NORTHERN ILLINOIS UNIVERSITY

Drone-Enabled Sensing and Monitoring of Tree Canopies

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HONORS CAPSTONE ABSTRACT

This multiphase project was proposed as a senior design project for the College of Engineering and Engineering Technology at Northern Illinois University by The Morton Arboretum, which is located in Lisle, IL. The ultimate objective of the project was to develop a universal sensor mount capable of accommodating small scientific instruments that can clamp onto tree canopy branches and is capable of being deployed and retrieved with a DJI Matrice 600 Pro unmanned aerial vehicle (UAV). The main motivation behind this project is that the tree canopy environment is difficult to study, as it cannot be easily accessed by humans. Research of tree canopies and the canopy environment is important, as it can help monitor tree health, monitor pest and disease outbreaks, provide a greater understanding of tree failure in storms, and support many other areas of biological research. Monitoring devices currently have to be deployed manually. The Morton Arboretum proposed that UAVs could be used to more efficiently deploy monitoring devices onto tree canopy branches. The team conceptualized and designed a novel system capable of achieving the ultimate project objective. Prototypes of the universal sensor mount and deployment system were fabricated and tested. The team successfully completed the first phase of the design project by producing a functional prototype of the universal sensor mount. The team also made significant progress in the second phase of the project by designing, fabricating, and testing an initial prototype of the deployment system. Further optimization of the DS is recommended before final integration with the UAV.
INDIVIDUAL CONTRIBUTION TO PROJECT

- Introduced USM torsional gripper design to the team
- Conducted patent search for similar designs
- Contributed to preliminary and alternative design ideas through design matrix
- Created a simplified mathematical model of the universal sensor mount (USM) clamps and derived equations for spring displacement angle, clamp contact force, spring torque, and minimum required contact force to support the USM on a vertical branch
- Conducted design parameter sensitivity study to relate the USM weight to minimum required clamping force for various static friction coefficients
- Sized torsional springs and servos to match performance requirements of the rotational clamps
- Introduced need for operational testing with the UAV at the Morton Arboretum
- Evaluated the results from the operational tests conducted at The Morton Arboretum
- Assisted in fabrication and testing of initial USM prototype on tree branches
- Refined USM design based on results of initial prototype testing
- Selected battery eliminator circuit used to convert the UAV’s 18 VDC output to 7.4 VDC to be compatible with the servo motors
- Designed deployment system testing circuit
- Wrote Arduino code used to control the deployment system servos during testing
- Refined design for UAV to pole mounting fixtures
- Contributed to project documentation
Final Report

Drone-Enabled Sensing and Monitoring of Tree Canopies

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ABSTRACT
This multiphase project was proposed as a senior design project for the College of Engineering and Engineering Technology at Northern Illinois University by The Morton Arboretum, which is located in Lisle, IL. The main motivation behind this project is that the tree canopy environment is difficult to study, as it cannot be easily accessed by humans. Monitoring devices, such as accelerometers and insect traps, currently have to be deployed manually. Research of tree canopies and the canopy environment is important, as it can help monitor tree health, monitor pest and disease outbreaks, provide a greater understanding of tree failure in storms, and support many other areas of biological research. As a consequence of the above reasons, The Morton Arboretum proposed that unmanned aerial vehicles (UAVs) could be used to more efficiently deploy monitoring devices onto tree canopy branches. The ultimate objective of the project was to develop a universal sensor mount capable of accommodating a wide range of small scientific instruments, that can clamp onto tree canopy branches and is capable of being deployed and retrieved with a DJI Matrice 600 Pro UAV. The team conceptualized and designed a novel system capable of achieving the ultimate project objective. An optimal design was selected that consists of three main subunits: the universal sensor mount (USM), deployment/retrieval system (DRS), and controller system (CS). The Morton Arboretum’s tree monitoring devices are secured to the USM, which employs a passive clamping system to remain attached to branches. Then, the USM is attached to tree canopy branches with the DRS, which is suspended from the arboretum’s UAV. To retrieve the USM from branches with the UAV, the DRS’s wrist is swapped out for a retrieval hook, which is used to capture a loop on the USM and remove it from branches. The operations of the DRS are controlled through the UAV’s stock controller with a channel expansion kit. The team fabricated and tested initial prototypes of the USM and DRS. The design’s realistic constraints, potential safety concerns, impact, and contribution to lifelong learning are addressed. Finally, the project’s budget and spending is discussed, and its timeline is presented.
1 INTRODUCTION
In this section, the background and motivation behind this senior design project, which was proposed by the Morton Arboretum in Lisle, IL, is discussed. Furthermore, the purpose of the project and operational design requirements for the design are presented. Finally, similar products to the design are noted and the results of a patent search are discussed.

1.1 Background
There is a need for a more efficient method of studying the canopies of trees and the unique environment within the canopies. Current practices of manually deploying data collection devices in the tops of trees have multiple shortcomings. Most of these shortcomings arise from the fact that tree canopies are difficult to access. Deploying devices in tree canopies by hand is time-consuming, labor-intensive, and can result in damage to the tree. Additionally, there is always an element of personal safety risk to the person placing the sensors in the trees. Thus, a method of deploying data collection devices onto tree canopy branches from existing unmanned aerial vehicles (UAVs) is desirable.

1.2 Purpose of the Project
To more efficiently deploy sensors and data collection devices in tree canopies, an electromechanical system is proposed that will enable an existing DJI Matrice 600 Pro UAV to deliver these scientific research payloads to branches in tree canopies. The finished design is capable of meeting the following design requirements:

1. The system shall weigh less than 2.0 kg.
2. The system shall be mounted to a DJI Matrice 600 Pro unmanned aerial vehicle.
3. The system shall be capable of securely attaching payloads weighing up to 250 g to tree canopy branches ranging from 3 to 10 cm in average diameter.
4. The system shall be capable of retrieving payloads weighing up to 250 g from tree canopy branches ranging from 3 to 10 cm in average diameter.
5. Any subsystems that remain secured to tree branches shall continue to operate effectively after exposure to water from rain or condensation.
6. Any subsystems that remain secured to tree branches shall not be easily removed from the tree by wildlife.
7. The system shall not cause radio frequency interference with the DJI Matrice 600 Pro flight controller, which operates at 2.400 GHz to 2.483 GHz.

To meet the above design requirements, a system consisting of three main subsystems was designed. The three subsystems include a Universal Sensor Mount (USM), Deployment/Retrieval System (DRS), and Controller System (CS). Initial prototypes of the USM and DRS were fabricated and tested.

Sensors and other data collection devices can be attached to the USM. The USM is the subsystem that gets deployed onto tree branches and left behind for a data collection period. The USM is resistant to adverse weather, as it may remain deployed on branches during rain and thunderstorms. The USM incorporates two torsional spring clamps that enable it to attach to tree branches. This gripping mechanism is actuated by the DRS. A model of the USM prototype is depicted in Figure 7.
The DRS subsystem employs two servo motors to actuate the torsional springs on the USM clamps and release the USM. The servo motors are surrounded by a housing and suspended from a tube that is connected to the bottom of the DJI Matrice 600 Pro UAV. The probe consists of a tube of standard modulus carbon and was chosen by the client. The second servo on the tube’s end effector locks the DRS to the USM until the USM has been successfully attached to a branch. The client will attach a camera to the DRS tube to allow the system operator to see the position of the USM relative to target branches. The DRS incorporates a separate retrieval hook end effector for the retrieval of the USM.

Finally, the CS is used to control the DRS’s deployment of the USM. The CS receives wireless communications from a system operator on the ground. The CS will consist of the stock UAV controller with a channel expansion kit. The CS is capable of performing the logic shown in Figure 1.

The block diagram of the overall system shown below in Figure 1 depicts how the design performs when deploying the USM onto tree branches.

![Figure 1: Block diagram of the selected design](image-url)

The design described in the paragraphs above was chosen as the optimal design over multiple alternative designs, primarily because of its superior weight savings and reliability. Other alternative designs involved servo motors, a microcontroller, and power supply being placed onboard the USM, so they were inherently much heavier than this design, so it would have been much more difficult for the USM to remain securely attached to tree branches. Weight is also saved in the DRS in the optimal design because it involves a separate end effector that gets swapped out for the deployment end effector for retrieval of the USM. Other alternative designs incorporated deployment and retrieval into one DRS end effector, so they were heavier.
Furthermore, these alternative designs would have decreased reliability, as they would have required the onboard electronics to be sheltered from the elements. Also, they would have required that power be delivered to the USM microcontroller at all times, so the deployment period length would have been limited by the battery-life of the USM onboard power supply.

1.3 Previous Work Done by Others

1.3.1 Existing Products

There is no single product currently on the market capable of meeting all the design requirements for this project.

The most closely related products to this project already on the market are drone claw attachments and payload release mechanisms. The drone claw found in [1] has no actuators, and is good at retrieving objects from flat surfaces. An example of a payload release mechanism on the market is the device made by Drone Sky Hook for certain DJI drones [2]. The device works by actuating a small hook to release a tether. Another payload release mechanism made by Urban Drones for the Splash Drone works by actuating a pin to release loads [3].

However, likely as a consequence of the rapid pace of evolution in the private UAV industry, most UAV devices relevant to this project have been custom-made by enthusiasts or scientific researchers. In fact, a prototype system with many similarities to the team’s final product was designed and successfully tested by environmental researchers in 2018. The prototype in [4] was used to collect samples from tree canopies with a DJI Matrice drone. The system consisted of a twig sampling mechanism suspended from the drone by a three-meter tether made from aluminum tubes. The twig sampling mechanism collected tree samples with servo-actuated grippers that grasped the target twigs and fed them to a circular saw [4]. While the system design proposed for this project does not have the same objectives as the tree sampling prototype in [4], there are multiple learnings that can be drawn from the study. For example, having at least two pairs of grippers separated by an appropriate vertical distance can help align the system with branches. Furthermore, the researchers incorporated motion dampers into the tether design to reduce the sway of the twig sampler. This is applicable to the proposed system as there will need to be very little sway of the USM and DRS in order to successfully attach and retrieve the USM from trees.

There are also many custom grasping and perching devices that have been made by scientific researchers. For example, in [5], a system consisting of two grasping mechanisms was created to enable a UAV to grasp target objects at speeds of 3 m/s. While the system design proposed for this project does not need to grasp target branches while moving horizontally, the gripping system used in the study in [5] was worth further investigation. Perching devices for UAVs are also of interest to researchers. For example, the engineers in [6] designed a prototype for a passive UAV landing gear gripper. While the proposed design for this project does not require landing the drone on a branch, it was worth considering implementation of passive components in both the USM and the DRS to reduce weight and conserve energy.

1.3.2 Patent Search Results

There were no patent searches that returned a system capable of meeting all the design requirements for this project. Most importantly, a patent could not be found for a system that
permits a UAV to retrieve a payload attached to a cylindrical target object, such as a tree branch. Thus, the design proposed for this project may be a novel system.

With the above statements in mind, there are many patents filed for UAV payload release devices and payload delivery systems. For example, Google Inc. has a device disclosed in [7] which specifies a retractable payload delivery system that can lower payloads to the ground and then release them. Unlike the system proposed in this project, this device is not capable of payload retrieval. Another device is disclosed in [8] which specifies a system that would permit a UAV to deploy and retrieve payloads with a tether-winch device. The system in [8] is capable of automatically detecting when a payload is attached to the tether. This system is similar to the design proposed in this project, except for the fact that the system uses a winch and is incapable of attaching and detaching payloads from cylindrical objects with a UAV.

