Dendrometer

Final Report

Team 104
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DISCLAIMER

ABSTRACT

A dendrometer is an agricultural sensor that measures minute fluctuations in plant stem diameter. While these tools have been around for decades, a new era of electronic sensors with Internet of Things (IoT) capabilities is on the horizon. Research into how dendrometers can be used to optimize water usage has spurred a race to develop a sensor that will meet this upcoming demand. Current mechanical dendrometers have design flaws that prevent the tools from being useful for anything but research. A project has been led by the OPEnS Lab since 2020 to develop a sensor that uses magnetic encoders to improve the resolution of readings and reduce error in data caused by friction.

This current V1 design has addressed these previously mentioned design flaws, but does not succeed outside of sterile greenhouse environments. A successful dendrometer for the commercial environment will need to be more robust to survive in the market.

Based on stakeholder input and prototyping, a V2.4 design was developed to meet the requirements set by the partnered researchers. A three-spring system was developed to reduce unrestricted degrees of freedom, which was the main philosophy for improving the reliability. A weather protection system was developed by this team to protect the sensor from physical disturbances and corrosion.

A testing rig was built for the specific purpose of verifying the determined engineering specifications. Field testing was conducted as well to verify the system's resistance to weather. This testing produced promising results that showed the design works as intended and can survive the rigors of commercial agriculture.

ACKNOWLEDGEMENTS

The project team would like to acknowledge several people that were involved with this project and helped guide it to a successful completion. The first being Dr. Chet Udell, the client for this project. Dr. Udell was heavily involved in the first several months and assisted in the identification of customer requirements and engineering specifications that were most critical. He also set up important meetings with other stakeholders which was critical for success. Next, Connor Moyce was an immeasurable help. He led the weekly check-in meetings, provided assistance with the electronic side of the dendrometer, and provided the majority of the initial knowledge in learning about the OPEnS Lab and their dendrometer project. The partnered researchers, Maria Zamora Re and Alec Levin, provided essential feedback from V1 dendrometers that enabled this team to design V2.4. These researchers work with Lewis Brown Research Farms and Southern Oregon Research and Extension Center Farms (SOREC) respectively.

The project team would also like to acknowledge the Industrial Engineering capstone team who will be taking ownership of this project and making further contributions. These students are Sydney Brown, Alexis Dinges, Samantha Hsu, and Griffin Scott.

TABLE OF CONTENTS

1 BACKGROUND

1.1 Introduction

Water is an essential element to life and influences almost everything humans do. Unfortunately, this is not an unlimited resource, and it must be managed efficiently to support a growing population surrounded by climate change. Crop health is vastly impacted by the amount and quality of water the soil receives, making it an important area for farmers and consumers to be involved in. Crops can die if there is too little or too much water and when looking at grapevines, which this project is primarily centered around, poor water conditions can affect the taste of the fruit produced. A dendrometer is a plant-based instrument that measures miniscule fluctuations of a plant stem diameter over a period of time. Changes in stem diameter correlate to the amount of stress a plant is under and how hard it is working to draw in water and perform other tasks [1]. The diameter will increase the more stress it is under as the plant is working harder to draw in moisture. This can be easily measured and analyzed with the use of a dendrometer.

Openly Published Environmental Sensing Lab at Oregon State University (OPEnS Lab) is currently working on creating an improved application of a stem dendrometer, using a linear magnetic sensor design. It has been tested on grapevines and blueberry bushes but it could be used for other woody perennials. By knowing when certain grapevines are experiencing stress, vineyards can better plan their irrigation systems and better manage their water. Stress early on in a plant's life is also believed to make it more resilient to future shocks, which is something researchers can test now with a dendrometer. As mentioned above, the plant is under stress when it does not have enough water. But when this occurs early on in a life cycle, the plant may send down deeper roots that allows it to be better at finding water, hence reducing future stress the plant will experience. This project will be focused on improving the mechanical components and design of the OPEnS Lab's dendrometer to create a product that will allow farmers to maximize their irrigation efforts. The primary goals are to increase the robustness and reliability of the dendrometer device to ensure accurate data collection. Currently the OPEnS Lab's dendrometers are just used in research applications but the end goal is having them purchased and used in commercial settings.

1.2 Project Scope

The goal of the OPEnS Lab is to address areas where other dendrometers on the market fail. *Figure 1* shows the lab's previous V1 dendrometer design. While the current working model is effective, there are several issue areas that the project team will be addressing over the next two terms. This includes developing a protective cover design to protect the components from rain, pickers, and other forces that might act on the instrumentation. The OPEnS Lab's dendrometer can currently measure up to half a micrometer in changes but significant noise can be introduced from the environment.

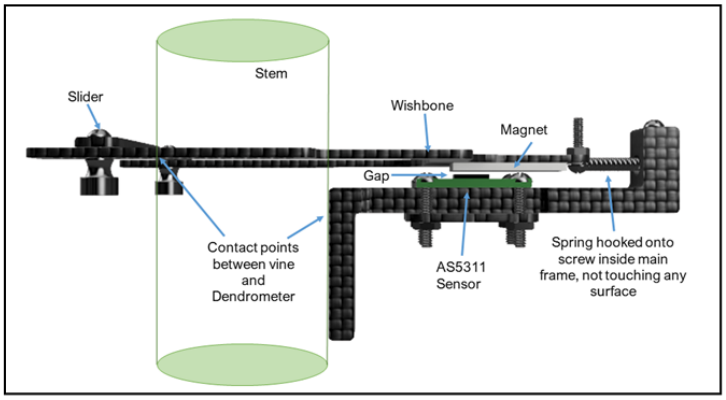


Figure 1. OPEnS Lab V1 dendrometer design. Adapted from: [2]

Future application of these dendrometers will likely see farmers using two to three per acre. There are additional issues with the dendrometer mounting apparatus staying level and being jarred out of position. The project team will focus on improving the sliding mechanism to create more reliable function and positioning to address this issue. Researchers and end users also want multiple methods for attaching the dendrometers to the plant stems as spacing and device weight can impact applicability. Lastly, improving manufacturing, assembly, and installation speeds are crucial for making this product marketable and accessible. The dendrometer project aims to improve dendrometer housing, sliding mechanism, attachment strategy, and manufacturing time. While these are all important issues, the project team concluded after having conversations with the stakeholders that the main goals of their project will be to reduce axial rotation, provide a water shield, and increase manufacturing simplicity.

2 DESIGN PROCESS

The design process started with meeting the stakeholders and researching current dendrometer designs. The research was important for familiarizing the team with what dendrometer models have already been produced and how the OPEnS Lab's dendrometer compares. From here the project team started formulating customer requirements and decided which design components they wanted this project to primarily focus on improving. After coming to a consensus on the main priorities of this project, reducing axial rotation, increasing ease of manufacturing, and improving overall robustness and data collection reliability, the team started concept generation. This can be found below in *Section 3.2*.

The next stage in the design process was prototyping. The team received feedback on concept generation and design plans from the stakeholders and then began low fidelity prototyping with cardboard. This allowed the team to visually see how their design would interact even if it was not to scale or the right material. From stakeholder input and cardboard prototyping, the team created a final design proposal towards the end of Fall Term, as seen in *Section 3.3*. After creating the design proposal, the next several rounds of prototyping were higher fidelity with 3D printing. This allowed the team to create a prototype that was the exact dimensioning as the final product but without the high costs and manufacturing time of using carbon fiber. The team also started performing tests to verify the selected engineering specifications would be met with the V2 dendrometer design. This included both in lab testing and deploying the proptypes in the field, and resulted in several design changes along the way.

Lastly the team manufactured a final prototype made out of carbon fiber. This incorporated all the previous design changes and feedback from stakeholders. Extensive testing performed on this prototype proved that all eleven engineering specifications were effectively met and that the V2 design was a significant improvement over the V1 design. From start to finish, this entire project was a strongly collaborative process between the project team as well as the stakeholders, resulting in a superior design product. *Figure 2* and *Figure 3* present the final designs the team created.

