USE OF AN AUTONOMOUS ALL-TERRAIN ROBOT FOR LOCAL WILDFIRE RISK ASSESSMENT

by

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A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Applied Energy and Electromechanical Engineering

Charlotte

2024

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ABSTRACT

WYATT MARCELUS LEDOUX. Use of an Autonomous All-Terrain Robot for Local Wildfire Risk Assessment. (Under the direction of DR. AIDAN BROWNE)

Current wildfire risk assessment methods use stationary automatic weather stations to collect environmental data for risk determination. These devices operate in locations where foliage cover is not present and are not capable of representing the conditions within forested areas. Modeling is the primary method in use to determine the moisture content of dead fuels, yet uses inputs gathered by non-representative automatic weather stations. Accurate fuel moisture determination requires laborious manual sample collection. This research addresses current limitations by developing a suite of devices for use with autonomous all-terrain electric vehicles, capable of collecting input data for fire risk assessment in specific forested locations. The prototype created is capable of autonomous measurement of temperature and relative humidity, wind speed, ten-hour time-lag dead fuel moisture, and soil moisture. The system includes a motorized weather mast for gathering data at a height of six feet, a Cartesian robot for precise positioning of a multifaceted end effector, a fuel sample holding station, and a color based real-time vision system for sample station detection and positioning of the vehicle and Cartesian robot. A theoretical operation scheme is provided for real-world implementation of the system. Testing was performed to determine the feasibility of each subsystem individually and combined in the context of practical application. The study resulted in an overall promising proof of concept, capable of meeting the objective of this research. Limitations presented through testing were found to be resolvable, and recommendations for improvement and future additions to the system are provided.

DEDICATION

I dedicate this work to my parents, without whom I would lack the great example of endurance and perseverance, as well as the ability to gain the achievements that I have. I also dedicate this to my wife, who has always encouraged me to be the best version of myself I can be.

ACKNOWLEDGEMENTS

I am grateful to Dr. Aidan Browne for his advisement, time, and the sharing of his expertise, without which this project could not reach fruition. I am also thankful to my committee members, Dr. Jeff Kimble and Dr. Wesley Williams, along with Dr. Elizabeth Smith, for their guidance, insight, and the sacrifice of their time. I would also like to acknowledge Mr. John Nettles who first encouraged me to pursue a graduate education.

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LIST OF ABBREVIATIONS

AT	Air Temperature
ATV	All-Terrain Vehicle
DFM	Dead Fuel Moisture
EV	Electric Vehicle
GPS	Global Positioning System
KDBI	Keetch-Byram Drought Index
MWRAD	Mobile Wildfire Risk Assessment Droid
NDFM	Nelson Dead Fuel Moisture
NFDRS	National Fire Danger Rating System
NIFC	National Interagency Fire Center
NWCG	National Wildfire Coordinating Group
RAWS	Remote Automatic Weather Station
RH	Relative Humidity
TL	time-lag
VMC	Volumetric Moisture Content
XYZ	Cartesian Coordinate Robot

CHAPTER 1: INTRODUCTION

1.1 Background

In 2021 alone, 2,233,666 acres of land in California were burned in wildfires and an estimated 2,040,600 properties were at extreme risk of being destroyed by a wildfire [1]. In addition, as time goes on, fires are becoming more serious and more prevalent, with an unsettling upward trend in the number of acres burned yearly in the US. The cause? While there are a few ways a wildfire can start, 85 percent of all wildfires are due to negligent human ignition from sources such as unattended campfires and imprudently discarded cigarettes [2].

The best way to deal with wildfires is to prevent them from happening in the first place, which traditionally consists of public education and awareness, data collection of fire-related factors, and modeling. It is clear from the statistics that prevention has yet to be fully realized, though, and while prevention methods have only improved over time, limitations remain. Manual data collection may be time and labor-intensive, automated data collection may be expensive and inadequate for all cases, and modeling relies on the availability and accuracy of the aforementioned collected data. Without a greater wealth of information, public education cannot effectively communicate the risks, as animated woodland creatures can only do so much on their own. However, with modern advancements in technology, many of these limitations can be overcome, particularly by way of robotics and autonomy.

To describe how these advancements can help, it is necessary to understand the components of the greater system. In the most basic terms, when a change occurs in an environment, the likelihood of a wildfire happening rises or lowers, depending on the change. The perceived likelihood of a wildfire then determines the level of vigilance required to prevent that fire. Since multiple continuously varying environmental factors are in play at one time, it is difficult to gauge how significant the fire risk is in exact terms, and therefore, it is difficult to apply the correct level of caution needed. Therefore, each environmental variable must be monitored for changes, and each type of change's influence must be considered. Organizations monitor environmental changes through various data-gathering methods, but the key factors remain the same. These key factors, such as temperature and precipitation, act as inputs for software models that combine them, apply weighting, and output a rating that is used to determine what actions must be taken.

The key focus of this thesis is on monitoring and data gathering, as it has a high potential for improvement. Presently, monitoring takes place in one of two ways; manual or automated data collection. For manual gathering, a human must physically go out to take readings, weigh fuel stick samples or collect natural samples, and record the data. This process requires a lot of care, time, and labor, to produce precise results. The second method, automated gathering, requires large and expensive equipment to be used, which due to its stationary nature, can only gather data from a single location to provide "worst-case-scenario" data. Therefore, there is a necessity for a method which would not only reduce the time and labor required, allowing Forest Service personnel to better occupy that time, but also provide a broader sample of data that may be more representative of a particular area.

1.2 Problem Statement

To combat the location coverage limitations of in-use technology, it is necessary to develop supportive measures that would fill in the gaps by providing the ability to gather more data and reinforce the present methods. There is a need for a system capable of gathering crucial preventative environmental data over a sizeable dynamic area while operating in an unmanned capacity to free up resources and expand upon what is presently known within the field of wildfire research.

1.3 Objectives and Scope

The goal of this research is to develop a suite of commercial sensors and instruments to be mounted to an autonomous trail-following ATV, to gathering environmental and ecological data within a local wooded area to aid in determining the daily wildfire risk and to assist in predicting future risks. This research focuses solely on a method of gathering data for use in current modeling methods, and does not introduce an independent system or definition of wildfire danger risk. In addition, while localized autonomy is included in this research, the implementation of autonomy related to trail-following and obstacle detection has already been explored in prior works [3][4].

CHAPTER 2: LITERATURE REVIEW

2.1 Current Methods

2.1.1 Modeling

Wildfire modeling plays a critical role in understanding the risk of a fire happening and the behavior of wildfires, which are essential elements for managing and preventing them. This research focuses on fire danger, which relates to the likelihood of a fire occurring, spreading, and requiring suppression within a large region, and not fire behavior, which relates to the characteristics of an in-progress fire [5]. However, it can be noted that the functionality of the proposed vehicle may also be the ideal framework for use in fire-behavior-related applications, for example, in prescribed burning.

2.1.1.1 Fire Danger Rating

It is necessary to define the characteristics of fire danger rating systems as a whole to discuss their function in the United States. According to the National Wildfire Coordinating Group (NWCG) [5], a fire danger rating system consists of five key components:

1. Models representing the relationships between fuels, weather, and topography and their impact on fire business.
2. A system to gather data necessary to produce the rating numbers.
3. A processing system to convert inputs to outputs and perform data analyses.
4. A communication system to share the fire danger rating information between entities.

5. A data storage system to retain data for historical reference.

Modeling, discussed in this section, relates to point one and two of that definition. The following section on monitoring focuses on point two.

2.1.1.2 NFDRS

The National Fire Danger Rating System is the primary method of modeling used in the United States. It was introduced in 1964 to standardize the factors used to provide ratings. The NWCG refers to it as

> "a numeric scaling of the potential over a large area for fires to ignite, spread, and require fire suppression action. It is derived by applying local observations of current or predicted fuel, weather, and topographic conditions to a set of complex science-based equations. A fire danger rating system outputs numeric measures of fire business that provide a tool to assist the fire manager in making the best fire business decisions." [5]

This definition can be most effectively broken down by observing the system's structure as in Figure 2.1 from [6].

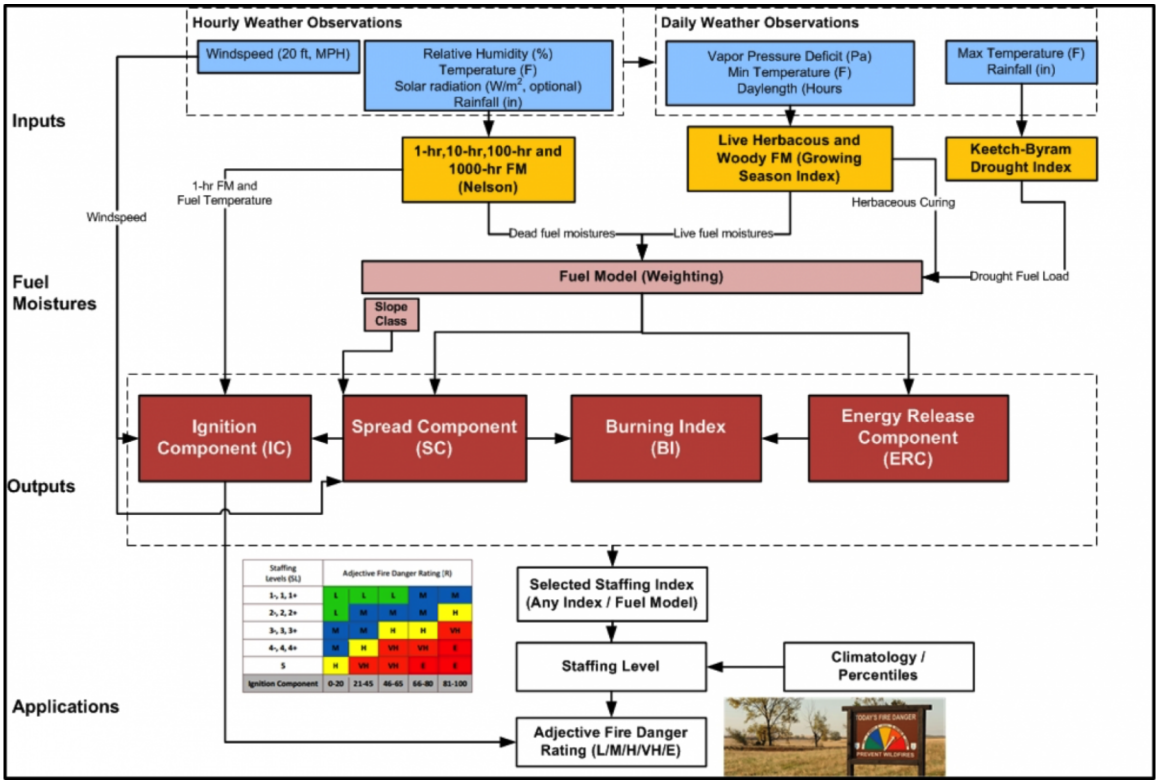

Figure 2.1: The 2016 National Fire Danger Rating System Structure

As shown, the inputs not only factor into the estimation of dead fuel moisture via the Nelson model but are also factored into the calculation of growing season and drought indexes. Therefore, they are the basis of the entire system, and as such the accuracy of the outputs depends heavily on the accuracy of these inputs.

2.1.1.3 Inputs

The exact calculations of the four output indices and the details of the model's applications, are not necessary to understand in detail concerning this research. However, it may be helpful to outline the relation of each input to the overall system. Wind speed is a critical input parameter in wildfire modeling as it affects fire behavior in several ways. Strong winds can spread fires rapidly, and the direction and variability of wind can influence the direction of fire spread. Relative humidity (RH) is the amount of water vapor in the air relative to the maximum amount the air could hold at that temperature. Low RH can cause fuels to dry out and become more flammable, while high RH can reduce fire spread by keeping fuels moist. Temperature is another critical input parameter in the NFDRS, as it affects the ignition and combustion of fuels. High temperatures also cause fuels to dry out and become more flammable, while low temperatures can slow down the combustion process. Solar radiation is an optional factor in the model and is the energy received from the sun that can influence fire behavior by drying out fuels and heating the ground. High solar radiation level can increase the risk of fire ignition and spread. Finally, rainfall is another critical input parameter as it affects the moisture content of fuels. Heavy rainfall can reduce fire danger by moistening fuels, while dry periods can increase fire danger by causing fuels to dry out.

2.1.1.4 Dead Fuel Moisture

The Nelson Dead Fuel Moisture Model (NDFM) is a model that attempts to estimate and predict the moisture content of dead fuels over time based on temperature, relative humidity, and precipitation. The reason a model or measure of DFM is necessary is because the moisture and temperature of fuel sources do not change at the same rate as the surrounding air, a consideration known as time-lag (TL). time-lag is the time required for two-thirds of a dead fuel to reach equilibrium with the surrounding atmosphere [7]. In the NFDRS, four fuel time-lag classes are considered: one, ten, one-hundred, and one-thousand-hour fuels. An example of this class distinction is that a ten-hour time-lag fuel would take approximately ten hours to reach two-thirds equilibrium. The NDFM is used in the current version of the NFDRS due to its accuracy, ability to be used with hourly observations, and ease when compared to manually sampling fuel sticks. However, it can be noted that this estimation may become unnecessary when the ability to measure actual samples at any hour of the day can be done autonomously. When comparing the accuracy of the Nelson model to a prior version of the NFDRS and the actual measured readings, as in Figure 2.2 from [8], it is clear that a great deal of "noise" can be prevented by taking real-world measurements.

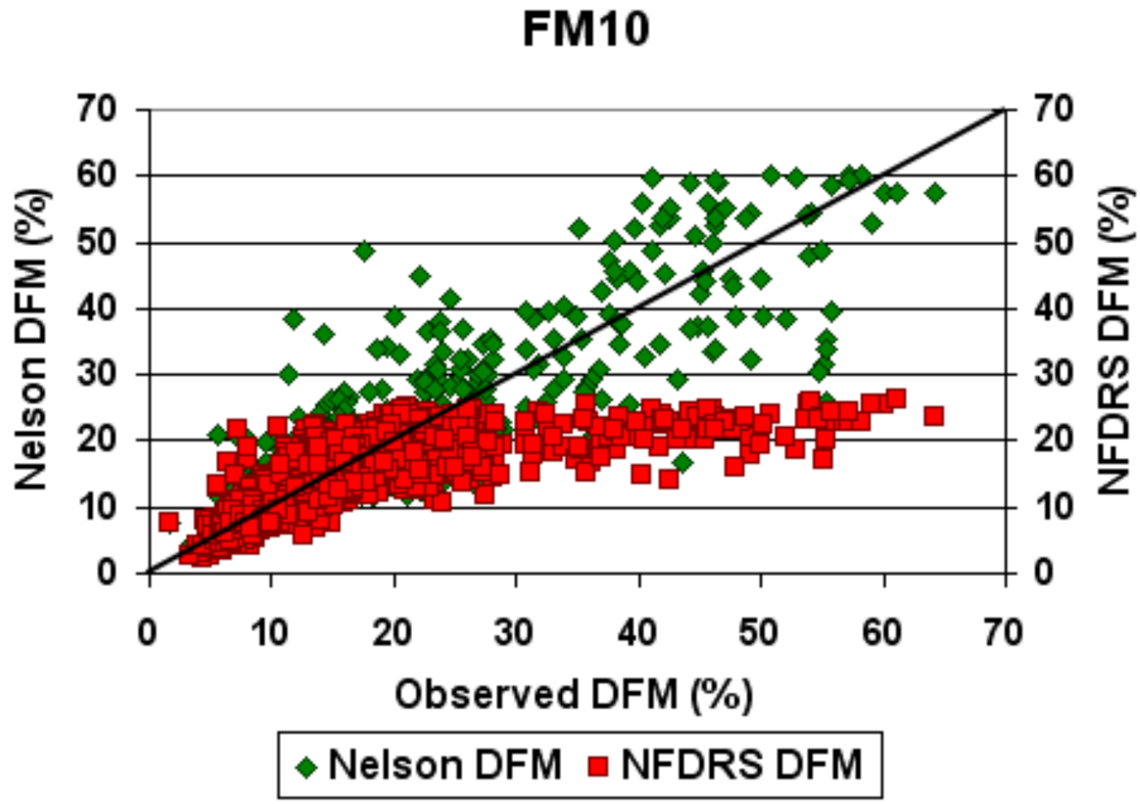

Figure 2.2: Comparison of Fuel Moisture Model Estimations to Observed Values

In a similar manner to the Nelson Model, the Keetch-Byram Drought Index (KBDI) is a method of estimating the moisture content in the top layers of soil, by assuming eight inches of moisture is fully saturated soil. It is expressed in hundredths of an inch of soil moisture depletion, meaning that an index of zero would be completely saturated soil, whereas a measurement of eight hundred would be completely dry soil [9]. The inputs are precipitation and temperature measured by weather stations, with values for regions between stations being interpolated. As of 2018, the KBDI was acting as a placeholder until improved metrics for drought were determined [10]. For this research, it is hypothesized that a direct measurement of volumetric moisture content via a probe may aid in this growing field.

2.1.2 Monitoring

Monitoring the environment is an essential aspect of wildfire management, acting as the basis for risk prediction by providing inputs into fire danger models such as the aforementioned NFDRS. Weather and fuel data monitoring can range from simple manual data collection to more complex solutions involving the use of electronic devices. While automated collection is the current standard, discussing each method to understand the processes is essential.

2.1.2.1 Manual Data Collection

Manual sampling has long been the most accurate method of collecting dead fuel moisture data. Various forms of manual sampling are done for different reasons. Collecting of natural samples is the most rigorous method and provides the greatest accuracy. It consists of selecting dead twigs and branches that fall into each size class, placing the samples into sealed containers, weighing the samples wet, drying them in an oven until the moisture has been eliminated, and weighing the dry samples [11]. The data is then recorded, and the moisture content is calculated. While the most accurate method, the labor required to carry out this process is too great for hourly use, as it typically requires a team of individuals to collect a large enough number of samples, deliberate and careful sampling procedures, transportation of samples to a lab, and manual record-keeping throughout the process. Another similar method that requires less labor is the use of ten-hour fuel stick samples. These standardized samples have an exact weight of 100 grams, making it possible to gain the wet weight in the field, only needing to be oven-dried for calibration purposes [12]. A great benefit to this method is that these standard sticks can be probed using an electronic pin-type moisture meter for rapid data acquisition, making the process far less time-consuming, allowing for more data to be collected daily.

