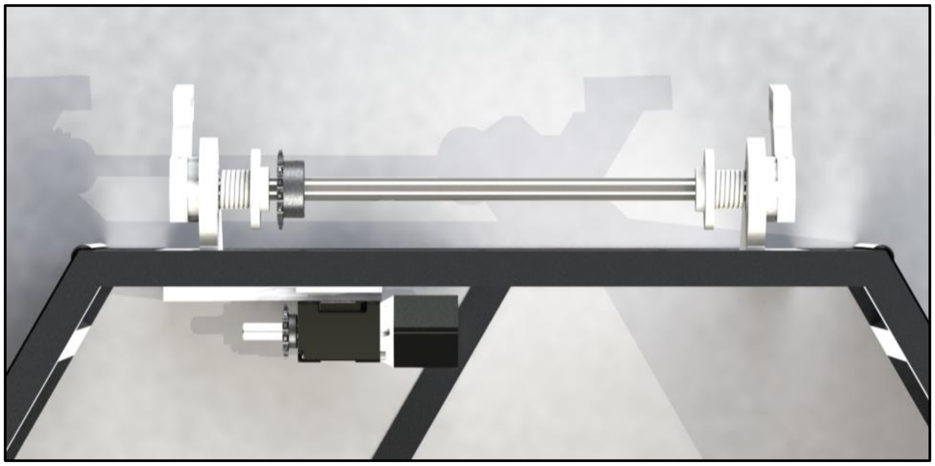

Figure 13: Render of Base Station Pivot Mechanism

Two counteracting torsion springs with a maximum torque of 3.3 ft-lbs. were used to counter the weight of the doors when opening and closing. These were attached to the pivoting shaft along with the sprocket for driving the whole mechanism. Because the overall mechanism would require 120 lbs. of force along the output shaft, a #35 roller chain is used to connect the shaft to actuating motor.

The motor chosen to drive the actuation was a NEMA 17 size stepper motor, adapted to a 100:1 Vex Robotics Versa planetary, as also seen in figure 13. This provides 63 ft-lbs. of torque to the open and close the doors while also giving precise position, velocity, and acceleration control provided the right driver and controller. The doors themselves require only 6.4 ft-lbs. which gives us a factor of safety of ~10 to account for stable acceleration and deceleration control. For that, we chose the Trinamic TMC5130 controller and driver chip, integrated into the base station controller. The combination of this motor, gearbox, and driver proved to be a cost effective solution to precise high-torque motion control.

Each side and top of the base station needed to be sealed with a panel able to withstand the weather elements. After completing a material study using CES Edupack, comparing water-resistance, UV-resistance, temperature-resistance, weight, strength, manufacturability, and cost, 1/16” FR-4 fiberglass was chosen as the material of choice since it excels the most in these categories. The only exception was FR-4 fiberglass mild UV-resistance, but this can be easily solved with a light aluminum coating or paint. These panels were attached to the aluminum panels using stainless steel fasteners and closed-cell neoprene to seal the station to the required IP32 standards. Lastly, gaps around the doors were sealed using high-compression D-profile weather stripping.

4.5 Landing and Takeoff Interface

One of the most important aspects of the base station design is how the drone will land and take off from it. The drone needs to be able to reliably land, charge, and take off from the station without interfering with the drone’s payload. There are many different ways this can be accomplished and in this section we will discuss our design choices for the landing ring, the charging lock system, and IR beacons.

The landing ring is a passive landing system that allows the drone to settle into the same position after each landing to allow for charging and storage. The design requirements for this system are that it must hold the drone at a known position for charging, and allow the drone for up to 130mm of positional error when landing. To accomplish this, a system of six planar v-channels was used which aligns with the drone’s six arms, shown in figure 14. When the drone descends onto the ring, the arms slide into place allowing the drone to be misaligned by up to 130mm and still successfully dock. This landing ring also holds the drone above the level of any nearby structures to remove the danger of propeller strikes on takeoff or landing.

Figure 14: Render of Base Station Landing Ring

We choose to use this passive landing system due to its low cost and simplicity since no additional actuation is required to align the drone with the charging system.

Attached to this landing ring are six locking mechanisms that hold the drone in place once it is landed. These are used both to charge the drone and to hold the drone for motor testing or transportation. Each mechanism is comprised of a four-bar linkage driven by a servo. The rocker link has a finger shaped extension that hooks over the drone's arm. When the finger is in its locked position, the four-bar is near it's toggle position which means the servo has a large mechanical advantage on the arm which prevents the mechanism from being back-driven and transfers any force from the drone directly to the pivoting joint. Figure 15 shows the locks in their open and closed orientations.

