Hardware Article

A low-cost open-source handheld LiDAR-based automated understory timber stand surveying device

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A R T I C L E   I N F O

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A B S T R A C T

Timber stand inventories are critical for making management decisions in both commercial and conservation related forestry applications. When taking these inventories, the most critical characteristics to record are diameter at breast height (DBH), stand density, tree height and tree species. As discovered in prior research, a relatively inexpensive device, which hereby will be referred to as AutoTSI (short for Automatic Timber Stand Inventory), can be assembled and deployed in the field to take accurate measurements of diameter at breast height (DBH) for timber stand sample plots in a short amount of time compared to the traditional method of manually measuring these trees. The specified range and angle of resolution of the sensor allows for estimation of stand density and basal area. Each element of both the hardware and software is modular by design allowing the user to customize according to whatever sensors may be readily available to the user. In silviculture research, methodical collection, and analysis of geometric measurements of trees is essential for developing land management plans that optimize biomass production, biodiversity, and other desired characteristics in a forest environment making this device useful to both tree farmers and researchers.

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Specifications table

| Hardware name | AutoTSI |
|----------------|---------|
| Subject area | Environmental, planetary and agricultural sciences |
| Hardware type | Field measurements and sensors |
| Closest commercial analog | No commercial analog available |
| Open-source license | Hardware: CC-By Attribution 4.0 International |
| | Software: GNU GPLv3 |
| Cost of hardware | $4,783 |
| Source file repository | http://doi.org/10.17605/OSF.IO/J8ZW7 |

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Hardware in context

AutoTSI is a handheld device made from a polyvinyl chloride (PVC) pipe frame, three-dimensionally (3D) printed housing, and a gimbal made from 3 concentric rings cut from large PVC pipe connectors which can be used to rapidly measure diameter at breast height (DBH) and catalogue its location using off-the-shelf Global Navigation Satellite System (GNSS) and compass sensors. DBH is the most commonly measured property of trees [1] which has allometric relationships with other tree properties like height and biomass as well as systematic relationships with the forest as a whole such as average basal area per acre, a whole-sample feature which influences growth amongst all trees within the sample [2]. Traditionally, DBH is measured manually using tape or calipers, however, several light detection and ranging (LiDAR) based methods have been explored over the last several years to ease the process [3]. These methods typically rely on proprietary point cloud processing software like Leica Cyclone 3D [4]. Open-source frameworks like Point Cloud Library do exist however and could potentially be used to create a similar pipeline. Point cloud processing is commonly used in autonomous vehicles, Robot Operating System (ROS) is an open-source robotics package used for this very purpose and was selected to use as a bridge to read the output of LiDAR sensors. This output can be written using ROS in a readable format for a custom lightweight pipeline that outputs a catalogue of measured tree diameters, their approximate coordinates, sample plot densities, and a map of their locations.

Hardware description

ROS is used to extract the LiDAR measurements from the sensor and output the stream directly to a file readable by a custom library built in Python 3 to process these measurements. There are two modes of operation to perform this analysis. The first is to use the entirety of this stream as the sample plot which is processed in post. This mode is generally not recommended unless the GNSS measurements are extremely accurate and stable which is unlikely if used under canopy cover. The recommended mode is to run the scanVis.py script on the Raspberry Pi after starting the output stream in ROS and following the instructions in the README to mark a position and take a stationary reading. The user will be shown each detected tree and be able to keep or remove any of the results that were falsely detected as trees such as large rocks, tall bushes, dead trees, and stumps. The resulting diameters, the average coordinates of sensor during that stationary period, and the relative positions of each tree will be saved to a separate file which can be analyzed in post to generate a map and calculate the stand density from each sample location. This uniquely allows for a layer of validation and allows for a map to be drawn of each sample plot, even in a remote area despite a high level of signal interference experienced in a dense forest. There is no need to worry about holding the device as a consistent angle during this period, the gimbal will keep it at the corrected orientation. Unlike the published approaches to two-dimensional point cloud measurement processing like the Hogue Transform [4], linear and nonlinear least circle fitting algorithms [3], a custom algorithm with less computational demand can be performed in real time and display the location and relative size of each one to tell the user that it is working properly. This algorithm estimates the diameter using the Intersecting Chords Theorem and averages the diameter and position of all intersecting circles other than outliers [5]. AutoTSI is made from off-the-shelf and 3D printable parts, a Raspberry Pi microcomputer with a standard Raspbian operating system, and a custom Python library for analysis. These features were chosen to make the device more accessible, modular, and easily customizable to different types of sensors that may be more accessible to the user. The open-source software also provides a backbone for researchers to augment their analysis to components beyond DBH and mapping such as species identification with deep-learning and photogrammetric height determination [5] both of which have examples for in the code repository.