Furthermore, one patent was found that discloses a system that would allow a UAV to deploy equipment onto a cylindrical target object. The system disclosed in [9] by AT&T Inc. would permit a UAV to deploy equipment on transmission mediums, such as telecommunication lines. The difference between this system and the proposed design in this project is that the system in [9] cannot retrieve the device after deployment.

1.4 Brief Overview of the Report
This document provides a detailed explanation of the project. The chosen optimal design is described in detail and justified over alternative designs. The prototype device manufactured for the client is also discussed. Furthermore, the realistic constraints for the design are identified and explained. Additionally, potential safety issues with the design are identified, and methods of mitigating these safety concerns are discussed. This report also addresses the potential impact of the engineering solution in the areas of arboriculture, industrial applications, and the environment. The contribution of this project to team members’ lifelong learning is also discussed. Furthermore, an estimated budget for the project and proposed project timeline are presented. Finally, an inexhaustive list of individual team member contributions to the project is included.

2 PROJECT DESIGN
This section includes a detailed description of multiple alternative designs, as well as the optimal design selected for the project and the manufactured prototype. In the design process, multiple alternatives were considered and evaluated in design matrices. Following the alternative designs section is a detailed description of the optimal design and its subunits. The final design was chosen as the optimal design over multiple alternative designs, primarily because of its superior weight savings and reliability. Other alternative designs involved multiple servo motors, a microcontroller, and power supply being placed onboard the USM, so they were inherently much heavier than this design, and it would have been much more difficult for the USM to remain securely attached to the full range of tree branches. Weight is also saved in the DRS in the optimal design, because it involves a separate end effector that gets swapped out for the deployment end effector for retrieval of the USM. Other designs incorporated deployment and retrieval into one DRS end effector, so they were heavier. Furthermore, these alternative designs would have decreased reliability, as they would have required the onboard electronics to be sheltered from the elements. Finally, the alternative designs would have required that power be delivered to the USM microcontroller at all times, so the deployment period length would have
been limited by the battery-life of the USM onboard power supply. The last topic in this section discusses the prototypes and testing of the USM and DRS created by the team.

2.1 Alternative Designs
2.1.1 Alternative Design 1

The first design alternative provides variations in each of the major systems. They consist of the Universal Sensor Mount (USM), the Deployment Retrieval System (DRS) and the Controller System (CS). With the mission statement in mind, “Safer, more efficient deployment of remote sensors can be accomplished using unmanned aerial systems. Development and application of a sensor deployment and retrieval system will expand the functionality and usefulness of unmanned aerial vehicle. The finished system will be intended for use in arboricultural applications”, design variations are developed and evaluated. The USM is capable of carrying sensor packages weighing up to 250 grams and has a method of being secured to tree limbs three to fifteen centimeters in diameter. The DRS is broken into two interchangeable subsystems. The Deployment System (DS) provides a means for delivery and securing the USM onto a desired limb. The Retrieval Hook (RH) provides a means to acquire, secure, and remove the USM from field service.

Each system has unique objectives to accomplish, and they are seamlessly integrated with each other. Starting with the primary project goal, the USM must provide a stable platform for a sensor to attach, securely hold a range of limbs, and provide an easily indexable fixture for removal. The main goal of the USM is to provide a platform that sensor housings of varying shapes and sizes can mount. The body of the USM has mounting holes or brackets where individual sensor housings can be fastened. The body does need to provide rigidity to support the sensor housing, clamping mechanism, and retrieval index. Structural plastics will allow the main body to be lightweight while maintaining ideal mechanical properties. The clamping mechanism, in conjunction with the subframe, must be able to lock onto and be removed with minimal harm to the tree. The design for the clamp is to use a passive clamping system, that is fully mechanical. This will reduce the weight and allow a more robust design to be made. A benefit of a passive mechanical system is its ability for extended deployment periods. The clamping is done using a spring system, equivalent to that found in clothespins. Using a torsional spring like a clothes pin allows for a passive design because the torsional spring will have potential energy stored. This design makes the clamping mechanism’s natural position in the closed state. This means that when the USM is clamped by the DS, it will be in the open position. Once the DS places the USM onto a branch and releases, the clamping mechanism of the USM will automatically close, connecting it to the branch. Also, a retrieval index will deploy on the USM. A loop of aircraft cable will be fixed to the body of the USM, so that it extends outward on the opposing side to the clamping mechanism. Two considerations will be explored, the size of loop and gauge of cable. This provides an optimized target for the RH to capture during retrieval operations. The loop will transfer an applied force to the USM so that it overcomes the clamping mechanism. While navigating out of the canopy, the loop provides enough swing so that the USM does not become entangled. The USM may be deployed in the elements for prolonged periods of time. The gripper spring must provide enough force to stay securely in position during inclement weather conditions. It must still be able to release from the limb upon intended retrieval. It must also be designed such that it can resist tampering from wildlife such as insects,
squirrels, racoons, and birds. A simplified schematic of the proposed USM is provided below in Figure 2 for reference.

Figure 2: Schematic of proposed USM design for alternative design 1

The DRS provides a stable fixture for the transfer of the USM. The Matrice 600 Pro’s existing payload rack provides a base to which the DRS mounts. Stability is necessary for controlled and safe docking of the USM on its target branch. The DRS and USM components must not exceed the maximum target payload weight of 3 lbs. A static probe that extends directly under the Unmanned Aerial System’s (UAS’s) center of gravity attaches to the mounting fixture with an emergency detachment actuator. This mounting fixture contains a microcontroller, TX, RX, power supply, and an emergency detachment actuator. The DS and RH attaches at the extension of the static probe during their respective tasks. All wiring is routed internally through the probe extensions and enables communication and power between the mounting fixture and the DS/RH. The UAS’s operational limitations restrict flight during any inclement weather conditions. This allows the DRS weather resistance to be a low priority in the design parameters. Environmental considerations to account for during the designing of the DRS include its ability to penetrate the exterior of a tree canopy and avoid entanglement within dense foliage. Desired design features include a streamlined static probe, internally routed wiring, and emergency detachment actuator joints.

The mounting fixture is the heart and structure of the DRS, as it will provide a platform for all DRS components to base off from and integrate with the UAS. It will be designed to attach to the Matrice 600 Pro’s existing structure. This framework must be robust enough to carry loads transferred by the static probe and DS/RH. It will also provide a mounting surface for the microcontroller, transmitters, receivers, and power supply. The attachment point between the mounting fixture and static probe would be secured by an emergency detachment actuator. The overall design will be balanced and centered under the UAS’s center of gravity. Other considerations include the mitigation of interference with the onboard landing gear.
The static probe will hinge mount to lower side of the mounting fixture. It will align in a vertical position below the UAS. Again, this will be fastened in place via the emergency detachment actuator. At this joint, all wire connectors will be emergency quick disconnect and held in place by the pin of the emergency detachment actuator. The static probe structure will be a hollow tube limited in diameter by the cables being ran internally. External rubber dampeners will be spaced along the length of the structure to reduce induced vibration and allow increased flexibility during flight operations. The overall length will be constrained by the weight of materials, components, and reasonable flight limitations. Optimization of static probe length will allow for increased canopy range with minimal obstructions.

The deployment system (DS) will be attached to the extended end of the static probe. Its primary function is transport and deployment of the USM. Additionally, an affixed camera will allow for navigation within the canopy. One actuator will be used to pivot the DS to align the USM with the desired mounting surface. A second actuator will open and release the clamps on the USM. A Third actuator will control the release/undocking of the DS from the USM.

For retrieval operations, the DS is replaced by the retrieval hook (RH). As was previously mentioned, the USM will have a metallic loop made of aircraft cable. The goal of the retrieval hook is to capture the loop and secure the USM for transport. Using the onboard camera, the operator will navigate the UAS until the hook has obtained the loop. This will be verified via an inductive proximity sensor. Autonomous, an actuator onboard the RH will rotate a gate closed to prevent the USM from falling off the hook. Through lift force from the UAS, the clamping force would become exceeded. Thus, the USM would ultimately release or slip off the branches in a controlled manner. A simplified schematic of this retrieval hook concept is shown below in Figure 3.

![Figure 3: Simplified schematic of retrieval hook design](image)

The CS will manage and TX/RX all commands, signals, or video for this payload system. The modularity designed into the DJI Matrice 600 Pro will allow for seamless integration and adaptation of additional implements and tools. This will require all code to be programmed
through DJI’s proprietary compiler and may have inherent limitations to be explored. Benefits in using this method of CS will allow for a simpler overall system design and a significant weight savings. This will also limit any conflict with signal transmission and operations of the UAS. Ultimately, the goal of using the onboard CS is to increase both fight time and safety.

This alternative provides uniquely different options for the overall design components. The USM and RH provide for more accurate, simpler docking during retrieval. This would expand the margin for operator error. The DRS will have two initial options for attachments, DR and RH with flexibility for future tools and implementations as the industry need grow. Use of the Matrice 600 Pro’s onboard flight controller system will provide for simpler design, weight savings, and increased flight time.

2.1.2 Alternative Design 2

Much like the first alternative design, the second design consists of a Universal Sensor Mount (USM), Deployment/Retrieval System (DRS), and Controller System (CS). However, in contrast to prior designs, the USM’s deployment onto branches would be actuated by an onboard microcontroller. The design would still be capable of satisfying all customer performance requirements.

To begin with, the USM would be capable of being attached to the tree branch with two clamps. The clamps would be designed so that their passive state is the closed position. The jaws of the clamps would be dimensioned such that they would be capable of clamping onto canopy branches ranging from 3 to 15 cm in average diameter. Each clamp would be loaded shut by a torsional spring. The ends of both springs would be connected by a bar. Thus, the two torsional springs would be connected in parallel. A linear actuator would be used to supply sufficient torque to hold the clamps open while the device is being deployed. When the USM clamps are in position around a branch, either a wireless signal from an operator or a proximity sensor will cause the linear actuator to release and shut the clamps. After the clamps are securely shut around a branch, the DRS will release the USM and the UAV will fly away. A microcontroller, such as a Raspberry Pi or Arduino, will need to be housed within the USM to control the linear actuator. Furthermore, a power supply would need to be housed within the USM to power the linear actuator’s servo and the microcontroller. Also, there would be a dedicated region on the USM for attaching scientific research payloads, such as accelerometers, that weigh up to 250 g. The housing of the USM would likely need to be custom-made with additive manufacturing methods. This housing would have a loop of material on top. This feature would allow the DRS to be capable of hooking and unhooking from the USM. The area of the loop would be dependent on the precision capable of being achieved by the drone pilot. Furthermore, the housing of the USM would need to be watertight to protect the onboard electronics from rain and condensation. This could be accomplished with water-resistant plastic and rubber seals on all entry points to the housing. A simple schematic of the proposed USM design is shown below in Figure 4.
Figure 4: Simplified schematic of the proposed USM for alternative design 2

The DRS in this alternate design would be simple relative to the USM. Its main component would be a tube between 10 and 15 ft (3.05 – 4.57 m) in length. Due to the weight constraint of 3 lb. (1.36 kg) for all components of this design, a material with a high specific modulus and specific strength is desirable for the tube. For this reason, the tube would likely be made from carbon fiber. The tube would be mounted beneath the DJI Matrice 600 Pro and capable of being released from beneath the UAV in the event that the USM or DRS became entangled in a tree. A hook would be connected to the end of the tube to enable the DRS to hook onto the loop in the housing of the USM for deployment and retrieval. The end of the hook would be capable of remaining in a closed position during flight and opening when the USM is ready to be deployed or retrieved. This could be accomplished either entirely mechanically, or electromechanically. Regardless, in its resting position on the hook, the USM will be in a nearly vertical position, as the majority of target branches will be nearly vertical with respect to the ground. Finally, a camera would be mounted either on the tube of the DRS or beneath the UAV. This camera would feed live video of the DRS end effector and USM clamps to the drone pilot. The camera will be necessary for precise positioning of the USM onto target branches in tree canopies.