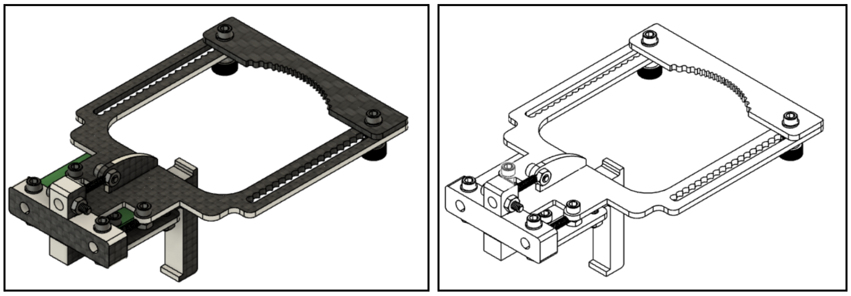


Figure 2. CAD of V2.4 dendrometer design.

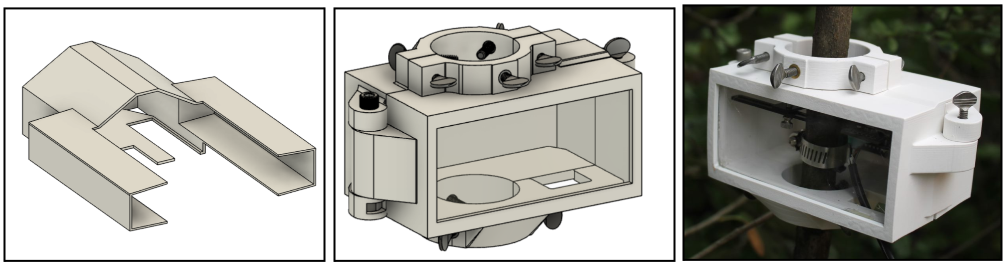


Figure 3. Final 3D printed protective cases. The far left image shows the Barn and the other two are of the protective enclosure.

3 DESIGN PROPOSAL – First Term

This section details more thoroughly the design process summarized above in *Section 2*. This includes a discussion of customer requirements, concept generation, and prototyping. A design proposal was reached from this extensive process which was presented to the client. After receiving approval of the design, the project team continued further prototyping and testing to allow for continual design improvements and development to occur. Some of these improvements will be discussed briefly in *Section 3.4* with the final design detailed in depth in *Section 4*.

3.1 Stakeholders and Customer Requirements

As mentioned in *Section 2 Design Progress*, the team started this project with extensive research and talking to stakeholders to determine where the dendrometer design could be improved and customer requirements. While not every concern from the stakeholders can be incorporated into the Dendrometer project, this is a crucial step for deciding which topics are most important. Each stakeholder is approaching this work from a different perspective and background, and the project team benefited exponentially through the high level of involvement from stakeholders. The main stakeholders included the OPEnS Lab, the researchers currently deploying the dendrometers, and the farmers who will be using them in the future.

From research and conversations with stakeholders, the project team concluded that the main goals of this project would be to reduce axial rotation, provide protection from outside forces, and increase the simplicity, both in terms of manufacturing, assembly, and installation. Several stakeholders stressed the importance of having a protective case around the dendrometer as it needs to stay aligned while in an active crop field. It must be resilient against rain, dust, trucks spraying pesticide, and workers picking. Currently it has no protective case and this fragility will limit the dendrometer's potential application environments. *Table 1* contains customer requirements (CRs) with weighted importance from stakeholders while *Table 2* shows the engineering specifications from these CRs. The full House of Quality can be found in *Appendix A*.

Table 1: Weighted Customer Requirements

(150 Points)	*(150 Points)*	*(150 Points)*	*(150 Points)*	*(150 Points)*	*(150 Points)*	*(100 Points)*		
Field Workers	Family Farm Owners	Researchers	Large Farm Managers	Dr. Udell	Mechanized Farming Facilities	Manufacturing Personnel	**SUMS**	
5	5	10	10	5	15	5	**50**	Resistant to knocking/Sturdy
10	10	5	10	10	5	10	**50**	Lightweight
5	15	15	15	15	10	0	**75**	Reliable data collection
5	15	15	15	15	15	0	**80**	Weather-resistant
15	10	5	10	10	5	0	**55**	Easy to install
15	5	5	10	10	5	20	**50**	Easy to assemble
15	15	10	15	15	10	20	**80**	Quality of user's life
15	10	10	15	5	15	0	**70**	Visible in field
15	5	15	10	15	10	0	**70**	Easy to recalibrate
5	10	5	5	5	10	5	**40**	Cost Effective
5	10	15	10	10	15	10	**65**	Long lifecycle
10	10	10	5	10	10	20	**55**	Manufacturing Speed
5	5	5	5	5	5	0	**30**	Damage to plants
10	15	10	5	15	5	10	**60**	Right-to-repair/Open source
15	10	15	10	10	15	0	**75**	Time between calibrations

Table 2: Engineering Specifications

	SENSOR WISHBONE	Reduced degrees of freedom that the wishbone can move	Static Friction on slider increased	SENSOR BODY	Sensor body should have more than one mounting option	PROTECTION	Waterproofing test according to IPX	SYSTEM	Dollar value of unit post production	% of drawings up to date and available	% reduction of time spent constructing units after manf. processes	% reduction of time spent manuf. components for new design	% reduction of time spent installing the sensor onto the stem	Time spent functional during vibration test	Number of knocks resisted and still functional	Interchangeable pieces in order to scale a sensor to a large stem
		Degrees of Freedom (DF)	Friction coefficient		Sturdy Fixturing		IP Rating		Production Cost	Part Files Available & Up to Date	Assembly Time	Manuf. Time	Installation time	Vibration Resistant Design	Knock Resistant Design	Scalable Design
Resistant to knocking	400	4	4	200	4	50	1	900	4	1	1	1	2	4	4	1
Lightweight	100	1	1	100	2	100	2	800	4	1	1	2	2	2	2	2
Reliable data collection	600	4	4	300	4	75	1	1425	4	1	1	1	2	4	4	2
Weather-resistant	240	1	2	320	4	320	4	1520	4	1	1	1	2	4	4	2
Easy to install	110	1	1	220	4	110	2	770	2	2	1	1	2	1	1	4
Easy to assemble	300	4	2	50	1	100	2	1100	4	4	4	2	2	2	2	2
Quality of user's life	480	4	2	320	4	320	4	2240	2	4	4	4	2	4	4	4
Visible in field	140	1	1	70	1	140	2	630	1	1	1	1	2	1	1	1
Easy to recalibrate	420	4	2	140	2	70	1	1050	4	1	1	1	2	2	2	2
Cost Effective	240	4	2	80	2	80	2	880	4	4	2	2	2	2	2	4
Long lifecycle	520	4	4	260	4	260	4	1170	4	4	1	1	2	2	2	2
Manuf. Speed	220	2	2	110	2	110	2	1265	4	4	1	4	2	2	2	4
Damage to plants	60	1	1	60	2	30	1	270	1	1	1	1	2	1	1	1
Right-to-repair/Open source	240	2	2	120	2	60	1	1080	2	4	1	1	2	2	2	4
Time between calibrations	300	2	2	150	2	75	1	900	1	1	1	1	2	2	2	2
| Max		2 DFs	N/A		N/A		IP67		$270	N/A	20%	20%	20%	TBD	TBD	10 Parts
| Target		2 DF restricted	Pass / No Pass		2 Fixturing Methods		IP66		$200	N/A	10%	10%	10%	TBD	TBD	7 Parts
| Min		1 DF	N/A		N/A		IP65		$100	N/A	0%	0%	0%	TBD	TBD	5 Parts

3.2 Concept Generation and Initial Prototyping

After determining the major customer requirements, the project team started the concept generation process. This entailed individual design work with each of the three group members coming up with designs on their own. *Figure 4* provides some examples of what the concept generation looked like. The project team then came together and selected the top designs to perform a Pugh chart on. For this analysis, the team compared two to three new design ideas to the current dendrometer design for each subsystem and ranked if they were an improvement or detraction in several categories. Some of these categories included weight, simplicity, durability, and axial rotation. After performing this evaluation, the team picked the top designs that were simple but still addressed the main needs of reducing axial rotation and being protected from the elements.