You may be interested in this hardware if you are:
A researcher interested in taking large sample sizes of timber stand measurements.
A tree plantation owner interested in maximizing growth without having to repeatedly invest in skilled labor to conduct timber stand surveys.
A conservationist interested in evaluating the maturity and density of a timber stand to make landmanagement decisions.
A researcher interested in expanding the design philosophy of automated forest mensuration.

Design files summary

| Design file name       | File type | Open source license                          | Location of the file                      |
|------------------------|-----------|----------------------------------------------|-------------------------------------------|
| LiDAR slip             | CAD file  | CC-By Attribution 4.0 International          | https://3dprint.nih.gov/discover/3DPX-016345 |
| Sensor Platform (Left) | CAD file  | CC-By Attribution 4.0 International          | https://3dprint.nih.gov/discover/3DPX-016345 |
| Sensor Platform (Right)| CAD file  | CC-By Attribution 4.0 International          | https://3dprint.nih.gov/discover/3DPX-016345 |
### Design file name | File type | Open source license | Location of the file
--- | --- | --- | ---
Battery Box | CAD file | CC-By Attribution 4.0 International | https://3dprint.nih.gov/discover/3DPX-016345
AutoTSI library | Github Repository | GNU GPLv3 | https://github.com/babessell1/auto-tsi