2.1.2.2 Automated Data Collection

RAWS devices are widely used for weather data monitoring in the United States with more than 2,000 permanent stations across the nation. These stations are designed to operate in remote areas and can provide real-time data on weather conditions. RAWS stations use a variety of sensors to collect data, including anemometers, which measure wind speed and direction, AT-RH sensors, which measure air temperature and relative humidity, and precipitation sensors, which measure rainfall [13]. The data collected by individual RAWS stations is transmitted to the National Interagency Fire Center (NIFC) via satellite, where it is stored in a database and made available to fire managers and similar parties. RAWS currently act as the primary source of weather inputs in the NFDRS. An example of a RAWS device is shown in Figure 2.3 from [14].

Figure 2.3: A Remote Automated Weather Station

When a device is set up, it must be placed in a large open area, far from any tree coverage and positioned so that it is free from the influence of wildlife [15]. This allows the device to get a high-level view of weather conditions in the area; however, it does not precisely match the conditions of forested areas nearby. In addition, even with the large number of stations in use, it is not possible to accurately interpolate the areas in between devices to gain an understanding of specific areas with varying topographies and vegetation coverage. Further, despite these stations having an electronic fuel stick to determine dead fuel moisture, they are not always used in relation to fire danger because of the aforementioned limitations and variability between manufacturers [15][8].

2.2 Related Research in All-Terrain Autonomy

Some prior research has already proven off-road autonomy, including object identification and with or without GPS, to be achievable [3][4]. Said research provides a basis for that which is covered in this document. To explain how an autonomous ATV might recognize fuel sampling stations, it is necessary to explain how it could identify any object or environment.

To create a vehicle capable of traversing a wooded area in the manner suggested, a mixture of localization and path detection must be used. Localization, or the ability of the ATV to know its position in an environment, allows the vehicle to have a greater sense of direction and, rather than constantly following a path, allows decision making such as how to handle curves and intersections. Localization can be performed through an onboard GPS and a predetermined route with set navigational waypoints.

Path detection has been done successfully using computer vision programs and depth camera hardware. These technologies allow an image to be taken and processed by various masking techniques such as filtering by color, depth, size, and shape. The example in Figure 2.4 shows masking implemented in prior research performed in 2022 [3]. In this case, a color image was masked based on saturation, binary threshold, and advanced morphology.

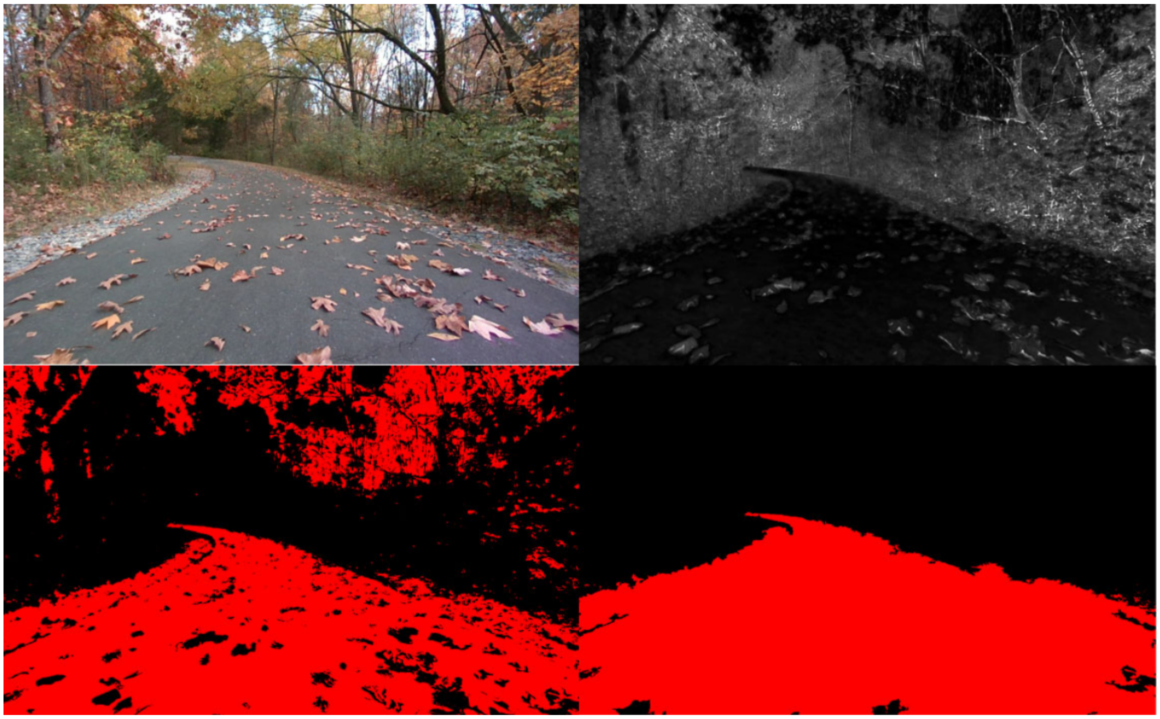

Figure 2.4: Path Detection Masking

The manipulated image can then be measured using a range of methods to find the center of the trail, which can then be adhered to based on the encoder and accelerometer information and by varying steering motor angle and throttle position. The combination of the two components, path detection, and localization, allows the vehicle to function through remote areas with weak GPS connectivity by using image processing to map the trail. Prior research also used computer vision to detect obstacles of various types along the path with a high degree of accuracy, and subsequently stop or move around the impedance in accordance with the type, pedestrian, or object. Obstacle detection is performed in a similar manner to that of path detection, where a depth image is masked using varying criteria. In the 2022 research, obstacles were detected using a depth image, which was then filtered to a black and white plane, followed by binary analysis, and finally, circle detection, as shown in Figure 2.5 [3].

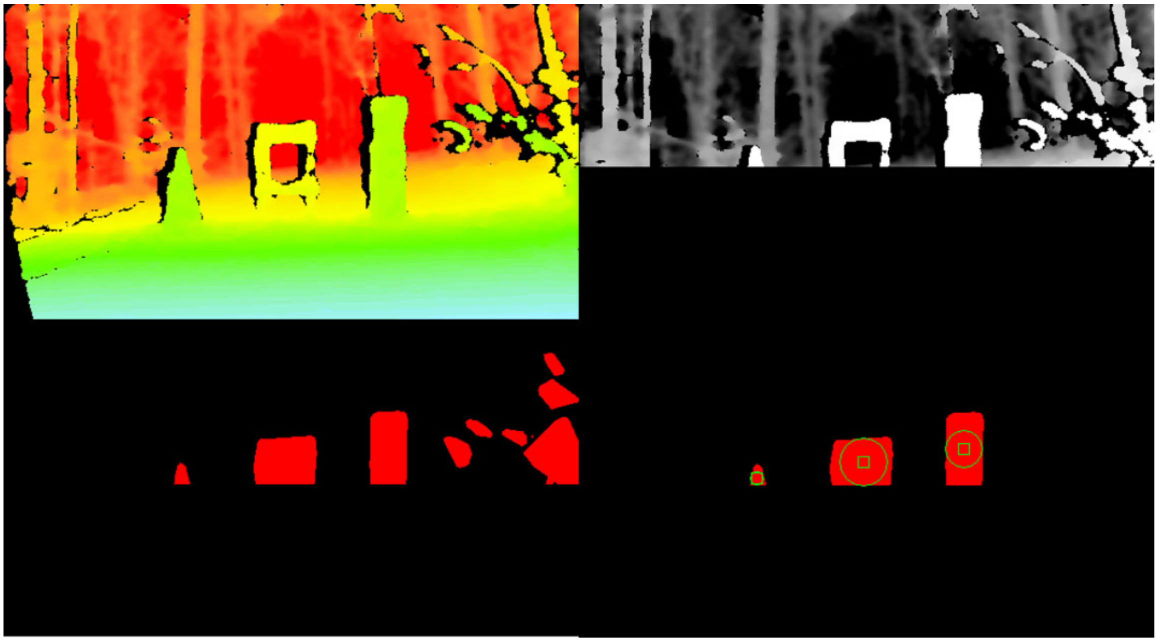

Figure 2.5: Obstacle Detection Masking

In that research, each obstacle was detected from a range of 3 to 8 meters with a success rate of 97.2 percent. In conjunction with GPS waypoint navigation, this same method could be used with even higher success to detect fuel sampling stations during vehicle operation, as station location will be predetermined, and size will remain consistent.

CHAPTER 3: DESIGN OVERVIEW

3.1 System Overview

The system that this research focuses on encompasses the necessary modifications and additions to the ATV required for autonomous data gathering, such as the sensors and mechanisms to gather weather data and fuel moisture data as well as the necessary programming to allow said operations to be automated. The system excludes the previous work done to the vehicle, such as its initial creation, conversion to electric, and added trail-following autonomy and object detection.

3.2 Initial Robot

The robot used for this project was initially created with the intention of bearing supplies and equipment for military applications. The gas-powered vehicle was based on a Scorpion HD Mini ATV, updated to include a flat load surface and a range of cameras and sensors that could be used to follow the user. The robot also included a feature that would allow it to retrace its path and return to its starting location for extraction. More recently, the robot underwent a conversion to an all-electric drive train based upon a Vevor 48 V 2000 W motor and was outfitted with a GPS and Intel RealSense camera. This allowed the robot to perform autonomous waypoint navigation for a range of five-hundred meters, employing obstacle and pedestrian detection [3]. The ATV also featured an onboard National Instruments myRIO, a reconfigurable I/O microcontroller made for use with the LabVIEW programming language, and a Lenovo laptop capable of running more computationally expensive processes. The initial vehicle is shown in Figure 3.1.

Figure 3.1: Initial MWRAD

3.2.1 Vehicle Modifications

The ATV was not fully operable initially, as the small linear actuator motor used to apply the hydraulic brake had previously failed due to overloading. Because the motor did not have the proper specifications to withstand the force required for braking, it was necessary to upgrade the actuation method to a more robust solution. In addition, the vehicle's load bearing platform used rails on either side to prevent cargo from falling off. However, for the current application, it was necessary to modify the platform by removing the rails from one side of the vehicle.

3.3 Hardware Additions

3.3.1 Wind Mast

To gather weather data inputs for use in the NFDRS model, multiple sensors were needed to capture temperature, relative humidity, and wind speed. To reduce the area taken up by these additions, a weather station design that combined all of these devices into a single unit was chosen. To operate the weather station at the recommended height, it was necessary to create a mast capable of positioning the device at a height of approximately six feet. However, since the ATV would likely be required to travel underneath low-hanging branches, the mast needed to be automatically deployable and stowable when not in use.

3.3.2 Cartesian Robot and End Effector

To gather dead fuel moisture data, it was required that the vehicle be able to physically interact with fuels in a precise manner. The chosen design for this was to use commercially available 10-hour time-lag fuel samples. These samples were favored over natural samples, as they are consistent and standard in shape and form factor, could always remain in the same location, and would be more cost-effective and versatile than electronic fuel sticks. For the determination of duff soil moisture, a similar sample setup was not required, as the ground could be probed. To facilitate this probing, the design of a Cartesian robot was chosen, as it could be precisely positioned over the test sample. In contrast, it would be far more complicated to position the entire vehicle in such a manner. However, as it was necessary to take measurements of both the wooden fuel sample and the duff soil layer, an end effector was required that could reach two different heights and operate the two respective probes. To aid precise positioning of the wood moisture probe, two guide rings would be included in the design that would operate in conjunction with the flag cone described in the following section.

3.3.3 Positioning System

To precisely position the MWRAD next to a sample when following a trail, a vision system was a necessary addition. Since the vehicle was already outfitted with a GPS and prior research had added object detection, placing a GPS waypoint for each sampling station along the trail and positioning the vehicle at an approximate 2.5-meter distance to that waypoint would be possible. It was then only necessary to precisely locate the sample upon coming alongside the sample station, and precisely find and probe the sample. The design chosen to accomplish both of these needs was a brightly colored cone that could be rigidly attached to the sample via a frame. With this in place, the RealSense camera on the front of the vehicle could locate the unnaturally shaped cone within the image, and an added side camera on the z-stage of the Cartesian robot could be used to position the probe above the sample. Further, the cone would aid in the precise positioning of the wood moisture probe by acting as a guide, as described in the previous section.

3.4 System Configuration

Figure 3.2 below shows the fundamental hardware additions to the ATV. The wind mast could be positioned along the right-side rail of the vehicle platform, allowing it to take up minimal space. The platform then provided adequate space for mounting the Cartesian robot, which, with the left side rail removed, could extend from the vehicle for probing of the sample station and soil.

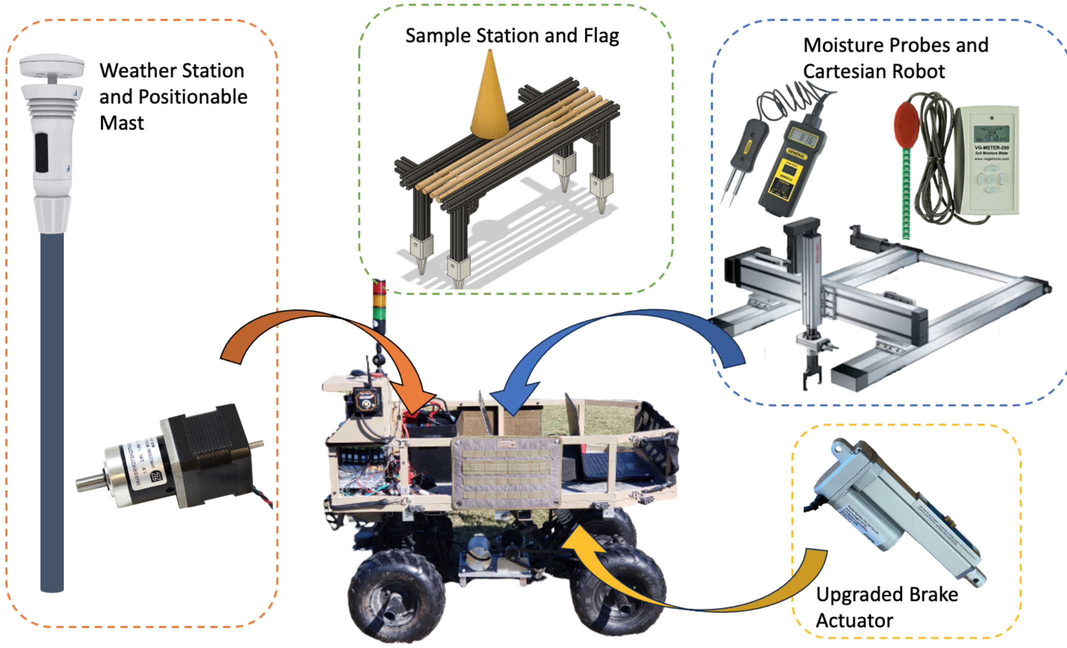

Figure 3.2: Configuration of Vehicle

CHAPTER 4: METHODOLOGY

4.1 Sensors Overview

4.1.1 Weather Data

To gather the weather-related inputs, specifically, temperature, relative humidity, and wind speed, a Tempest weather station was chosen. This weather station had the benefit of being lightweight, affordable, and precise while including a few desirable features. Rather than measuring wind using blades and a vein, the Tempest uses an ultrasonic wind sensor, eliminating the need for moving parts, which may have made the device prone to damage when the mast was in the stowed position. In addition, the Tempest functioned entirely wirelessly via a WIFI-enabled hub and was solar-powered, reducing additional weight and space usage. Further, the device featured the ability to communicate via WebSocket, which allowed the data to be easily retrieved using a LabVIEW VI, rather than having to go through a third-party interface. Finally, an added benefit of the Tempest was its capability to take additional measurements such as wind direction, solar radiation, precipitation, lightning activity, and barometric pressure, which, while not used in this research, allow for future expansion.

4.1.2 Moisture Data

To gather data related to fuel moisture, two devices were chosen: a Lutron MS-7002 pin-type moisture meter and a Vegatronix VG-METER-200. Both devices featured external corded probes, making them ideal for use with the Cartesian robot, as the units themselves could remain on board the ATV, reducing the size and weight of the final end-effector design. In addition, each meter could remain powered on, a feature that was not readily available in most commercial units, yet was necessary for autonomous function, where a power button could not easily be pressed without additional actuators. Finally, each meter featured a serial output, making it possible to obtain the data with the onboard computer.

4.2 Mechanisms Overview

4.2.1 Vehicle Modifications

To upgrade the underpowered actuator for the vehicle's hydraulic brake, a Firgelli adjustable stroke linear actuator was used, which was capable of applying a force of 135 pounds and included an internal limit switch that could be adjusted to a specific extended length. This adjustability was desirable as it would prevent the need for an external limit switch and allow the brake to be precisely set to fully apply the brake without risk of damage to the master cylinder. However, the new actuator did not include an internal potentiometer, an important feature of the previous brake setup. The potentiometer allowed the position of the brake to be known remotely, and, as such, provided important feedback for control. To work around this, it was originally thought that a slide potentiometer could be employed; however, further inspection of the original actuator revealed that its potentiometer functionality remained despite the damaged motor, meaning that it could be retrofit to the new actuator and require only minimal changes to the already present braking VI in the LabVIEW code. Additionally, the new linear actuator could be applied much faster than the original, which meant that the vehicle could now deceleate much more rapidly and effectively.