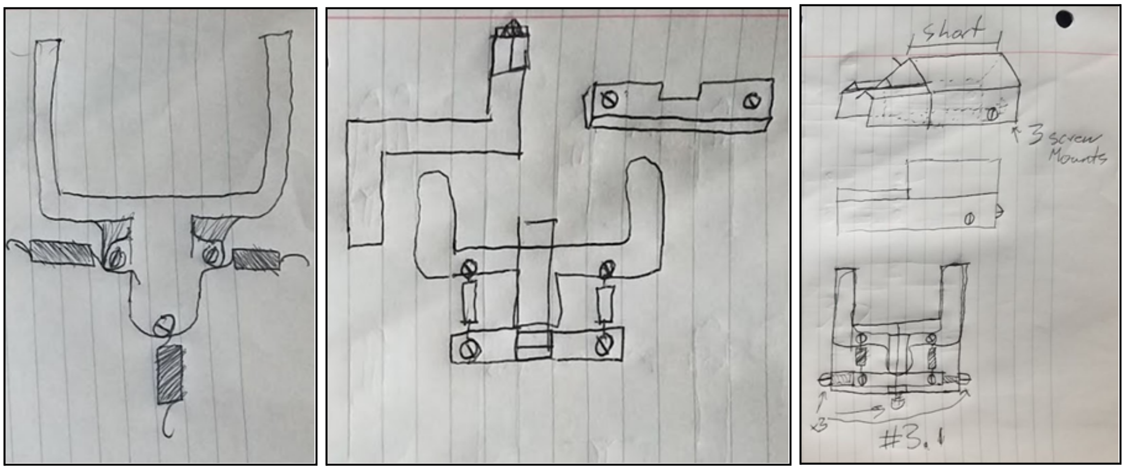


Figure 4. Early-stage concept generation drawings. The left image is a potential spring placement design, the middle image shows a new mounting system, and the right image is a proposed cover idea.

Once the team had selected the designs that best match the customer requirements from the Pugh chart analysis and received input from stakeholders, low fidelity prototyping began. *Figure 5* includes images of this prototyping process. The team used this preliminary round of prototyping to begin visualizing how the components would interact together. The dendrometer was made from cardboard and PVC was used to represent the plant stem. Using this set up, the team was able to test different spring configurations and shapes to determine which design would be best. Reducing axial rotation was the main focus of these design tests. After the concept generation and prototyping, the project team moved forward with the best concepts and started incorporating these design changes in the CAD files.

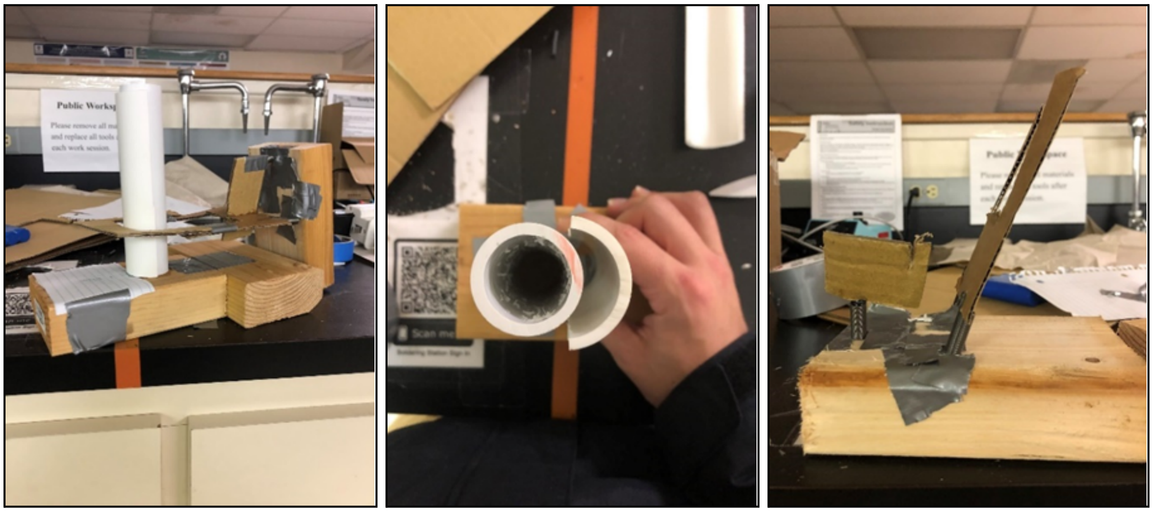


Figure 5. Low fidelity prototyping to test different concepts.

3.3 Design Proposal

From the concept generation and prototyping detailed above, the project team selected the design that best fit the customer requirements within the limitations of this project. One of the main changes was the team decided to use three springs, as opposed to the current model using only one spring, to keep the dendrometer wishbone on one plane. While having two springs reduced the motion along one axis, the team determined it was not sufficient as only using two did not stop vertical movement. Looking at the customer requirements in the above *Table 1,* this design addresses the calibration concern as the dendrometer is significantly less likely to move once it is set up in place. It does, however, increase assembly time but as this is a lower concern for the stakeholders it was concluded that this sacrifice was worth it. Further validation of this design will be conducted in the field once a higher fidelity prototype using carbon fiber is created. Another design change minimized the length of the mounting components and wishbone. This reduces manufacturing time as well as material cost, while still allowing the dendrometer enough sliding movement to capture all diameter changes. These changes are all reflected in *Figure 6* below.

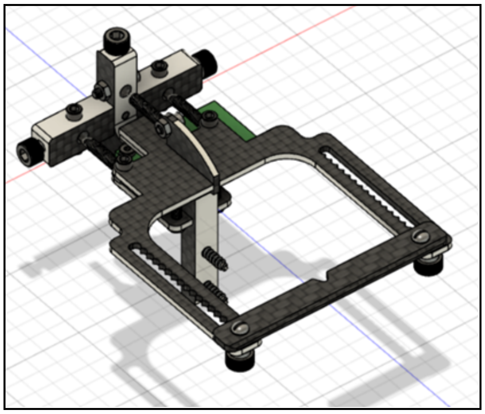


Figure 6. An early V2 design modeled in Fusion 360. This shows the three springs attaching the wishbone to the mount. There are two springs on the side, with one on top to stop vertical motion

Lastly, the team picked two designs for protecting the system from rain and unintended contact as this ranked high in the customer requirements. The first design is called the Barn and it fits snuggly around the dendrometer body. This would be a 3D printed piece that slides onto the back of the dendrometer and screws into the mounting piece once the wishbone is calibrated in place. This will protect the sensor and magnet from rain and still have enough clearance around the wishbone to not introduce friction which would ruin the accuracy of the system. The second design is a larger protective case that encompasses the entire dendrometer and mounting setup. While this option also waterproofs the dendrometer, it adds additional protection from outside sources. These sources could be a truck driving by and spraying pesticide or pickers working directly next to the dendrometers. If the case is shaken, since it is only attached to the plant, it will not move the dendrometer or cause inaccurate data collection to occur. Both designs are inexpensive as they will be 3D printed. While the case is more protective, the Barn does offer some advantage for applications where space is tight. This could happen on blueberry bushes where there are numerous stems all growing in one area. The CAD models of these two designs are shown below in *Figure 7*.

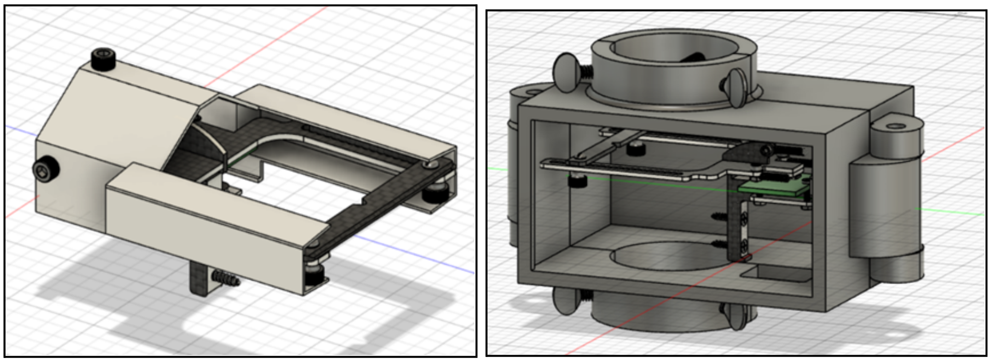


Figure 7. The Barn is shown attached around the dendrometer in the left image. The protective case is shown in the right image. This is larger and will encompass the entire system.