### Bill of materials summary

| Item Description | Component | Number | Unit Cost | Total Cost | Source of Materials | Material Type |
|--- | --- | --- | --- | --- | --- | --- |
| 1/4"-20 Jam Nuts | 1 | 5 | $0.04 | $0.18 | https://www.mcmaster.com/91078A029/ | Zinc Plated Steel |
| 1/4"-20 2" Hex screw | 2 | 3 | $0.20 | $0.60 | https://www.mcmaster.com/91309A550/ | Zinc Plated Steel |
| Bronze Sleeve Bearings 1/4" x3/8" x 1/2" | 3 | 6 | $2.09 | $12.54 | https://www.mcmaster.com/6381K415/ | Bronze |
| Standard-Wall PVC Pipe Fitting for Water, Straight Connector, 8 Socket-Connect Female, White-4.5x 8" | 4 | 1 | $25.30 | $25.30 | https://www.mcmaster.com/4880K132/ | PVC |
| Standard-Wall PVC Pipe Fitting for Water, Straight Connector, 8 Socket-Connect Female, White-3.5x6" | 5 | 1 | $13.55 | $13.55 | https://www.mcmaster.com/4880K131/ | PVC |
| Standard-Wall PVC Pipe Fitting for Water, Cap, White, 5 Pipe Size Socket-Connect Female – 3" x 5" | 6 | 1 | $10.13 | $10.13 | https://www.mcmaster.com/4880K298/ | PVC |
| BH Fender Washers (½" x 1.5") | 7 | 25 | $0.28 | $6.88 | https://www.lowes.com/pd/Hillman-25-Count-1–2-in-x-1–1–2-in-Zinc-Plated-Standard-5AE-Fender-Washers/3032342 | Zinc Plated Steel |
| Hillman ½” x 12” Galvanized Coarse Thread Carriage Bolt | 8 | 1 | $3.68 | $3.68 | https://www.lowes.com/pd/Hillman-1–2-in-x-12-in-Coarse-Thread-Carriage-Bolt/100037973 | Galvanized steel |
| Hillman ½” x 12” Galvanized Coarse Thread Carriage Bolt | 9 | 1 | $3.68 | $3.68 | https://www.lowes.com/pd/Hillman-1–2-in-x-12-in-Coarse-Thread-Carriage-Bolt/100037973 | Galvanized steel |
| Hillman ¼” x 2 ½” Stainless Coarse Thread Hex Bolt | 10 | 2 | $1.99 | $3.98 | https://www.lowes.com/pd/Hillman-1–4-in-x-2–1–2-in-Stainless-Coarse-Thread-Hex-Bolt-2-Count/999995832 | Stainless Steel |
| Hillman M3-0.50 × 16 mm Phillips Drive Machine Screws | 11 | 4 | $0.17 | $0.66 | https://www.lowes.com/pd/Hillman-3mm-0-5-x-16mm-Phillips-Drive-Machine-Screws-12-Count/999994900 | Steel |
| Hillman M3-0.50 Zinc-Plated Metric Nylon Insert Lock Nuts | 12 | 4 | $0.25 | $1.98 | https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594 | Zinc Plated Steel |
| Item Description                              | Component | Number | Unit Cost | Total Cost | Source of Materials                                                                 | Material Type                        |
|-----------------------------------------------|-----------|--------|-----------|------------|-------------------------------------------------------------------------------------|--------------------------------------|
| 1–1/2-in dia × 3-in 330 PSI PVC Pipe           | 13        | 2      | $0.14     | $0.29      | [https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594](https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594) | PVC                                  |
| 1–1/2-in dia × 6.65-in 330 PSI PVC Pipe        | 14        | 1      | $0.32     | $0.32      | [https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594](https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594) | PVC                                  |
| 1–1/2-in dia × 6-in 330 PSI PVC Pipe           | 15        | 2      | $0.29     | $0.57      | [https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594](https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594) | PVC                                  |
| 1–1/2-in dia × 9-in 330 PSI PVC Pipe with cut slot | 16    | 2      | $0.43     | $0.86      | [https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594](https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-dia-x-20-ft-L-330-PSI-PVC-Pipe/3359594) | PVC                                  |
| 1–1/2-in × 1–1/2-in dia Cap PVC Fitting        | 17        | 2      | $1.50     | $3.00      | [https://www.lowes.com/pd/Dura-Plastics-1–1-2-in-x-Diameter-Cap-Cap-PVC-Fitting/5001208435](https://www.lowes.com/pd/Dura-Plastics-1–1-2-in-x-Diameter-Cap-Cap-PVC-Fitting/5001208435) | PVC                                  |
| 1–1/2-in × 1–1/2-in × 1–1/2-in dia Slip Elbow PVC Fitting | 18    | 2      | $2.48     | $4.96      | [https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-PVC-Sch-40-Coupling/3505964](https://www.lowes.com/pd/Charlotte-Pipe-1–1-2-in-PVC-Sch-40-Coupling/3505964) | PVC                                  |
| 1–1/2-in × 1–1/2-in × 1–1/2-in dia Tee PVC Fitting | 19    | 2      | $3.15     | $6.30      | [https://www.lowes.com/pd/LASCO-1–1-2-in-x-1–1-2-in-x-1–1-2-in-x-1–1-2-in-dia-Tee-PVC-Fitting/3344584](https://www.lowes.com/pd/LASCO-1–1-2-in-x-1–1-2-in-x-1–1-2-in-x-1–1-2-in-dia-Tee-PVC-Fitting/3344584) | PVC                                  |
| LiDAR Slip (3D Printed)                        | 20        | 1      | N/A       | N/A        | N/A                                                                                 | Acrylonitrile butadiene styrene(ABS)  |
| Battery Box (3D Printed)                       | 21        | 1      | N/A       | N/A        | N/A                                                                                 | ABS                                  |
| Electronics Platform-Left Side (3D-Printed)    | 22        | 1      | N/A       | N/A        | N/A                                                                                 | ABS                                  |
| Electronics Platform-Right Side (3D Printed)   | 23        | 1      | N/A       | N/A        | N/A                                                                                 | ABS                                  |
| Pixhawk2.1/Carrierboard/Core                   | 24        | 1      | $300      | $300       | [https://www.getfpv.com/pixhawk-2–1-standard-set.html](https://www.getfpv.com/pixhawk-2–1-standard-set.html) | N/A                                  |
| Here + External GPS + RTK GNSS Kit             | 25        | 1      | $600      | $600       | [https://www.getfpv.com/here-rtk-gnss-gps-kit-m8p.html](https://www.getfpv.com/here-rtk-gnss-gps-kit-m8p.html) | N/A                                  |
| Young RC 3DR Radio Telemetry 915Mhz Air and Ground Modules | 26 | 1 | $23.99 | $23.99 | [https://www.amazon.com/YoungRC-Telemetry-Transmit-Pixhawk-Controller/dp/B07Y4P3MN8](https://www.amazon.com/YoungRC-Telemetry-Transmit-Pixhawk-Controller/dp/B07Y4P3MN8) | N/A                                  |
| (OPTIONAL: only if expanding computer vision elements) Adafruit Flex Cable for Raspberry Pi Camera – 24"/610 mm | 27 | 1 | $2.95 | $2.95 | [https://www.adafruit.com/product/1731](https://www.adafruit.com/product/1731) | N/A                                  |
| MakerFocus Raspberry Pi 4 Battery Pack, RPI UPS Pack Standard, New Expansion Board Power Supply with Switch | 28 | 1 | $20.99 | $20.99 | [https://www.amazon.com/MakerFocus-Raspberry-Standard-Expansion-Cellphone/dp/B01LAEX7J0](https://www.amazon.com/MakerFocus-Raspberry-Standard-Expansion-Cellphone/dp/B01LAEX7J0) | N/A                                  |
| Item Description                                                                 | Component | Number | Unit Cost | Total Cost | Source of Materials                                                                 | Material Type |
|---------------------------------------------------------------------------------|-----------|--------|-----------|------------|-------------------------------------------------------------------------------------|---------------|
| Raspberry Pi 4 Model B (4 GB RAM)                                               | 29        | 1      | $55.00    | $55.00     | https://www.adafruit.com/product/4296                                            | N/A           |
| MazerPi Raspberry Pi 4 Touchscreen with Cooling Fan and Case                     | 30        | 1      | $29.99    | $29.99     | https://www.amazon.com/Raspberry-Touchscreen-MazerPi-480x320-Resolution/dp/B07WXXH1DR8 | N/A           |
| Samsung 32 GB 95 MB/s MicroSDXC EVO Select Memory Card with Full-Size Adapter    | 31        | 1      | $7.49     | $7.49      | https://www.amazon.com/Samsung-MicroSDHC-Adapter-MB-ME32GA-AM/dp/B06XWN9Q99/ref=psdc_301543011_t1_996654075X | N/A           |
| (OPTIONAL: only if expanding computer vision elements) Raspberry Pi Camera Module V2-8 Megapixel, 1080p | 32        | 1      | $28.20    | $28.20     | https://www.amazon.com/Raspberry-Pi-Camera-Module-Megapixel/dp/B01ER2SKFS           | N/A           |
| Hokuyo UTM-30LX LiDAR Sensor                                                    | 33        | 1      | $3,500    | $3,500     | https://www.robotshop.com/en/hokuyo-utm-03lx-laser-scanning-rangefinder.html      | N/A           |
| DBPOWER 800A 1800mAh Portable Car Jump Starter                                 | 34        | 1      | $65.99    | $65.99     | https://dbpowershop.com/products/dbpower-djs50-800a-peak-1800mah-portable-car-jump-starter | N/A           |
| Hoovo 6000 mAh 14.8 V Li-Po Battery (for Pixhawk2.1)                             | 35        | 1      | $49.99    | $49.99     | https://www.amazon.com/HOOVO-Connector-Airplane-Helicopter-Quadcopter/dp/B07PDGFQY/ref=psdc_2234134011_t3_B086C3KSW1 | N/A           |
| 1–1/2” screw                                                                    | 36        | 4      | $0.11     | $0.44      | https://www.mcmaster.com/92470A157/                                              | Stainless Steel |