The CS will be used to wirelessly control the deployment of the USM. The CS will also be used to wirelessly control the emergency release of the DRS and USM subsystems in the event that they become entangled in a tree, begin oscillating uncontrollably, or experience a catastrophic malfunction. Finally, the CS will receive a live video feed from a camera onboard the DRS. The CS consists of a microcontroller onboard the USM, a secondary controller for the drone pilot or operator on the ground, and the stock controller for the DJI Matrice 600 Pro itself. The microcontroller and secondary controller will interface using Wi-Fi, Radio Frequency (RF), or Bluetooth communication protocols. Interfacing the controllers with Wi-Fi would likely be the simplest route, however, in remote areas with poor cellular coverage the controller would not work well. If RF communication was used, the locations that the device could be used would no longer be dependent on the cellular coverage in the area. Like Wi-Fi, Bluetooth communications would be relatively simple to implement, however, the controller range would be poor and the response times of the device would be slower.
In conclusion, the second alternative design is different from other alternative designs in that a microcontroller used to control the opening of the USM clamps will be mounted onboard the USM itself. Furthermore, the actuator used to open the clamps would also be housed onboard the USM. A power supply for the actuators and microcontroller would also need to be housed inside the USM. Finally, in this design, the DRS would be much less complicated, as it would simply consist of a tube and hook.

2.1.3 Alternative Design 3
The last alternative design is broken down into three parts, much like the first two alternative designs. The Universal Sensor Mount (USM), the Deployment/Retrieval System (DRS), and the Controller System (CS). The job of the USM is to securely hold a variety of sensors and clamp onto tree branches with no damage done to the branches. The job of the DRS is to safely deploy the USM onto the tree branches and collect the USM. The DRS also must have fail-safes to detach from the drone in case of a failure to deploy the USM that could result in the drone crashing. Lastly the job of the CS is to control any actuators with a microprocessor onboard the UAV, and a separate controller on the ground to communicate with the microprocessor.

Starting with the USM, the design will be an electronically controlled clamping mechanism. The job of the USM is to stay in the tree canopy for a data collection period. It also must not fall from tree branches, possibly rendering any data collected to be useless. This means that the design must be sturdy enough to hold the individual sensor and lightweight to meet the 3-pound weight restriction. To increase its sturdiness once deployed onto the tree, the USM will have a clamping mechanism controlled through the CS that operates actuators to clamp the device to the branch. The actuators must be lightweight to meet the weight requirements yet provide enough force to ensure the USM will not fall from any branches. Some of the circumstances the USM could face and must combat are high wind scenarios, rainy and cold conditions, and tampering due to native wildlife. To help reduce the amount of clamping force needed from each actuator, there will be two clamps on the USM. This will allow for the clamping force to be spread out over a larger area. This will also reduce the degrees of freedom of the USM. Each clamp arm will also be coated in a high friction coefficient material that will increase the amount of force needed to detach the USM from the branch unwillingly. These actuators will be controlled through the CS, so an onboard microprocessor is needed to send commands to the USM. For the actuators and microprocessor to work there will be an onboard battery source to power all onboard controls. This power source will be temperature resistant and must hold enough charge to power the actuators during deployment and retrieval of the drone. Due to all the electronics onboard, the entire system must be weatherproof. If water or moisture were to enter the main body housing the electronics, everything could fail, resulting in the USM stuck in the tree with no easy method of retrieval. To ensure a weatherproof system, the body will be made of a corrosion resistant plastic. The compartment used to house the electronics in the body will be sealed with a hinge and clasp mechanism. The lip of the opening will then be sealed with a gasket to prevent moisture leaking into the compartment. In order to deploy the USM a loop of twisted steel cable will be attached to the USM housing. The purpose of the loop will be explained in greater detail later in the explanation of the DRS. To secure the sensors to the USM, the top of the main body will have a raised lip, with straps running the two directions. The sensor will be placed on the top of the USM and the lip will prevent the sensor from slipping off the main body. The straps will secure the sensor to the main body. The straps will consist of heavy-duty Velcro, allowing the straps to be easily replaced based on size of the sensor that will be deployed. The Velcro straps
will be weather resistant and be strong enough to hold the maximum sensor weight of up to 250 grams. A simplified schematic of this alternative USM design is given below in Figure 5.

**Figure 5: Simplified schematic of the proposed USM for alternative design 3**

The DRS will be attached to the underside of the drone via the pre-existing mounting rails on the DJI Matrice 600 Pro. Spanning across the mounting rails will be a flat platform to mount the rest of the DRS. This platform must be sturdy enough to hold up to a 10-foot-long structure, along with multiple actuators and wiring. This platform will be made from lightweight aluminum to ensure a stable mounting base. Above this platform there is a small space between it, and the body of the drone. The onboard microprocessor and battery pack will go in this space. Since the drone cannot fly in inclement weather, these components will not need to be weatherproof. The arm of the DRS is the portion that will extend down vertically from the base of the drone. This portion will be made up of lightweight tubing, such as carbon fiber tubing. Since the drone still needs to take off and land using the built-in landing gear, the arm must not interfere with this process. To combat this issue, the arm of the DRS will be broken into sections and connected with pliable rubber to allow the arm to self-straighten after takeoff. These rubber sections will also act as dampeners for the arm during flight, allowing minimal swaying movement of the arm due to drone flight. The arm must also be able to release from the drone in case of emergency situations to prevent the drone from crashing into the canopy of the tree. To accomplish this, a solenoid will actuate a pin. This pin will be placed into the top tube and through a mounting bracket affixed to the underside of the mounting body. This solenoid will be wired to the microprocessor so that with the press of a button the pin will actuate outward, dropping the arm of the DRS. On the bottom of the DRS arm, will sit an actuator and hook mechanism. As stated above, the USM will have a wire loop attached to the body. The job of the hook on the DRS arm will be to latch onto the loop of the USM, the USM will then actuate to open its clamping mechanism, and the drone will then be able to safely fly away with the secured USM. This hook will have two jaws mounted with the opening of the jaw facing in a horizontal direction. The job of the actuator affixed at the end of the arm will be to open and close the hook to secure the USM. The claws of the hook will be made of a lightweight plastic to help reduce overall weight of the system. The claws will also be aggressively knurled to provide a better purchase when clasping onto the loop of the USM. The DRS will also have a small camera mounted to the bottom portion of the arm. This will allow a live camera feed to be transmitted to the CS to help
in deployment of the USM. The camera will be mounted facing downward to give a bird’s-eye view of the operation at hand. The wiring to power the actuator and the camera feed will be run from the microprocessor and battery supply that is mounting above the mounting base. The mounting base will have a hole drilled in to allow the wire to pass through the base, down through the middle of the carbon fiber arm, and to the actuator. This will prevent any wires getting caught on branches during flight. During landing of the drone, a second operator will be waiting underneath the drone. Once the arm reaches the second operator, they will then walk the pliable arm out from underneath the drone allowing a safe landing without damaging the DRS or drone in the process.

The CS is the brains of the device and has two main parts. The first part is the onboard microprocessor that will communicate with the actuators. The second part will be a handheld device used by a second ground operator. This device will also contain a microprocessor with an array of buttons or switches. These buttons will each control a different actuator allowing the system to complete each task labeled above. To communicate with each microprocessor, both on the USM and DRS, the CS will have a Bluetooth transmitter. The transmitter will also give the live video feed from the camera on the onboard the DRS. The CS will also have its own battery power supply to operate the controls. The CS will be used in congruent with the flight of the drone, so no weather proofing will be necessary. To give a better feel to the CS, a 3D printed body will be made to house the power and processor internally. On the face of the body will be a small screen for the video transmission along with each button to control the USM and DRS.

Overall, the design of the tree canopy sensing device will contain the USM, the DRS, and the CS. The USM will have an onboard processor and actuators to control the clamping of the device to the tree. The DRS will have a long arm with a hook mechanism that will deploy and retrieve the USM. Finally, the CS will communicate with both the USM and DRS.

2.2 Optimal Design

2.2.1 Objective

The team has conceptualized and designed a novel system capable of achieving the ultimate project objective. An optimal design was selected and prototyped that consists of three main subunits: The universal sensor mount (USM), deployment/retrieval system (DRS), and controller system (CS). An overview of the system is presented below in Figure 6. The Morton Arboretum’s tree monitoring devices are secured to the USM (assembly number 2 in Figure 6), which employs a passive clamping system to remain attached to branches. Then, the USM is attached to tree canopy branches with the deployment system wrist (assembly number 3.1 in Figure 6), which is suspended from the arboretum’s UAV (assembly number 1 in Figure 6). To retrieve the USM from branches with the UAV, the deployment wrist is swapped out for a retrieval hook (assembly number 3.2 in Figure 6), which is used to capture a loop on the USM and remove it from branches. The deployment system wrist and retrieval hook are connected to the UAV with a carbon fiber pole and extruded polylactic acid (PLA) fixtures (assembly number 3.3 in Figure 6). The operations of the DRS are controlled through the UAV’s stock controller, with a channel expansion kit (assembly number 4 in Figure 6).
2.2.2 Subunits

2.2.2.1 Universal Sensor Mount (USM)

The Universal Sensor Mount (USM) is a device that is made to hold onto tree limbs, while safely carrying any sensor package up to 250 g provided by the client. The main goals of the USM are to safely clamp onto tree limbs, be able to be deployed and removed via the UAV, and to have a mounting platform that will permit secure attachment of sensor packages to the device.

The clamping mechanism is an integral part of the USM. Its main job is to clamp onto the tree branches, and it must support the weight of itself and the sensor package. To achieve rigid clamping, enough force must be used to overcome the gravitational forces, as well as any outside forces that the branch may be exposed to. Some forces that the USM will encounter outside of the system will be weather related, such as wind. The USM is left in the canopy of the trees for an extended period, and the USM must be able to withstand any weather conditions that arise during that period. Some conditions that could arise are high wind scenarios, rain, humidity, and temperature variation. Although the sensor package will not be deployed during the winter months, the design still needs to hold up to varying temperatures to compensate for the drop of
temperature during the night. Other forces acting upon the system could arise from native wildlife tampering with the mount. To combat these issues, the structure must be mechanically sound, as well as weather resistant. The materials that are used need to be strong, yet lightweight. With a three-pound weight restriction of the entire system, the USM will be a place where weight can be thoroughly reduced due to the lack of actuators onboard, as opposed to the other systems. Making the USM lightweight greatly reduces the amount of clamping force needed to keep the system attached to tree branches. The clamping is achieved through torsional springs, as seen in Figure 7 below. There are two torsional springs, one for each of the rotating clamps. These springs act like a clothespin, such that in the resting position the clamps are forced closed by the springs. This passive clamping allows the device to be fully mechanical, further reducing the weight and complexity of the USM. The clamps themselves are made from 3D printed polylactic acid (PLA). This material is lightweight and strong using a high infill ratio on the printer. Printing the clamp arms allows for the complex geometry of the arms to be made with ease. The PLA will allow for a strong enough clamp arm that will not fail from the stressed experienced in operation.

