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Design, Development, and Testing of a Wi-Fi Enabled Minirhizotron for Ag Farms

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1. Introduction

Real-time monitoring of plant roots, mycorrhizal dynamics, and ecosystem processes can be achieved with minirhizotron modules, and they have become key tools for the non-destructive investigation of plant roots, specifically in major agricultural farmlands. These camera systems have the potential to detect and aid in the mitigation of cyst nematode infestations, and prevent the destruction of entire multi-million dollars crops. Real-time monitoring and recording of the images of living roots, mycorrhizal hyphae, soil fauna, and invasive beetles over the course of a day, a crop cycle, or even multiple seasons may reduce potential destruction of farmlands especially in the southern United States.

This paper describes a project conducted by Sam Houston State University undergraduate engineering technology and computer science students who were mentored by multi-disciplinary STEM faculty and staff. The project, funded through the United States Department of Agriculture (USDA), aimed to design, develop, and test a cost-effective smart minirhizotron module for agricultural use in the field. The minirhizotron captures photographs of nursery crop roots, and provides early detection technology of cyst nematode infestation.

Utilizing Wi-Fi capability, the camera captures pictures via a command from a computer connected wirelessly to the same network and then sends the images to the user for image processing utilizing a Raspberry Pi 4B and a Geekworm Raspberry Pi 4B full function motor HAT to receive and execute operation commands.

Depending on the types of environments it may be subjected to, an outer casing with small openings for ventilation and solar power capability was built into the minirhizotron's design. The resulting minirhizotron device is complete and fully operational, and we have successfully captured images of the root system of healthy plants and plants suffering from infestations. The overall minirhizotron system uses a solar powered camera capable of capturing quality root images and deliver these images to the cloud, which is a vast network of interconnected servers with remote access whose purpose is to store, manage data, and run applications in remote farmlands.

While small scale farms could use a minirhizotron (probe) in the field via file transfer to a Universal Serial Bus (USB), this may be impermissible solution in the long term and for many larger farms. This project will be Wi-Fi enabled to eliminate this waste of resources and time, streamlining what would be an arduous process. Labor cost is expected to be reduced significantly as crop disease status can be observed with a single command.

2. Problem Definition and Climate Challenges in the Southern United States

Cyst Nematodes are a major parasitic pest present on a variety of different crops throughout the world [1]. These pests feed on plant roots, weakening the host plant. As the female nematodes mature, their bodies swell to become round or lemon-shaped with the rear protruding outside the root. After the female nematodes die, their bodies harden forming a cyst, change color, and become visible on a macroscopic level [2]. The current methods of surveying fields for cyst nematode infestation require uprooting agricultural crops to examine the root system and/or signs of crop contagion which can result in the termination of uninfected plants [3].

The objective of this multidisciplinary senior design project is to assist in rapidly identifying the aforementioned parasite on diseased plants without compromising the health of neighboring uninfected plants. Should infection be discovered after human or machine analysis of the returned data from the minirhizotron, all contaminated vegetation and soil will be removed more accurately, improving both crop retention and yield in all farms plagued by cyst nematodes. One of the biggest requirements for the design portion of this project is weather resilience. As an electronic outdoor application, water and wind are a significant factors. Using the proper materials is essential to the success and longevity of the device. Inferior materials could result in a faulty design. Therefore, the limitation of parts equipment to design this probe has led the utilization of best materials based on given the current resource constraints.

There are three main materials applicable to the probe. Due to unique part specifications, the majority of the probe must be 3D-printed at the Engineering Technology's 3D printers. This limits suitable materials to Grey Pro resin, polylactic acid (PLA), and acrylonitrile styrene acrylate (ASA). The only exception is the minirhizotron tube itself. This material must be clear with very low warpage to ensure quality photographs. All other available materials are sensitive to UV light, rain, heat, and time. The suitability of each of these materials is entirely dependent on the size and complexity of the part required.