3.4 Design Iterations and Further Prototyping

After the design proposal, during the end of Fall Term and the majority of Winter Term the project team continued prototyping and created design iterations based on the prototype testing. Some of these tests included using a test rig designed by the team that allowed them to perform vibration, static friction, and knocking tests. The test rig is shown in *Figure 8.* The prototypes were mounted to a PVC pipe that was attached to a motor that could vibrate the PVC at varying levels of intensity. Weights were also added to the crossbeam slider to look at friction and the system's resistance to slipping. Other tests included validating designs in the field, using plants outside of the OPEnS Lab and blueberry bushes at LB Farms. Weather resistance of mechanical components and performance over time were primarily evaluated in these testing deployments.

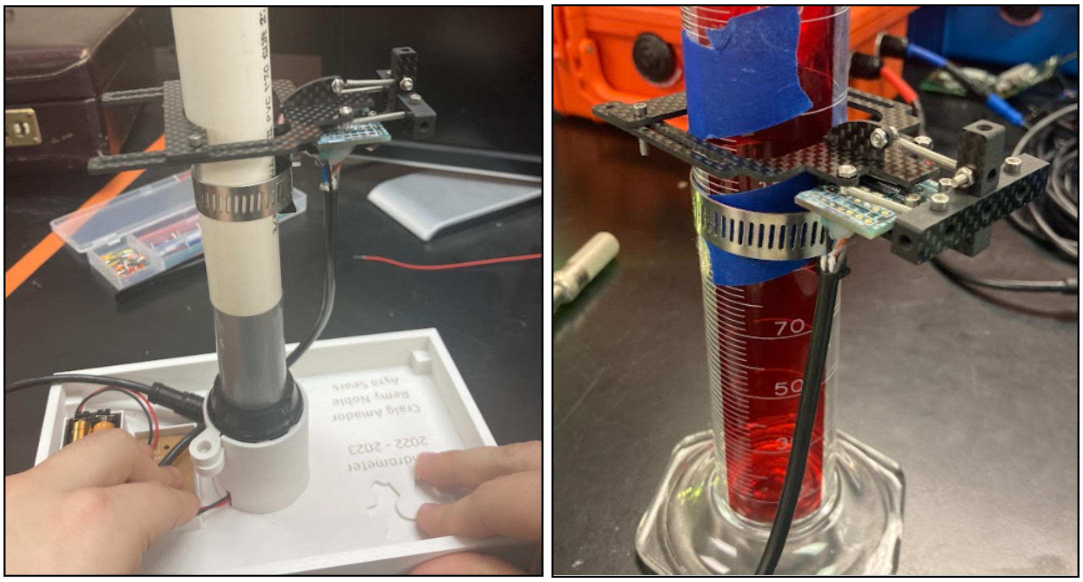


Figure 8. The vibration testing rig is shown on the left. This was used to compare the different dendrometer models. The base and holder were 3D printed and the PVC pipe represents a plant stem. Pyrex cylinders were also used for testing and design evaluation as shown on the right.

A complete Change Log of design changes between prototyping versions can be found in *Appendix B*. One of the more major design interactions was the use of all stainless steel corrosion resistant mechanical components. This was quickly determined a necessity from the field testing as non-stainless steel components readily showed signs of rust and corrosion. Another important feature of the team's design was the three springs. Originally the team was using the same type of spring as the V1 design. While this was functional, the tension felt on the wishbone by the springs was now three times the original amount, dampening the magnitude of the diameter change measurements as more force was required. The team changed their desire to mitigate the effects of this by sourcing a new spring that was still stainless steel but half the tension strength. This resulted in only one and a half times the V1 spring strength which was deemed acceptable by stakeholders and plant testing. Lastly, another major change was the crossbeam slider. The V1 design and prototypes early on in the process only had a simple notch in the middle of the slider. This helped the user align the device on the middle of the plant stem during installation but it did not significantly increase the grip on the stem. The team decided to instead use a shark bite design on the slider to increase grip and resistance to unwanted movement. The original notch design can be seen in the leftmost image in *Figure 9* and the new shark bite design in the right image.

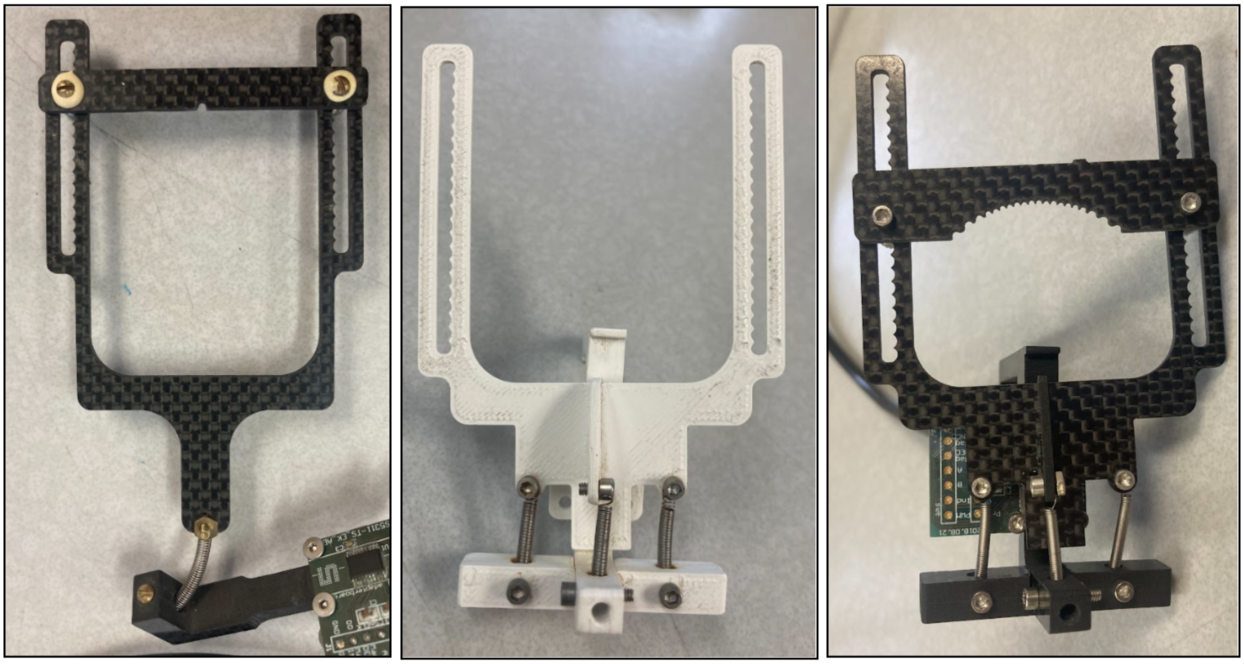


Figure 9. These images show the progression of dendrometer versions. The left image is the V1 dendrometer design that the OPEnS Lab created. The middle image is one of the final 3D printed prototypes, V2.2, that the project team created. The right image is the final V2.3 carbon fiber prototype.

The protective enclosure also went through several iterations. While the overall design stayed relatively the same, there were increases in dimensions, water proofing, and robustness. The inclusion of four water drainage holes and the heat set inserts increased the longevity of this device significantly. More details about the protective enclosure are discussed below in *Section 4.1.1*. *Figure 10* depicts the four iterations that this enclosure went through before the design was finalized.