![Figure 7: CAD Model of USM](image)

The clamping mechanism works on a range of branches from 3 cm to 10 cm in diameter. To achieve the clamping force on the broad range of branches, the fixed clamp arm has four indexing positions. These positions allow the user to move the fixed arm closer or further away from the rotating clamps. The reason for this design choice is that torsional springs increase in force depending upon the degrees rotated. So, to achieve the same clamping force on small and large branches, the fixed clamp is moved. The client uses a software system to map out trees, and has an understanding of which specific branches they would like to deploy the USM. Knowing
the approximate branch size beforehand allows them to change the fixed arm setting to the desired indexing position. With the four clamping arms, the degrees of freedom of the USM are reduced, restricting any further movement during the deployment period.

For the USM to be deployed, the Deployment Retrieval System (DRS) needs to do two things. The first thing is to index onto the body of the USM to hold on to the body. To achieve this, there is an indexing slot on the bottom and holes on top of USM as seen in Figure 7. The USM will rest on the indexing slot, while a servo from the DRS will push a fixture into the holes on the top clamping it into place. The holes and slot give a strong purchase onto the main body of the USM to secure it and limit motion during flight. This clamping mechanism also allows for a smooth transition of the USM from the DRS onto tree branches. Once the servo unlocks the top pinholes of the USM, the indexing slot allows the main body of the USM to freely rotate and clamp onto branches. The USM may run into small twigs and branches during deployment and must be able to be clamped tightly to ensure the system will not fall from the drone. The second is to press on the rotating clamp arm to hinge the clamp open under tension. To deploy the USM, the rotating clamp must be in the open position, which means the torsional spring and clamp arm must be depressed to open the clamping mechanism. The DRS presses on the upper portion of the rotating clamp arm, so a solid surface must exist to allow for purchase of an actuator. As seen in Figure 7, the rotating clamp arm curves upward to allow for a vertical surface to push upon during deployment.

For retrieval of the USM, the clamp arms must not impose too much force onto the tree branches that the drone would not be able to extract it. The arms must also not damage the tree branch. To retrieve the USM, a twisted steel cable loop will be attached to the main body of the USM and stick outward. The clamp arms of the USM are rounded on the edges to prevent scoring of the tree branch during removal. Once the data collection period is complete, the cable would be hooked with the DRS. Once the cable is hooked onto the DRS and the drone starts to pull away, the torsional springs will not have enough force to keep the USM on the branch. The rounded edges of the clamp arms then allow for the USM to smoothly be pulled off the tree with no damage. The cable will be strong enough to endure the forces of the DRS pulling the USM and the weight of the sensor package off the tree.

To secure the sensor package to the USM, a mounting system was created. Sensors are mounted to the main body of the USM. To mount sensors, there is an array of tapped holes that the base of the sensor package can securely bolt to in different orientations. This array of tapped holes also allows for the possibility of multiple smaller sensor packages to be deployed onto one USM to permit more data collection in one deployment session. To keep the weight down, the main body of the USM is printed from PLA. This material is lightweight and corrosion resistant. Using a polyester material such as PLA allows for a lighter overall construction of the USM, while not compromising on structural integrity. Using PLA also allows the material to be tapped, as some plastics are brittle and prone to cracking or breaking threads once tapped. If a material such as ABS plastic was used, this would compromise the integrity of the mounting system, with the possibility of bolts stripping out during a deployment period, causing the sensor package to fall. Using a robust, yet lightweight material is integral to the mounting system and body of the USM.
To assist in the design of the USM, a simplified mathematical model was created, as shown in Figure 8.

From the mathematical model, equations for the spring displacement angle $\theta$, torsional spring torque, rotational clamp contact force, and minimum contact force required to keep the USM clamped to a vertical branch were derived. Details of this derivation and the relevant equations can be found in section 12.2.1 of the appendices. Through calculation with a USM width $W$ of 10 cm and in fixed clamp setting number 4 (widest setting), it was determined that the spring angle, $\alpha$, needs to be $180^\circ$ to ensure that there is enough clamping force on the smaller branches and not too much force on the larger branches. Figure 9 contains two helpful plots.

The plot on the left is of the minimum contact force required to support the USM on a vertical branch, plotted against the weight of the USM (weight is inclusive of the 250 g sensor package).
for various static friction coefficients. The plot on the right is a plot of both the minimum and maximum contact force plotted against the torsional spring constant, as well as the minimum and maximum spring torques plotted against the torsional spring constant. The magenta arrows are intended to be illustrative of how the plots in Figure 9 were used. For example, with a USM weight of 1.5 lbf. and a coefficient of static friction of 0.4, a contact force of around 0.8 lbf. is required to support the USM on a vertical tree branch. Then, moving to the plot on the right with a minimum contact force of 0.8 lbf., a torsional spring constant of approximately 1.6 [in-lbf/rad] is needed. Then, with a torsional spring constant of 1.6 [in-lbf/rad], it can be seen that the maximum spring torque (when the rotational clamps are fully open on the largest branch diameter) would be approximately 3 [in-lbf]. However, since there are two rotational clamps on the USM connected in parallel, the maximum torque experienced by the device is actually approximately 6 [in-lbf]. This model can be used to create a design with reduced weight and increased rigidity. To keep a comfortable factor of safety on the USM clamps to ensure that the USM would remain secured to tree branches, springs with a torsional spring constant of 2.93 [in-lb./rad] were selected. Since the team’s USM prototype actually ended up weighing only 1.1 lbf. with a 250 g (0.55 lbf.) sensor payload (instead of the design weight of 1.5 lbf.), the prototype’s gripping force factor of safety is around 2.9.

2.2.2.2 Deployment and Retrieval System (DRS)
The DRS provides a stable fixture for the transfer of the USM to branches. The Matrice 600 Pro’s existing payload rack provides a base to which the DRS will mount. Stability is necessary for controlled and safe docking of the USM on its target branch. The DRS and USM components must not exceed the maximum target system weight of 2 kg. A carbon fiber pole that extends directly under the Unmanned Aerial System’s (UAS’s) center of gravity attaches to the UAV mounting fixture. The deployment system (DS) and retrieval hook (RH) attach at the extension of the static probe during their respective tasks. All wiring is routed internally through the probe extensions and enables communication and power between the mounting fixture and the DS/RH. The DS is depicted in Figure 10. The UAS’s operational limitations restrict flight during any inclement weather conditions. This allows the DRS weather resistance to be a low priority in the design parameters. Environmental considerations to account for during the designing of the DRS include its ability to penetrate the exterior of a tree canopy and avoid entanglement within dense foliage. Design features include a streamlined static probe and internally routed wiring.

Figure 10: CAD model of deployment system
The mounting fixture is the heart and structure of the DRS, as it provides a platform for all DRS components to base off from and integrate with the UAS. It is designed to attach to the Matrice 600 Pro’s existing structure. This framework is robust enough to carry loads transferred by the static probe and DS/RH. This framework is to be made from printed PLA. A model of this framework is depicted in Figure 11. It also provides a mounting surface for future additions such as microcontrollers, transmitters, receivers, and power supplies. The overall design is balanced and centered under the UAS’s center of gravity. Other considerations include the mitigation of interference with the onboard landing gear.

![Figure 11: CAD model of UAV to pole mounting framework in the DRS](image)

The pole hinge mounts to lower side of the mounting fixture. It aligns in a vertical position below the UAS. At this joint, all wire connectors are emergency quick disconnect and the pole is held in place by a lock pin. The static probe structure is a telescoping hollow carbon fiber tube limited in internal diameter by the cables being ran internally. The overall length of the probe is a maximum of around 12 feet. Optimization of static probe length allows for increased canopy range with minimal obstructions. The arboretum will fix a camera on the lower end of the static probe for navigation and alignment of the DS/RH attachments. The DS/RS attachments can index into the end of the static probe and be interchanged for appropriate operations.

The DS in Figure 10 is attached to the extended end of the pole. Its primary function is transport and deployment of the USM. Prior to flight, the user sets the DS to align the USM with the desired branch inclination, as seen from the incremental adjustment hinge in Figure 12.
The DS incorporates two 35 kg-cm servos. The primary servo operates the drive shaft, which has push harms that actuate the USM rotational clamp arms. The second servo rotates an indexing fixture to lock the USM into the DS housing until the USM has been secured to a tree branch. The main body of the deployment wrist is printed from PLA with cutouts to reduce the overall weight. To prevent twigs and branches from penetrating the body, it is closed off with acrylic panels on the interior. Some other features constructed from PLA are the mounting fixtures and brackets. The bushings and rollers for the drive shaft are made from nylon to reduce wear between parts, and the pivot joint is made from aluminum. The desired material for the drive shaft is aluminum.

For retrieval operations, the DS gets swapped out for a retrieval hook (RH). The goal of the retrieval hook is to capture the USM retrieval loop and secure the USM for transport. A simple diagram of the retrieval hook is shown below in Figure 13.

![Figure 13: CAD model of the retrieval hook](image)
Using the camera on the DRS pole, the operator navigates the UAS until the hook has obtained the loop as shown in Figure 14. Then, up to 54 newtons of lift force from the UAV is used to overcome the USM clamps and remove the USM from the branch. A stock hook could also be purchased and modified to serve the purpose of the RH.

![Diagram of RH collecting USM](image)

**Figure 14: Diagram of RH collecting USM**

### 2.2.2.3 Controller System (CS)

The CS is used to wirelessly control the deployment of the USM. The CS is also used to wirelessly control the emergency release of the DRS and USM subsystems in the event that they become entangled in a tree, begin oscillating uncontrollably, or experience a catastrophic malfunction. Finally, the CS receives a live video feed from a camera onboard the DRS. The CS is capable of performing the logic shown earlier in the block diagram in Figure 1.

The CS consists of the stock DJI Matrice 600 Pro UAV controller with the eight-channel expansion kit, which is depicted below in Figure 15. The controller’s functions (controlling the DRS wrist servo motor) will be programmed using the DJI Assistant 2 software, which is pictured below in Figure 16.

![Stock UAV controller with channel expansion kit](image)

**Figure 15: Stock UAV controller with channel expansion kit [11]**
2.3 Prototype
This section discusses the prototype systems fabricated and tested by the team.