4.2.2 Mast

To create the positionable mast, a lightweight and robust design was desired. To do this, a rigid carbon fiber tube was used in conjunction with a high torque geared stepper motor that was repurposed from a different project. The diameter of the tube was chosen based on the mounting specifications of the Tempest weather station. To join the tube to the motor, a custom mount and motor coupler were designed. The motor coupler was designed with two inline set screws such that a shaft key would not be needed, thus simplifying the machining process. The coupler also featured a simple rectangular section to slot into the tube mount. The coupler was then machined out of a short section of 6061 aluminum round stock. For the mount, the design was created such that the tube would be securely bolted in, with some thin rubber sheet included to prevent rotational movement. The design was also made to be easily produced using a FDM 3D printer, while having the necessary strength for the application. Since the vehicle was to theoretically be exposed to outdoor elements, polyethylene terephthalate glycol (PETG) was chosen for the material of the mount, due to its strength and comparatively high resistance to heat and chemicals when compared to the more conventional printing material polylactic acid (PLA). The mount is shown in Figure 4.1.

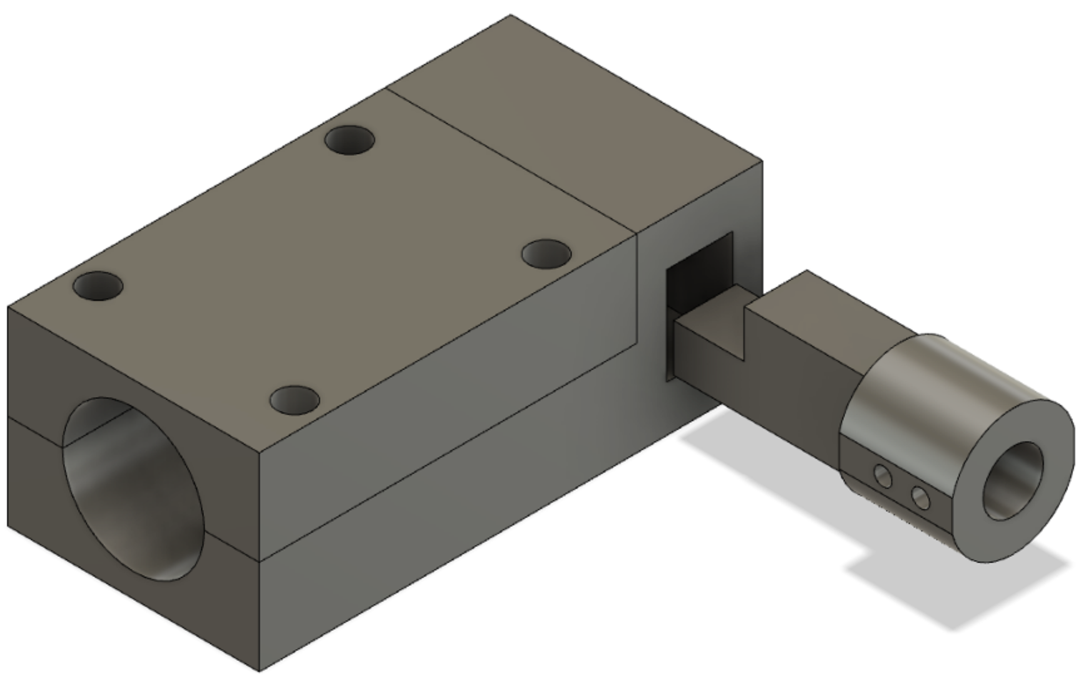

Figure 4.1: Mast Mount CAD Model

Once the parts of the mast were assembled, the precise mounting location was determined, and the assembly bolted in place. Additionally, some thin aluminum sheet metal and adhesive-backed felt was used to make a vertical stop for the mast, providing a stable rest that would ensure minimal movement when taking wind readings.

4.2.3 Cartesian Robot

The Cartesian robot (XYZ) selected to facilitate probing of the wooden fuel samples was a PLC training device repurposed from previous research. The design, therefore, included a great deal of hardware to accomplish the intended function, including a large frame, motorized pick and place table, Allen-Bradley PLC, two NI myRIOs, four power supplies, wiring and components necessary for cross-communication between the controllers. Because this research did not necessitate most of the hardware, many components and connections were removed and rewired. The original frame, table, and PLC were removed, along with the PLC power supply, original end effector, and other assorted components. Figure 4.2 shows the original XYZ electronics assembly.

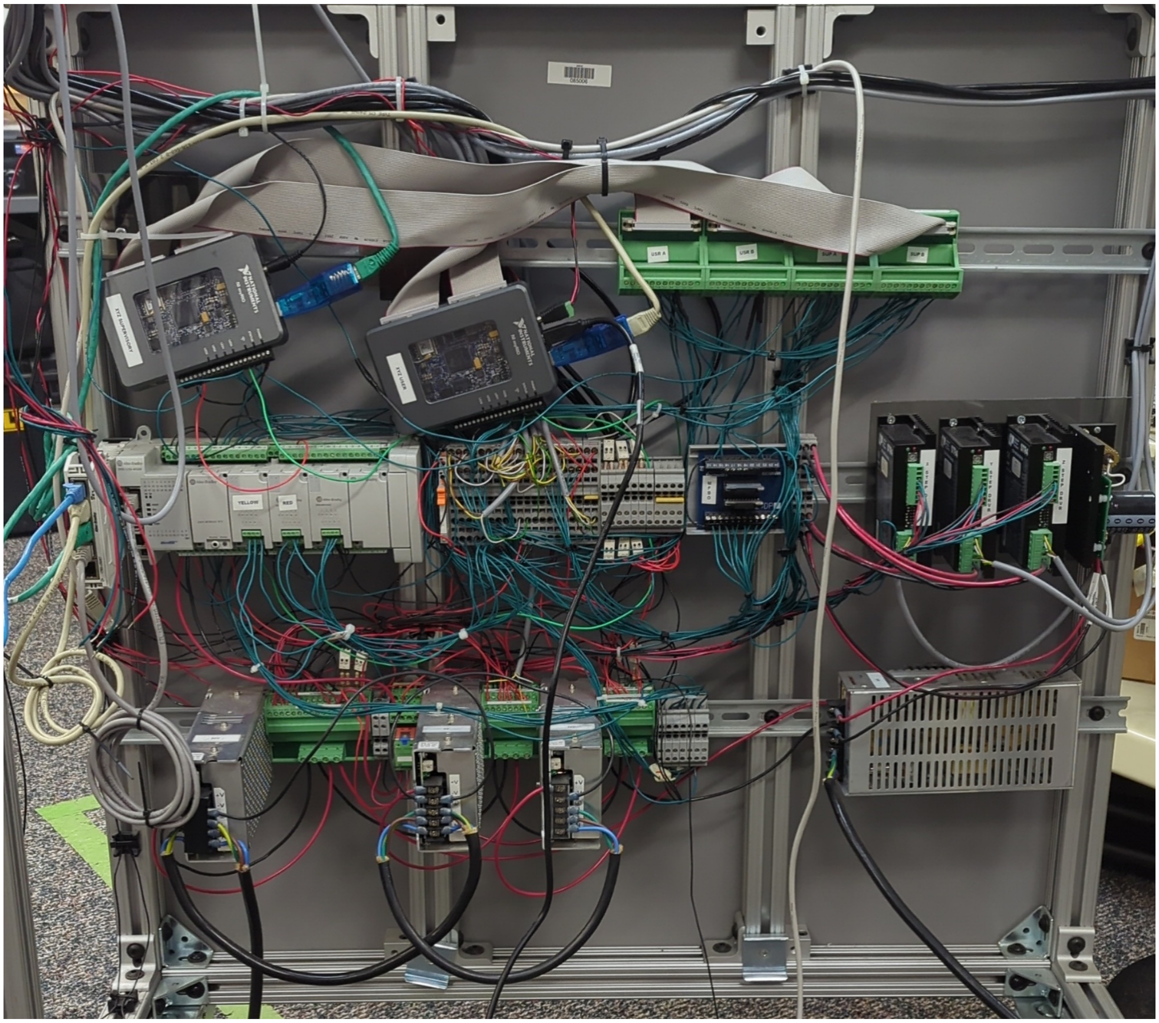

Figure 4.2: Original XYZ Electronics

To ensure that the original functionality of the different stages remained, the myRIOs were both kept, which not only decreased the overall workload but also allowed for additional I/O to be used for communication with newly added components. Further, the original 24 V, 12 V, and 5 V ADC power supplies were left in place, as an AC/DC power converter was already on board the vehicle, allowing for simple integration of the XYZ into the overall system. Moreover, to save space, a small frame was fabricated from the 1.5-inch aluminum extrusion left over from the old frame, which allowed all XYZ electrical hardware to remain on the original DIN rail setup. Some simple hangers were also fabricated, allowing the new frame to be mounted to one side of the ATV, as shown in Figure 4.3.

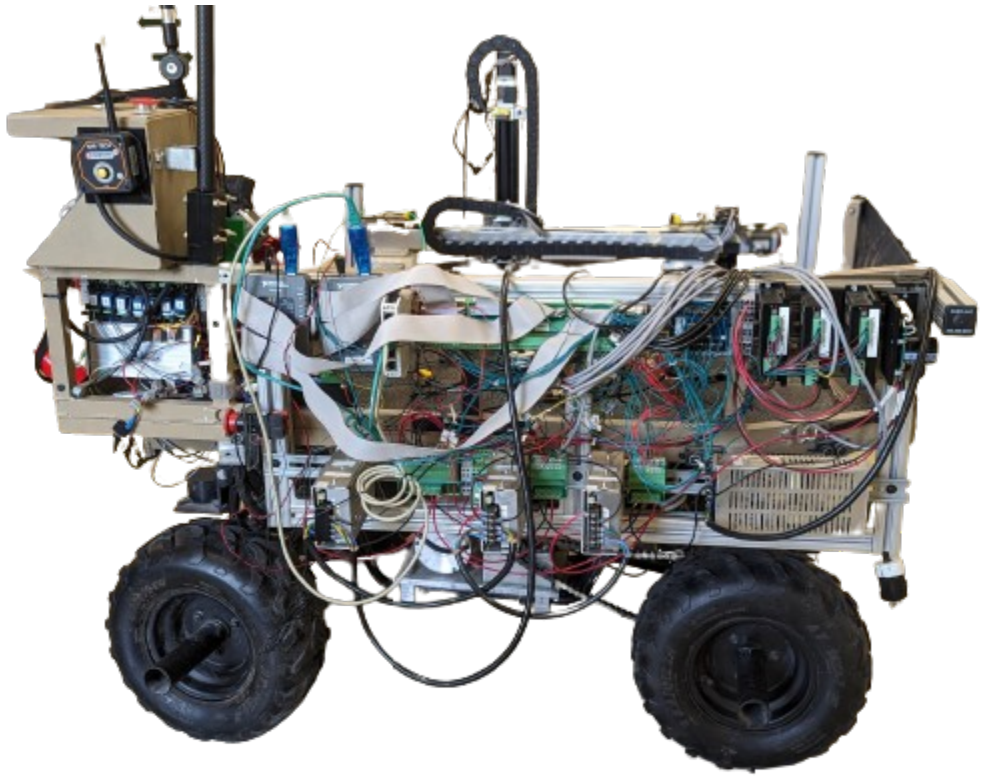

Figure 4.3: MWRAD with Side Mounted XYZ Electronics

With these modifications complete, the XYZ stages could be reconfigured and mounted to the ATV platform. To reconfigure the stages, it was necessary to affix the y-axis rail rigidly to the rails of the x-axis using some 3D-printed PLA mounts. This was done such that actuation of the x-axis motor would result in outward extension of the y- and z-stages from the side of the vehicle rather than moving said stages along the rails of the x-stage. Figure 4.4 shows this configuration.

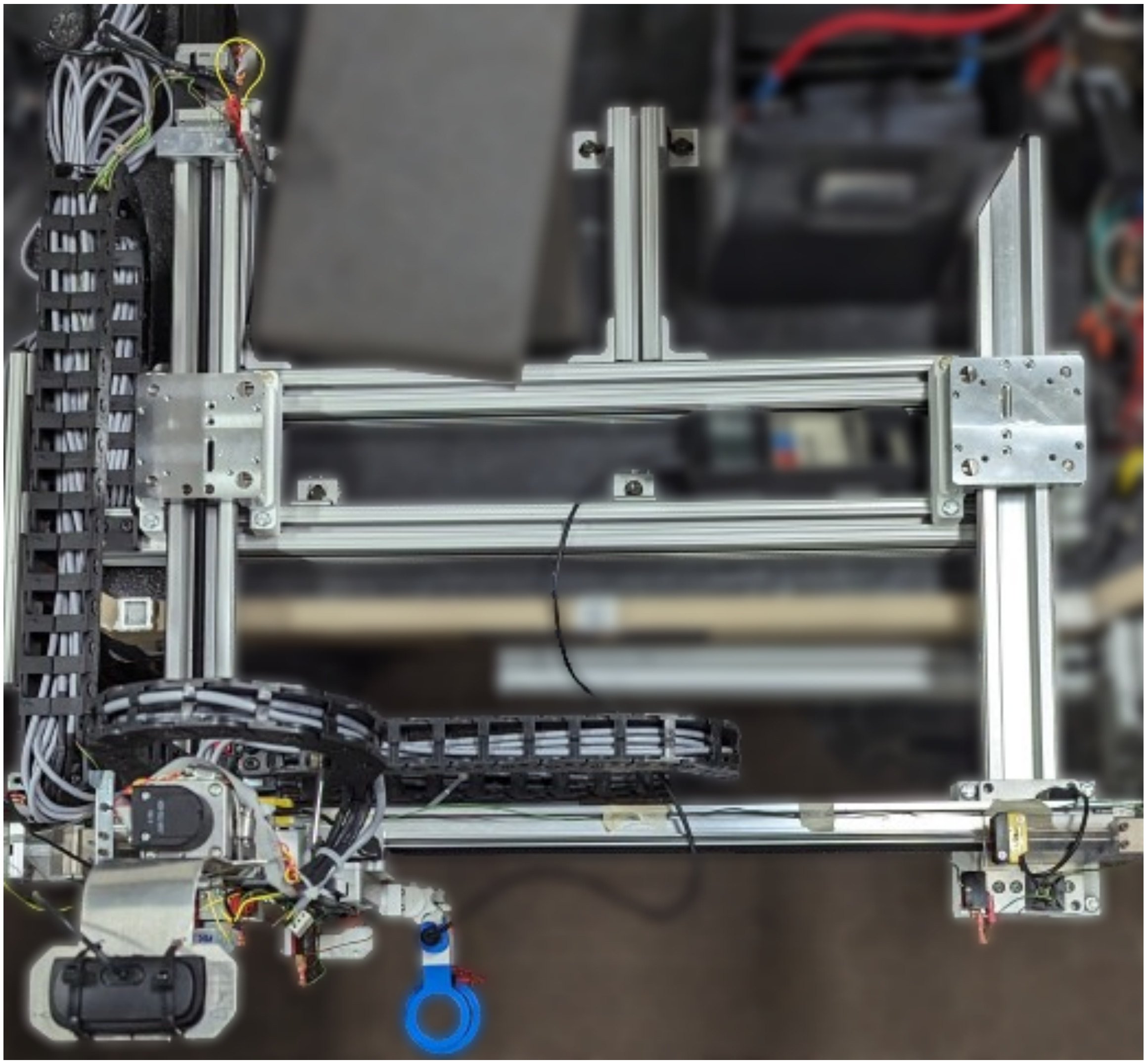

Figure 4.4: Cartesian Robot Mounted to MWRAD

In addition, 3D printed mounts were also created to allow the x-stage rollers to be mounted to a sturdy aluminum extrusion frame, bolted to the platform. This robust mounting solution provided ample support for the XYZ in its fully extended position. After mounting, some simple protective bumpers were created from aluminum flat stock and leftover extrusion and bolted to the vehicle to prevent damage to portions of the XYZ, which lay outside of the boundary of the platform. Finally, the two myRIOs could be connected to the onboard myRIO using an ethernet cable, allowing for communication between all controllers, and the power supply cord plugged into the converter.

4.2.4 Sample Station and End Effector

As mentioned in the previous chapter, a sample station was devised that would use a single yellow cone to act as a flag for autonomous navigation of the vehicle and simultaneously act as a method of precisely positioning the wood moisture probe pins onto the ten-hour fuel sample. For accurate results, it was desired that the station be simple enough to not interfere with the environment or the effects that the environment would have on the fuel sample, yet still be supportive enough to allow mechanical probing of the sample. The solution used one-inch aluminum extrusion to create a rigid frame around the sample, which was minimally supported using two 3D-printed PLA components. The contact area of these supports was only slightly larger than the industry standard sample holders and would therefore not add any additional interference. The frame also included four PLA stakes that, when driven into the soil, would prevent any movement of the frame. Figure 4.5 shows the station assembly.