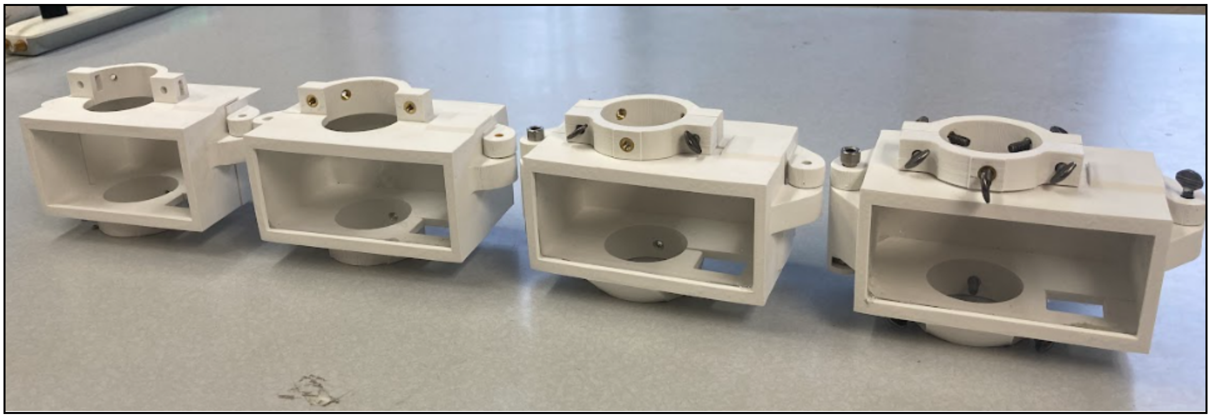


Figure 10. The four iterations that 3D printed protective enclosure went through.

4 Design Solution

The final design solution successfully met all of the engineering specifications and customer requirements that the team had sought out to accomplish. The project team produced a final carbon fiber prototype, V2.3 shown in *Figure 11*, and a final CAD prototype, V2.4. The below descriptions of the solution will detail both versions as well as the project results. There was extensive testing and validation that went into every prototyping round to produce the best possible final product.

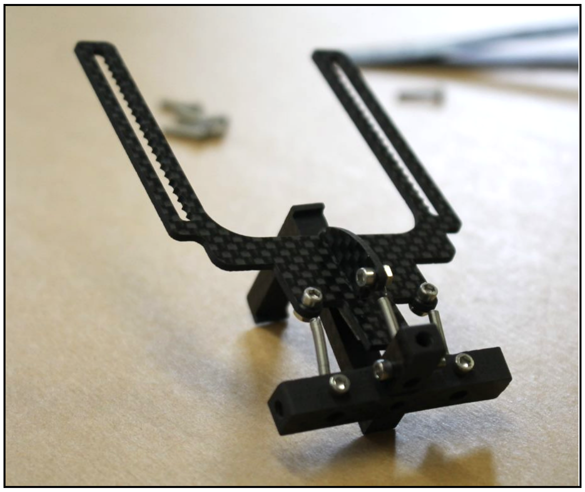


Figure 11. An assembled V2.3 carbon fiber dendrometer

4.1 Description of Solution

4.1.1 Carbon Fiber Manufacturing V2.3 Dendrometer

The final physical prototype was made out of carbon fiber after several rounds of 3D printing prototypes. Carbon fiber is expensive and also harder to machine which is why the project team did not use it until the final round of testing. The manufacturing process consisted of using a water jet for cutting out the individual dendrometer components, depicted in *Figure 12,* and using a milling machine to drill holes and take away material on the spring holder.

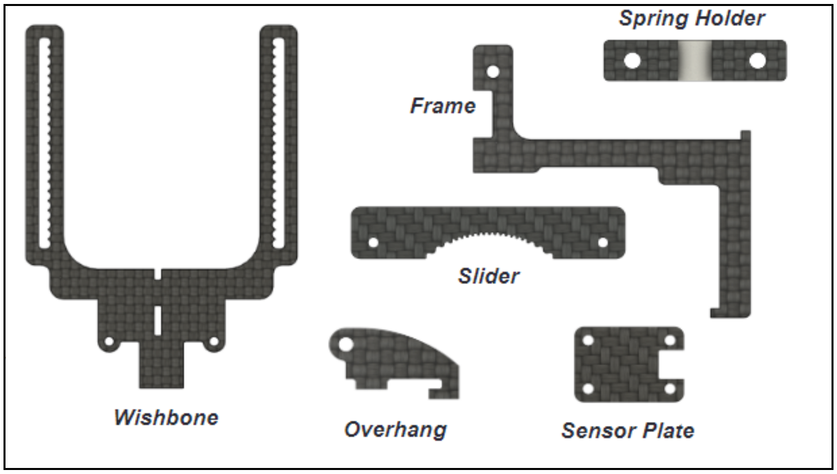


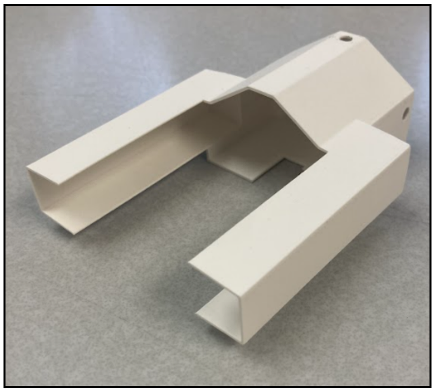
Figure 12. Components cut on the water jet.

The final design uses the same concepts of frictionless movement through the usage of springs as the V1 dendrometer did but with several significant changes. The inclusion of three springs allowed the team to significantly reduce the axial rotation and misalignment that was prevalent in the original V1 dendrometer model. The overhang piece allows the third spring to be situated above the other springs and limit vertical movement without the need to machine a complicated part. The shark bite design in the crossbeam slider also limits misalignment. It increased the static friction felt between the device and the plant stem. *Figure 13* shows how the slider on the final prototype goes around a plant stem and provides a secure fixturing.

Figure 13. V2.3 prototype recording diameter changes on a plant outside the OPEnS Lab.

The final design also has a slimmer magnet which attaches to the underside of the wishbone with either tape or glue. The magnet is situated right above the sensor which tracks and records the movement of the magnet and therefore the diameter fluxations. Previously the magnet used would interfere with the fixturing of the circuit board and require the grinding of four screw heads. By clipping off material on either side of the magnet and narrowing the width, it fits within the screws and has enough clearance to not introduce friction and interference. This was a large positive aspect of the design as it cut down on manufacturing time and costs. Multiple rounds of testing, both on a Pyrex cylinder and on a plant were conducted to ensure that reducing the width of the magnet did not compromise its ability to accurately measure diameter changes. The data remained consistent and the client approved the magnet alterations.

Another critical aspect of the final design is the Barn and protective enclosure. The Barn is a 3D printed device which provides some water resistance and protection from potential knocks. It is shown in the image to the right. Accidental hits to the Barn will affect the dendrometer device as it mounts directly to the frame, but it will protect the wishbone component, which is responsible for tracking the diameter movements, from being moved. The Barn is important for applications where space is limited or the plant can not support significant weight. An example of this would be the blueberry bushes at LB Farms that have multiple stems growing together in close proximity that are easily bent when force is applied.



The other protective alternative the team designed is the enclosure. This device wraps around the entire dendrometer system and attaches directly to the plant stem. There is an acrylic window on the front of the protective enclosure that allows users to visually inspect the dendrometer without needing to remove anything. The enclosure is also designed in such a way to allow it to be opened while still being fixtures in place to the stem. The user can make adjustments to the dendrometer system as needed and then easily close the protective enclosure without needing to remove anything. There are also drainage holes in each corner of the enclosure to allow water to easily exit if some enters from the top hole, although during testing the water enterage was minimal. Manufacturing and assembly of the protective enclosure were also relatively straightforward procedures. *Figure 14* shows the assembly components and the only step requiring tools was the installation of the heat set inserts. The installation of the protective enclosure around the dendrometer device mounted on a stem can be seen in *Figure 15*.