2.3.1 Universal Sensor Mount (USM)
The main purpose of the USM is to secure a payload containing sensors and affix itself onto tree branches without failure. First to secure the payload the main body of the USM is created from 3D printed PLA. The main body contains an array of holes as shown in Figure 17a to secure the payload. The holes shown are mean to fit the shaft of any length ¼-20 bolt. The size of the holes were picked for this bolt size as this is one of the most widely available bolts used.
To deploy the USM, the main body will be clamped inside the DRW. On the bottom side of the USM there is a female end slot cut out. This slot will rest on a male end fixture on the DRW. Once the USM is placed on the slow, a servo will clamp onto the top end of the USM. There are two holes the servo will clamp to as seen on the top leading edge from Figure 17. To clamp onto the tree branches the USM has two different styles of clamp arms to make up the design. The first is the rotational clamp. The rotational clamp acts like a clothes pin, in that the resting position is closed. This is made possible by a steel wire torsional spring as seen in Figure 17b. The other clamp arms do not rotate and are fixed in position. There are four different indexing positions for the rigid clamp arm. The indexing position depends upon the branch size being targeted for that specific deployment. Moving the rigid clamp closer to the rotational clamp allows for similar clamping force on small branches as on larger ones in a different indexed position. The clamp arms are made from 6061 aluminum in the final revision. Although for rapid prototyping and demonstration, the clamp arms were printed from PLA as pictured above. All the clamp arms also have a rounded tip. The purpose behind this is that during extraction of the USM from tree branches as the UAV pulls the arms off, the rounded tip will allow for the USM to easily slip off the tree with minimal damage to the branch. The top edge of the clamp arms are also rounded which contrary to the bottom edge are not. The reasoning behind this concept is the top edge will also allow for minimal damage upon extraction, while the bottom edge will dig into the bark minimally to prevent slippage down a tree limb. On the front face of the USM pictured in Figure 17a there are two small sets of holes. This is to mount the braided steel cable. The steel cable will extend horizontally outward from the USM, allowed the retrieval hook of the DRW to have easy access upon removal from the tree.

During the design process there were multiple revisions of the USM. To validate the work put into the design there were multiple tests that took place. The first test to take place was on the initial USM prototype. The original tree branch constraints for this test were 3 to 15 centimeter diameter branches. There was also a payload attached to the base of the USM that...
weighed 285 grams. This was 35 grams over the maximum sensor package weight given to the team by the client.

![Image](https://example.com/image1.png) ![Image](https://example.com/image2.png) ![Image](https://example.com/image3.png)

*Figure 18: Testing of initial USM prototype*

The USM was first tested on branches of different orientations and fixture placements, as shown in Figure 18a and b. The USM was placed on these branches in different orientations such as vertical, horizontal, right-side-up, and upside-down. Under all the configurations the USM never failed to remain clamped onto the tree. The branches were also shaken repeatedly to simulate wind without failure of the USM. In Figure 18c a force gauge was used to pull the USM off the team’s indoor test stand. The maximum recorded force was 26.7 Newtons (6 lb). This force is half that of the UAV’s capability to produce force from lift, giving us enough force to remove the USM successfully.

![Image](https://example.com/image4.png) ![Image](https://example.com/image5.png) ![Image](https://example.com/image6.png)

*Figure 19: Final USM prototype testing*

The second test conducted on the USM was of the final prototype. From the first test, it was concluded that towards the top of the tree canopy the branch diameters would not be 15 centimeters. This caused the upper constraint to be reduced to 10 centimeters in diameter while retaining the lower limit of 3 centimeters. Due to the branch size constraint decreasing, the base of the USM was able to reduce in size. This reduction in size lowered the overall weight of the final prototype to 0.5 kg (1.1 lbs.) with the maximum payload attached. This reduction in weight
was a positive outcome of the initial test, as it allowed more freedom in the design of the DRS to meet the weight requirements. The final prototype was successfully placed on multiple branches without failure, proving the prototype’s functionality.

2.3.2 Deployment/Retrieval System (DRS)

The team fabricated a prototype of the deployment system (DS). This prototype is depicted in Figure 20 in both an unloaded and loaded configuration.

![Figure 20: Empty deployment system prototype (a) and loaded deployment system prototype (b).](image)

The DS employs two 35 kg-cm servos. The first servo is used to power a drive shaft, which has push arms that will actuate the USM rotational clamp arms. The second servo is used to clamp the main body of the USM to secure it during flight and deployment. To accommodate all branch sizes, the deployment wrist has a pivot joint at the top that attaches to the pole. This pivot joint allows the user to angle the deployment system before flight, depending on the orientation of the targeted branch. The main body of the deployment wrist is printed from PLA with cutouts to reduce the overall weight. To prevent twigs and branches from penetrating the body, it is closed off with acrylic panels on the interior. Some other features constructed from PLA are the drive shaft, mounting fixtures, and brackets. The bushings and rollers for the drive shaft are made from nylon to reduce wear between parts, and the pivot joint is made from aluminum. A stock servo-coupler joins the drive shaft servo to the drive shaft. The DS prototype is shown attached to a 38 to 146” telescoping standard modulus carbon pole in Figure 21 below.
The DS prototype’s capabilities of actuating the USM were bench tested on a setup designed to simulate the capabilities of the UAV platform as closely as possible. This setup is depicted in Figure 22 below.

The DJI Matrice 600 Pro is capable of supplying 18 VDC and the operating voltage of the servos is 7.4 VDC. So, a battery eliminator circuit was used to step down the 18 VDC to 7.4 VDC for the servos. Potentiometers and an Arduino Uno microcontroller were used to independently control both servos on the device. Testing of the DS showed that the PLA drive shaft used in the
initial prototype was not capable of withstanding the torque required to fully open the rotational clamps on the USM, because shearing occurred between the servo shaft coupler and the drive shaft. So, in future revisions of the prototype, an aluminum servo drive shaft is recommended. The prototype could be even further improved by increasing the mechanical advantage of the drive shaft servo. One method of increasing the mechanical advantage include moving the drive shaft rotational axis closer to the USM clamp rotational axis. Another method of increasing the mechanical advantage of the drive shaft servo is to externally gear up the servo to increase the output torque. The locking/unlocking mechanism powered by the second servo motor functioned as intended. As long as the second servo remains energized, the USM remains firmly secured in the DS housing.

2.3.3 Controller System (CS)
The prototype controller system used in the bench test setup consisted of an Arduino Uno microcontroller, two potentiometers, an 18 VDC power supply, and a battery eliminator circuit (BEC) set to convert 18 VDC to 7.4 VDC to power the servo motors. Simple code was written in the Arduino Uno IDE to rotate the servos based on the potentiometer positions. A simplified wiring schematic of the setup is depicted below in Figure 23.

![Figure 23: Wiring schematic of the controller system used to test the DS prototype](image)

3 REALISTIC CONSTRAINTS
Throughout the project, there were many constraints that needed to be considered. Many of these considerations are for the welfare of the public to ensure safety, while others are individual constraints that are independent of the project or people. Stated below are all the constraints and considerations taken into account throughout the design process.

3.1 Engineering Standards
The are many standards applicable to this design, given its cross-discipline nature. Standards pertaining to UAV operation, wireless communications, mechanical devices, and forestry are relevant.
The design abides by regulations and standards for unmanned aerial systems put forth by the Federal Aviation Administration (FAA). The UAV must abide by all relevant regulations.
Furthermore, all payloads remain securely attached to the UAV during flight operations. Finally, the system should never be flown directly over people, to avoid putting people at risk of injury or death. Standards from other bodies regarding UAVs are also relevant. Examples of other relevant standards regarding UAVs are ASTM F2909-14, ASTM F2910-14, and ASTM F3002-14a. Furthermore, the airborne equipment testing standards and procedures provided in RTCA DO-160G should be consulted in the testing stages of the prototype.

The wireless communications method employed by the CS will abide by regulations put forth by the Federal Communications Commission (FCC). Thus, any method of wirelessly actuating the DRS will adhere to FCC laws. There are also many standards relevant to the CS from other bodies. These include IEEE Std C95.7-2014 and IEEE 802.11-2016.

It would be irresponsible for this design to not respect and consider regulations and standards regarding environmental protection and forestry. This means that laws and values of bodies such as the Environmental Protection Agency and United States Forest Service should be respected by the design.

3.2 Economic Constraints
The costs associated with the design, development, materials, fabrication, assembly, and testing of the systems were limited by the client. The costs associated with the entire system were originally estimated to fall around a maximum of $2,000. This initial estimate and justification were approved by the client with significant flexibility for expansion once initial goals were achieved. As vetted designs were approved by all parties, financial support was assessed and provided. The project’s budget and actual cost are discussed later in the budget section of this report.

3.3 Environmental Constraints
There are multiple environmental constraints that apply to this design. The environmental constraints of the USM are different from those of the DRS and CS, since the USM gets left behind on tree branches.

The DRS and CS subsystems are always attached to the UAV, so their primary environmental constraints are dictated by the environmental limitations of the DJI Matrice 600 Pro UAV itself. Thus, the DRS, CS, and UAV are unable to be used in rain, snow, fog, and wind speeds greater than 8 m/s (18 mph). The UAV is also restricted to operation at altitudes under 2500 m (8200 ft) above sea level. Furthermore, the suggested operation temperature range of the UAV is -10°C to 40°C (14°F to 104°F) [10]. The UAV operating temperature range dictates the DRS and CS operating temperature ranges.

Relative to the DRS and CS, the USM needs to be much more robust in terms of environmental constraints. Since the USM may be left in tree canopy branches for a user-chosen deployment period, it needs to operate effectively after exposure to the elements, with the exception of winter conditions. The USM must continue to operate effectively after exposure to water from rain or condensation. For this reason, the USM will be fabricated from corrosion-resistant materials to prolong its service life. The USM must also be able to remain securely attached to tree branches in strong winds, such as those produced in typical midwestern thunderstorms. Finally, the USM must not be easily removed from tree branches by wildlife, such as squirrels.
3.4 Sustainability Constraints
The sustainability of an engineering design refers to its ability to perform under given specifications for a certain length of time. The device that has been designed must withstand multiple environmental factors and be robust enough for the customer to use the design for years to come. Choosing materials that can be subjected to environmental conditions without significant degradation over the life of the design is critical. Different materials degrade through humidity, rain, and sun exposure. If these materials are not chosen correctly, the design would begin to degrade quickly, rendering the design unusable in a short time frame. Along with material selection due to environmental conditions, the design is subjected to repeated use and must be designed for a part life. The USM repeatedly clamps onto branches, and parts such as the clamps and springs must not lose performance over time through deformation or other factors. For the DRS system, the actuators are also repeatedly used to deploy the USM and must not fail after limited use. The actuators and fixtures on the DRS are subjected to the same forces as the USM and must hold up to the stress and strain put on the device by normal operations.

3.5 Manufacturability Constraints
Manufacturing of the initial project was constrained by NIU’s limited tooling, vendor relationships established with the arboretum, and cost of materials. The machines provided by NIU limit some more complex geometry and very detailed designs. The shop currently provides a set of machines that students can use, which influences the design. The mills provided for student use are Bridgeport manual mills. These mills require manual machining in the x, y, and z directions. This limits geometry as more complex designs cannot be achieved through this machine. Other constraints regarding manufacturing are the size of parts that can be fabricated. With the machines given, there are set limits to the size of parts that can be made. Any parts that are manufactured using additive manufacturing will also have some limitations. The machines available through the school have certain limits and abilities that drive some of the alternatively manufactured parts. The type of material and method used to print will constrain some of the design and what can be done. Most of the 3D printing available is with plastics such as PLA and ABS. Although this may work for prototyping parts, this may not be viable for all components in the final design. The design can also be constrained in size by the type of 3D printer used. Large parts, such as the deployment system housing, had to be broken down into multiple constructed pieces as they were too big for the print bed. Failed prints can add more time to the manufacturing process and had to be considered as well.

3.6 Ethical Considerations and Constraints
The National Society of Professional Engineers code of ethics states: “Hold paramount the safety, health, and welfare of the public” [12]. Keeping this in mind, the design must not affect the safety of the public while in use. The design has fail-safes in place to uphold this standard. If the design were to have a catastrophic failure during use, the DRS could break away from the drone to prevent a crash that could compromise the safety of any persons in the vicinity. The product must also not be designed in such a way that the public could use the product for objectives other than its given purpose. Another constraint to consider is the impact on the environment the product will have. Materials used in the product must not pose any health hazards towards the public or wildlife.