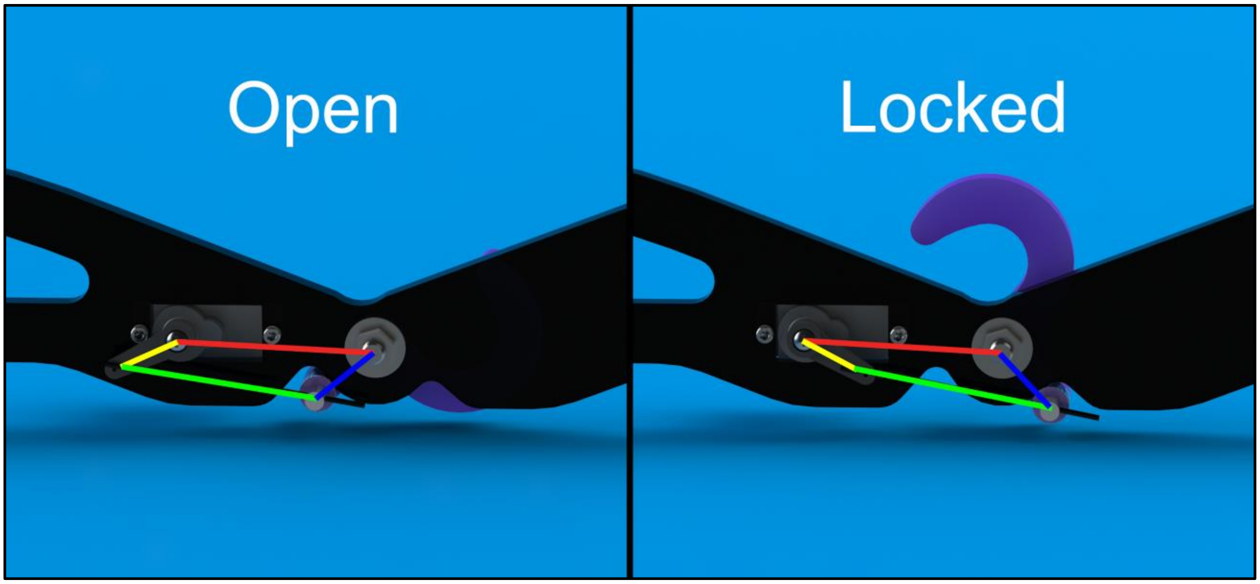

Figure 15: Render of Four-bar Locking Mechanism Open vs. Locked

Two of these locking mechanisms also hold the connectors responsible for interfacing with the drone for charging. To do this, we used 2.5mm AVX battery pad connectors which can transfer 3 amps per pin resulting in 15 amps per connector. A dual purpose circuit board was made which can both mount the connector or act as the receiving pad to reduce the cost, both with gold plating to prevent corrosion. The motion of the charging connector onto the pad was designed so that the pins had a small scraping movement to ensure proper contact while not degrading the surface of the connector.

4.6 Sensor Systems

With the mechanical interface decided, the next challenge was to accurately control the drone. Due to the structure of the landing interface, the drone needed to maintain greater than 130mm positional accuracy during landing in order to settle into the charging ring. Additionally the drone needed the ability to rapidly respond to gusts of wind that could change its trajectory. In order to achieve this level of accuracy, we used 3 sensors pictured in figure 16.

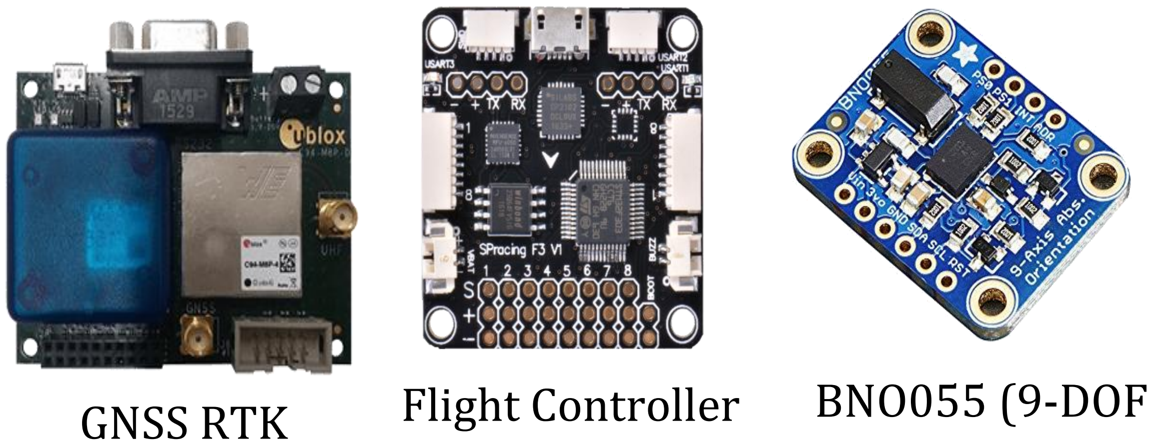

Figure 16: Sensors Used on the Drone with Data Rates

The first and most important sensor was the real time kinematic (RTK) GNSS. This type of GNSS measures the phase of the signal as well as the information encoded in the signal to increase the accuracy of the position estimate. In order to do this calculation the GNSS requires an additional non-moving base station which calculates correctional data to account for atmospheric effects. When both parts of the system have a clear view of the sky, this sensor reported the drones position within 1.4cm accuracy, though obstructions during flight could reduce its precision. This particular sensor also reported the estimated velocity of the drone. All of this data however, was only available 4 times a second. This slow update rate meant that this sensor alone was not sufficient for controlling the drone.