Build instructions

**Gimbal assembly**

Using a handsaw or miter saw, cut off a roughly 3/4” wide ring from each large PVC coupling (part no. 4 and 5). PVC shavings can be harmful if inhaled and for the environment so be sure to wear a mask and cut indoors so the shavings can be disposed of properly. Sand down any burs from the cut ends of the rings to smooth them down and make them as even and close to the same width as possible. Take these rings and align the smaller one (no. 5) inside the center of the larger one (no. 4). Then align the PVC end cap (no. 6) concentrically inside part no. 5 oriented such that the convex side of the cap is facing up. Ensure the concentric position of these 3 pieces are maintained using either spacers (cardboard works great for this) or by gluing each piece to the surface (use glue that can be dissolved or manually removed later). Once the pieces are stably positioned, take a ruler, lay it flat across the edges of each ring and mark lines across the edge of each ring. Then take a right angle, such as a carpenter’s square to mark a perpendicular set of lines across the edge of each ring. Make sure you cross these perpendicular lines in the center of part no. 6 so the dead center of piece is clearly marked. Once marked, holes should be drilled in line with these marked lines with a 3/8” drill bit. If available, use a longer drill bit capable of drilling through each ring so that the holes are perfectly aligned. These rings will rotate gyroscopically inside of each other, so it is critical that these holes are meticulously aligned. At the intersection of the perpendicular lines, dead center of part no. 6, drill a hole through the piece using a ½” drill bit.