3.7 Health and Safety Constraints
With the transportation and deployment of testing devices by unmanned aerial vehicle comes safety constraints. Typical with most aerial based systems, redundancy should be built in to
mitigate failures resulting in equipment falling from an elevated position. All payloads, while deployed or in transport, must maintain a suitable fixture to their intended location. This helps prevent any damage to the delicate experimental sensors. The DS is designed so that indexing and moving clamp servos are engaged and disengaged at independent times. This assures that the USM is docked securely to the desired branch prior to fully releasing it from the DS.

While the USM is deployed, patrons of the Morton Arboretum may have access to the grounds beneath the target canopy. The USM jaws are designed to ensure that safe operation is maintained over an extended period. The selection of torsional spring and jaw profile optimizes the contact forces. This allows the USM to stay securely adhered to the branches while they move and grow and are exposed to varying environmental conditions.

Proximity to the dynamic movement of a tree canopy generates a need for significant safety of flight constraints. Maintaining a safe proximity while accurately deploying the sensor fixtures is a concern. The static probe is black to contrast the skyline. The last two-foot section should be fluorescent red. The operator and spotters should verify that the probe never inserts far enough that the canopy engages the red section. A potential future addition The Morton Arboretum could introduce is the DJI proximity sensor package.

### 3.8 Social Constraints

The use of UAVs (also known as drones) in public spaces raises concerns of personal privacy, safety, and equipment security. Operations must be conducted in a manner as to reduce the invasion of personal privacy. Posted notification at the gate would provide patrons an idea of what the use of the UAV is for and approximate location on property they may want to avoid. Providing adequate communication will help promote a positive public image for this program. Community safety also affects public perception.

By establishing a standard practice for safe operation and maintaining a visual zone of protection, patrons can be reassured that this equipment is safe and value to their community. Establishing a positive public image will ensure longevity and support for current and future commercial applications of UASs.

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**Figure 24 Safe Operation Zone**

By establishing a standard practice for safe operation and maintaining a visual zone of protection, patrons can be reassured that this equipment is safe and value to their community. Establishing a positive public image will ensure longevity and support for current and future commercial applications of UASs.
4 SAFETY ISSUES
Taking a deep look upon the safety constraints outlined above, the final system needs to be designed and operated safely. Use of system redundancy allows for secure operations. The deployment of the USM, has been identified as a critical safety point in the operation of the device. By separating the operations of engaging the grippers and undocking of the DRW, the risk of equipment damage and injury is greatly reduced. On recovery this can be accomplished through the addition of a spring gate across the opening of the hook. Operational standards, policies, and procedures will be established as operational testing is conducted. Any time overhead operations are conducted, a zone of protection should be established to ensure equipment cannot fall on operators or bystanders. Personnel that are within the zone of protection must wear appropriate PPE. This would include high visibility vest, eye protection, and hard hats. Public safety is addressed by the zone of protection and properly displayed signage.

Proper public education will help reduce curious patrons from putting themselves in a dangerous situation. An established zone of protection via cones and traffic horses will also add in keeping patrons from getting too close to the operation. This also keeps Arboretum personnel from being distracted during critical flight operation. These considerations, along with items described in the safety constraints, provide an acceptable level of risk management.

5 IMPACT OF ENGINEERING SOLUTIONS
The design could have potential impacts in several areas.

The largest area of impact of the engineering solution will be in the fields of arboriculture and forestry. In arboriculture and forestry, there is a need to be able to more efficiently deploy monitoring devices into trees, as they are currently placed manually. Consequently, this engineering solution may inspire researchers and businesses in these fields to develop similar devices. Since these fields already employ UAVs for monitoring purposes, the creation of a few spinoff devices would be a natural outcome.

This engineering solution could also have foreseeable applications in areas besides the arboriculture and forestry fields. In general, the design could be applied to any situation in which
it would be desirable to remotely secure objects to cylindrical structures. For example, in addition to tree branches, this design could be used to remotely attach objects and devices to structures such as railings, fences, poles, antennae, radio masts, and telecommunication lines with a UAV. By nature of the design, basically any small object or device under 250 g (0.55 lb.) can be fixed to the USM, which opens a wide variety potential USM payloads. These include devices such as cameras, microphones, speakers, accelerometers, insect traps, wireless communications routers, wireless communications transmitters and receivers, etc. Thus, the academic, commercial, military, and private sectors across the globe could all potentially have needs that could be fulfilled with this engineering solution.

From an environmental standpoint, the USM subsystem could become litter if it ever became stuck in a tree in a location where it was impossible or impractical to manually retrieve the device from a tree. If the USM was ever going to be manufactured in large quantities, this would be an important point to consider.

6 LIFE-LONG LEARNING
Throughout the senior design program, there were many opportunities that arose for the team to learn new techniques and skills. The program combines a multitude of skillsets, such as teamwork, organization, design, manufacturing, and dealing with new problems as they arise.

Teamwork is one overarching skill that entails most, if not all the work done in the program. Every week, it was the team’s responsibility to come together, cover any new ideas discovered separately, and consolidate thoughts to be able to see progress on the project as a group. Like industry, the team set goals for each week and gained experience setting timelines for these goals. On top of weekly team meetings, the team communicated often through email, phone, and in person nearly every day. This kind of collaboration taught the team responsibility and how to better communicate as a group to achieve goals.

Organization was a large part of keeping the project on track. The team made a Gantt chart that identified all major deadlines and assessed how far along on the specific deadline the team was. Along with that, the team also communicated with The Morton Arboretum regularly to make sure they were happy with the direction being taken in the design. Organizing a meeting every week or two with the client was critical to assess their happiness and to combine ideas to make progress with the project.

With a project of this scale, extensive research and design was done to successfully fulfill the goals set forth for the project. This skill will greatly translate to the work force as coworkers will not always know the answer to every problem. Being able to effectively research and sift through multiple articles and research done by others was a beneficial experience. Once research was complete, the design phase of the project began. The team learned how to effectively make CAD models and gained experience with digital file management. Learning how to effectively model a design taught team members that not all ideas conceived on paper translate perfectly to a real-world design.

Effectively designing a product results in a smoother manufacturing process. Throughout the year, the team learned how to machine and make multiple parts that had been created using CAD. Translating these skills from the computer to the real world showed how easily or
difficultly different designs translated to manufacturing. In industry this a critical skill, as everything employees do translates to a product of some sort. Understand the manufacturing processes helped the team become better engineers.

New problems arise weekly when completing a large design and build. Learning how to deal with these problems in a level-headed manner can save time and make working on the project go more smoothly. Some of these problems could be a failed design that was unexpected. Taking these opportunities to learn from mistakes, note them down, and keep pushing forward is critical to success. Other problems could be constraints put on the project from outside sources. For example, the pandemic faced during this project caused many unexpected problems that needed to be dealt with. It was a major lesson on keeping communication lines open, dealing with problems in a positive way, and working around unforeseen circumstances.