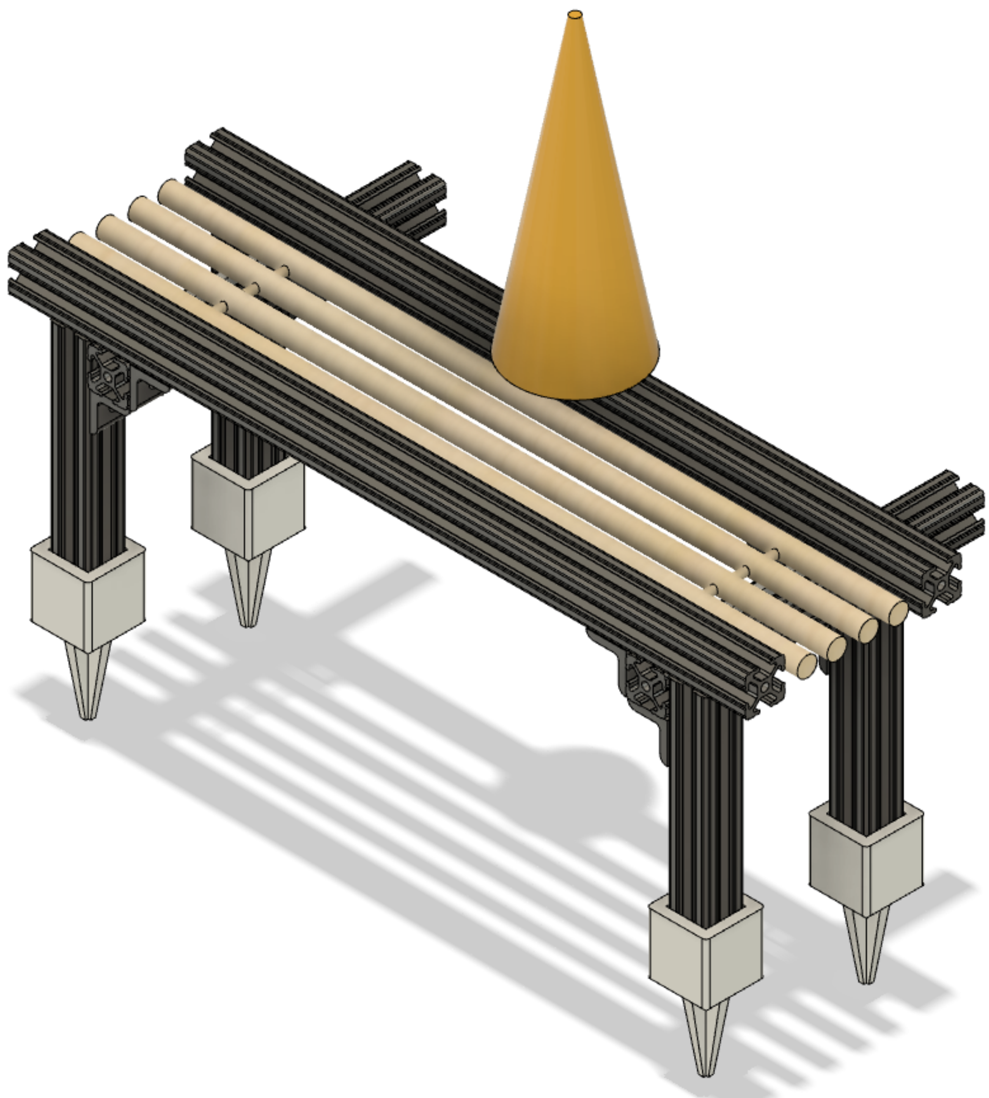

Figure 4.5: Fuel Stick Sampling Station

The guide cone was 3D printed from Acrylonitrile styrene acrylate (ASA), a material chosen for its weather-resistant properties [16]. Initially, a yellow color was chosen for the cone as it was thought to be an unnatural enough color to be easily spotted by a camera against the natural environment. However, preliminary testing showed that glare created by the yellow color made it very difficult to pick up by the color filtered camera. To remedy this, the cone was painted with a dull blaze orange marking paint. Further testing revealed that the new color performed far better in outdoor environments and was not affected by glare. The cone included a T-slot design allowing it to be positionable along the rear frame rail. This design would prevent the sample from wearing out prematurely due to over-probing, as the cone could be easily moved to allow a different section of the wooden sample to be probed once the prior section was no longer usable. In addition, the rear frame rail was created to be easily positioned back and forth to change which of the four wooden dowels would be probed and for alignment purposes. The functionality of the station is exemplified in Figure 4.6.

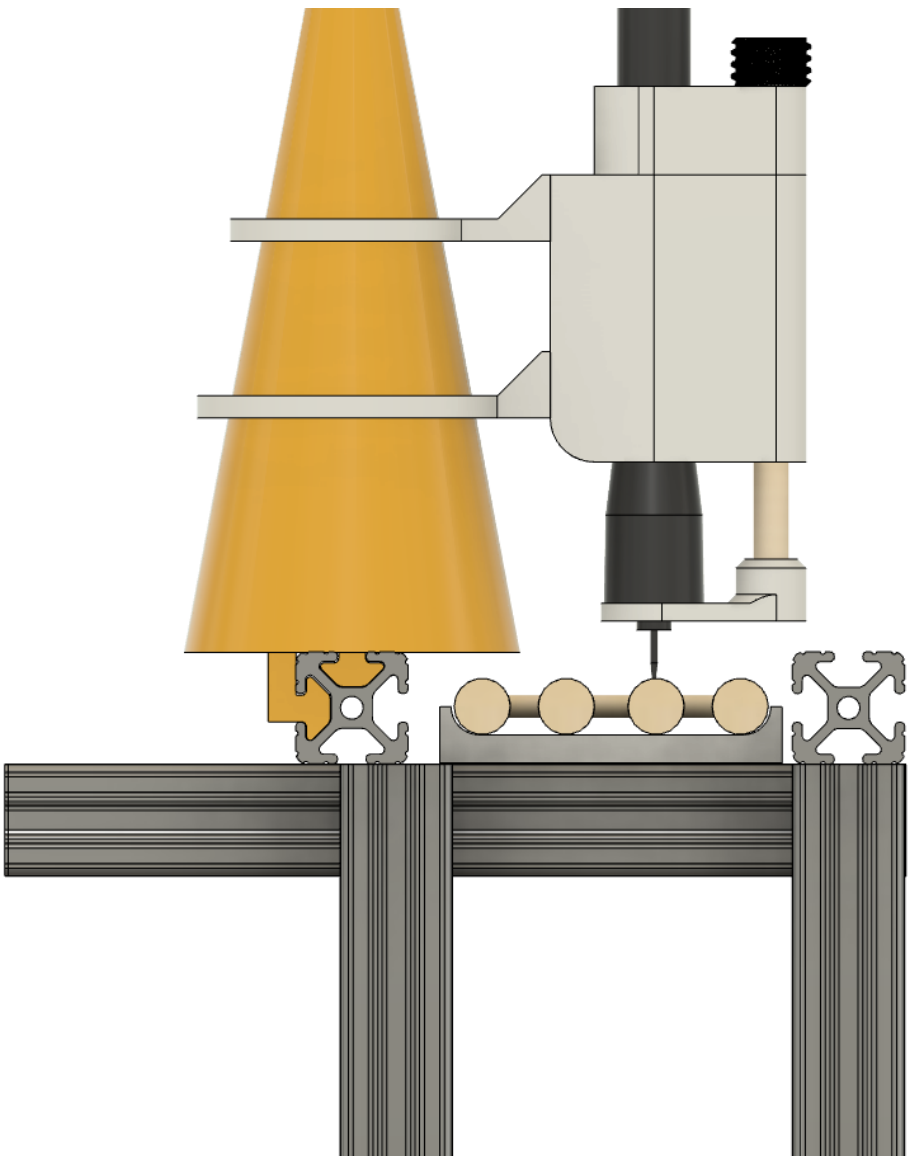

Figure 4.6: Fuel Probe Alignment Using Cone

To create a multifaceted end effector that could switch between probing the wooden sample and the soil, a design was chosen using a servo motor that could deploy and retract the soil probe. The soil probe would be attached to a 5/16-inch wooden dowel with sufficient rigidity to penetrate the soil, while remaining lightweight. A servo horn attachment was printed in PLA to attach the arm to the motor, and a housing was printed to hold the probe to the arm securely. The end effector assembly is shown in Figure 4.7.

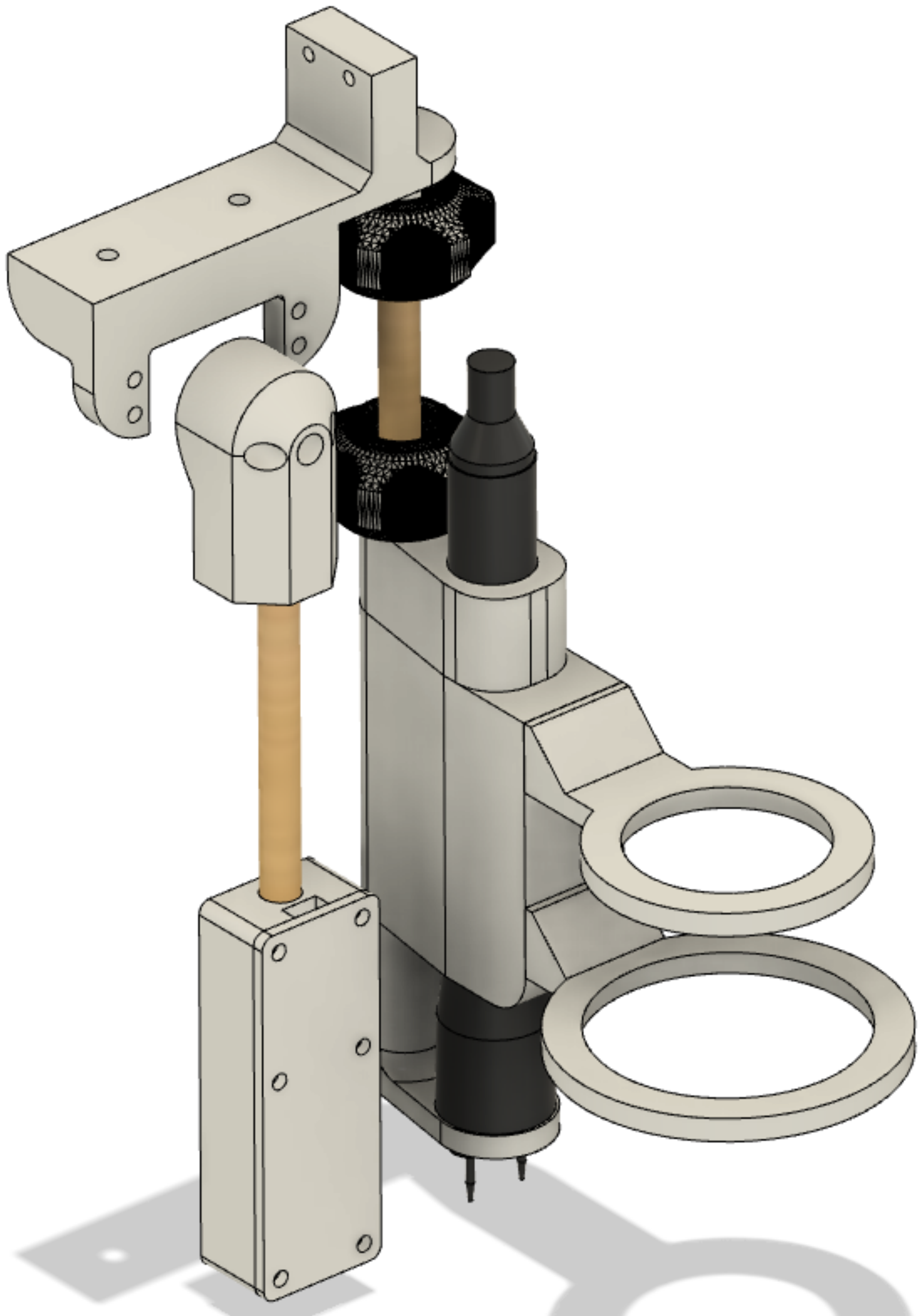

Figure 4.7: End Effector Assembly

For the wood probe, a housing was printed that included two alignment rings that would guide the probe down onto the cone, as shown in Figure 4.8. The inner geometry of these rings were designed to match the outside profile of the cone perfectly. The housing of the wood probe was initially attached to the mounting point with two 3D-printed ball joints to allow for micro-adjustments to be passively made as the alignment rings interact with the guide cone. These were later found to be unnecessary and were removed in favor of a rigid design.

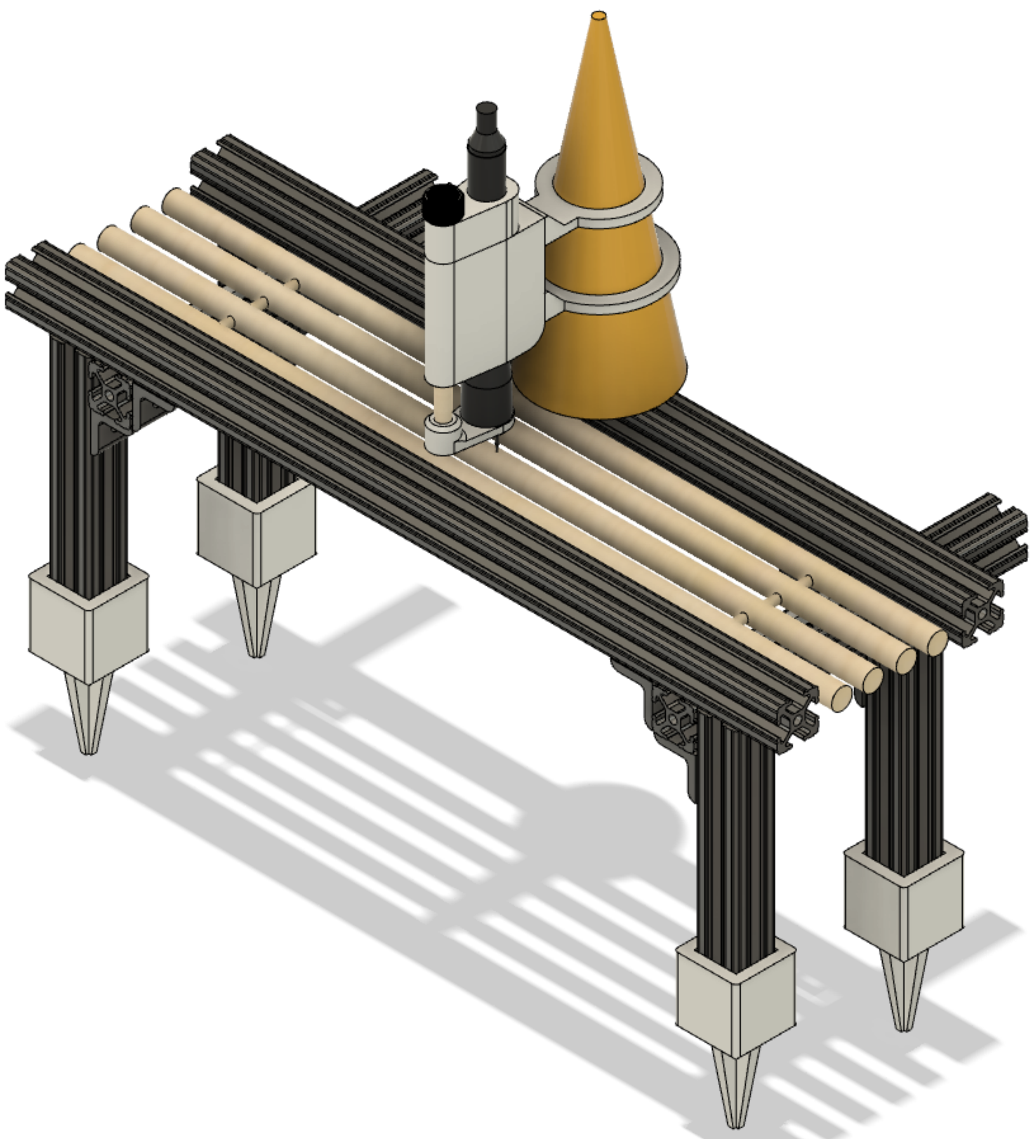

Figure 4.8: Sample Station with Probe

4.3 Autonomy

As mentioned, prior works have already covered object detection and autonomous trail traversal. Therefore, the autonomous processes necessary to define this research are the identification of the sampling station flag cone by the vehicle's side-mounted camera, vehicle positioning, end effector probe positioning, and data acquisition.

4.3.1 Theoretical Operation

To better understand the required functionality, a breakdown of the proposed method in which a final version of this vehicle would operate is given. The desired area for the vehicle to traverse would first be defined. Depending on the location of use, a wide range of variables may be desirable to consider, for example, whether public or private access, dry and flat, mountainous, cold, or warm. These variables could present differing regions of particular interest for prevention or research. In addition, vehicle and on-foot accessibility would also be considered when choosing a location.

Station locations would then be determined. A knowledgeable individual would select appropriate placement of the station for the given task, while taking into account vehicle accessibility by avoiding areas with low hanging foliage, challenging terrain, and considering the likelihood of environmental factors such as flooding or fallen debris which could damage or prevent access to the station. A GPS map with navigational waypoints placed at station locations could then be created, selecting the most efficient and appropriate route based on topography and station spacing. Following this, stations could be placed in the chosen locations adhering to the conventional processes used for fuel moisture sticks.

No further manual work should be required until a change of station location is desired, except in the case of damage from inclement weather or other disturbances. The MWRAD could then be deployed on a daily schedule or singularly as needed.

Upon deployment, the vehicle would follow the route to the first station, stop, and begin taking measurements. To properly align with the station, the vehicle may move to place the flag cone in range of the XYZ, which would then place the probe over the sample and take a reading. At the same time, the wind mast would be deployed to gather wind data for the area. The soil probe would then deploy and collect moisture data from the area next to the station. Upon retracting all hardware, traversal to the following stations would commence. After all data gathering has taken place, the MWRAD would then return to the desired location, where data would then be accessible in the form of a CSV file either wirelessly or by a wired connection. This entire process can be summarized by the flowchart in Figure 4.9.