To augment the GNSS data, 2 additional inertial measurement units (IMU) were utilized due to their fast update rate. The first IMU was built into the flight control unit (FCU) and was a 10 degree of freedom sensor. It measured (x, y, z) accelerations, (x, y, z) angular velocities, and (x, y, z) absolute angle using a magnetometer. Additionally it utilized a barometer to measure the altitude of the sensor. Using these sensors the FCU additionally reported a fused measurement of the attitude of the sensor (roll, pitch, yaw) which utilized all of the sensor to report the absolute angles. Due to the limited bandwidth of this sensors serial output, the barometer messages were not used as this slowed down the output of the acceleration and angular velocity messages. In the future it would be better to disable USB support and utilize the primary serial output port on the device as it can support faster data rates. This would allow for better altitude estimates of the overall system and enable streaming the full update rate of the sensors. In the final system we used, these sensor values were streamed at 50Hz. To further augment this data and to help filter out noise in the system a secondary 9 degree of freedom (without barometer) was added. This IMU performed the same functions as the other IMU but could output at a full 100 Hz update rate.

To combine this sensor data we created a custom Kalman filter, utilizing the Eigen library to enable fast matrix operations. This filter was responsible for tracking 12 total states: XYZ position, heading, XYZ velocity, rate of change of heading, XYZ acceleration and heading acceleration. By having the Kalman track these states we were able to fuse all the sensors to form a more accurate estimate of where the drone was and utilize the lower level state information such as velocity, to augment the controls. In order to allow the Kalman filter to work with varying sensor update rates it was designed to accept varying sensor update matrices depending on which sensors had updates. By allowing the Kalman filter to update at a variable rate with varying sensors, we ensured that the information the Kalman reported was always up to date. An example of the positional data during a takeoff and landing process can be seen in figure 17. This figure shows when each GNSS update happened and shows the smoothing between this data.