3. Literature Review

This project is a conglomerate of several existing technologies. The first product is *SoilCam*, a main inspiration for the physical design of this minirhizotron. It is a "low-cost and fully automated minirhizotron system for use in a real-time root monitoring application" [4]. The primary advantage of *SoilCam* is the low cost. The entire project reportedly costs about $1000. However, it does not include a photovoltaic (PV) panel, so the batteries must be recharged more often with potential challenges in remote farmlands. Svane et al., worked on a multispectral minirhizotron imaging system where the base for the camera and image analysis modules included an in-depth focus on multispectral imaging [5]. This proposed project employs a compatible camera to allow for further collaboration by future team members even after the current team's graduation. Therefore, a megapixel camera and LEDs with the single board controller (SBC) was used. These products and other technologies focus on either specific nematodes or they are simply for root maintenance. An example of the former is a patent by Hugh Lu et al. [6], who investigated soybean cyst nematodes (SCN) and their identification. This project concerns any cyst nematode ensuring widespread business application.

4. Engineering Design Approach

The functional block diagram of the proposed probe is depicted in Figure 1. It is essentially a solar powered camera capable of capturing high quality images of a plant root system to which it is assigned and delivers the image to the cloud. The requirements for the electronics are as follows: the device must be capable of receiving commands via Wi-Fi, interpret and execute commands while sending requested pictures to the cloud. This requires a Raspberry Pi microprocessor (for Wi-Fi capability), an IP address for receiving commands, data storage for images, and be coded to control a stepper motor in order to lower and raise the camera. Also, a Wi-Fi router and online interface is required to transmit and receive data to and from the Raspberry Pi module. The sectioned 3D model of this final design is shown in Figure 2 to provide a visual aid for the assembly of the project. All electrical wires and the transparent tube have been eliminated for ease of explanation.

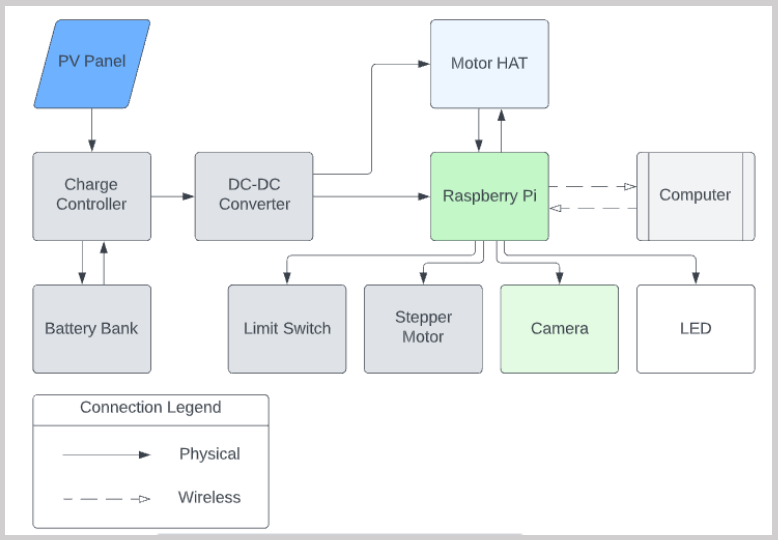

Figure 1. Functional block diagram of the proposed project.

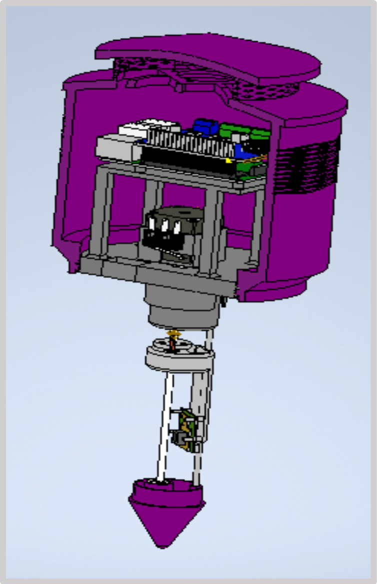

Figure 2. Simplified sectional view of the proposed probe.