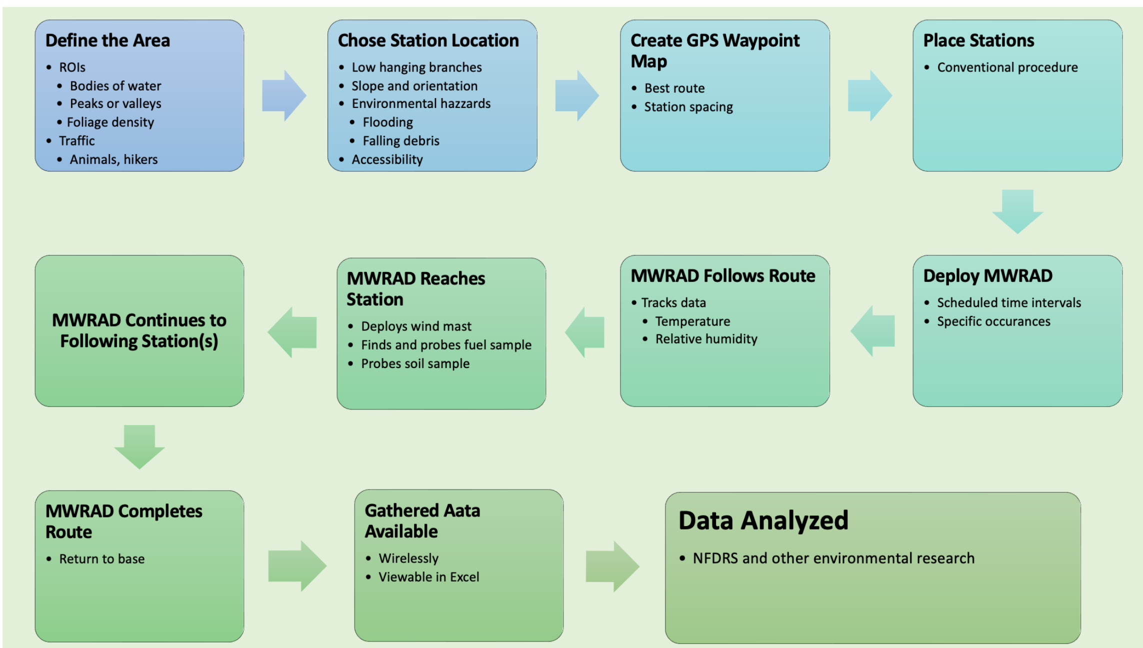

Figure 4.9: MWRAD Operation Process

4.3.2 Data Collection Procedure

Once the vehicle has come alongside the sampling station, the data collection procedure begins with identification of the flag code by the side-mounted camera. The camera used was a simple 720p resolution USB webcam, chosen over high resolution options to reduce the computational load, as will be discussed. The webcam image was fed into NI's Vision Assistant within the LabVIEW software. This allowed masking to be applied to the image to filter out all colors except that of the cone. The masking consisted of a color threshold which allowed any objects in the image not close to the orange color of the cone to be filtered out. Following this, an advanced morphology mask was used to remove non-consistent small particles, leaving only the cone remaining. Particle analysis was then used to find the center of mass in both X and Y pixel coordinates. The effects of the image masks are shown in Figure 4.10.

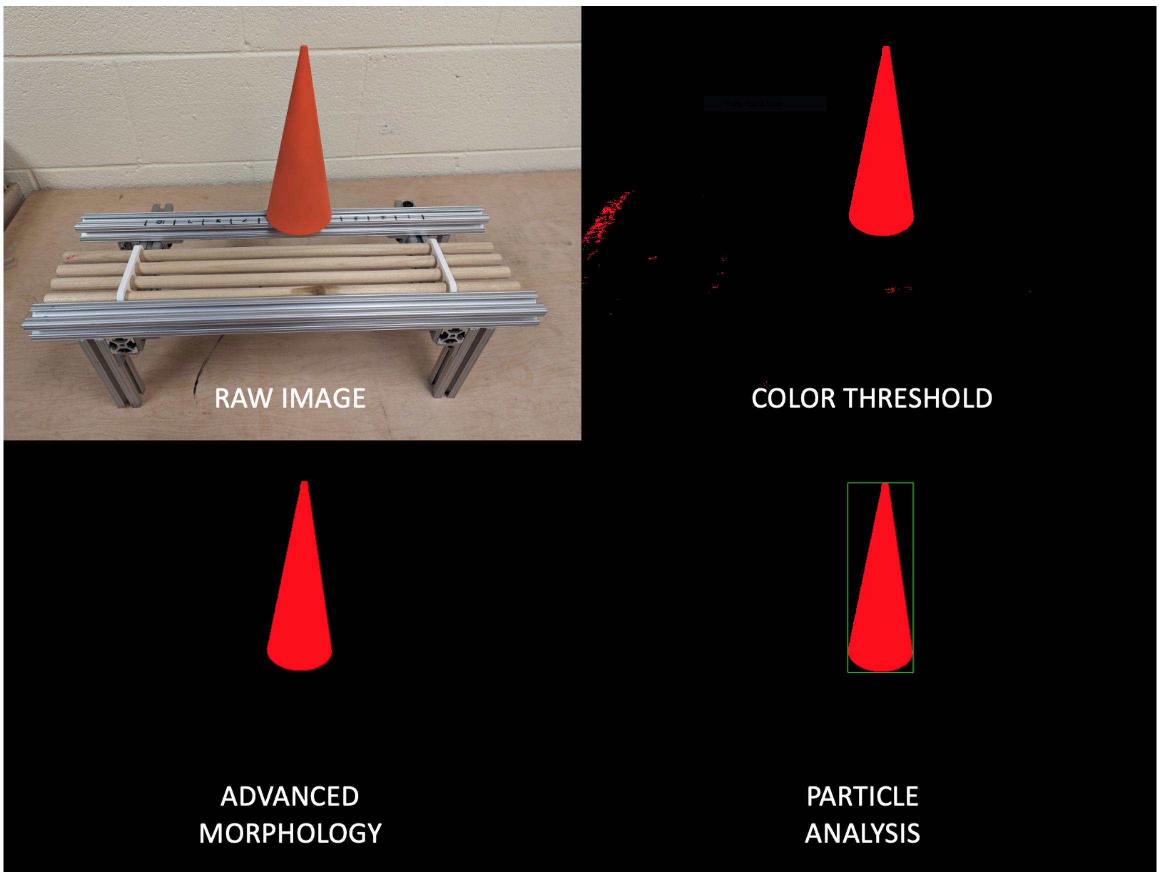

Figure 4.10: Vision Assistant Masking of the Guide Cone

The pixel values were then converted into a step value for the X and Y stage stepper motors on the Cartesian robot based on a conversion factor determined through preliminary testing. This allowed the fuel probe to be positioned over the cone with accuracy, by simply moving the stepper motors the pixel value between the given coordinate position of the cone within the visible area of the camera and the coordinates of the center of the probe guides. This is best illustrated by Figure 4.11.

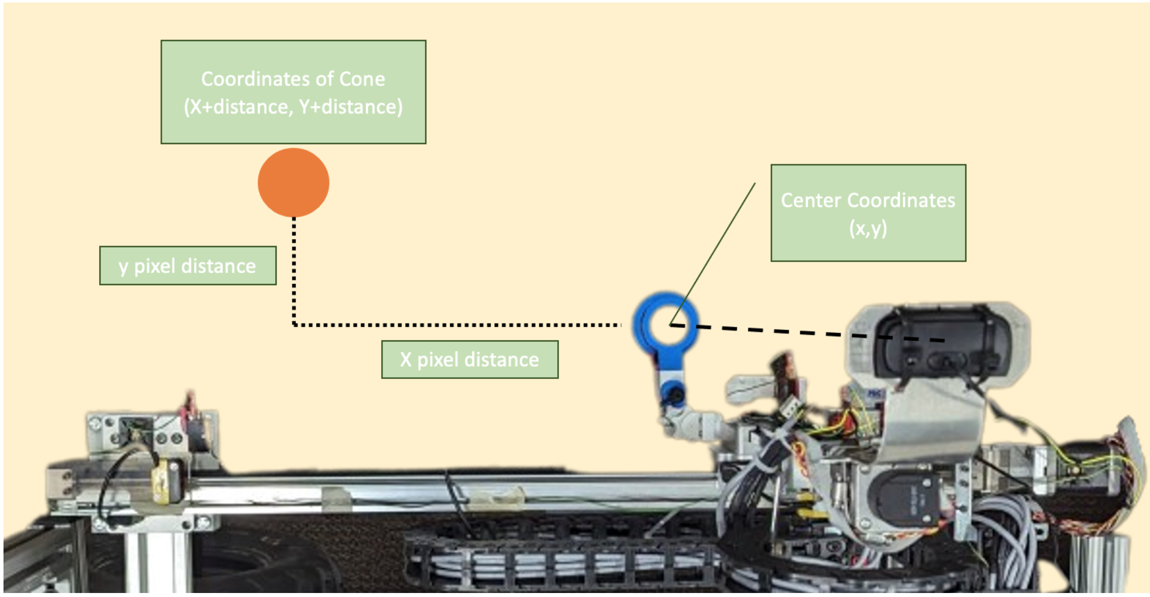

Figure 4.11: Cone Centering Process

It was found that the best accuracy results were obtained when the motors were first moved approximately half the distance to get to the cone, at which point the image was checked again, and the distance recalculated. In this way, the effects of camera parallax could be reduced, and the camera could be given a more top-down view of the cone, further correcting the center of mass provided by the particle analysis.

4.3.2.1 Sample Station and Probe Positioning

4.4 Testing Methods

To provide a proof of the methodology used and ensure that the data from each device was being correctly retrieved, saved, and displayed, tests were devised. The autonomous processes were also tested to ensure repeatability. In addition, these tests would determine if the results of the automated data-gathering process were representative of the manual processes currently in use. The data gathered from the meters was subject to some uncertainty due to the accuracy and resolution of said devices. It was defined that for practical implementation of this vehicle, a knowledgeable individual would select devices with appropriate accuracy and precision. For this research, the fuel moisture meter had a claimed accuracy of plus or minus five percent plus five digits, and a resolution of 0.1. The accuracy of the soil moisture meter was plus or minus two percent with a resolution of one percent. Finally, the advertised weather station accuracy was plus or minus 0.2 degrees Celsius for temperature, plus or minus two percent for relative humidity, and the greater of plus or minus 0.5 MPH or plus or minus 2 percent for wind speed. The weather station resolutions were 0.1 degrees Celsius for temperature, 1 percent for relative humidity, and 0.1 MPH for wind speed.

4.4.1 Baseline Testing

Before initiating the assessment of the automated process, it was desirable to perform initial baseline tests to determine typical values for the meter in use to aid in subsequent comparison of the methods. In addition, the manual process of determining moisture content of the ten-hour fuel stick through weighing was performed. All three of the following fuel stick testing procedures, sample weighing, manual probing, and automated probing, were performed in as timely a manner as possible to more effectively compare the data from each method. Manual sampling of the fuel stick was performed as follows. The fuel sample was first weighed using a digital hanging scale to ensure it was dry, having a weight of 100 grams. The sample was then carefully secured into the frame and placed outdoors in an open area. The sample was given five days to reach equilibrium moisture content with the surrounding air before being removed from the frame and weighed once more to determine the percent moisture content. When using ten-hour fuel sticks, the difference between the wet and dry weight of the sample is equal to the percent moisture content due to the calibration weight of 100 grams, as is expressed be the standard percentage difference equation.

To determine typical values for the wood moisture meter the following procedure was performed. The pins of the probe meter were pressed approximately 1/8th of an inch into one of the four dowels of the fuel stick sample, as per the meter instructions, at the first tick mark on the station, and the reading from the unit was recorded. This process was repeated for the remaining nine tick marks. The tick marks were used to account for any deviations in the sample. Likewise, the process was then repeated for two more of the dowels on the sample, for a total of thirty readings, a number thought to be more than sufficient to eliminate error. A top view showing the dowels and tick mark spacing is given in Figure 4.12.

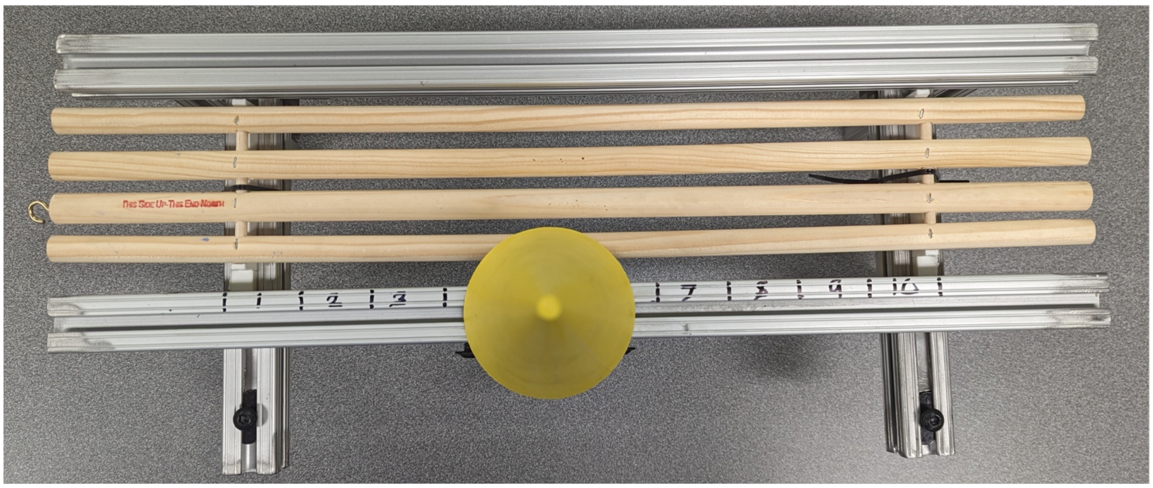

Figure 4.12: Fuel Sample Station Top View

The typical values for the soil moisture meter were also gathered using a similar method. Samples of soil were first collected into three identical plastic vessels with a depth of four inches, which was chosen to be sufficient enough depth for the length of the probe. The soil probe was then placed into the first sample at a depth of 60 mm, and the reading from the unit was recorded. This process was repeated for the two remaining samples. All three samples were then probed two additional times in different locations to account for any deviations in technique or errors, resulting in a total of nine readings.

To determine typical values for the Tempest weather station, the following procedure was performed. The station was placed in a random outdoor location with no regard to current weather conditions. Locations were ensured to have a diversity of characteristics, such as whether the location was in direct sunlight or in shade, to verify the data. Per convention and to replicate how it would be mounted on the vehicle, the station was placed at a height of approximately six feet and given sufficient time to adjust to the environment, around five minutes. The data from the station was gathered through the Tempest application and recorded for comparison with the Nation Weather Service. To gain a large enough sample size, this process was repeated on five separate days. It should be noted that The National Weather Service requires a device accuracy of plus or minus one percent with ninety-five percent confidence for temperature and measures air movement using a totalizing anamometer, with a required accuracy of plus or minus thirty-three percent of the actual air movement in miles at the end of 24 hours [17].

4.4.2 Automated Testing

The following test was conducted to determine the functionality of the fuel moisture meter when data was obtained through the automated system. The environment-equalized sample station was placed in a random location within the reachable area of the XYZ. The station guide cone was positioned at the first tick mark and automatically located by the side camera. The XYZ then probed the sample and recorded the reading. The cone was then moved to the next tick mark, and the process was repeated, and so on and so forth for all ten tick marks. These steps were repeated for three random locations and thirty probe readings. Following this, the gathered data was inspected to ensure a reading was taken each time probing took place and that all readings were sufficiently similar to the typical meter values.

Similarly, the functionality of the soil moisture meter was tested when data was obtained through the automated system. The same three sample vessels used in the manual soil probe test were again used. The soil probing functionality was deployed, and the first sample, placed in the first position as in Figure 4.13, was subsequently probed. The sample was moved to the remaining eight different XYZ locations, being probed at each location to test the probing function over the entire reachable area of the XYZ. After this, the procedure was repeated for the remaining two soil samples. The data gathered was viewed through LabVIEW and was cross-referenced for similarity with the typical meter values to determine if the system gathered and displayed data correctly.

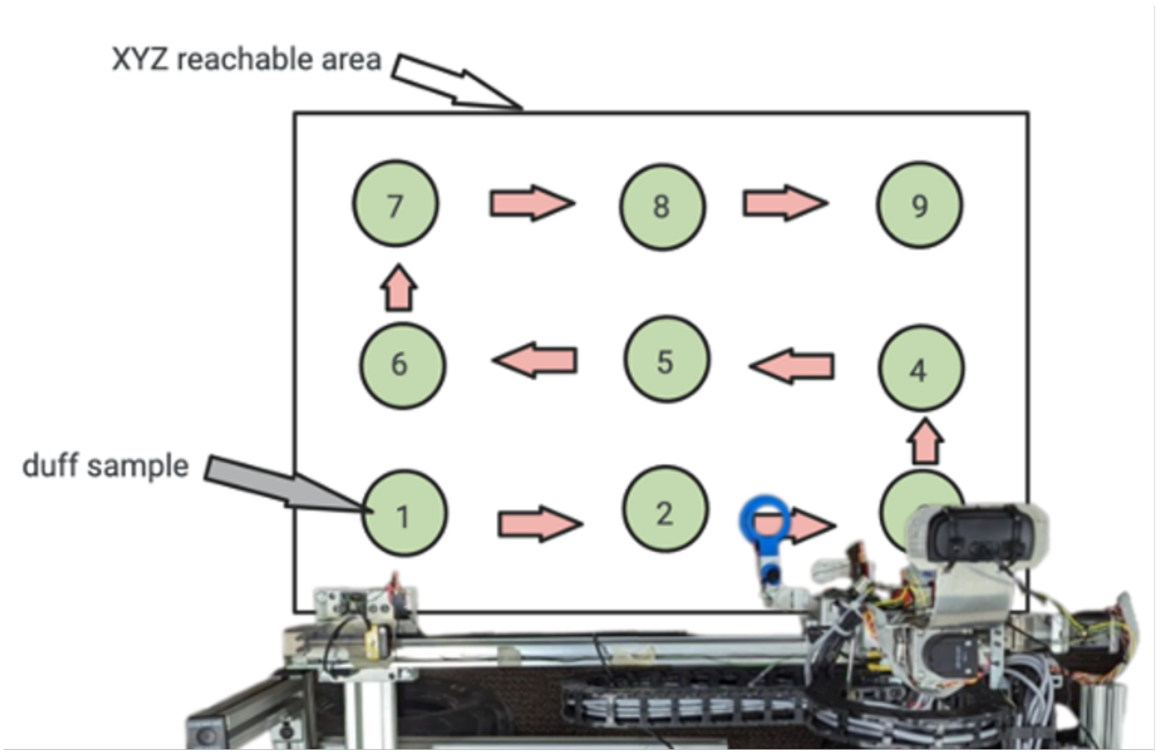

Figure 4.13: Automated Soil Probing Test Procedure

The following test was conducted for the automated function of the weather station. The entire ATV with the mounted weather station was placed in a random outdoor location and given sufficient time to adjust to the environment, as with the baseline test. The data from the station was gathered through the LabVIEW program, and the values were cross-referenced to the National Weather Service and typical station values to ensure the code was correctly outputting the data. As before, this test was performed on five separate days.