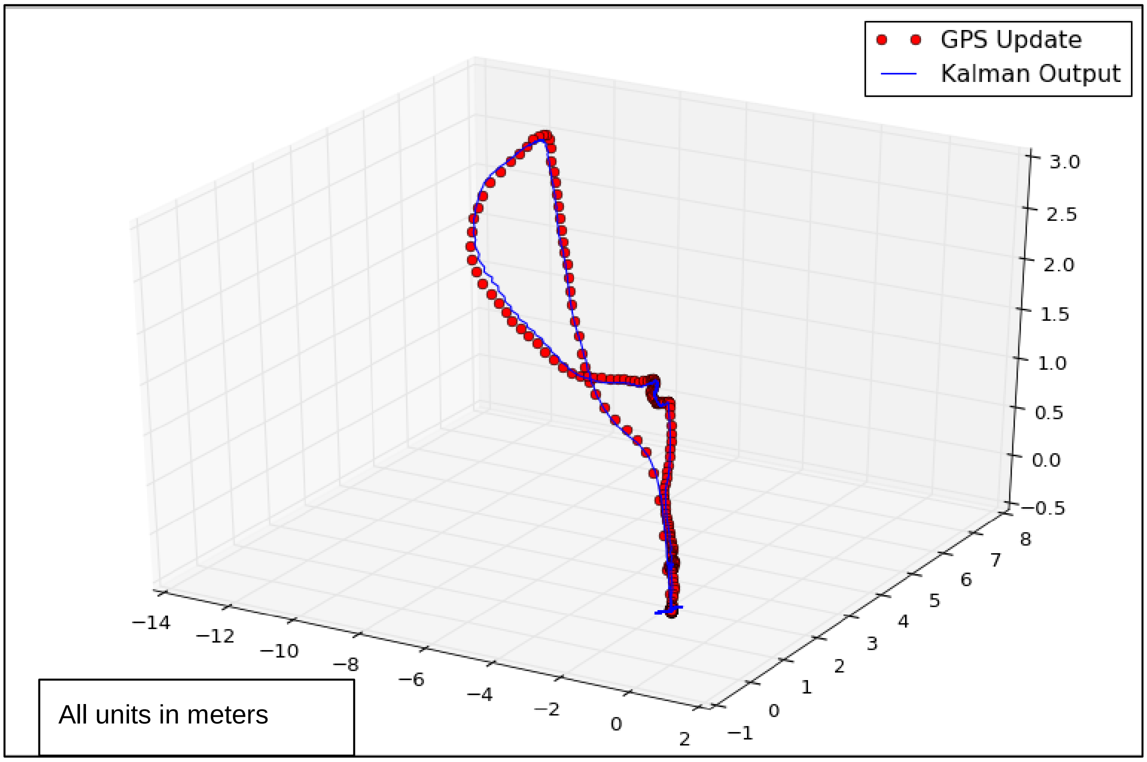

Figure 17: Graph of GNSS Update locations and Kalman Predicted Locations

Once the framework of the Kalman filter was completed, we started the process of tuning the parameters of the filter to best combine the data. This process was accomplished by logging example flight data and passing that data through various Kalman parameter sets to determine which gave optimal performance. Optimality was decided through graphical inspection of each of the state variables. Since we were unable to collect ground truth data we generally trusted that the GNSS data was very accurate and tuned to create smooth paths between each GNSS update. During this tuning however, we discovered 2 issues with our data that were greatly affecting the accuracy of the filter. The first problem was with the RTK velocity and position data. This data, while very accurate, was delayed by around 200ms when compared to the accelerometer data. This is likely due to the transmission time of the GNSS signal as well as the transmission time between the drones subsystems. This caused issues with the Kalman filtering as the misalignment of data created very jagged edges as the IMU tried to follow the true path but the delayed GNSS data pulled it off course. In order to correct this, we augmented the GNSS velocity and position data with the integrated IMU data over the past 200ms. This was able to account for the delay and was not subject to much drift due to the accuracy of the IMU data over short time periods.

The second issue we encountered was a non-constant bias in the IMU data. When integrating the raw IMU data during a hover test, we could clearly see that the velocity estimates were continuously increasing. This meant that the IMU was recording accelerations that were not actually happening which was skewing our Kalman results and making very jagged position and velocity estimates. From additional testing we determined that these offsets were due to vibrations in the drone causing noisy readings in the sensor. To combat this we increased the vibration dampening of the sensor by adding foam tape underneath the sensor, but this did not eliminate the sensor bias. To further address this problem, we created a custom real-time calibration routine to learn the sensor offsets and account for them. The start of the calibration routine recorded the current time, (x, y, z) accelerations and the roll, pitch and yaw of the drone over a period of 1 second. The acceleration values were then transformed into the global frame (North, West, Up) using the roll, pitch, and yaw at that time step. These values were then integrated to get an IMU estimated velocity. This velocity was then compared to the GNSS estimated velocity to get an IMU to GNSS error value for each of the axes (NWU). This error was then divided by the number of readings to determine how much each IMU message contributed to the error. To then transform the global error into the local sensor offsets, we determined the average roll, pitch and yaw over the 1 second period. Transforming the errors by this average orientation resulted in correctly calculated offsets for each axis of the sensor. This calibration was repeated every second to ensure the IMU data remained accurate throughout the entire flight. This type of calibration worked well because IMUs are generally accurate on a very short time scale, and calibrating on a longer timescale (1 second) does not impact the short term performance. This greatly improved the IMU accuracy and provided much better filtering results. Figure 18 shows the difference in uncalibrated IMU data against the calibrated data. The calibrated data closely tracks the true velocity while the uncalibrated data continues to increase. Since the IMU data is integrated to get the velocity, the difference between the real data and the estimated data is not important. Better calibration will result in data that remains parallel to the real data after the calibration happens.