A Raspberry Pi 4B single board computer (SBC) is responsible for driving the majority of the tasks necessary and is thus the primary component and microprocessor of the device. Connected to the SBC is a NEMA 11 stepper motor, a limit switch, and a Geekworm Raspberry Pi 4B Full Function Motor HAT. The motor HAT allows the Raspberry Pi to have full control of the stepper motor, providing thermal shutdown protection and internal kickback prevention diodes to inhibit reverse current from leaking back to the SBC. Initially, an optocoupler was used to prevent the motor from turning too far when sending the camera back to the home position after deployment. This would also ensure that the camera mount would not collide with the probe base and destroy the equipment. However, due to the size of the motor and location restrictions, the optocoupler proved too inconsistent upon physical testing. The code was adjusted for use with a limit switch instead, which provided more dependable results.

A wiring diagram detailing the current electrical setup is detailed in Figure 3. Note that although this diagram only depicts the internal wiring, all external metal enclosures including the PV panel are grounded to the earth for safety purposes. Additionally, the wires on the 5 V side of the DC-DC Converter are not shorted together, although they may appear so at first glance. In reality, the DC-DC Converter provides 5 V to the Raspberry Pi and 5 V to the HAT via two USB cables. This has been simulated in the wiring diagram via two 5 V ports connected to “PWR”, which represents both the power to the SBC and the power to the HAT as shown in Figure 3.

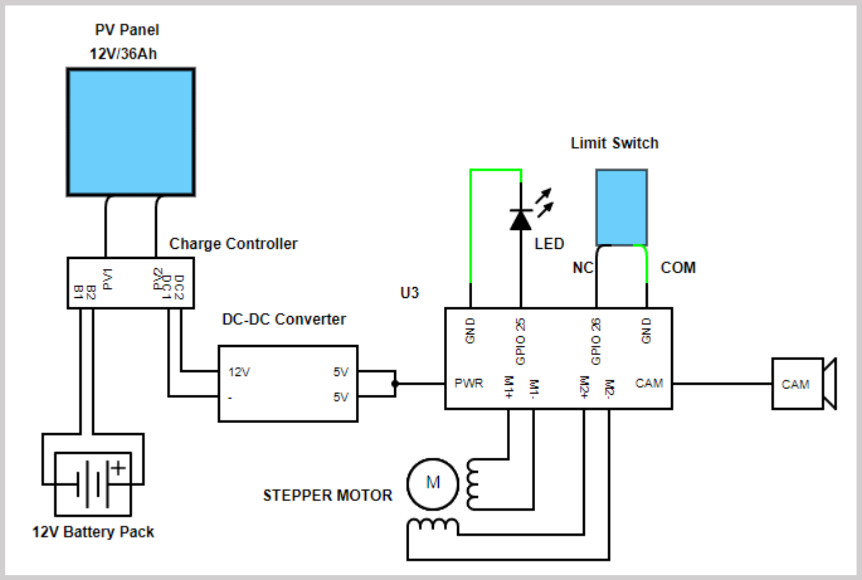

Figure 3. Wiring diagram of the proposed probe.

The Raspberry Pi and the stepper motor is an Arducam megapixel camera, which captures images at the direction of the Raspberry Pi. The internal code for the Raspberry Pi allows for images to be captured at several different heights with the motor moving the physical camera position. Additionally, the code allows for secure access to the Raspberry Pi through a Wi-Fi connection. This wireless connection uses a router with a static IP address to ensure stable access to the internet, to which an online user interface and data cloud are connected on the consumer side. The online interface allows the user to view pictures in the data cloud and request pictures to be taken directly from the device itself. A plan to possibly be implemented by future researchers is for the device to capture images and send them to the cloud at regular intervals, but the current focus of the team is to have the device send pictures per request of the user.