7 BUDGET AND TIMELINE

7.1 Budget
The projects initial budget and actual expenditures are reported below in Table 1.

Table 1: Design Expenditures and Budget

<table>
<thead>
<tr>
<th>Components</th>
<th>Total</th>
<th>Budget</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Material</td>
<td>$106.82</td>
<td>$50.00</td>
<td>$-56.82</td>
</tr>
<tr>
<td>Clear Acrylic Sheet</td>
<td>$15.93</td>
<td>$20.00</td>
<td>$-4.07</td>
</tr>
<tr>
<td>Torsional Springs</td>
<td>$17.82</td>
<td>$50.00</td>
<td>$32.18</td>
</tr>
<tr>
<td>PLA Filament</td>
<td>$119.86</td>
<td>$50.00</td>
<td>$69.86</td>
</tr>
<tr>
<td>Steel Rope</td>
<td>$26.13</td>
<td>$10.00</td>
<td>$-16.13</td>
</tr>
<tr>
<td>Nylon Rod</td>
<td>$4.76</td>
<td>$0.00</td>
<td>$-4.76</td>
</tr>
<tr>
<td>Servos</td>
<td>$75.92</td>
<td>$100.00</td>
<td>$24.08</td>
</tr>
<tr>
<td>Servo Shaft Coupler</td>
<td>$5.99</td>
<td>$0.00</td>
<td>$-5.99</td>
</tr>
<tr>
<td>Solenoid</td>
<td>$12.29</td>
<td>$0.00</td>
<td>$-12.29</td>
</tr>
<tr>
<td>Arduino Uno R3</td>
<td>$18.00</td>
<td>$100.00</td>
<td>$82.00</td>
</tr>
<tr>
<td>2 Channel DC 5V Relay Module</td>
<td>$7.99</td>
<td>$0.00</td>
<td>$-7.99</td>
</tr>
<tr>
<td>Panel Mount 10K Potentiometer</td>
<td>$3.98</td>
<td>$0.00</td>
<td>$-3.98</td>
</tr>
<tr>
<td>DC Voltage Converters (BECs)</td>
<td>$71.07</td>
<td>$100.00</td>
<td>$28.93</td>
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<tr>
<td>UAV Remote controller Expansion</td>
<td>$400.00</td>
<td>$400.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Hardware</td>
<td>$61.32</td>
<td>$100.00</td>
<td>$38.68</td>
</tr>
<tr>
<td>Carbon Fiber Pole</td>
<td>$275.00</td>
<td>$150.00</td>
<td>$-125.00</td>
</tr>
<tr>
<td>Wiring and connectors</td>
<td>$25.76</td>
<td>$50.00</td>
<td>$24.24</td>
</tr>
<tr>
<td>Camera</td>
<td>$100.00</td>
<td>$100.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Shipping and Handling</td>
<td>$26.19</td>
<td>$0.00</td>
<td>$-26.19</td>
</tr>
<tr>
<td>Totals</td>
<td>$1,374.83</td>
<td>$1,280.00</td>
<td>$-94.83</td>
</tr>
</tbody>
</table>
Overall, the project went around $100.00 over the team’s target budget of $1,280.00. However, the team’s spending remained comfortably below the client’s budget of $2,000.
<table>
<thead>
<tr>
<th>Activity Description</th>
<th>START</th>
<th>END</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Preliminary design</td>
<td>Team</td>
<td>10/14/19</td>
</tr>
<tr>
<td>2 Analytical study of springs required for design</td>
<td>Peyton</td>
<td>10/20/19</td>
</tr>
<tr>
<td>3 3 Alternative designs</td>
<td>Team</td>
<td>10/25/19</td>
</tr>
<tr>
<td>4 Prototype USM Base mount</td>
<td>John</td>
<td>10/25/19</td>
</tr>
<tr>
<td>5 Make design matrix for each Sub system components</td>
<td>Paul</td>
<td>10/28/19</td>
</tr>
<tr>
<td>6 Optimal design selection from design matrix</td>
<td>Team</td>
<td>11/1/19</td>
</tr>
<tr>
<td>7 Initial model of USM</td>
<td>John</td>
<td>11/1/19</td>
</tr>
<tr>
<td>8 Detailed design finalization</td>
<td>Team</td>
<td>11/8/19</td>
</tr>
<tr>
<td>9 Create testing target design</td>
<td>Peyton</td>
<td>11/10/19</td>
</tr>
<tr>
<td>10 Prototype testing hook, and camera mount</td>
<td>Paul</td>
<td>11/10/19</td>
</tr>
<tr>
<td>11 DRW modeling</td>
<td>Paul</td>
<td>11/15/19</td>
</tr>
<tr>
<td>12 FINALS (End of semester meeting with client)</td>
<td>Team</td>
<td>12/8/19</td>
</tr>
<tr>
<td>13 1st Parts order finalized</td>
<td>Paul</td>
<td>12/29/19</td>
</tr>
<tr>
<td>14 Build testing structure</td>
<td>Paul</td>
<td>1/7/20</td>
</tr>
<tr>
<td>15 Finalize model of initial USM</td>
<td>John</td>
<td>1/7/20</td>
</tr>
<tr>
<td>16 Finalize modeling of initial DRW</td>
<td>Peyton &amp; John</td>
<td>1/7/20</td>
</tr>
<tr>
<td>17 Manufacture initial prototype - USM</td>
<td>John</td>
<td>1/14/20</td>
</tr>
<tr>
<td>18 Build testing computer/program</td>
<td>Peyton</td>
<td>1/19/20</td>
</tr>
<tr>
<td>19 Testing: USM's ability to hold securely to branches</td>
<td>Peyton</td>
<td>1/20/20</td>
</tr>
<tr>
<td>20 Make adjustments to CAD models</td>
<td>John</td>
<td>2/1/20</td>
</tr>
<tr>
<td>21 Testing: REV 1 USM's ability to hold securely to branches</td>
<td>Peyton</td>
<td>2/15/20</td>
</tr>
<tr>
<td>22 1st Team Evaluation 2/21/2020</td>
<td>Class</td>
<td>2/21/20</td>
</tr>
<tr>
<td>23 Manufacture REV 1 prototype - USM</td>
<td>John</td>
<td>2/21/20</td>
</tr>
<tr>
<td>24 1st Client Grade Sheet 2/28/2020</td>
<td>Class</td>
<td>2/28/20</td>
</tr>
<tr>
<td>26 UAS and subsystem integration and coms check</td>
<td>Peyton</td>
<td>3/11/20</td>
</tr>
<tr>
<td>27 Testing: REV 1 DRW's ability to Dock/Operate REV 1 USM</td>
<td>Paul</td>
<td>3/13/20</td>
</tr>
<tr>
<td>-add retrieval loop holes</td>
<td>-add indexing slot for servo lock arm</td>
<td></td>
</tr>
<tr>
<td>29 DRW Prototype Housing Modifications:</td>
<td>Paul</td>
<td>3/18/20</td>
</tr>
<tr>
<td>-resize pole mount</td>
<td>-secondary servo mounting to housing</td>
<td></td>
</tr>
<tr>
<td>30 DRW Prototype Housing Modifications:</td>
<td>Jack</td>
<td>3/18/20</td>
</tr>
<tr>
<td>-housing cutouts for weight reduction</td>
<td>-acrylic covering holes</td>
<td></td>
</tr>
<tr>
<td>-revise DRW code to incorporate second servo</td>
<td>-address cable management</td>
<td></td>
</tr>
<tr>
<td>-modify pole to UAV mounting fixture</td>
<td>-address cable management</td>
<td></td>
</tr>
<tr>
<td>-print USM prototype</td>
<td>-print secondary servo mount to DRW housing</td>
<td></td>
</tr>
<tr>
<td>-print DRW to pole mount</td>
<td>-print UAV to DRS mounting fixture</td>
<td></td>
</tr>
<tr>
<td>34 Final testing and refit</td>
<td>Team</td>
<td>3/27/20</td>
</tr>
<tr>
<td>35 Print DRW housing</td>
<td>Paul</td>
<td>3/30/20</td>
</tr>
<tr>
<td>36 Assemble USM prototype</td>
<td>Paul</td>
<td>3/30/20</td>
</tr>
<tr>
<td>37 Assemble DRW prototype</td>
<td>Paul</td>
<td>3/30/20</td>
</tr>
<tr>
<td>38 DRW actuation bench testing</td>
<td>Peyton and Paul</td>
<td>3/30/20</td>
</tr>
<tr>
<td>39 Final prototype modifications</td>
<td>Team</td>
<td>4/1/20</td>
</tr>
<tr>
<td>40 Final testing and refit</td>
<td>Team</td>
<td>4/1/20</td>
</tr>
<tr>
<td>41 PUBLICATION/PRESENTATION</td>
<td>Team</td>
<td>4/1/20</td>
</tr>
<tr>
<td>42 Design Functionality Review Due 4/24/2020</td>
<td>Class</td>
<td>4/24/20</td>
</tr>
<tr>
<td>43 Abstract For Demo Day 4/24/2020</td>
<td>Class</td>
<td>4/24/20</td>
</tr>
<tr>
<td>44 Poster For Demo Day 4/24/2020</td>
<td>Class</td>
<td>4/24/20</td>
</tr>
<tr>
<td>45 2nd Team Evaluation 4/24/2020</td>
<td>Class</td>
<td>4/24/20</td>
</tr>
<tr>
<td>46 Final Report 5/1/2020</td>
<td>Class</td>
<td>5/1/20</td>
</tr>
<tr>
<td>48 Liability Form 5/1/2020</td>
<td>Class</td>
<td>5/1/20</td>
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<tr>
<td>49 2nd Client Grade Sheet 5/1/2020</td>
<td>Class</td>
<td>5/1/20</td>
</tr>
<tr>
<td>50 Demonstration Day</td>
<td>Class</td>
<td>5/8/20</td>
</tr>
</tbody>
</table>
Figure 26: Gantt chart of project timeline
8 TEAM MEMBERS’ CONTRIBUTIONS TO THE PROJECT

8.1 Team Member 1: Peyton Brudi
- Introduced USM torsional gripper design to the team
- Conducted patent search for similar designs
- Contributed to preliminary and alternative design ideas through design matrix
- Created a simplified mathematical model of the USM clamps and derived equations for spring displacement angle, clamp contact force, spring torque, and minimum required contact force to support the USM on a vertical branch
- Conducted design parameter sensitivity study to relate the USM weight to minimum required clamping force for various static friction coefficients
- Sized torsional springs and servos to match performance requirements of the rotational clamps
- Introduced need for operational testing with the UAV at The Morton Arboretum
- Evaluated the results from the operational tests conducted at The Morton Arboretum
- Assisted in fabrication and testing of initial USM prototype on tree branches
- Refined USM CAD based on results of initial prototype testing
- Selected battery eliminator circuit used to convert the UAV’s 18 VDC output to 7.4 VDC to be compatible with the servo motors
- Designed deployment system testing circuit
- Wrote Arduino code used to control the deployment system servos during testing
- Refined design for UAV to pole mounting fixtures
- Contributed to project documentation

8.2 Team Member 2: John Byrnes
- Introduced USM base design and mounting geometry to the team.
- Researched clamps and gripper types used in robotics and to hold vegetation.
- Designed gear set to increase mechanical advantage of the DW cam-drive servo
- Contributed to preliminary and alternative design ideas through design matrix.
- Created preliminary design for USM and DRS using SolidWorks
- 3D printed prototypes of the USM for operational testing.
- Modeled articulating wrist joint for the DW
- Refined preliminary design for deployment system housing
- Conducted FEA studies on UAV mounting fixture and DW housing
- Manufactured parts for USM final prototype
- Designed drive shaft and roller arms for DW
- Manufactured roller arms from aluminum for DW
- Manufactured bushings and rollers from nylon for DW
- Updated previous parts for 3D printing
- Conducted testing on USM prototype
- Created renders and technical drawings for all design components
8.3 Team Member 3: Paul Wohler

- Identified the need for possible targeting sensors and camera for emplacement and displacement of USM
- Identified multiple procurement options for each of the project components.
- Introduced DRS pole and DW design to the team
- Developed servo cam drive for DW index gripper and USM rotational jaws
- Researched options for flight controllers and determined the Matrice 600 Pro onboard flight controller system would handle the project design’s needs
- Researched types of available servo options compatible with the Matrice 600 Pro
- Established components and preliminary budget
- Established the nomenclature for project design systems
- Established criteria for the operational testing of conceptual flight operations
- Prototyped components for operational testing (retrieval hook and loop, camera mount)
- Developed and processed design matrix based on team design features for each subunit
- Contributed to preliminary and alternative design ideas through design matrix
- Modeled preliminary design for DW
- Built and tested wiring circuit for DW servos based on Peyton’s design
- Built final prototypes for DW, USM, pole mount, and wiring package
- Conducted final testing of full system prototype and identified key improvements for future development
9 CONCLUSION

Overall, The Morton Arboretum aims to employ a DJI Matrice 600 Pro unmanned aerial vehicle (UAV) to more efficiently deploy and retrieve small scientific instruments onto tree canopy branches, since the tree canopy environment is difficult for humans to access. To help the arboretum move towards accomplishing this goal, the team conceptualized and designed a novel system. From multiple alternative designs, an optimal design was selected that consists of three main subunits: the universal sensor mount (USM), deployment/retrieval system (DRS), and controller system (CS). The Morton Arboretum’s tree monitoring devices are secured to the USM, which employs a passive clamping system to remain attached to branches. Then, the USM is attached to tree canopy branches with the DRS, which is suspended from the arboretum’s UAV. To retrieve the USM from branches with the UAV, the DRS’s wrist is swapped out for a retrieval hook, which is used to capture a loop on the USM and remove it from branches. The operations of the DRS are controlled through the UAV’s stock controller with a channel expansion kit. The team fabricated and tested prototypes of the USM and DRS. The final USM prototype was successfully tested on various tree branch sizes and meets The Morton Arboretum’s design requirements. The initial deployment system prototype was bench tested. It was found that the USM locking/unlocking function worked as desired. However, test results indicated that the drive shaft should have been fabricated from aluminum as was originally intended. In the arboretum’s future revisions of the deployment system prototype, the team also recommends making modifications of the geometry to further increase the mechanical advantage of the drive shaft servo.

The design’s realistic constraints, potential safety concerns, impact, and contribution to lifelong learning were also addressed. Finally, the project’s budget and spending was reported and its timeline was presented.
10 REFERENCES
11 ACKNOWLEDGEMENTS

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Lastly, the team would like to thank its educational institution, Northern Illinois University.
12 APPENDICES
12.1 Updated Specifications

Physical: Lightweight materials such as aluminum alloys, plastics, and carbon fibers

Mechanical:
  Size: Device cannot adversely affect flight characteristics of the UAV
  Weight: Less than 4.4 pounds (lbs.) 2 kilograms (kg)

Electrical:
  Wireless:
    Range: FCC Compliant: 5 km (3.1 mi), (unobstructed line of sight)
    Protocol: DJI Assistant 2

Environmental:
  Storage Temperature: 72 to 82 ºF
  Operating Temperature: 20 to 100 ºF

Operational Environment:
  UAV Fixture: Outdoors during mild, dry weather conditions
  Clasping Device: Outdoors during all growing season weather conditions
  Other Considerations: Resistant to animal tampering

Software:
  User Interface: DJI Matrice 600 Pro flight controller
  Hardware Interfaces: A3 Microprocessor, wireless receiver/transmitter
  Communication Protocols: DJI Assistant 2

Safety:
  Device must remain securely attached to UAV prior to deployment.
  Any wiring or electronics must be weatherproof to prevent electrical hazards while device is fixed to the tree.