Next, ensure the LiDAR fits inside the LiDAR slip (part no. 20). Even if using the provided LiDAR slip STL file with the Hokuyo UTM-30LX, a few small modifications need to be made. If the printer made the square slot too small for the LiDAR to be seated properly inside it, sand down the edges until it can. The LiDAR slip also should be able to seat inside the PVC cap.
(part no. 6). If it is too large sand down the inside of the PVC cap to allow it to fit. Depending on the quality of the print, the 3 mm mounting holes will need to be drilled through, and the holes for the wires may need to be slightly expanded to allow the wires to be comfortably routed through. To allow the slip to securely mount to part no. 6, drill a hole straight through with a 1/2” drill bit perpendicular to the angle the LiDAR sensor faces (see the bold dashed line on Fig. 1). To secure the LiDAR (part no. 33) in place, thread its wires through the hole on the side of the square slot and out through the hole in the back of the shell of the LiDAR slip. Seat the LiDAR in the square slot and screw in the 3 mm screws (no. 11) to secure it in place.

The gimbal should now be ready for assembly, refer to for the following instructions. Insert brass sleeve bearings into the holes of the PVC cap (no. 6) and each PVC ring (no. 4 and 5). The bearings should have a press fit tolerance, but if they feel loose, they can be glued in place.

Thread all 25 1/2” washers (no. 7) through the 1/2” carriage bolt (no. 8) and partially thread one 1/2” hex nut (no. 10) through the same bolt. Then insert the bolt into the 1/2” hole on the PVC cap (part no. 6) and thread a second 1/2” hex nut and tighten both simultaneously to secure the bolt in place.

Seat the LiDAR slip (no. 20) into the PVC cap (no. 6) and align the 1/4” holes from each part. Align the smaller PVC ring (no. 5) concentrically with the PVC end cap and align the holes of the ring with the holes on the end cap and LiDAR slip. Partially thread a 1/4” hex bolt (no. 8) through on of the bearings in the PVC ring (no. 5), as soon as the tip of the hex bolt pokes through the other side, hand thread a 1/4” jam nut (no. 1) over the bolt and then hand tighten the bolt all the way through, allowing it to thread through the sleeve bearing on the PVC end cap (no. 6) and the LiDAR slip (no. 20). A drill with a 1/4” hex bit can be used here to make the process easier but is not required. Repeat this process on the opposite side, threading a 1/4” hex bolt through the smaller PVC ring (no. 5), a jam nut (no. 1), the PVC end cap (no. 6) and the LiDAR slip (no. 20). If done correctly, the end cap should be able to rotate on a single axis. If not, check that the holes are properly aligned. To create the second axis of rotation, align the larger PVC ring (no. 4) concentrically with the inner ring. Thread a 1/4” hex bolt (no. 2) through the bearing on the outer ring, then through two jam nuts (no. 1) and then through a bearing on the smaller PVC ring (no. 5) that is perpendicular to the ones that were threaded in the previous step. There should be a small amount of bolt poking through the smaller PVC ring, thread a third jam nut onto this space to secure the bolt in place. The reason to use two jam nuts in between the larger and smaller rings is to allow the adjustment of spacing between the rings to ensure they remain concentric. Repeat on the opposite side. The end cap at the center of the assembly should be able to freely rotate.

![Fig. 1. 3D printed LiDAR slip; bold line shows where hole should be drilled to interface with gimbal.](image_url)
on two axes. Hold the outer ring up in the air and ensure the LiDAR orients itself to remain flat regardless of the angle the outer ring is held at. Once working properly, put the gimbal aside you are ready for final assembly.