4.4.3 System Functionality

A comprehensive test was performed to validate the function of all subsystems of the MWRAD, automated probing functionality and weather data gathering in a practical and authentic context of application. Testing was performed outdoors along a section of pathway with a sufficient shoulder to place the sampling station. The vehicle was then placed parallel to the station at a random distance within three to six feet, as it would be following autonomous trail traversal and approach. The program was run, and data was collected for fuel and soil moisture, ambient temperature and relative humidity, and wind speed. The station and vehicle were then randomly reoriented to either a new location along the path or a different cardinal direction, introducing variability to assess performance under more diversified conditions. The testing process was repeated five times to validate consistency and reliability. Data was then observed to determine if proper functionality was achieved.

CHAPTER 5: RESULTS AND DISCUSSION

Testing of the mobile wildfire risk assessment droid provided valuable insights into the feasibility of using an autonomous platform to comprehensively gather environmental data. Testing encompassed the assessment of fuel stick moisture, soil moisture, temperature, relative humidity, and wind speed data. The primary testing objectives were to determine if the devised solution was applicable to enhance the existing toolkit available to field personnel engaged in wildfire prevention and analysis, and secondly, to establish a comparative analysis between autonomous data collection and manual data collection. In addition, the results allow conclusions to be drawn about the methods employed in this research to achieve data collection autonomously and what improvements may be made in the future.

5.1 Testing

5.1.1 Manual Fuel Moisture Data

Upon allowing the ten-hour time-lag fuel stick sample to become acclimated to the surrounding environment, the sample was carefully removed and weighted. The initial weight, as mentioned previously, was calibrated to 100 grams. After adjusting to the environment, the new weight was found to be approximately 114 grams. By taking the difference of the two weights, a resulting fuel moisture percentage was found to be fourteen percent. After a weight was acquired, the sample was carefully placed in an airtight plastic bag for transportation to the testing environment in an attempt to prevent as much moisture loss as possible. Testing of the probe digital pin type fuel moisture meter was then performed. Following the test procedure outlined in the previous chapter, thirty manual readings were gathered. Initial observation found that the data closely resembled what was measured by weight, as shown in Figure 5.1.

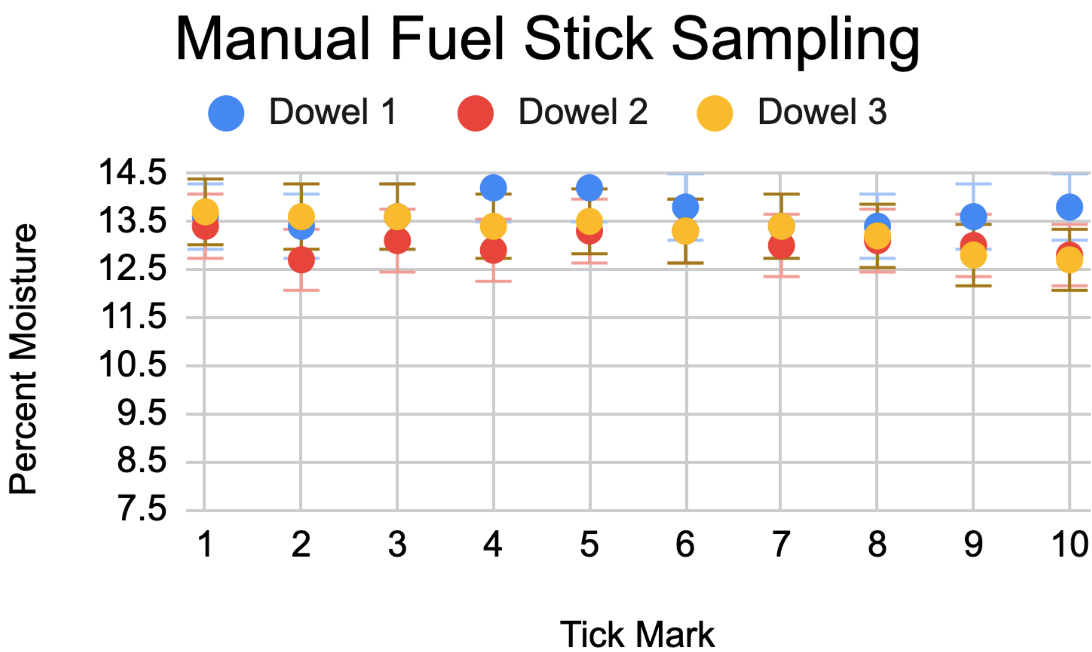

Figure 5.1: Manual Fuel Stick Sampling Results

The data gathered from each dowel had only a small variation, with a maximum moisture reading of 14.2 percent and a minimum value of 12.7 percent, resulting in a range of 1.5 percent. The data from each dowel was then averaged, and a resulting value of 13.36 percent was yielded, a deviation of 0.64 percent from the value gathered by weighting the sample. The manual probing process was performed within a day of removing the sample from the environment, which is paramount to note when observing data from the automated probing procedure.

5.1.2 Automated Fuel Moisture Data

Following manual probing, automated probing then commenced. In this test, regard was not given to which dowel was being probed instead the primary objective was to ensure that the automated system was capable of processing the data correctly and maintaining functionality over the full range of travel of the Cartesian robot. For the first location, data was collected within one day of manual data collection; however, due to time constraints, the later locations were taken approximately two to three days later, with the sample being placed back in the sealed bag to prevent moisture loss. One factor not considered however, was loss due to condensation of moisture within the bag. The results for automated probing are shown in Figure 5.2.

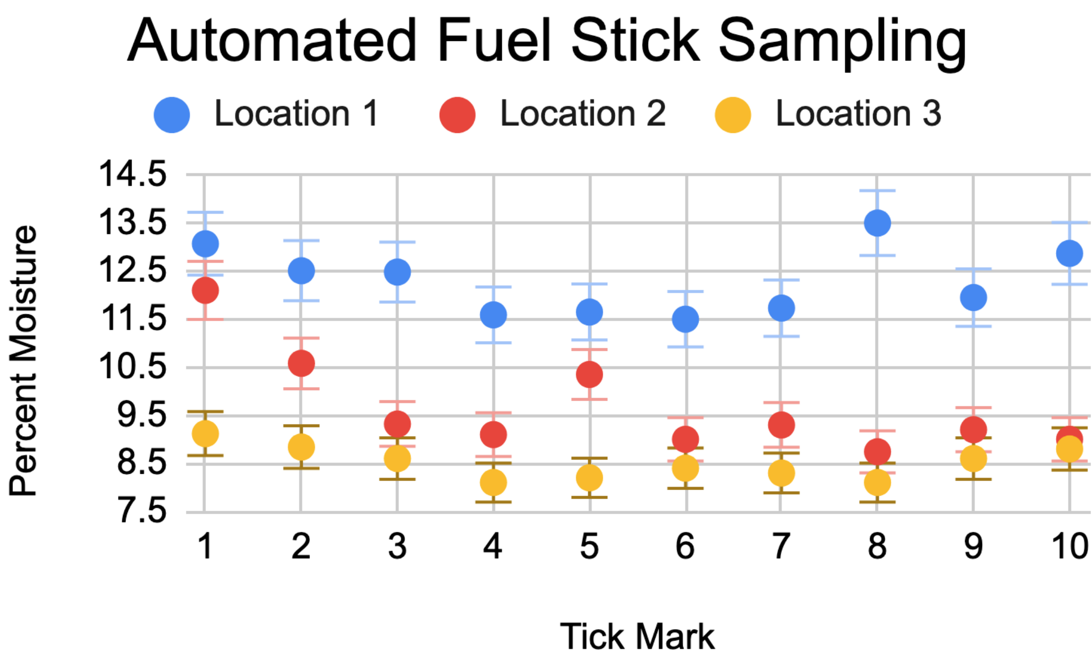

Figure 5.2: Automated Fuel Stick Sampling Results

For the automated test, the maximum moisture value from location one was 13.5 percent, while the minimum moisture value, occurring at location three was 8.1 percent, a range of 5.4 percent. Observing the figure, it is hypothesized moisture loss occurring between testing days can account for much of the deviation. When considering only the first location, automated probing appeared anecdotally similar to the data gathered manually.

In addition to moisture loss, another factor that may have caused some deviations to occur throughout the test was the number of holes present in the sample from ongoing probing. For the meter to provide a correct result, the probe pins must make full contact with the material surrounding them. Due to the high number of probes, the damage to the sample was accelerated far more than it would be in regular usage, preventing a good connection in some cases. Despite the variability introduced by these factors, testing showed that the Cartesian robot and probe end effector could automatically probe the sample over the full reach of the XYZ.

Testing to determine the rate of successful sample probing was also conducted as previously outlined. This test of twenty-five sample probes resulted in a success rate of eighty-eight percent, with twenty-two of the tests yielding a measurement. It should be noted that the lighting source during testing remained consistent along with the position of the vehicle, narrowing the variables of the test to focus solely on the efficacy of the hardware. Two main factors were hypothesized as being responsible for the non-successful probing, relating to station position in relation to the vehicle and the relationship between the camera and the XYZ stepper motors. In cases where the station was positioned very close to the vehicle, the end effector could overshoot the cone due to the two-stage acquisition process. In a practical application, the approach method would likely prevent the vehicle from being as close to the station as in testing.

Another factor that may have created error relates to the relationship between the camera pixel and stepper motor values. The conversion factor between steps and pixels was not exact, being determined through a method of testing and checking, and may have created deviation when stacked with variables such as camera parallax, which could cause the center of mass of the cone to be read incorrectly, and power supplied to the motors, which may have not remain constant depending on the state of battery charge or draw from other devices. Due to the small size of the cone rings, a difference of approximately an inch could cause the cone rings to land slightly on top of the cone, preventing the probe pins from making a good connection. Potential remedies for the errors discussed in this section are given in the following chapter.

5.1.3 Fuel Moisture Data Comparison

Comparing the two methods of fuel moisture gathering, manual and automatic, provides a clearer picture of the results. A failure of the automated system's ability to correctly gather data would likely result in an apparent inconsistency of the data due to a failure within the code itself. However, the more gradual decline of the gathered data collected from testing appears to show a functional system. This is most readily illustrated by Figure 5.3. Note that the colored bars indicate each of the ten tick marks.

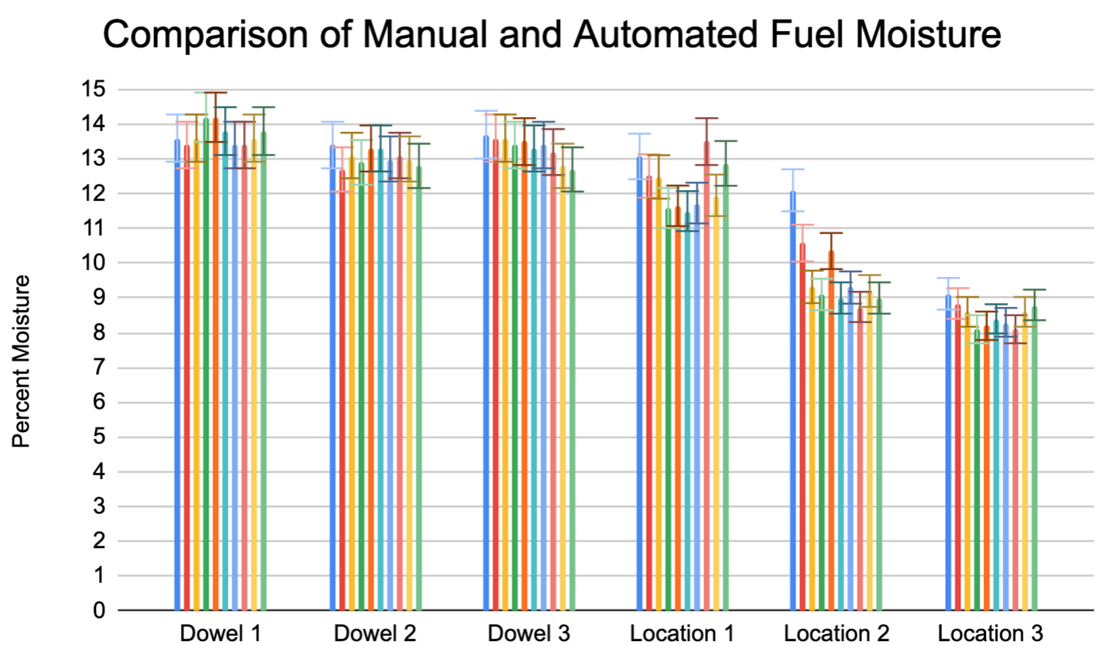

Figure 5.3: Comparison of Fuel Moisture Data Gathered Manually and Automatically

As shown, the automated data, despite being lower, remains relatively consistent in appearance with the exception of a few outliers. These discrepancies may have been due to a probe taking place on a less dry section of the sample or a section with fewer holes from previous penetration of the probe pins. However, to gain a better understanding of the dissimilarity of the test results, a non-paired two sample t-test was performed. To accomplish this, the three data points from each of the ten tick marks were averaged, resulting in two sets of ten values for the manual and automated tests. Calculations were then performed using data analysis tools with an alpha value of 0.5, a hypothesized mean difference of zero, and equal variances assumed. The results of the analysis are shown in Table 5.1.

Table 5.1: Two Sample Fuel Moisture T-Test with Assumed Equal Variances

	Manual Average	*Auto Average*
Mean	13.36	10.153
Variance	0.037688889	0.294934444
Observations	10	10
Pooled Variance	0.166311667	
Hypothesized Mean Difference	0	
df	18	
t Stat	17.58419957	
P(T<=t) two-tail	8.77789E-13	
t Critical two-tail	2.10092204	

The results of the t-test show that the null hypothesis must be accepted as there is not sufficient evidence to show statistical similarity between the manual and automated sample sets. Observing the critical value, it is far lower than the t-statistic. In addition to the aforementioned factors, a large portion of the inconsistency can be contributed to the meter accuracy of plus or minus five percent and five digits being too high for the application, as most of the data fell within that range. To further test this, the same t-test was performed for the data from dowels one and two, as the values were taken at approximately the same time and under the same conditions. This test also revealed a lack of statistical evidence for similarity, having a critical value of 2.10 and a t-statistic of 5.36. As this testing was performed manually, it was shown that the meter itself may have been responsible in part for the deviations.

5.1.4 Manual Soil Moisture Data

Probing the soil test vessels manually resulted in twenty-seven readings. Probing, as outlined, took place one container after another to ensure as much randomization as possible. The primary objective of manual soil testing was to determine typical values for the meter and the variation of values. Testing showed vessel A to have an average volumetric moisture content of 18.1 percent, with a spread of five percent. Vessel B had an average VMC of 15.1 percent and a spread of five percent. Vessel C had an average VMC of 13.9 percent, with a spread of nine percent. The overall average of all twenty-seven readings was 15.5 percent VMC. The results of the test are shown for each vessel and nine sample sets in Figure 5.4.

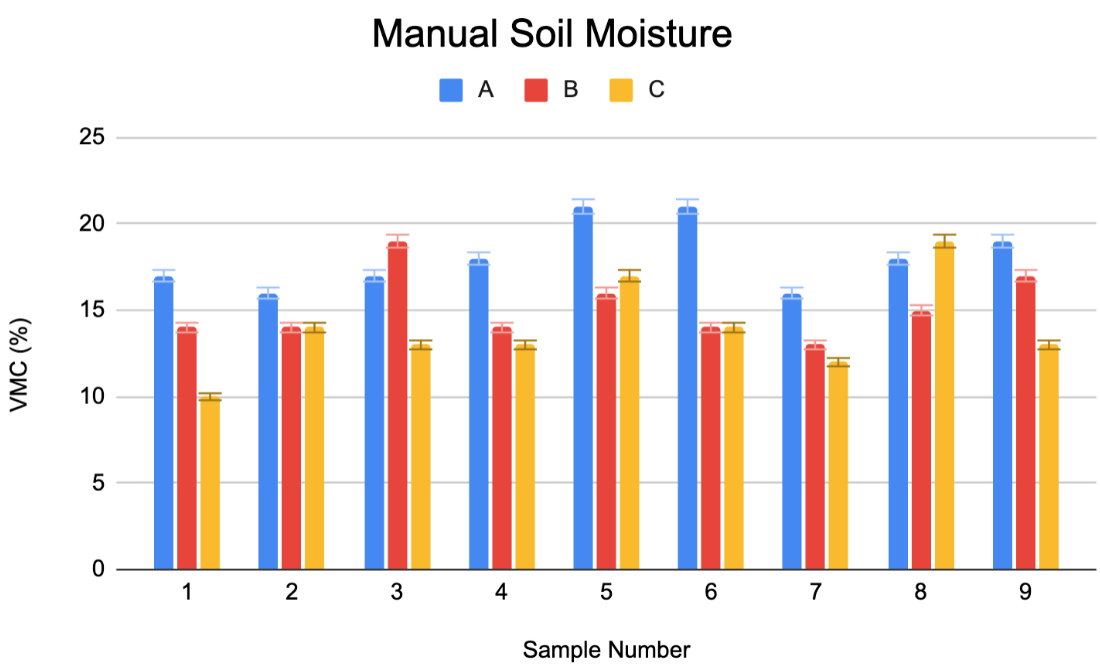

Figure 5.4: Manual Soil Volumetric Moisture Results

The wide range of data may be contributed to a heterogeneous soil mixture, having some dry top soil along with more moist soil from deeper in the ground. Additionally, it was found that depth of penetration had a significant effect on the meter reading, with deeper penetration resulting in a higher soil-to-water ratio. In practice, the duff layer of soil, which is desirable to measure for wildfire-related research, can range from one to twelve inches deep depending on the environment [18]. Therefore, it is thought that a standard system based on the depth of the layer may be necessary to determine the required depth of probing for the given area.