Maintenance:
  UAV Fixture: None
  Clasping Device: Cleaning of the device and lubrication of actuators between deployment periods
12.2 Supplemental Material
12.2.1 USM Mathematical Model: Detailed Results

Consider the schematic of the mathematical model in Figure 27:

Where:
– \( W \) is the width from the fixed clamp to the torsional spring center
– \( r \) is the branch radius \( (0 < r \leq W) \)
– \( \alpha \) is the rest angle of the torsional spring
– \( \theta \) is the displacement angle of the spring
– \( \beta = 180^\circ - (\alpha - \theta) \)
– \( \gamma = 135^\circ - \frac{\beta}{2} \)
– \( L_c \) is the length from point of contact to the torsional spring center

Key derived equations:
1. \( \beta = 2 \cdot \tan^{-1}\left[\frac{\sin 135^\circ}{W r/\sqrt{2} \cos 135^\circ}\right], 0^\circ \leq \beta \leq 90^\circ \)
2. \( L_c = \frac{r}{\tan \frac{\beta}{2}}, 0^\circ \leq \beta \leq 90^\circ \)
3. \( \theta = \beta + \alpha - 180^\circ \) (when \( \alpha = 180^\circ, \theta = \beta \))

Then it follows that:
4. \( T_s = k\theta \)
– $T_s$ is the spring torque  
– $k$ is the torsional spring constant  
– $\theta$ is the displacement angle of the spring (in radians)

5. $F_c = \frac{k\theta}{L_c}$

– $F_c$ is the contact force on the branch perpendicular to the clamp  
– $k$ is the torsional spring constant  
– $\theta$ is the displacement angle of the spring (in radians)  
– $L_c$ is the length from point of contact to the torsional spring center

From the design’s operational specifications, the USM must be able to clamp onto branches ranging from 3 cm to 10 cm (1.181 in. to 3.937 in.) in diameter.

– Then it follows that $1.5 \text{ cm} \leq r \leq 5.0 \text{ cm} \ (0.591 \text{ in.} \leq r \leq 1.969 \text{ in.}).$

– To avoid having a component of $F_c$ pushing the branch away from the USM, let $W = 10 \text{ cm} \ (3.937 \text{ in.}).$

– The lowest spring displacement angle $\theta$ will occur at the smallest branch radius for a given fixed clamp position on the USM. In this condition, the torsional springs will always be preloaded to $\theta \cong 90^\circ$. Thus, for this design, it is a requirement that the torsional spring rest angle $\alpha$ be greater than $90^\circ$. A spring angle of $\alpha = 180^\circ$ was chosen to preload the springs with enough torque to clamp securely on branches.

**Calculation Results (USM in Fixed Clamp Position 4):**

– Minimum $L_c = 5.0 \text{ cm} \ (1.969 \text{ in.})$ will occur at the maximum value of $\theta$, which occurs at largest branch radius $r$, 5.0 cm

– Maximum $L_c = 6.0 \text{ cm} \ (2.362 \text{ in.})$ will occur at the minimum value of $\theta$, which occurs at the smallest branch radius $r$, 4.0 cm

– Maximum $F_c$ occurs at the maximum value of $\theta$, which occurs at the largest branch radius $r$, 5.0 cm. This value depends on $k$.

– Minimum $F_c$ occurs at the minimum value of $\theta$, which occurs at the smallest branch radius $r$, 4.0 cm. This value depends on $k$.

– Maximum $T_c$ occurs at the maximum value of $\theta$, which occurs at the largest branch radius $r$, 5.0 cm. This value depends on $k$.

– Minimum $T_c$ occurs at the minimum value of $\theta$, which occurs at the smallest branch radius $r$, 1.5 cm. This value depends on $k$. 
Note: In the actual design, the maximum force and torque values will be slightly larger than calculated when deploying the USM on the largest branch size, because the clamp will need to open slightly wider than 10 cm to fit the clamp around the branch.

Now, considering the USM in fixed clamp setting number 4 with $W = 10$ cm, $\alpha = 180^\circ$, $r_{\text{min}} = 4.0$ cm, $r_{\text{max}} = 5.0$ cm, $1 \leq k \leq 10$ [in-lbf/rad] the minimum and maximum $F_c$ and $T_c$ values were plotted against varied values of the torsional spring constant $k$. All SI unit values were converted to English unit values before the calculations were performed and the plot was generated. The MATLAB plot of the results is shown below in Figure 28:

![Contact Force and Spring Torque vs. Spring Constant](image)

**Figure 28:** Contact force and spring torque vs. torsional spring constant with USM in fixed clamp setting number 4

As expected, the maximum contact force $F_c$ and spring torque $T_c$ vary linearly with the torsional spring constant $k$. It is important to note that since there will be two clamps on the device connected mechanically by two parallel torsional springs, the DRS servo motor will need to overcome twice the maximum spring torque values in the plot.

Now, before selecting torsional springs and a servo motor, it was very important to consider the minimum $F_c$ that will permit the USM to support itself on tree branches without sliding down. Obviously, this will depend on the static friction coefficient between the USM clamp and the tree branch, as well as the mass of the USM. Consider the free body diagram (FBD) of the branch drawn below in Figure 29, which was derived from simple statics performed on Figure 27.
Now, based on the calculations above, the worst-case scenario in this calculation will occur when the USM is clamped onto a vertical branch of the smallest allowable radius at a given fixed clamp setting. Bear in mind that the minimum friction force holding up the USM on the branch will actually occur at the largest allowable branch radius $r$, 5.0 cm. However, the largest clamping force will also occur on the largest branches, so the contact force that actually governs the design will be the force at the smallest branch radius at a given setting.

Based on the FBD in Figure 29 and assuming two clamps on the USM and assuming a vertical tree branch, the following calculation was performed:

\[ \sum F_z = 0 \text{ (let } +z \text{ go out of page and acceleration due to gravity } g \text{ be going in } -z \text{ direction)} \]

Let static friction force $F_s = \mu_s N$ where $\mu_s$ is static friction coefficient and $N$ is normal force. Then it follows that:

\[ 2[\mu_s F_{c,\text{min}} \cos(90^\circ - \beta) + \mu_s F_{c,\text{min}} \sin(90^\circ - \beta) + \mu_s F_{c,\text{min}}] - mg = 0 \]

\[ F_{c,\text{min}} = \frac{mg}{2\mu_s[1 + \cos(90^\circ - \beta) + \sin(90^\circ - \beta)]} \]

Where:
- $F_{c,\text{min}}$ is the minimum required contact force to prevent the USM from sliding down the branch
- $mg$ is the weight of the USM (including the 250 g sensor package)
- $\mu_s$ is the coefficient of static friction between the USM clamp and branch
With the above equation derived, $F_{c, \text{min}}$ was plotted against various values of $mg$, as well as with multiple values of $\mu_s$. A MATLAB plot of these results is shown below in Figure 30:

![Minimum Contact Force vs. USM Weight](image.png)

**Figure 30:** Minimum required contact force plotted against the weight of the USM in fixed clamp setting number 4

From Figure 30, the minimum required contact force $F_{c, \text{min}}$ varies significantly with different values of $\mu_s$ and $mg$. Higher values of $F_{c, \text{min}}$ are required for a given USM weight because of factors such as branch disturbances in the wind and torque from the weight of the USM sensor package.

Thus, it is imperative that the USM weight is minimized and the static friction coefficient between the clamps and the branch is maximized, as was suspected.
12.2.2 Finite Element Analyses of Key Subcomponents

There were some key subcomponents of the design that wanted to be validated through Finite Element Analysis (FEA). The first subcomponent was the frame of the DRW. Below in Figure 31 you can see the model of the FEA done on the frame. The boundary conditions of this analysis were as listed:

1. The fixture was mounted by the main mounting holes on the top of the frame
2. The gravitational force using the mass of the DRW was applied
3. The torque produced from the drive shaft servo was applied to the servo mounting hole and the drive shaft bearing mount
4. The torque produced from the servo that secures the USM was applied to the underside of the top USM mounting holes

![Figure 31: FEA conducted on the DRW](image)

The results of this analysis were positive. The highest stress points of the DRW frame from the above listed conditions were an order of magnitude below the yield strength of the material used for the frame. This means that under normal operation of the DRS, the frame in question will not succumb to failure.

The next key component that was analyzed was the tube mounting fixture that will be attached to the mounting rails on the underside of the drone. This mounting fixture holds the carbon fiber telescopic pole that will hold the DRW during deployment of the USM. Two different scenarios were conducted on this model. The first scenarios boundary conditions were as listed:

1. The tube mounting fixture had a fixed constraint on the four mounting holes atop the mounting bracket
2. The gravity of the mounting bracket was applied
3. The weight of the pole and DRW were applied to the two main mounting holes in the center of the bracket

![Figure 32: FEA on the Tube Mounting Fixture](image)

Shown above in *Figure 32* is the results from the first scenario on the tube mounting. The high stress points were around the main mounting holes for the tube supporting the weight of the system below. The highest stress of the analysis was also multiple orders of magnitude below the yield stress of the component’s material.

The second scenario that was considered for the tube mounting fixture was a bump scenario. The premise behind this analysis was to show the results of the drone operator bumping into tree branches when going to deploy the USM. This scenario would cause a force in the horizontal direction as the carbon fiber pole flexed. The second scenarios boundary conditions were as listed:

1. The tube mounting fixture had a fixed constraint on the four mounting holes atop the mounting bracket
2. The gravity of the mounting bracket was applied
3. The weight of the pole and DRW were applied to the two main mounting holes in the center of the bracket
4. The force from the bump was applied to the lower clip portion of the bracket under the assumption of the UAV moving at a speed of 0.5 meters per second.
Shown above in *Figure 33* is the results from the bump scenario on the tube mounting fixture. The bump caused slight deflection in the lower tube clip portion of the model. This deflection in turn caused increased stress on the bracket when compared to the results shown from the first scenario in *Figure 32*. Although there was increased stress on the part from the bump, the highest stress was still an order of magnitude under the respective yield strength of the material.
12.2.3 Deployment System Bench Testing Arduino Uno Code

The following code was constructed in the Arduino IDE and used to test the deployment system prototype. The variables “range_1” and “range_2” can be modified as needed to fine-tune the displacement angles of the servos.

CODE:

```
#include <Servo.h>

Servo myservo1;  // servo object to control DRW drive shaft servo
Servo myservo2;  // servo object to control DRW indexing servo

void setup() {
  myservo1.attach(9);  // attaches the servo on pin 9 to the servo object
  myservo2.attach(7);  // attaches the servo on pin 7 to the servo object
}

void loop() {
  val_1 = analogRead(potpin1);  // reads the value of the potentiometer (value between 0 and 1023)
  val_1 = map(val_1, 0, 1023, 0, range_1*conv);  // scale it to use it with the servo (value between 0 and 180)
  myservo1.write(val_1);  // sets the servo position according to the scaled value
  delay(15);  // waits for the servo to get there

  val_2 = analogRead(potpin2);  // reads the value of the potentiometer (value between 0 and 1023)
  val_2 = map(val_2, 0, 1023, 0, range_2*conv);  // scale it to use it with the servo (value between 0 and 180)
  myservo2.write(val_2);  // sets the servo position according to the scaled value
  delay(15);  // waits for the servo to get there
}

```