The device itself is enclosed in a mixture of Grey Pro resin and PLA. It is powered by a 12 V solar PV panel installed beside the probe itself as shown in Figure 4. This PV module includes several valve-regulated sealed lead acid/absorbent glass mat (AGM) batteries, a charge controller, and a weather resistant junction box. A DC-DC converter is attached via screw terminals to the load side of the charge controller and connected to the Raspberry Pi and Motor HAT, converting the 12 V output to two separate 5 V output USB 2.0 terminals. The Motor HAT accepts a range of 5 to 12 V, but the maximum allowed voltage suppliable to the SBC is 5 V, so both outputs have been chosen specifically due to necessity and market availability.

Figure 4. Setup of the minirhizotron in the field.

The final version of the probe was designed to eliminate two concerns. The first concern was initially a dimensional error regarding the location of the optocoupler in relation to the motor itself, and ultimately became an issue of the optocoupler. Two rods are attached to the fitting for the camera and, as the motor rotates to return the camera to the top of the probe, these rods slide into a space beside the motor and are meant to trigger the optocoupler sensor, which would then send a signal the motor to stop running. The optocoupler was too far away from the rods to sense them, so this dimension was decreased, and the part was reprinted, processed, and all electronics from the older design were transferred and reconnected. Unfortunately, the optocoupler still would not sense the rods after this effort and a test of a different optocoupler proved that the electrical part itself was not reliable enough for the application. Therefore, a limit switch was used to replace the optocoupler, and provided the stability necessary for consistent performance. The second concern was related to the ventilation capability of the initial housing design, shown previously in Figure 2. Although both the Raspberry Pi and the Motor HAT have heat sinks and the motor no longer overheats as in the beginning of the project, it is common knowledge that heat rises. The initial probe has no outlets for air near the top of the housing in order to provide weather protection. The only entry point, once assembled, is a small hole on the underside for the power cables to the Raspberry Pi and Motor HAT. While the air entering and exiting through this area could possibly be enough to provide sufficient ventilation, it is better to err on the side of caution and ensure that hot air cannot escape. Thus, the final version of the housing was completed to mitigate this issue as shown in Figure 5 (left). An optional area for a fan was created in case additional airflow was required as seen in Figure 5 (right), but it had to be cut out of the PLA housing during post processing as the support material had fused to the underside and could not be removed without removing the entire internal structure. This is not likely to cause issues in performance as each hole in the top was drilled through to ensure that air is allowed to flow in and out of the housing in every direction.