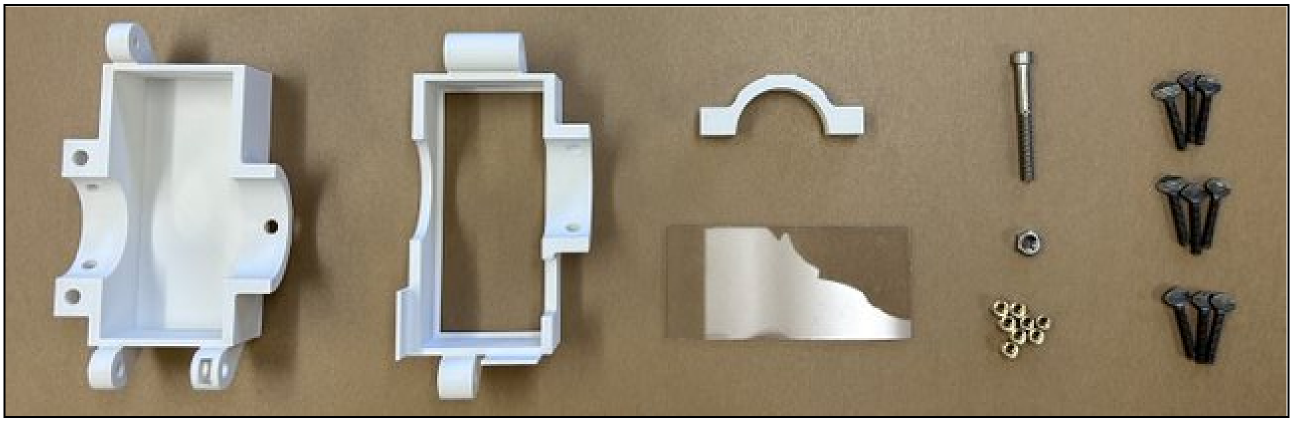


Figure 14. View of protective case assembly components.

Figure 15. Installing protective case around the V2.3 dendrometer carbon fiber prototype.

4.1.2 CAD V2.4 Dendrometer

The majority of the testing and design changes made for the carbon fiber V2.3 prototype still apply to the final CAD V2.4 design but there are four major design changes between the two versions. The frame and spring holder became a press fit, the Barn attachment method was changed, the wood screw holes were removed, and robustness was increased through the incorporation of split washers. Each of these changes are detailed more thoroughly below.

The first change is the removal of the center hole for connecting the spring holder and the frame mount. Previously there was a bolt connecting these two components but this was unnecessary and excessive. The components fit snugly in a press fit and do not pose a threat of disconnecting. This also saves manufacturing time as this hole needed to be drilled on the pieces together to ensure alignment. This change is reflected in the CAD models shown in *Figure 16.* The next design change was removing the holes at the end of the frame and spring holder that mounted the Barn. This decision was made in order to reduce manufacturing time and risk of delamination. While the previous method provided a secure fixturing of the Barn around the dendrometer device, it was deemed not worth the manufacturing cost. The proposed alternative design is using velcro to attach the Barn. The velcro would attach to the back of the frame and the inside of the Barn. This would be protected from rain and other elements and would not degrade over time. This change is also shown below in *Figure 16* with the shortened ends of the spring holder and frame.

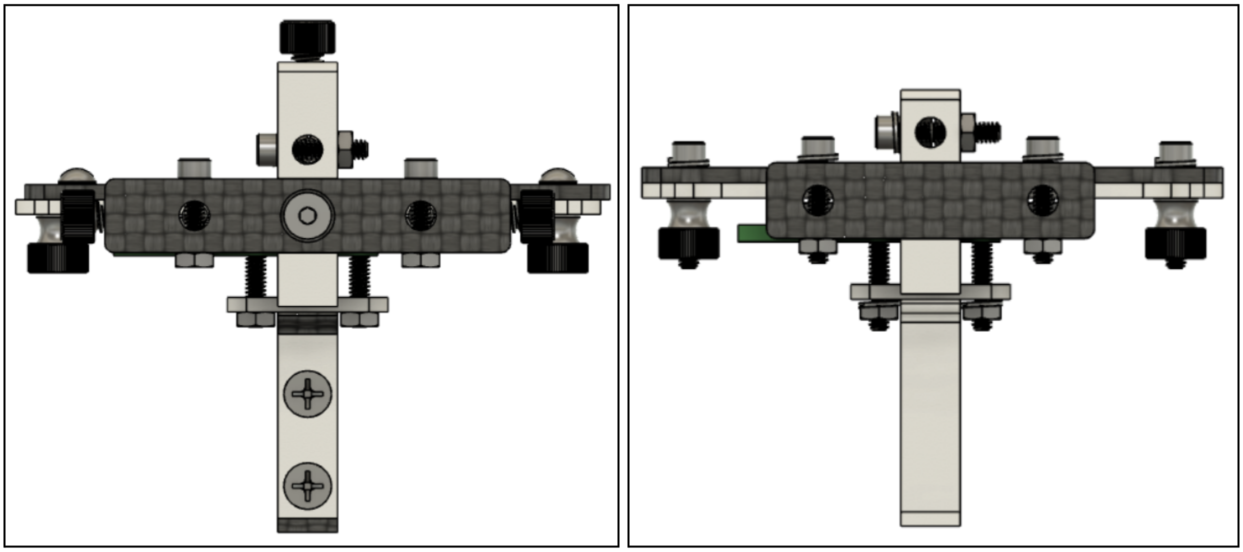


Figure 16. CAD modifications on the mounting frame and spring holder. The left image is Dendrometer V2.3 and on the right is Dendrometer V2.4. This final version, V2.4, was only modeled in CAD and not carbon fiber manufactured due to the water jet cutter breaking and timing. This was approved by the client.

Lastly the project team tried to optimize the design wherever possible, which created a tension between cost, ease of use, and functionality. One change made in this regard was the incorporation of split washers to increase robustness. A split washer is better than using no washers as it is more resistant to vibration and helps lock the bolt and nut in place. This could be needed in some dendrometer applications that experience a lot of forces and disturbances acting on the device. They also were used to provide a more distributed connection between the bolts and the mating surface. There was some concern of nuts being lost or falling off and this reduces the risk if this occurs. The team decided to put the split washers on all of the bolts where applicable and clearance allowing, resulting in nine in total. While these changes increase the cost of the overall device, it makes it easier for the users as well as more robust. A CAD model showing the split washers is shown in *Figure 17.*

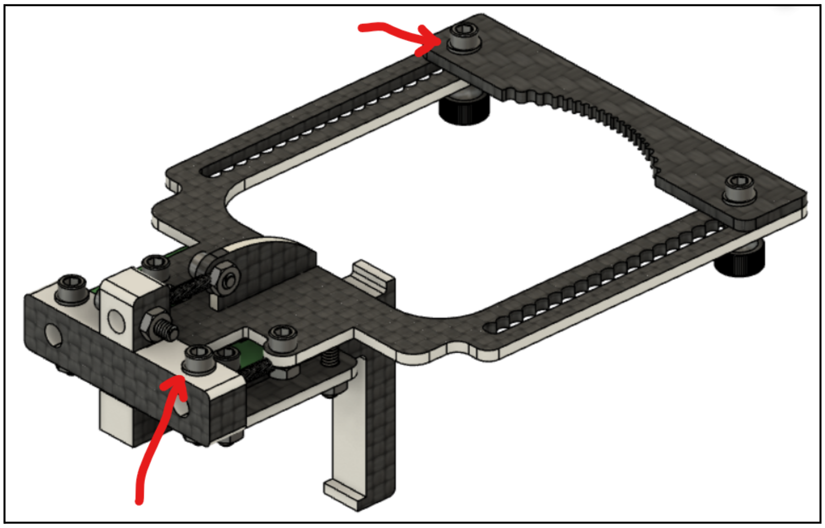


Figure 17. Split washers were added to the majority of bolts in the system, the red arrows highlight some of them.