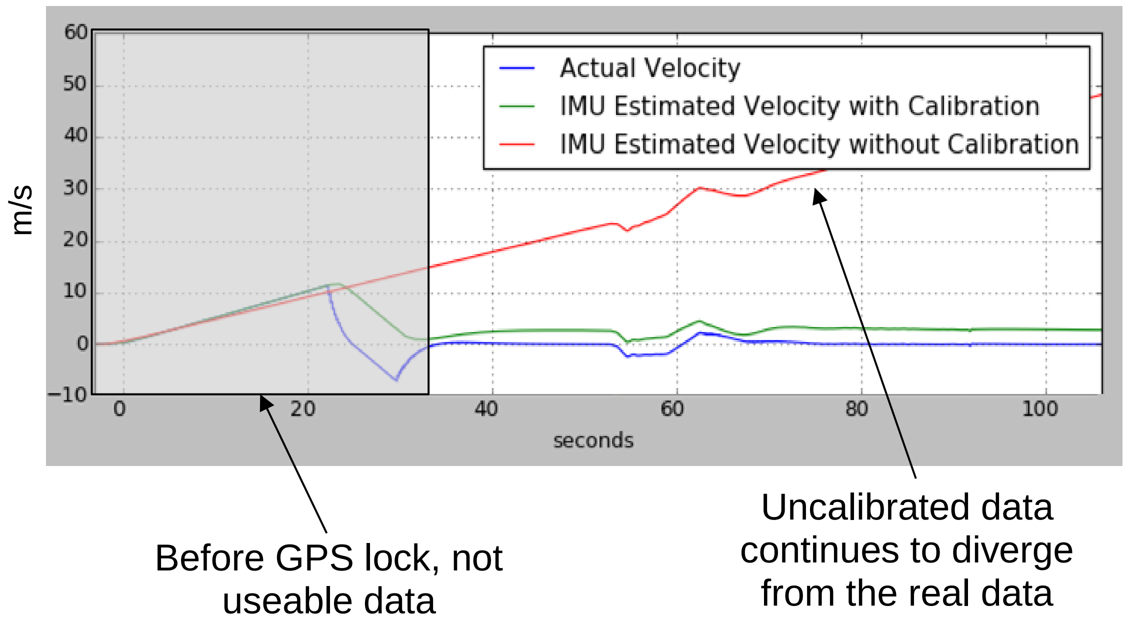

Figure 18: Graph of Predicted Velocity Showing IMU Calibration

4.7 Controls

With accurate position and velocity estimates of the drone, the next design challenge was controlling the drone to reach a desired position and velocity. The first step in this process was receiving user input for where the drone should be. Since the end use application was outside the scope of this project, drone waypoints were simply loaded from a file onboard the drone computer. These waypoints were then used to calculate a velocity trajectory for the drone. This trajectory took into account the max drone acceleration, max drone velocity and the distance from the target.

The distance from the target was used to linearly decrease the speed as the drone neared the end target and the max acceleration made sure the velocity setpoint was never too far from the drone's current velocity. This enabled us to have more aggressive tunings for the lower level control while maintaining a stable system.

Since we were using an off the shelf flight controller we did not have to manually control individual motor powers which greatly simplified the low level control problem. Instead we could send RC values which dictate the angle and throttle of the drone. In order to calculate the proper RC values to send, we used a velocity PID controller. This controller utilized the estimated position and velocity states and compared them to the desired velocity trajectory to generate the RC outputs. We decided to use a velocity controller because it enabled the drone to follow a trajectory more accurately than a position PID controller. Additionally, a velocity controller can handle constant wind offsets better because the I term in velocity directly counters the velocity of the wind. This also ensures that the controller can adapt to slight imbalances in the drone that cause it to drift in one direction.

In order to properly tune the PID controller, we utilized a custom-made logging system to track the drone's velocity and position and compared that to the set value. We tuned all 3 axes, x, y, and z, simultaneously by setting the desired velocities to out-of-phase sine waves. These sine waves were useful for tuning because they allowed us to visualize how the drone tracked a constantly changing velocity setpoint. The amplitude and frequency of the sine waves were comparable to the expected accelerations seen in the velocity planner onboard the drone. An example of an untuned sine wave and a tuned sine wave can be seen in figure 19 and figure 20 respectively.