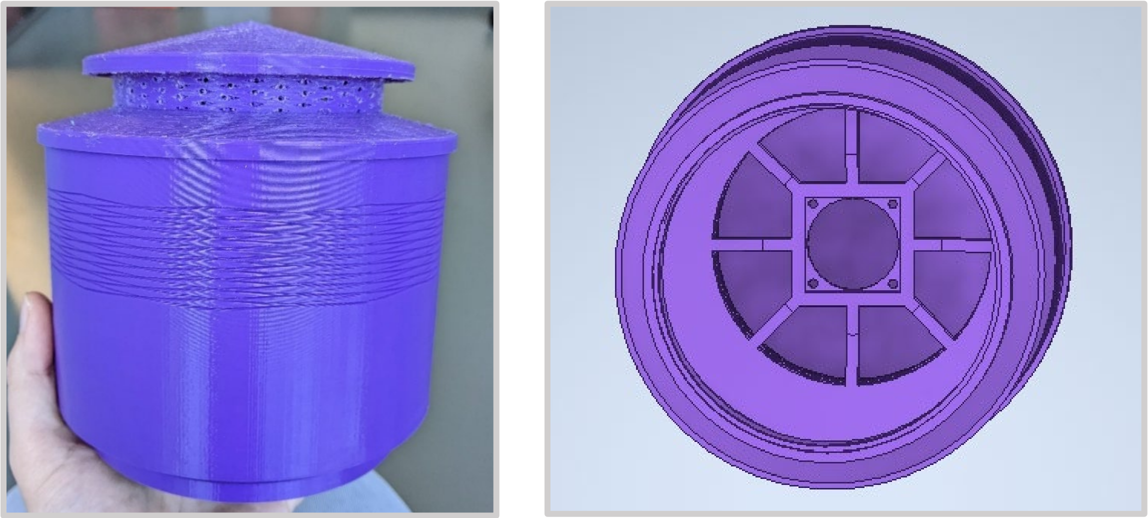

Figure 5. Final Ventilated Probe Housing Exterior (left) and Optional Fan Location Inside the Probe Housing (right)

A Finite Element Analysis (FEA) using AutoDesk Inventor has been employed to identify the greatest points of weakness in the design (Figure 6). The project team members analyzed specific locations and parts identified as most inclined towards physical failure. In particular, thin, and high stress areas were evaluated for displacement. Twenty-twenty-five lbf has been applied in each location that an arrow is present as an estimation of possible human force employed during installation as seen in Figure 6. This displacement is objectively minor, with a maximum of 0.03 mm in the polycarbonate tube, so material failure will be unlikely.

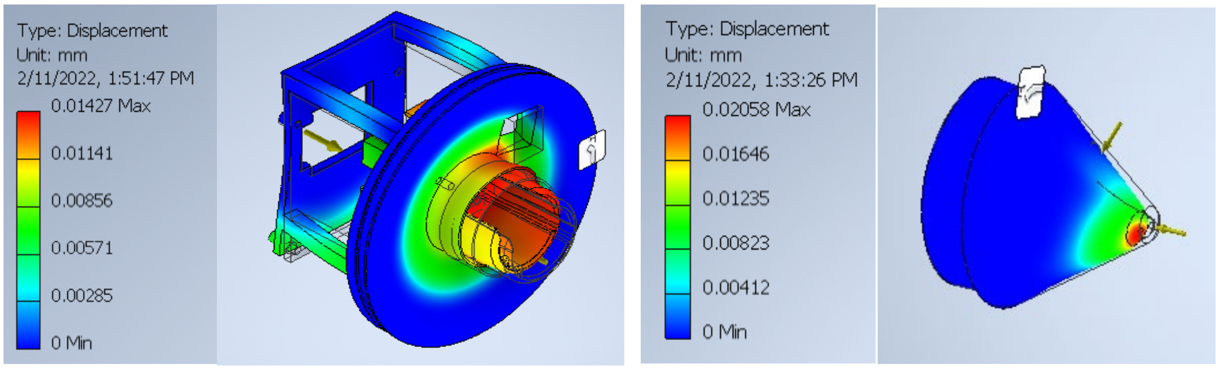

Figure 6. Probe top displacement analysis (left) and probe cap (right).

The multidisciplinary technical background knowledge being brought in for this project are as follows: Programming Fundamentals, Microcontroller Applications, Advanced CAD and Modeling, 3D Parametric Design, Materials Engineering, Introduction to Circuits, Circuits and Systems, Solar and Wind Energy Systems, Analog Electronics, and Materials Science and Engineering, all offered in the bachelor's degree programs in the Department of Engineering

Technology. Each of these provides the fundamental background necessary for the design and implementation of this project. All knowledge gained throughout the semester duration include, but are not limited to, information regarding interacting with the Python programming language and Raspberry Pi interface, as well as methods of stress analysis and tolerancing with AutoDesk Inventor.

5. Tasks and Deliverables

This project is focused on two main objectives: debugging the code in order for the stepper motor and camera to operate properly, and on finishing the enclosure of the device. The online interface had few issues before completion. The router, which the device is wirelessly connected to, required a static IP address. Considering the ease of acquiring a static IP address for the router, it was placed as a low priority and was completed after the device code itself was done. The stepper motor, on the other hand, proved to be much more difficult than previously anticipated. The motor was partially functioning, but not as intended. Initially, it would only rotate in one direction, moving down but not up. There was also a heating issue that has been resolved later and the electrical motor functioned in both directions as intended.