4.2 Project Results

The design solutions mentioned above in *Section 4.1* directly meet all of the requirements and engineering specifications determined from the stakeholders and project team. The majority of these engineering specifications revolved around increasing the robustness and reliability of the device. To ensure that the project team was adequately meeting them, extensive testing took place during both early rounds of prototyping and with the final carbon fiber prototype. These testing results were then compared against the results of the V1 dendrometer and evaluated if the engineering specifications were indeed passed. The following paragraphs will detail some of the main testing results. Not only did the final designs meet the engineering specifications, they also reduced overall cost by 37% as well as made the production of these devices simpler and faster. All iterations of the dendrometer and protective case designs have been overseen and approved by the client. The client is satisfied that the testing performed by the team verifies and validates all design changes made and that the final carbon fiber prototype is a significant improvement over the V1 design.

One of the major tests was vibration. These dendrometers will be deployed in working fields and there could be a variety of physical disturbances to the device throughout the growing season. It is important that when the dendrometer or the plant it is on is shaken or hit that this does not cause the dendrometer to shift and become misaligned. To test this, the team created a testing rig as mentioned in *Section 3.4.* The testing rig was designed and 3D printed by the team and then connected to a motor. The model then vibrates a PVC pipe at varying levels of intensity from low to high to simulate forces that the dendrometer might experience in the field. During the vibration test, the vibrations started off low and were increased every 30 seconds. The dendrometer was also connected to a light that would turn red if the device moved enough to become misaligned. This test was performed on both V1 and V2.3 as shown in *Figure 18*. When the V1 design was being vibrated, the wishbone almost immediately dropped down and allowed the magnet and the sensor to touch. This would create an error in the data and would not be functional if this occurred during operation of the device. When testing V2.3, there was no vertical slipping of the wishbone and the device remained exactly where it was positioned. These tests were carried out multiple times and it was conclusive that the new design was more durable and retained alignment significantly more than the old design.

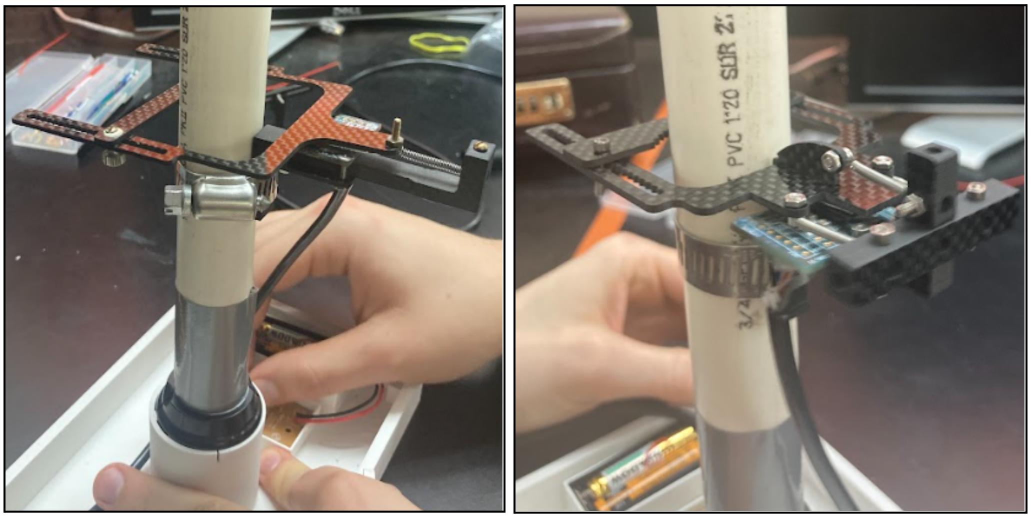


Figure 18. A V1 dendrometer is being tested in the right image while the left image shows the V2.3 design. The results from the vibration test were conclusive that the V2.3 dendrometer is significantly better at staying calibrated.

Other important testing looked at if the new design of three springs and the shark bite cutout in the crossbeam slider were effective. The shark bite should improve the grip that the device has on the surface of the PVC pipe or plant stem while the third spring adds to the clamping force of the wishbone and resists vertical movement.To test this, each version of the dendrometer was installed to the testing rig and calibrated.. Hooks made of metal wire were wound together through the openings on the wishbone. The team added increasingly more hooks to weigh down the wishbone until it was out of alignment. This test evaluates how much force it takes to overcome friction forces correcting the dendrometer's alignment. The V2.3 dendrometer was tested to have an average 32% increase in static friction over the original V1 dendrometer over three tests. This significant improvement is a result of the three springs and the shark bite design.

Figure 19. The left image shows V2.3 being tested. The middle picture shows the metal hooks used to weigh down the wishbone for V2.3 which failed at 10.45g. The same metal hooks caused V1 to fail at 7.92g, shown on the right.

5 LOOKING FORWARD

5.1 Finishing the Project

The desired conclusion of this project was the manufacturing and testing of a final carbon fiber prototype design. The project was able to carry out multiple rounds of prototyping and testing, each time creating improved iterations of the previous design. Due to the complications of the OSU Machine Shop water jet cutter frequently breaking and the unsuccessful attempts to outsource this portion of the manufacturing, it was approved that the project team only needs to display their final design in CAD. It is important to note that the design between the V2.3 manufactured carbon fiber prototype and the final V2.4 design in CAD only have minimum changes that would not invalidate the product testing and verification conducted. Future work for the OPEnS Lab involves manufacturing the V2.4 design and deploying the dendrometers for a growing season (several months) as the last validation that this design will be applicable for their researchers and customers. The results of the static friction, vibration, and knock tests prove that the inclusion of three springs on the dendrometer is a significant improvement over the V1 design of only one spring. While improvements can be made in regards to how these springs are assembled and attached to the mounting pieces, there should not be design changes surrounding the number of springs unless there is concern experienced from researchers regarding cost, assembly, or installation. The substantial improvements to reliability and robustness through the additional springs have been thoroughly validated by the project team.

There is currently a Capstone IE Team working on producing manuals for the manufacturing, assembly, and installations of the final V2 design. The project team has been working closely for the past few months on explaining the design and documenting what has already been done. All documentation and CAD files are accessible by the OPEnS Lab. The IE Team will likely help transition this design from a prototype stage to a device that the OPEnS Lab will be frequently using and testing with their collaborators.

5.2 Capstone Experience Observations

There were several aspects that helped lead the team towards a successful completion of this project. The first one was early on there was communication with a multitude of stakeholders that helped the team clearly understand what the OPEnS Lab's dendrometer was lacking and what improvements would be more beneficial to the users. This allowed the team to identify specific design improvements they would focus on in the coming months and also provided a wide range of perspectives involved with the project. Another positive aspect was that early on the project team established several times throughout the week that they would meet in person. This allowed for extensive collaboration and communication between all members, resulting in a better design than if this project had been approached more individually.

6 CONCLUSIONS

Based on the OPEnS Lab's vision for a tool that will optimize water usage and can be deployed at any scale, this design puts reliability and simplicity as a top priority. This project's main objective was to innovate on a current OPEnS Lab dendrometer design for future commercial use. However, developing a tool for the agricultural sector must also transcend language barriers, economic barriers, and environmental barriers. Design ethnography was the principle used by this capstone team to identify which customer requirements were most important. After interviews with the stakeholders, deliberation of these requirements was conducted using a House of Quality. With the guidance provided by the team's partnered researchers, design choices were made to reflect their concerns.

Above all, this system will be more reliable than its competition. Using the team's three-spring orientation, testing has verified that the data collected will be more resistant to vibrations and knocking from the environment. Different weather protection systems were developed to protect electronic components from the weather; data was collected to verify the systems could withstand the weather. Building a robust system that can last multiple growing seasons is key for convincing smaller scale farms to commit to the price point for a dendrometer.

Yet, this system is expected to be a cheaper alternative to modern commercial dendrometers. V2.4's features were modeled to eliminate as many unnecessary manufacturing steps as possible. Every component on the V2.4 system can be cut using a water jet and drilled with a drill press; the cost benefit of these changes can only grow when production is scaled up. Already, component costs for the sensor have dropped due to changes made to sensor geometry compared to V1 versions.

When this sensor is deployed in the field, it will often be handed to an operator with no knowledge of what a dendrometer is, nor how to use it. Changes were made to improve the ergonomics of the installation of V2.4 dendrometers, such as offering multiple options for fixturing. This switch greatly improves installation time and removes one of the largest pain points of installation.