5.1.5 Automated Soil Moisture Data

As with the manual soil test, the automated test produced twenty-seven readings. The primary objective of the automated soil test was similar to that of the automated fuel stick test, ensuring that the automated system was able to process values while functioning over the entire range of travel of the XYZ robot. Vessel A was shown to have an average VMC of 14.5 percent, with a spread of 9.2 percent. Vessel B had an average VMC of 15.1 percent, with a spread of 14.3 percent. Finally, vessel C had an average of 16.9 percent and a spread of 7.9 percent. The overall average of the total readings was 15.7 percent. The results of the automated test are shown in Figure 5.5.

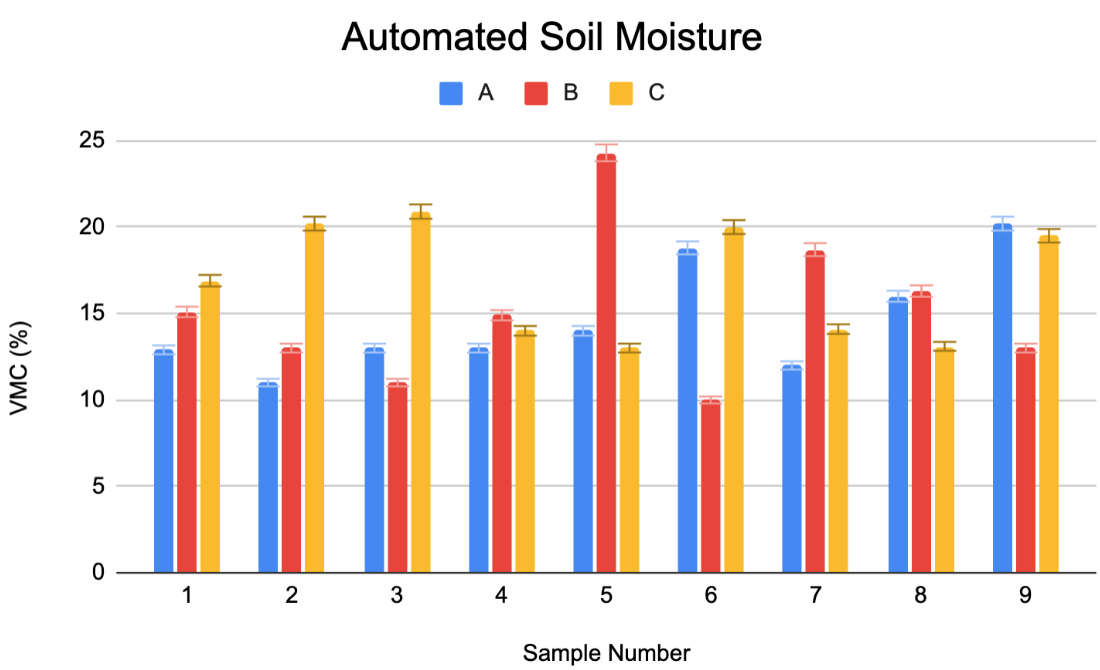

Figure 5.5: Automated Soil Volumetric Moisture Results

The automated test was performed a day after the manual test, and the sealed vessels notably developed condensation. Testing showed that this had changed the average VMC of each vessel but had not necessarily decreased the average. It is thought that the settling of moisture in each vessel, combined with repeated probing, had served to fluff and create more variation in the mixture. It was shown that soil probing was functional over the full XYZ range.

5.1.6 Soil Moisture Data Comparison

Separate observation of the manual and automatic soil data results can appear inconsistent due to the variable nature of the values. However, when averaging the data points from each test, the results are similar in appearance, with the manual average being 15.7 percent VMC and the manual average being 15.5 percent VMC, as previously stated. Figure 5.6 provides a visual comparison of the data.

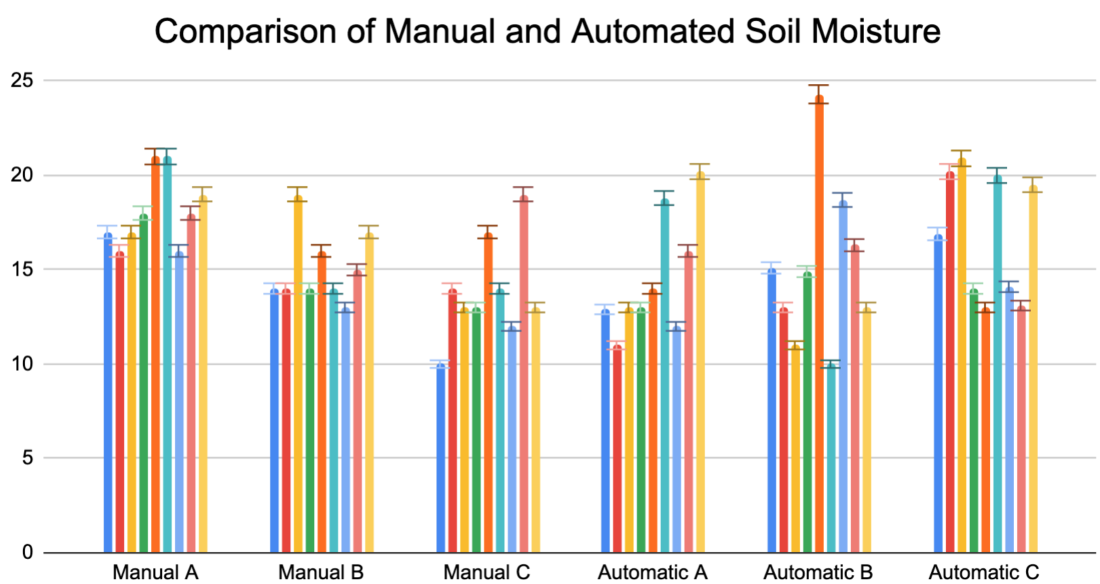

Figure 5.6: Comparison of Soil Moisture Data Gathered Manually and Automatically

A notable observation between the data is the variation within each vessel itself, which one may expect to remain the same for each vessel. The effects of the previously described inconsistencies within the soil mixture are responsible for this, as a failure of the system itself likely would not result in a near exact average for each of the two tests. It can also be noted that the current methods employed within the field use weighing to determine soil moisture [19], thereby negating any inconsistencies introduced in the collection procedure. In a practical application, the settled soil would not be subject to any disturbance therefore it is hypothesized that a single probe taken by the vehicle would sufficiently indicate the environment. To determine if the observed similarity was statistically correct, a paired sample t-test was performed similarly to that described in the fuel results section. The values from each vessel were averaged to yield a set of nine values for both the manual and automated methods. An alpha value of 0.5 was used along with a null hypothesized difference. The results of this test are shown in Table 5.2.

Table 5.2: Paired Two Sample Soil Moisture T-Test

	Manual Average	*Auto Average*
Mean	15.70333333	15.51555556
Variance	2.366275	1.424127778
Observations	9	9
Pearson Correlation	0.587563768	
Hypothesized Mean Difference	0	
df	8	
t Stat	0.440804991	
P(T<=t) two-tail	0.671023217	
t Critical two-tail	2.306004135	

This test resulted in a rejection of the null hypothesis based on the critical value being larger than the t-statistic, thereby showing sufficient evidence for statistical similarity between the manually and automatically acquired data.

5.1.7 Manual Weather Data

The objective of manual weather data collection was to ensure that the data taken via the weather station was representative of the actual weather conditions in the area and, in addition, to have a baseline for comparison with the automated collection process. As stated, data was collected on five different days at selected locations regardless of conditions. When selecting a location, the environment's characteristics were considered to ensure diversity was integrated into the readings. Location one was located in close proximity to a large area of foliage with tree coverage. The second location was semi-covered and closely adjacent to a building. The third location was in an open, uncovered area near flowing water. Location four was in an uncovered area directly between two buildings. Finally, the fifth location was in an open and uncovered area. A satellite image of the selected locations is shown in Figure 5.7. A summary of the specific location data is given in Table 5.3.

Table 5.3: Location Data Summary

Location	Characteristics	Coordinates
A	Adjacent foliage, shaded	35.306496,-80.731651
B	Adjacent building, semi-shaded	35.306473, -80.732323
C	Adjacent water, open	35.305033, -80.730851
D	Adjacent building, non-shaded	35.307323,-80.731445
E	semi-open, non-shaded	35.305927, -80.733192

Figure 5.7: Satellite View of the Weather Testing Area

The resulting data from the test was not unexpected. The data appeared to remain approximately the same between the device and that taken from the weather station, with a few notable exceptions. Wind speed from the station did not closely correlate with the weather service data. This is most likely due to the data being taken relatively close to the ground where wind speed is lower and more variable due to the environment. The wind result yielded at location three exemplifies this. At this point, due to the flowing water, a clear breeze was present on an otherwise nonwindy day, resulting in the reading from the station being higher. For temperature measurements, the maximum deviation in the data data remained was 3.3 degrees Fahrenheit. Likewise, for relative humidity, the maximum deviation was five percent. The data gathered from the manual test is shown in Table 5.4.

Table 5.4: Baseline Comparison of Tempest Weather Station (MT) to the National Weather Service (WS)

Day	Date, Time	Location	Wind Speed (mph)		Temperature (ºF)		RH (%)	
			MT	WS	MT	WS	MT	WS
1	8/28/2023 16:45:00	A	0	4	79.7	83	72	72
2	9/26/2023 19:23:00	B	5.7	9	71.8	72	69	74
3	9/28/2023 19:25:00	C	11	3	70.5	71	65	67
4	1/11/2024 20:05:00	D	0.3	1	47.7	45	63	64
5	1/13/2024 16:35:00	E	11	14	51.4	51	29	31

To determine the statistical similarity between the output values of the weather station and that of the weather service, paired two sample t-tests was performed comparing the wind speed, temperature, and relative humidity. A null hypothetical difference and alpha value of 0.5 were used. The results of the tests are shown in Table 5.5.

Table 5.5: Paired Two Sample Manual Weather T-Test

	Wind Speed (mph)		Temperature (°F)		RH (%)	
	MT	*WS*	*MT*	*WS*	*MT*	*WS*
Mean	5.6	6.2	64.22	64.4	59.6	61.6
Variance	29.445	27.7	193.447	250.8	304.8	308.3
Observations	5	5	5	5	5	5
Pearson Correlation	0.568994019		0.997958679		0.994307508	
Hypothesized Mean Difference	0		0		0	
df	4		4		4	
t Stat	-0.27025382		-0.187317162		-2.390457219	
P(T<=t) two-tail	0.80033579		0.860529716		0.075130455	
t Critical two-tail	2.776445105		2.776445105		2.776445105	

The test resulted in a rejection of the null hypothesis with a t-statistic far lower than that of the critical value. Therefore, the resulting data from the weather station when gathered manually is statistically similar to that of the National Weather Service in regard to each of the data types being measured.

5.1.8 Automated Weather Data

The objective of automatically taking weather data from the Tempest device via the LabVIEW program was to validate the code's functionality and ensure correct results. Data was collected at the same locations and times as the manual test. The results of this procedure remained essentially unchanged from the manual test. Some exceptions were present with regard to wind speed and temperature. These changes are due to the data being averaged within the code. With wind speed being highly variable, averaging the values raised or lowered the read speed, as shown with days two and five, respectively. Temperature changes appeared mostly unaffected except in cases where small changes occurred during the period in which readings were taken, such as on days two, three and five. The data gathered is presented in Table 5.6.

Table 5.6: Comparison of Automatically Gathered Tempest Data (AT) to the National Weather Service (WS)

Day	Date, Time	Location	Wind Speed (mph)		Temperature (ºF)		RH (%)	
			AT	WS	AT	WS	AT	WS
1	8/28/2023 16:45:00	A	0	4	79.7	83	72	72
2	9/26/2023 19:23:00	B	5.89	9	72.1	72	69	74
3	9/28/2023 19:25:00	C	11	3	70.88	71	65	67
4	1/11/2024 20:05:00	D	0.3	1	47.7	45	63	64
5	1/13/2024 16:35:00	E	6.9	14	50.72	51	29	31

5.2 Overall Integration

Overall system testing resulted in five successful cycles. While traveling to the station, the system was capable of finding the cone and stopping adjacent to it regardless of approach distance. Therefore, it was determined that the side-mounted camera was a sufficient means of in-motion vehicle positioning. In addition, the fuel probing functionality was able to correctly position over the sampling station and probe the fuel stick, using the alignment rings and guide code to create a solid connection. Further, the system was found to be functional with varied location and orientation.

Temperature and relative humidity data were also correctly gathered continuously, with identical readings for each cycle. The soil probing function operated properly; however, it was found that the flexible fiberglass construction of the commercial probe was not sufficiently rigid to penetrate the ground, due to hardened soil during winter climate conditions. Limited wind speed data was available from this test, not related to system function, but rather due to a hardware failure preventing the mast actuation. Table 5.7 shows the viable data collected from each cycle. It can be noted for fuel moisture that the spread of the collected data was within the advertised accuracy range of the meter.

Table 5.7: System Functionality Testing Data

Cycle	Temperature (ºF)	Relative Humidity (%)	Fuel Moisture (%)
1	40.8	29	10.2
2	40.8	29	12.08
3	40.8	29	10.1
4	40.8	29	8.54
5	40.8	29	9.2

CHAPTER 6: CONCLUSIONS

6.1 Summary

The research recorded in this document resulted in the creation of a working prototype for a wildfire risk assessment data collection system, capable of automatically gathering ten-hour time-lag fuel moisture, duff layer volumetric soil moisture, continuous temperature and humidity data and local wind speed. These newly developed innovations act as an excellent proof of concept for further improvement and research and have great potential to expand the crucially important field of wildfire research and management.

A color-based flag detection system was integrated with a Cartesian coordinate robot suitable for use with an autonomous all-terrain vehicle while maintaining the capability to precisely orient a multifaceted end effector. A small footprint flag station system was developed to hold a ten-hour fuel moisture specimen securely, expanding the usability and applications of said samples. A robust and compact automatically deployable wind mast was created, having a vast range of applications. A method of rendering acquired data was successfully implemented, able to store a large amount of data in a widely accessible manner. The final prototype was found to be capable of producing results similar to those currently provided by manual data retrieval techniques in a manner requiring far less human effort.

6.2 Findings and Limitations

The primary objective of this research was to develop and determine the feasibility of using an automated system to gather data, which would usually only be possible though labor-intensive manual collection. Additionally, it was desired to create a method of providing additional location-specific weather information to expand upon what is currently available through the use of remote automatic weather stations. The research ultimately accomplished these goals. Testing showed that the prototype system was a feasible solution to acquiring moisture data for fuel and soil in a manner similar to humans. Additionally, by gathering accurate information from the weather station during testing, it was possible to acquire a greater range of weather data through the mobile platform than can be collected with current stationary methods.

The system was, however, identified to be limited in some respects. It was observed that a color filtering flag detection method was vulnerable to lighting changes and often required calibration of the program to the current conditions. However, it was also found that more suitable alternative detection methods may be employed even when using the existing low-cost camera hardware. Shape matching and line detection are suggested methods for further research which may perform more efficiently in varying lighting conditions. Additionally, more advanced forms of supervised machine learning may significantly improve the system's ability to detect the flag and is also recommended for exploration. These methods may also have the benefit of preventing the need for physical probe guiding rings.

Another limitation of this research using a destructive pin-type moisture meter. It was determined that in a practical scenario, repeated probing of this variety may prematurely wear or reduce the accuracy of the fuel stick samples. Alternative pin-less methods are available that measure moisture non-destructively through an electromagnetic field and may be a more viable solution. Additionally, a continuation of this research may explore alternative dead fuel moisture samples that could aid probing accuracy, such as a flat sample rather than separated dowels. Further, functionality testing revealed that the chosen soil probe did not have the rigidity required to penetrate soil in cold weather conditions. It is recommended that a more capable metal soil probe be implemented.

6.3 Future Work

This research focused on prototype development using available budget and resources to create a functional system and, in addition to rectifying the limitations discussed in the previous section, could be refined in a variety of ways. The initial vehicle was chosen based on availability; however, all functionality developed could be readily implemented in a smaller form factor robot to aid usability, transportation, and storage. Further, many of the electronics used in this prototype, such as the onboard laptop, could be replaced with smaller, more suitable hardware capable of achieving greater reliability and maintainability, and allowing the development of an interface more friendly to end-users. The existing Cartesian robot could be replaced with a purpose-built mechanism to reduce overall dimensions and improve probe functionality, along with providing efficiency improvements to increase the speed of data collection, allowing a larger amount of data to be gathered in a single day. Further, a program could be developed to provide accurate wind direction data independent of the vehicle's orientation. Even while maintaining the current weather station, GPS location information from the predetermined path could be used to correct the output data from the device at any given point.

While this study mainly focused on gathering data to be used in the wildfire risk assessment research such as the NFDRS, more active methods of fire prevention could be implemented using the platform created in this project as a starting point. By outfitting the system with additional sensors such as a thermal camera and smoke detecting device, the vehicle could be used to autonomously patrol wooded areas such as parks, campgrounds, and hunting grounds during periods of high fire risk and alert officials such as park rangers to potential hazards such as unsanctioned campfires or smoldering cigarettes. The benefits of these additions are numerous, as a more significant area could be thoroughly inspected in less time than it would take an individual, and in addition would not need to be manually checked by a human, further saving time and resources.