After the test for the Wi-Fi connection was completed, work began on programming the Raspberry Pi to capture images and save them to a micro-USB and the cloud. After a short testing phase, the entire device was placed inside the newly designed enclosure and re-tested. Outdoor testing of the electronics and design began during the first week of April (Spring semester). A pole mount for the solar panel was obtained at no additional cost from a faculty member and assembled to the panel as shown in Figure 7. The angle of the panel relative to the pole was calculated following an equation given in the setup manual using the approximate latitude of the building at 30.71˚. 30.71(.9) + 30 = 57.6 ˚. After connecting the batteries and charge controller, the panel was set outside to verify working conditions and began charging the batteries when under sunlight. Due to the weight of the panel and junction box with all electronic components inside, the box was placed beneath the pole during deployment (Figure 7).

Performance tests have been conducted throughout the spring semester in an outdoor environment to guarantee smooth execution of the program and electronics controls. The test revealed certain engineering challenges related the design of the device. Specifically, the camera apparatus was slowly sliding off of the camera base during operation due to motor vibrations, and the polycarbonate tube surrounding the camera base was discovered to easily slide in and out of the enclosure after a few tests. This was deemed unacceptable for the project and the design team modified the necessary parts, reprinted them using the *Makerbot Replicator* + and *the Formlabs Form 2* printers, completed post-processing, and installed them into the device prior to any subsequent field tests. The mofifictaions and team work resulted in a turning point for the project, proving it to be complete. The probe ran as intended multiple times, and no new issues with either the device or the code were observed. Testing has continued following this deployment, including visitation to a greenhouse, which has widely been considered by the team as an ideal location for the probe to monitor nursery crops. It is through the tests and deployments mentioned previously that the shortcomings of the device were discovered, which can be navigated and possibly eliminated by future parties privy to the project. Firstly, the probe must always have a stable Wi-Fi connection. Several tests failed due to the deployment location being slightly outside of stable range. The initial location for the official deployment proved just slightly too far from the router, and as such, the website could not connect to the Raspberry Pi to send the instructions to run. A new location in an overgrown flowerbed much closer to the router was considered and this area, seen in Figure 7 (right) is the final deployment implemented.

Figure 7. Outdoor Device Testing & Troubleshooting (left) and Field Deployment Location (right).

This completed product is a far cheaper alternative than any currently available commercial minirhizotrons. Specifically, this product has a high specialization in identifying cyst nematodes on a large scale with its Wi-Fi capability. The software configuration allows several probes to be deployed in different locations without overcomplicating the user interface. Wi-Fi capability allows anyone with proper clearance to check the status of their crops from anywhere on the planet, allowing quick identification of any potential problems and ensuring a swift reaction should infection be discovered. The online connection itself also supports a secure connection to the device to ensure security for clients. The specific software intended for this task is OpenSSL, which is a general-purpose program for secure communication [7].

6. Challenges

The first roadblock was troubleshooting the stepper motor. A team of three researchers solved the movement issue through alterations of the code written for it and altering the type of microcontroller directing it. This problem was a major concern for the project and took several weeks to resolve. Next was the online code testing. There were some issues with the camera not sending pictures to the cloud as intended and there were a few design problems that revealed themselves during the first field test. This meant the design team needed some time to rectify the concerns and reprint the necessary parts. Following the implementation of the required corrections, the second field deployment was conducted and was largely successful. After resolving certain instability issues regarding the Raspberry Pi connecting to Wi-Fi, the device ran successfully. Further field deployments are expected to take place up until the final presentation to ensure consistent operation. Once the motor issue was resolved, work on the remaining electronics portion of the project increased greatly. The next issue was with the optocoupler used in the initial design. The optocoupler was inconsistent in stopping the motor once it had reached the upper most point where the camera apparatus was meant to go. After some deliberation, it was decided that the optocoupler would be replaced by a limit switch. Once replaced, the motor was finally functioning properly by stopping in the correct position. Tests of the final device have been conducted to ensure that the probe functions reliably and consistently.