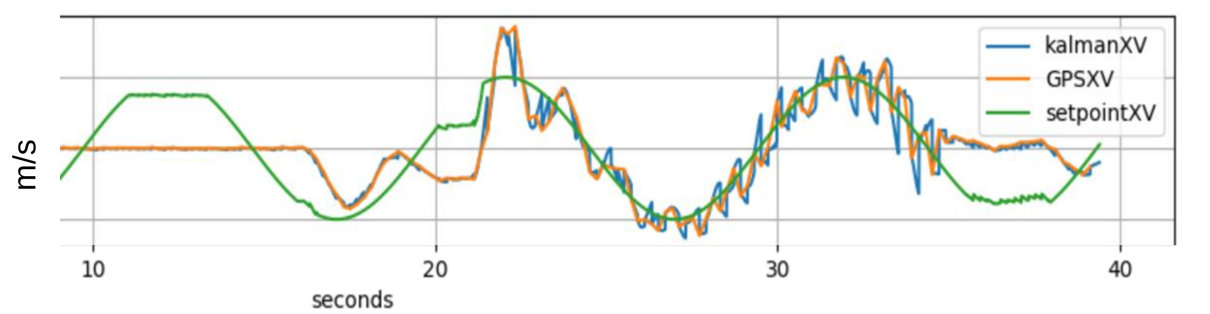

Figure 19: Example of X-axis Velocity Response using Poorly Tuned Parameters

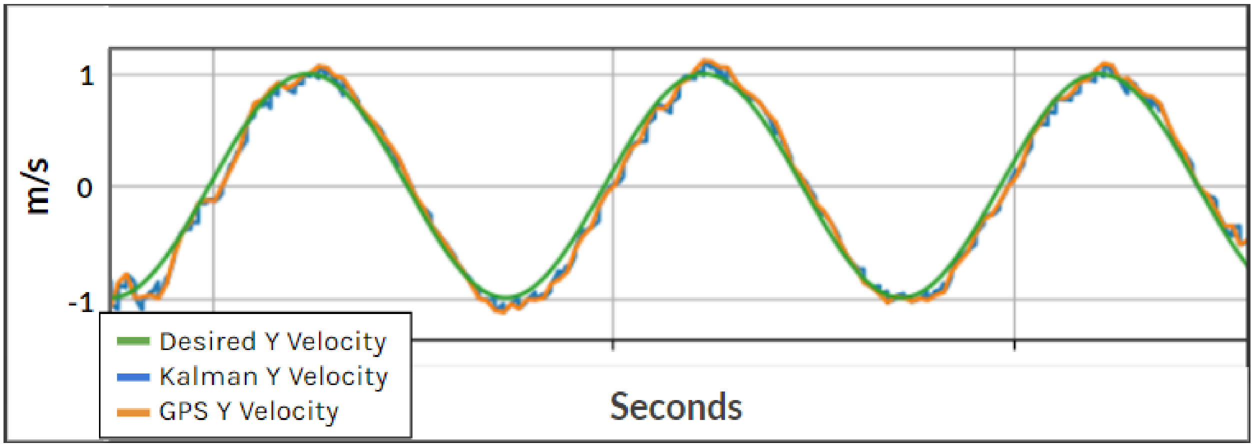

Figure 20: Example of X-axis Velocity Response using Well Tuned Parameters

4.8 State Machine

Once the drone was able to accurately follow velocity setpoints, we created a state machine to control how the drone proceeded between tasks. This state machine consisted of 10 separate states that will be detailed below:

1. Setup: This state was responsible for preparing the drone for takeoff after being stored for some amount of time. This state sent the messages requesting that the base station doors open, the servo locks open, and started the GNSS calibration process. Since GNSS does not work well while the doors are closed, it was important to restart GNSS calibration after the doors opened. Once this had finished it proceeded to the Wait for Auto Mode state.

2. Wait For Auto Mode: this state was used to allow the user to control when the drone should takeoff. This was important for debugging as we could manually check that all the sensors were working as expected before the drone would try and takeoff. This state also checked that the drone was in an acceptable state for takeoff. It ensured that the current position was within 1 cm of 0,0 and if it wasn't, it recalibrated GNSS to ensure that the base station was always in the correct position relative to the drone. In a final system this would not be needed as the base station would not move between runs and the latitude and longitude could be hard coded. Once the user switched to takeoff mode and the GNSS was well calibrated the drone proceeded to the Takeoff state.
3. Takeoff: This state was responsible for ramping the throttle up to the takeoff throttle until the takeoff height of .25m was reached while keeping the roll pitch and yaw inputs at 0. Since extra inputs affecting the system during takeoff could potentially result in a crash it was important to have a consistent takeoff routine. Since biases learned on previous flights could be incorrect if the wind changed, this constant takeoff routine ensured the drone would be out of harm's way before making adjustments. Once the drone reached the takeoff height it proceeded to the Follow Waypoints state.
4. Follow Waypoints: This state used the user defined waypoints to command the drone where to go using the velocity PID outputs. If the user flipped the land switch or if the target position was near 0,0 the drone would proceed to the Approach Landing state. This Follow Waypoints state could change depending on the final application.
5. Approach Landing: This state was used to get the drone in the general vicinity of the base station and request that the doors and servo locks open for the drone. This ensured that the drone would approach at a safe height and caused the drone to wait for confirmation that

the doors were open before descending. Once the drone was near the base station and the doors were open, it proceeded onto the Approach Landing 2 state.

6. Approach Landing 2: This state brought the drone much closer to landing and had it hover .35 meters above the Base Station until it was within very tight tolerances of the landing ring. This state requested that drone was within a 5 cm (x, y) tolerance and ensured that the velocity was less than 0.2 m/s. Once these conditions were met it proceeded into the Landing state.
7. Landing: This state commanded the drone to approach the landing ring and descend at a rate of 0.25 m/s until it was 5 cm above the landing ring. This state also checked that the drone was within the landing tolerance of 7cm. If it went out of tolerance it returned to the Approach Landing 2 state. Once the drone was within 7cm (x, y) and 5 cm above the landing ring it moved into the Dropping state.
8. Dropping: Once in this state the drone is guaranteed to land. This state is responsible for decreasing the throttle smoothly to reduce the impact on the drone and to slowly turn off the propellers. This state increased the landing speed as once the drone was 5 cm above of the landing ring, aborting the landing was no longer necessary. Once the throttle reached zero the drone transitioned to the landed state.
9. Landed: This state closed the servo locks, closed the doors, and started charging. Once these were all started the drone moved onto the Storage state.
10. Storage: This state waited until the next mission was started and ensured the throttle was kept at 0.

5 Results

As the system was being designed and constructed, it was empirically tested. We performed all testing on the WPI athletics fields, since these were the only large enough areas that could be easily cleared of all people. Final testing was performed on 4/13/19, after the final software and hardware changes were implemented. A brief break down of the results of different aspects of the system is provided below.