The OPEnS lab has expressed much excitement for the changes made to the dendrometer and plan to adopt all changes the project team has made.

7 REFERENCES

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[2] C. Clonch, M. Huynh, B. Goto, A. Levin, J. Selker, C. Udell, High precision zero-friction magnetic dendrometer, June 2021. [Online]. Available: https://www.hardware-x.com/article/S2468-0672(21)00078-X/fulltext

8 APPENDICES

8.1 Appendix A: House of Quality

150 Points	150	150	150	150	150	100)			SENSOR WISHBONE	Reduced degrees of freedom that the wishbone can move	Static Friction on crossbeam/slider increased	SENSOR BODY	Sensor body should be able to use wood screws or rubber hose clamps to fixture to the stem.	WEATHER PROTECTION	Water proofing test according to IPX	OVERALL SYSTEM	Dollar value of unit post production.	Percentage of drawings up to date and available	Percentage reduction of time spent constructing unit after manufacturing processes	Percentage reduction of time spent manufacturing components for new design	Percentage reduction of time spent installing sensor onto stem.	Time spent functional during vibration test	Number of knocks resisted and still functional	Pieces that need to be interchanged in order to scale a sensor to a small/large tree
Field Workers	Family Farm Owners	Researchers	Large Farm Managers	Dr. Udell	Mechanized Farming Facilities	Manuf. Personel	**SUMS**			Degrees of Freedom (DF)	Friction coefficient		Sturdy Fixturing		IP Rating		Production Cost	Part Files Available and Up to Date	Assembly Time	Manufacturing Time	Installation time	Vibration Resistant Design	Knock Resistant Design	Scalable Design
5	5	10	10	5	15	5	50	Resistant to knocking/Sturdy	400	4	4	200	4	50	1	900	4	1	1	1	2	4	4	1
10	10	5	10	10	5	10	50	Lightweight	100	1	1	100	2	100	2	800	4	1	1	2	2	2	2	2
5	15	15	15	15	10	0	75	Reliable data collection	600	4	4	300	4	75	1	1425	4	1	1	1	2	4	4	2
5	15	15	15	15	15	0	80	Weather-resistant	240	1	2	320	4	320	4	1520	4	1	1	1	2	4	4	2
15	10	5	10	10	5	0	55	Easy to install	110	1	1	220	4	110	2	770	2	2	1	1	2	1	1	4
15	5	5	10	10	5	20	50	Easy to assemble	300	4	2	50	1	100	2	1100	4	4	4	2	2	2	2	2
15	15	10	15	15	10	20	80	Quality of user's life	480	4	2	320	4	320	4	2240	2	4	4	4	2	4	4	4
15	10	10	15	5	15	0	70	Visible in field	140	1	1	70	1	140	2	630	1	1	1	1	2	1	1	1
15	5	15	10	15	10	0	70	Easy to recalibrate	420	4	2	140	2	70	1	1050	4	1	1	1	2	2	2	2
5	10	5	5	5	10	5	40	Cost Effective	240	4	2	80	2	80	2	880	4	4	2	2	2	2	2	4
5	10	15	10	10	15	10	65	Long lifecycle	520	4	4	260	4	260	4	1170	4	4	1	1	2	2	2	2
10	10	10	5	10	10	20	55	Manufacturing Speed	220	2	2	110	2	110	2	1265	4	4	1	4	2	2	2	4
5	5	5	5	5	5	0	30	Damage to plants	60	1	1	60	2	30	1	270	1	1	1	1	2	1	1	1
10	15	10	5	15	5	10	60	Right-to-repair/Open source	240	2	2	120	2	60	1	1080	2	4	1	1	2	2	2	4
15	10	15	10	10	15	0	75	Time between calibrations	300	2	2	150	2	75	1	900	1	1	1	1	2	2	2	2
150	150	150	150	150	150	100		**| Max**		2 DFs Restricted	N/A		N/A		IP67		$270	N/A	20%	20%	20%	TBD	TBD	10 Parts
150	150	150	150	155	150	100		**| Target**		1 DF Restricted	Pass / No Pass		2 Fixturing Methods		IP66		$200	N/A	10%	10%	10%	TBD	TBD	7 Parts
								| Min		1 DF Restricted	N/A		N/A		IP65		$100	N/A	0%	0%	0%	TBD	TBD	5 Parts

8.2 Appendix B: Change Log

Dendrometer V2.1 (3D printed):

- Wishbone:
    - Added mounts for additional screws
    - Added slot for Overhang component
- Overhang
    - Created new Overhang component to mount vertical spring
- Sensor Mount
    - Added slots to mount the component as far forward as possible
- Spring Holder
    - Added new component to hold additional horizontal springs
    - Added mounting holes for cover
- Springs
    - Added additional springs and tried cheaper ones to minimize cost
- Sharkbite Crossbeam
    - Remade the stem mounting location by changing to a shark bite shape
- Sensor Screws
    - Changed to ultra-low-head screws for mounting the sensor
- Frame
    - Shortened the Frame length to the minimum possible
    - Created flange for hose clamp mounting
    - Created edge for sensor plate mounting
    - Created cutout for Spring Holder mounting
    - Added holes for vertical screws and cover mounting
    - Shrank Frame width for cost and manufacturing benefit
- Screws
    - Changed to steel from brass for cost issues

Dendrometer V2.2 (3D printed)

- Spring
    - Changed to stainless steel due to corrosion issues
- Screws
    - Changed to stainless steel due to corrosion issues
    - Changed to longer screws for spring mounting due to height issues
    - Tried many different sensor mounting screws: none worked
- Frame
    - Lengthened Frame due to dendrometer non-functioning issues from being too short

Dendrometer V2.3 (Carbon Fiber Manufactured)

- Sharkbite Crossbeam
    - Adjusted pattern to enable waterjet cut manufacturing
- Springs

  - Purchased springs with lower spring constants to increase from V1 to V2.3 50% in spring force.
- Magnet
  - Trimmed magnet to resolve screw and sensor mounting issues
- Screws
  - Minimized screw variety by using similar ones in multiple locations

Dendrometer V2.4 (CAD): Simplified manufacturing

- Sharkbite Crossbeam
  - Adjusted hole locations for better Wishbone mounting
  - Changed screws to the widely used SHCSs
- Spring Holder
  - Removed mounting holes for cover
  - Removed mounting holes to frame (Press fit now)
- Frame
  - Removed mounting holes for cover
  - Removed mounting holes to frame (Press fit now)
  - Removed wood screw mounting holes (Not useable)
- Nuts
  - Switched to Nylocks to increase robustness
- Screws
  - Increased screw length to account for new Nylocks
  - Added Split washers

Cover [Barn] V1.1

- Created new Cover Component

Cover [Barn] V1.2

- Adjusted wingspan to allow wiggle room for dendrometer
- Added holes for sensor wires

Cover [Barn] V1.3

- Added water drainage holes
- Removed holes for mounting (switching to velcro)

Protective Case V1

- Created new dendrometer covering Case with the following components
  - Front Case
  - Back Case
  - Polycarb Window
  - Top Arc Mount

Protective Case V1.2

- Acrylic Window
    - Switched from polycarbonate to acrylic for better UV resistance
- Top Arc mount
    - Switched to using heat-set inserts instead of nuts for mounting
- Front Case
    - Switched to using heat-set inserts for mounting
    - Adjusted width to give more room for dendrometer mounting
- Back Case
    - Switched to using heat-set inserts for mounting
    - Adjusted width to give more room for dendrometer mounting

Protective Case V1.3

- Front Case
    - Adjusted slants and curves to 3D print without needing supports
    - Added more water protection covering
    - Removed heat-set insert for easier opening and closing
- Back Case
    - Adjusted slants and curves to 3D print minimize supports

Protective Case V1.4

- Screws
    - Switched to Stainless Steel screws for corrosion resistance
    - Added Stainless Steel SHCS option for cheaper manufacturing
- Front Case
    - Added holes for water drainage
- Back Case
    - Added holes for water drainage