There are a few safety concerns regarding the components and location of the device. As with any electronic apparatus, overheating and degradation due to humidity are distinct possibilities. The current stepper motor originally elevated to an unsafe temperature after a short amount of time and use, which could have led to the plastic enclosure melting or even fusing together. After weeks of troubleshooting, we found that insufficient current was being supplied to the motor because the motor was attempting to pull more current than the Motor HAT would allow in an attempt to successfully begin turning. However, the demand continually activated the Motor HAT's internal circuit breakers, preventing the motor from ever reaching the starting current required to run properly. This resulted in the motor being kept in a state of constant high power.

The melting point of the weakest material to be used, PLA, is between 170 and 180 ˚C, so great care must be taken to ensure that the heat produced by all the electronic components stays within a range well below these temperatures. The ASA plastic originally considered in the pre-proposal has a higher melting point of up to 280 ˚C but it is not environmentally friendly like PLA and releases a toxic gas when burning. Grey Pro resin releases irritating vapors when burning, so it is only being used for one threaded part that requires such high accuracy as can only be obtained by the Formlabs printer. Upon further research and consideration since the pre-proposal, it has been determined that ASA will not be utilized in the Senior Design project for numerous reasons. The only part that could benefit from UV resistance was originally too large to print in the Method-X and would not fit in the post-processing chamber necessary for ASA prints. After the final ventilated redesign, it was decreased enough in size to allow printing in ASA.

7. The Cost Analysis and Bill of Materials (BOM)

The various software tools used include AutoDesk Inventor, Makerbot Print 3D interface software, Digikey's Scheme-It, Lucidchart, and the Microsoft Office Suite. As these are free of charge for current students at Sam Houston State University, they have not been included in the bill of materials. Physical resources required to produce unique probe parts consist of mostly the Makerbot Method-X and the Formlabs Form 2 printers, which are also available on campus. A student in this project (who is currently working as a manufacturing engineer in a major engineering company) used both Makerbot Method-X with PLA filament and FormLabs Form 2 printer for flexibility on different materials such as grey pro for more effective and better results. Appropriate PLA filament, resin, and various pre- and post-processing tools are also required. The final bill of materials (BOM) with the specific physical supply requirements are detailed in Table 1. All items listed are either present in the final project or, in the case of support material, necessary for production of the final product. Costs are estimated along the right side of this BOM, and shipping is not included in this estimate. All tools and machines used are property of the Engineering Technology Department and are thus not counted in cost estimation.

8. Student Assessment

The senior design project presented in this paper is one of the 12 capstone projects completed in the 2022-2023 academic year. The project included multidisciplinary students from Electronics and Computer Engineering Technology and Mechanical Engineering Technology in the Department of Engineering Technology, and Software Engineering students from the Computer Science Department. Engineering Technology programs contain five Student Learning Outcomes

(SLOs) and their corresponding fourteen Key Performance Indicators (KPIs) that are all measured for completed capstone projects. Out of five SLOs, assessment results for SLO2 entitled as “design systems, components, or processes meeting specified needs for broadly defined engineering problems appropriate to the ECET discipline” is shown on Table 2.