5.1 Takeoff and Landing

Flight testing was performed in parallel as the controlling software was developed and as the physical components were being constructed. No formal tests were performed until the final software and hardware revisions were completed. The final testing was performed during the evening hours on 4/13/19 due to limited time and filming constraints. On this night the drone was cycled through 15 complete takeoff-waypoint-landing routines. The drone was able to successfully takeoff, navigate, and safely land in all 15 of these tests. To verify that our system met the requirements of a 15 second takeoff and 45 second landing, each of these tests was timed. The average takeoff time including the time to open the doors was 8 seconds, and the average landing time including opening the doors was 24.7 seconds with a 2.9 second standard deviation. Since we are only running the door motors at 10% speed, opening and closing each took 7 seconds. This time could be reduced to under 2 second by increasing the speed and acceleration, taking 5 seconds off both the takeoff and landing times.

5.2 Sensors and Controls

Utilizing the GNSS RTK, the BNO IMU, and the IMU built into the flight controller, and filtering the data with the Kalman Filter, the drone was able to locate itself within 5cm of the requested location. This enabled the drone to consistently land in the same position and ensured navigational accuracy when following the different waypoints. This contradicted the results of previous drone landing systems which generally require a camera to achieve this level of precision.

5.3 Communication

The majority of our communication systems had very robust channels with plenty of bandwidth to support all of the required messages. The Raspberry Pi to Flight Safety Handler serial connection was capable of sending data at a rate of 1Mb/s with a dropped packet rate of less than 1%. This enabled the 2 systems to pass commands quickly and efficiently and ensure that the Raspberry Pi always had up to date sensor information. The high bandwidth also enables the addition of new messages or sensors without any decrease in communication speed. The Flight Safety Handler to Flight Controller similarly had very fast data rates nearing 500Kb/s enabling the FSH to send RC commands at 100 Hz enabling fine level control. The drone to base station communication was the only source of communication issues. This channel did not have as much range as we expected likely due to poor antenna placement in the base station which meant that many door or servo messages were missed when the drone came in for landing. The acknowledgement system we implemented combatted the issue but increasing the communication range would improve the reliability.

5.4 Charging

The lithium charger was capable of charging up to 17 amps at a voltage of 25V for a total of 425 Watts. This current limit was due to the absolute limit on the 28V power supply used to power the Base Station. After multiple tests the charger was then connected to the landing servo charging hooks where upon connecting the charger exploded. We believe that this was due to a cracked shunt resistor. A new charger was designed in the last week of this project to fix small issues, but due to a shipping delay, these parts did not arrive in time.

The charging and locking servo actuated mechanisms were constructed using ABS plastic which resulted in small bending motion which added compliance to the charging pad engagement. After properly sizing the landing hooks to the frame of the drone, engagement of the locking mechanism had a 100% success rate from our testing. The electrical connection between the pad on the drone and the actuated pin interface was tested at 10 amps and resulted in no noticeable heating which verified a stable connection. However this was never tested at the full required 15 amps due to problems with the lithium charging board itself.

5.5 Base Station Construction

Using the final design, we were able to construct the Base Station using WPI's manufacturing labs. The aluminum frame proved strong enough support the system's own weight, as well as the torques and forces applied when actuation the Base Station's doors. The only material choice that proved problematic was the use of acrylic for the landing ring. During normal landings the acrylic was plenty strong enough to support the weight of the drone however on certain landings during the tuning process there was a chance of cracking the acrylic. While better drone control eliminated this issue, using a stronger material such as Lexan would be preferable.

All weather sealing components were also constructed and installed should the system be subjected to weather-resistance testing. However, due to time constraints, no weather-testing was performed, and thus the IP32 rating cannot be assured.

6 Discussion

In this section we will cover what aspects of the system that performed notably well or otherwise. Additionally we will provide any recommendations on for future work, or things we would try differently if we had the opportunity to redesign the ODDISY system.

6.1 Flight Safety

The safety systems in the Flight Safety Handler were one of the most important components during the development stages of the project. We did not use a simulation suite to test any of our autonomous flight control which meant there was no easy way to find bugs before testing in flight. Having a robust RC limiting and user override system allowed us to confidently test new code without any dangers of crashing the drone. Every time we set out testing the autonomous code and tuning the PIDs we would have ~15-30 manual overrides during the course of 1 battery life of the drone. This system allowed us to quickly make changes on the field and have the drone up and running minutes later. Having this system did not prevent the user from making mistakes however, one of our only crashes occurred during a manual override due to a low throttle input from the controller letting the drone fall too quickly at low altitude. Flight checklists were stressed after this event to ensure user controls were safe before taking over.

All of our crashes occurred within feet of the base station and only resulted in minimal damage to propellers and frame parts that were easily replaced within the hour. Had these safety system not been put in place, the potential for major damage or complete loss of the drone would have been guaranteed based on our testing.