The quiet nature of the small electric vehicle would have the additional benefit of preventing disturbance to the natural environment that would typically be caused by an automobile patrolling the area, maintaining repose for wildlife and campers.

Another inclusion which could benefit this platform is an aerial drone. When equipped with the required sensors, such a device would have the capacity to collect data from above the tree line, providing a comprehensive perspective of the area. A small drone could seamlessly integrate with the ATV; docking and charging on the ground robot, and automatically deploying at predetermined locations. This addition could, for example, gather wind-related information from higher altitudes, or conduct scans of the vicinity for potential fire threats. Upon completing its task, the drone could then be autonomously homed to the ATV for recharge and further deployment.

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APPENDIX A: Raw Data Tables

A.1 Fuel Moisture Tables

Table A.1: Tabulated Manual Fuel Moisture Test Data

Manual Fuel Moisture Test (% Moisture)				
Tick	Dowel 1	Dowel 2	Dowel 3	Manual Average
1	13.6	13.4	13.7	13.57
2	13.4	12.7	13.6	13.23
3	13.6	13.1	13.6	13.43
4	14.2	12.9	13.4	13.5
5	14.2	13.3	13.5	13.67
6	13.8	13.3	13.3	13.47
7	13.4	13	13.4	13.27
8	13.4	13.1	13.2	13.23
9	13.6	13	12.8	13.13
10	13.8	12.8	12.7	13.1
Average:	13.7	13.06	13.32	

Table A.2: Tabulated Automated Fuel Moisture Test Data

Automated Fuel Moisture Test (% Moisture)				
Tick	Location 1	Location 2	Location 3	Auto Average
1	13.07	12.1	9.12	11.43
2	12.51	10.58	8.84	10.64
3	12.48	9.32	8.6	10.13
4	11.59	9.1	8.1	9.6
5	11.65	10.35	8.2	10.07
6	11.5	9	8.4	9.63
7	11.73	9.3	8.3	9.78
8	13.5	8.74	8.1	10.11
9	11.95	9.2	8.6	9.92
10	12.87	9	8.8	10.22
Average:	12.285	9.669	8.506	

A.2 Soil Moisture Tables

Table A.3: Tabulated Manual Soil Moisture Test Data

Baseline Soil Moisture Meter Test		
Sample Number	Sample Vessel	Value (% VMC)
1	A	17
2	B	14
3	C	10
4	A	16
5	B	14
6	C	14
7	A	17
8	B	19
9	C	13
10	A	18
11	B	14
12	C	13
13	A	21
14	B	16
15	C	17
16	A	21
17	B	14
18	C	14
19	A	16
20	B	13
21	C	12
22	A	18
23	B	15
24	C	19
25	A	19
26	B	17
27	C	13

Table A.4: Tabulated Automated Soil Moisture Test Data

Sample Vessel A		
Sample Number	Location (X,Y)	Value (% VMC)
1	0,0	12.9
2	0,5750	11
3	0,11500	13
4	4400,11500	13
5	4400,5750	14
6	4400,0	18.8
7	8800,0	12
8	8800,5750	16
9	8800,11500	20.2
Sample Vessel B		
10	0,0	15.1
11	0,5750	13
12	0,11500	11
13	4400,11500	14.9
14	4400,5750	24.3
15	4400,0	10
16	8800,0	18.7
17	8800,5750	16.3
18	8800,11500	13
Sample Vessel C		
19	0,0	16.9
20	0,5750	20.2
21	0,11500	20.9
22	4400,11500	14
23	4400,5750	13
24	4400,0	20
25	8800,0	14.1
26	8800,5750	13.1
27	8800,11500	19.5

APPENDIX B: Additional Figures

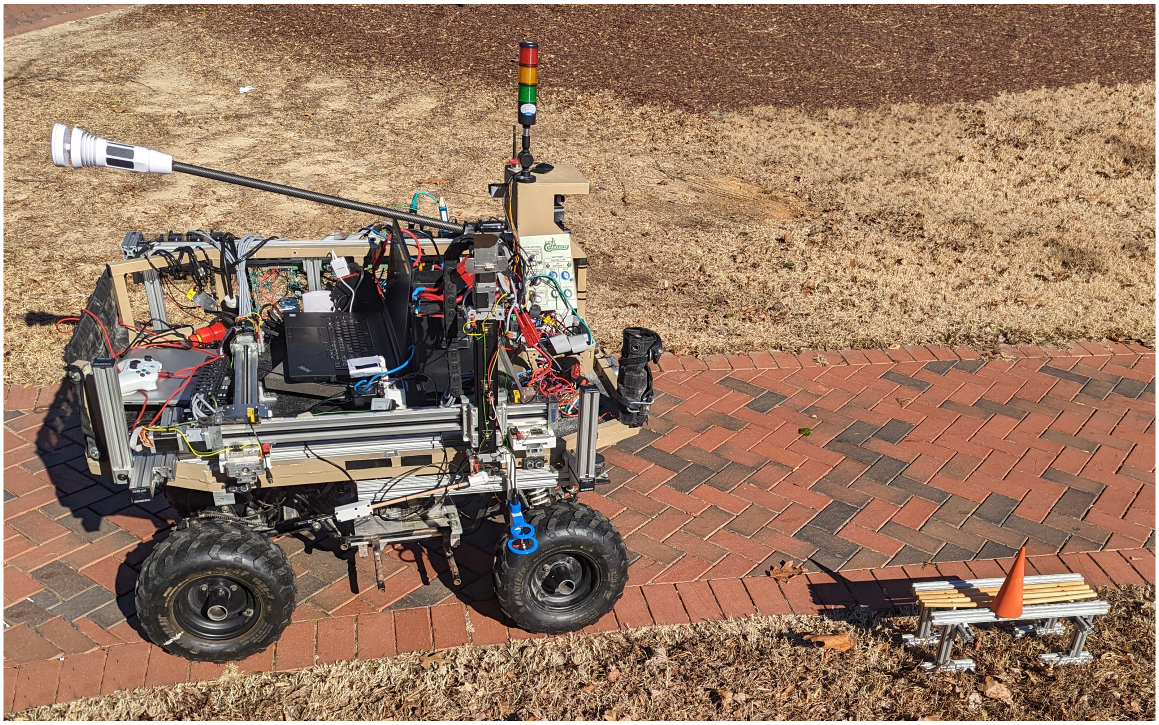

Figure B.1: MWRAD Functionality Testing

Figure B.2: Conventional Fuel Stick Testing

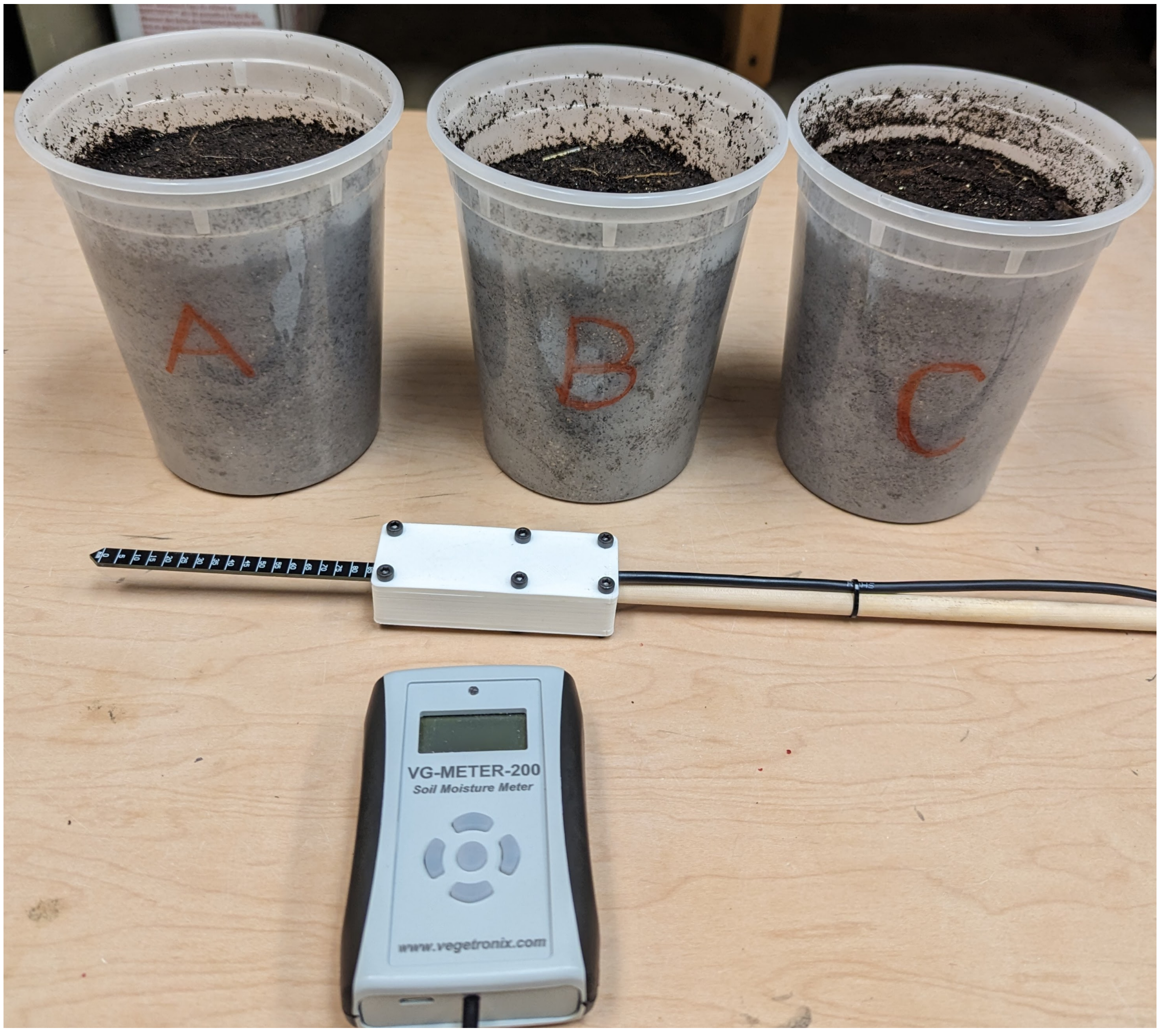

Figure B.3: Soil Samples

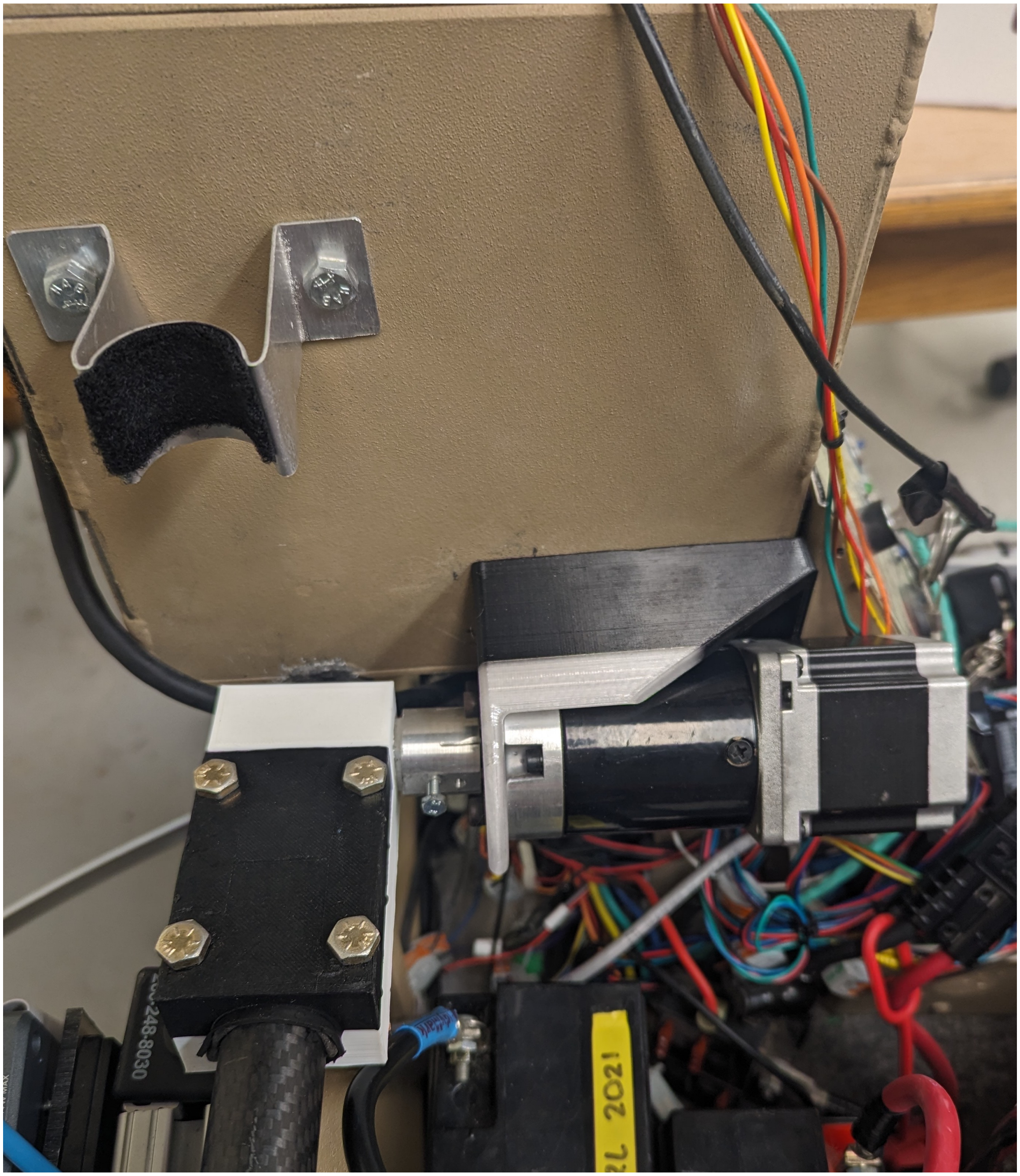

Figure B.4: Weather Mast Components

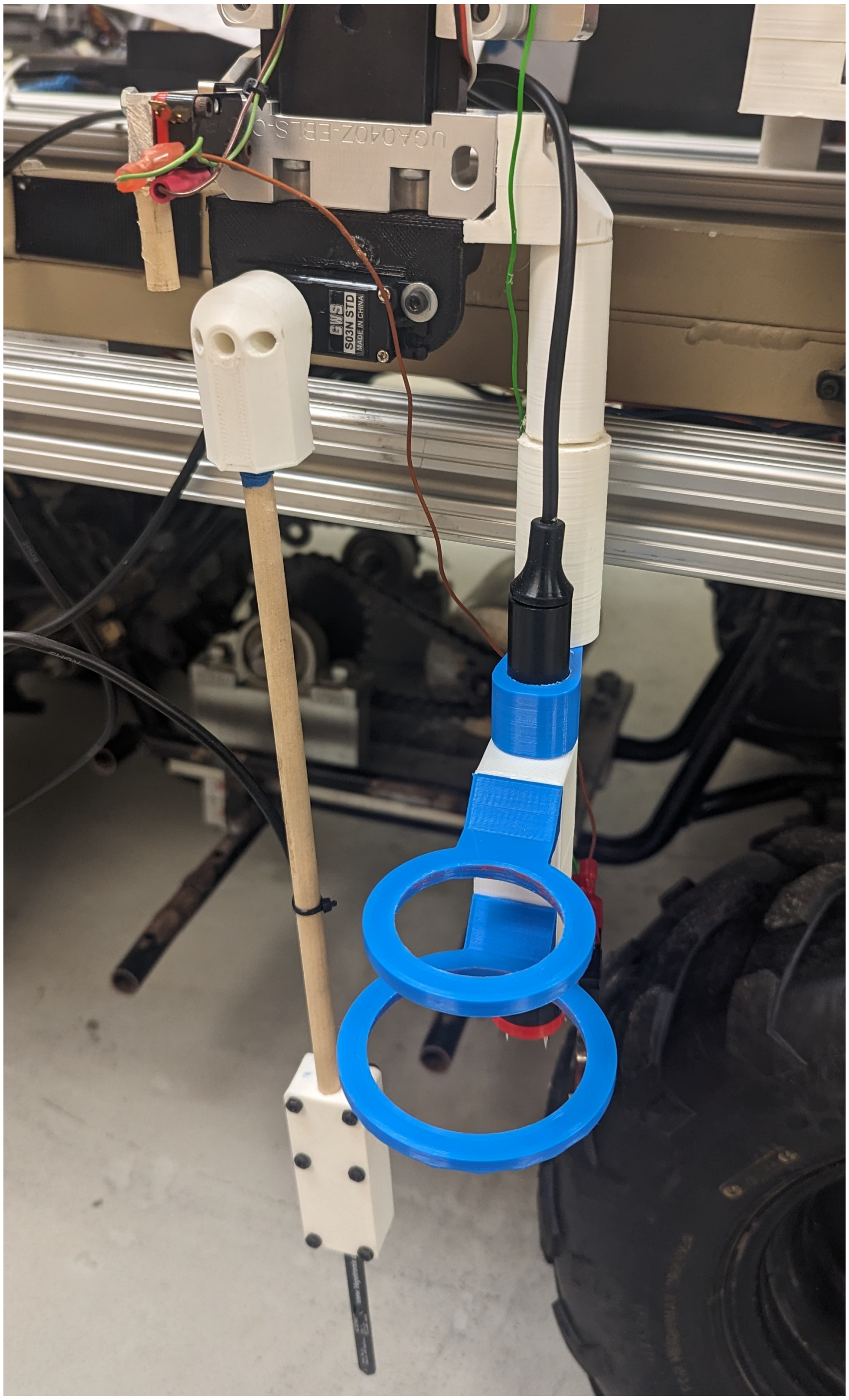

Figure B.5: Mounted End Effector Assembly

Figure B.6: Improved Brake Actuation