Table 1. Final Bill of Materials

Bill of Materials				
Hardware	**Qty.**	**Vendor**	**Item #**	**Price**
Geekworm Raspberry Pi Motor Hat	1	Amazon	B0721MTJ3P	$ 29.99
Arducam Megapixel Camera	1	Amazon	B083HF2S8C	$ 61.99
Optocoupler **	1	Amazon	B081W4KMHC	$ 6.79
Raspberry Pi 4B kit	1	Canakit	PI4-8GB-STR32F-C4-BLK	$ 139.95
128 GB SD Card	1	Amazon	B07FCMKK5X	$ 21.69
DC-DC Converter	1	Amazon	B09B2Y71F7	$ 13.99
Rankie USB 3.0 Cable, 6ft	1	Amazon	B01KRO8D20	$ 8.99
USB to USB-C cord, 6 in	1	B&H	PEUSB33CA06	$ 8.99
NEMA 11AW Stepper Motor	1	Anaheim Automation	11AW1021X12-LW4-EL	$ 141.00
12 V/36 Ah PV Panel *	1	Digikey	2414-RPPL12-36-35-PUMP-ND	$ 499.95
M2 Screws	1	Amazon	B09D8ZZ9YM	$ 10.99
Guide Rod	1	Amazon	B07B6MFB3N	$ 9.99
Formlabs Grey Pro Resin	1	Formlabs	RS-F2-PRGR-01	$ 175.00
Makerbot Replicator + PLA Filament	1	Makerbot	N/A	$ 50.00
Polycarbonate Tubing	1	Amazon	B000OMHJHQ	$ 23.99
Makerbot Method PLA Filament	1	Makerbot	N/A	$ 65.00
Makerbot Method PVA Filament	1	Makerbot	N/A	$ 84.00
LED's	1	Amazon	B07T5K4M8B	$ 5.85
Donepart Bearing	1	Amazon	B07X6DK946	$ 11.89
Limit Switch	1	Digikey	SS-3GL13PT	$ 1.49
O-Ring Pack	1	Grainger	711Y96	$ 8.62
Total Cost				$ 1,380.15
* Batteries and Charge controller included. ** Removed from project due to inconsistent behavior.				

Table 2. Sample assessment selected for SLO2.

SLO 2. Design systems, components, or processes meeting specified needs for broadly defined engineering problems appropriate to the ECET discipline.

Key Performance Indicators	**Unsatisfactory < 60%**	**Developing 60-69%**	**Satisfactory 70-79%**	**Exemplary >80%**
a) Identify problem, criteria, constraints	0	16.67%	50%	33.33%
b) Define the problem, review possible solutions, select design	0	25%	33.33%	41.47%
c) Design, assess, refine and conclude the model or prototype	0	16.67	41.67%	41.67%

Ave of all KPIs for SLO2	0	19.45%	41.67%	38.82%
STDEV,S	0	9.504229	0.08335	0.047584
Indicate possible data collection items (i.e. lectures, assignments, quizzes, lab reports, projects, test questions) that may be used by the department in the annual assessment: *Senior Design Projects; average of one initial report, one midterm report, and one final technical report.*				

Students previously worked on this project also stated their satisfaction on preparing themselves on real-life engineering challenges while working on a federal government-sponsored project. They also mentioned that describing their senior design project work and their project success stories were their most comfortable and convenient part of their interview with many companies.

9. Conclusion

This senior design project is a low-cost Wi-Fi enabled minirhizotron for rapid detection of cyst nematode infection in greenhouses and farms completed by multidisciplinary engineering technology and computer science faculty and students. While minirhizotrons for the purpose of root system monitoring exist, they are still either in the research phase or too expensive to be a viable option. This project is a lower cost and a more expensive version is capable of specialization depending upon need. Overall cost is below $1,500 and will become more affordable for each probe when buying in bulk. This completed project has the potential to lay the foundation for an industrial-scale, network connected, rapid monitoring system for farms and greenhouses with remote access. Live monitoring of crop infection could help reduce the spread of cyst nematodes, decrease losses, and increase yield around the world, possibly resulting in an incremental economic boost given the widespread effects that cyst nematodes have on the market. The online interface can be coded to include multiple devices and has an encrypted online connection to ensure security.

10. Acknowledgements

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