6.2 Basic Drone Design

The drone for this project was designed to act as a placeholder for any flight capable drone so that our system could be modified to function with most commercially available drones instead of making the drone its own product. For our project however, the drone worked very well and had no problems carrying large payloads and acting as a platform for testing sensors and interfacing with our charging system.

The motor redundancy in our frame also proved to also be very useful for . During a payload capacity test, a stressed wire loosened and caused a motor to be disconnected but the flight controller was able to compensate quickly and maintain stable flight.

6.3 Storage

The construction and performance of the Base Station were mostly as expected. In the end we were able to build it per the CAD design. However the roof frame proved difficult to manufacture and took much longer than anticipated to build. Unlike the lower half of the base station, with a frame constructed mostly of square aluminum tubing, the frame of the doors required aluminum of various angles with various miters for their ends. Since we lacked access to a water-jet or CNC break, this required manufacturing custom bending dies for each angle, and remanufacturing 90 degree aluminum angle to the correct shape. If we were to redesign the roof the components we would explore using large riveted sheet metal components to greatly reduce the number of individual components and overall complexity of manufacturing it.

6.4 Landing and Takeoff

The drone is subjected to the most risk during takeoff and landing. Minimizing potential for a collision during these times was essential to our design. For this reason, all the areas immediately above the landing ring is clear of obstruction to allow for drift an unexpected drift in the drone's position. Once the drone positioned itself above the landing ring, it descended rapidly to minimize any chance for a wind to push the drone into a collision. This, in conjunction with the centering aspect of the landing ring proved very effective at capturing the drone and preparing it for storage and the next flight.

This system assumes that the drone is always able to land, waiting only short amounts of time. However, if for some reason the drone is not able to land (e.g. too windy, doors don't open correctly, etc) the drone currently has no other option but to wait until it runs out of charge. In the future we recommend implementing actuating landing gear to allow it to temporarily land elsewhere before retrying the landing in more acceptable conditions.

One of the most surprising results that came out of this project was the precision we were able to achieve without using vision systems. We spent a long amount of time designing a system to support camera localization in anticipation of accuracy problems, but it was proven to be an unnecessary sensor. This contradicted prior work and showed that using the correct sensors with proper calibration enabled very precise control of the drone. By not having a camera we are able to increase the size of the payload without worrying about obstructing the camera view. This of course assumes a good GNSS signal and further testing is required to determine how our visionless system performs in other environments. For agricultural uses however, a clear view of the sky is almost guaranteed meaning GNSS signal should be sufficient.

6.5 Data Collection and Logging

Something that is often overlooked when operating under a strict time constraint is the development of systems that are only useful during development and don't serve a real purpose in an end system. In the early stages of this project we developed a system to record all of the data the drone collected and created a graphing system to allow us to easily visualize the data. While this did not add any additional functionality to the drone, this system proved invaluable when debugging the system performance and enabled us to detect problems that would not present themselves without careful data analysis. Additionally, the ability to playback the recorded sensor data offline, in faster than real-time, was integral in our success of tuning the Kalman filter and analyzing how changes in code affected the system. Having consistent data to use enabled more complex analysis without requiring the drone to fly every time. We recommend that all projects utilize a logging system that is capable of recording all relevant data and encourage developers to spend time in the beginning to make future development easier.

7 Conclusion

With each passing day autonomous UAVs or drones and suitable applications become more prevalent. As they become more commonplace the barrier cost of using an autonomous drone has decreased significantly. They are already being used for inspection of agricultural crops, solar panels, and infrastructure. Drones are also being embraced by first responders to gather information with lower response time than they ever could. However all these applications still require a human in the loop. Currently, at the very least the operator must prep the drone for flight, place it outside, and retrieve it after its flight, but often they also must fly it above to a safe clearance height requiring a skilled pilot. This required human intervention limits the usefulness of autonomous drones as reduces the at which they can be deployed.

To remove humans from the loop, we identified that the replacement system would have two major components: an autonomous drone, and an autonomous ground station or Base Station

The drone must:

- Be capable of autonomous flight and navigation
- Have control accurate enough to land in the designated Base station
- Be large enough that it could lift the inspection/other equipment needed for the application
- Provide inflight monitoring and status updates

The Base Station must:

- Be able to shield the drone from the outdoor elements between flights
- Provide a clear path for drone deployment and landing
- Have a physical interface capable of capturing the drone
- Have a charging interface capable of charging the drone between flights

From this list of requirement we designed and built the ODDISY Drone Dispatch System (ODDISY). As an initial prototype, ODDISY consisted of an autonomous drone and autonomous Base Station, that met all of the requirements above in a succinct, remotely deployable package. From this prototype ODDISY could be modified to implement expanded capabilities and serve the need real-world autonomous drone applications.

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