Frame assembly

Cut the purchased 1.5" PVC to length. You will need two 3" pieces (no. 13), one 6.65" piece (no. 14), two 6" pieces (no. 15), and two 9" pieces (no. 16). On one end of each 9" piece, use either a hacksaw or miter saw to cut about a 3/4" wide, 3" long slot. The slot should be just wide enough to slide the outer ring of the gimbal into it. At the center-width of each slot, one half inch from the edge of the pipe, drill a 1/4" hole. These 2 holes will be used later to attach the gimbal to the frame. The frame should be assembled following Fig. 3. If the PVC slides around, use PVC cement to seal the frame together.
Full assembly

Refer to Figs. 1–4 for the following instructions. Attach the two ends of the sensor platform (no. 23 and 24) together with either glue or any type of fastener. Attach the join platform to the frame by putting the top handles of the frame through the holes of the platform and let it sit flat on top of the front arms. Use a 1.5" screw (no. 36) to fasten the platform to the frame. Adhere the battery box (no. 21) to the bottom rung of the frame and adhere with 1.5" screws. The gimbal can be attached by first unscrewing the bolts from the outermost ring and rethreading them through the holes on the arms of the frame (no. 16). The platform has slots for housing the sensors and Raspberry Pi (inside the touch screen case), if you need additional support, Velcro tape is a good option. The battery box provides space to store the batteries for the LiDAR, Raspberry Pi, and Pixhawk. Refer to the connection diagram (Fig. 5) for attaching the sensors. Use any type of string or strap you have available such as shoelaces to create a sling to help carry the device. A render (Fig. 6), side-view (Fig. 7), front-view (Fig. 8) and top view (Fig. 9) of the completed design can be used as reference to ensure correct fabrication.

Operation instructions

Setup on laptop

Install uBlocks firmware according to manufacturer instructions. Install Mission Planner and calibrate the inertial mass unit (IMU) and GNSS to their instructions. Install Python 3. Clone the AutoTSI GitHub folder. Install drivers for telemetry radio and GNSS.

Setup on raspberry Pi

Install a Raspbian distribution on the Raspberry Pi compatible with Robot Operating System (ROS) such as Raspbian Buster. Install ROS distribution compatible with urg_node such as ROS melodic. Clone the AutoTSI GitHub folder. If you did a custom Raspbian installation that did not include Python, install Python 3.

Operation

Power on the Raspberry Pi, the Pixhawk and the LiDAR. Make sure the telemetry radio on the Pixhawk is communicating with the telemetry radio connected to the laptop. On the Raspberry Pi, in a new terminal, run: `roscore`. In a new terminal, run `rosrun urg_node urg_node _serial_port:=/dev/ttyACM0`. This will activate the LiDAR, do NOT look directly at the laser on
Fig. 4. Full Assembly, 20 - LiDAR Slip (3D Printed), 21 - Battery Box (3D Printed), 22 - Electronics Platform-Left Side (3D-Printed), 23 - Electronics Platform-Right Side (3D Printed), 24 - Pixhawk2.1/Carrierboard/Core, 25 - Here + External GPS + RTK GNSS Kit, 26 - Young RC 3DR Radio Telemetry 915Mhz Air and Ground Modules, 28 - MakerFocus Raspberry Pi 4 Battery Pack, RPI UPS Pack Standard, New Expansion Board Power Supply with Switch, 29 - Raspberry Pi 4 Model B (4 GB RAM), 30 - MazerPi Raspberry Pi 4 Touchscreen with Cooling Fan and Case, 32 - (OPTIONAL only if expanding computer vision elements) Raspberry Pi Camera Module V2-8 Megapixel, 1080p, 33 - Hokuyo UTM-30LX LiDAR Sensor, 35 - Hoovo 6000 mAh 14.8 V Li-Po Battery (for Pixhawk2.1).

Fig. 5. Electronics diagram.
the LiDAR. On the laptop computer, open Mission Planner and start a new mission. This will start collecting and writing information from the Pixhawk.

In a new terminal on the Raspberry Pi, run `rostopic echo/scan > SCAN_FILENAME.txt`. This will start collecting data from the LiDAR. Next run `scanVis.py -i SCAN_FILENAME.txt -o OUTPUT_FILENAME.txt` which will open a plot showing a visual dis-

**Fig. 6.** Rendered Full Assembly.

**Fig. 7.** Full Assembly Side View.
play of the LiDAR as well as any interpreted trees in each frame. Open a touch keyboard on the Raspberry Pi. Move to the location you want to sample, press “m” on the keyboard to start sampling. The points on the plot should turn blue during sampling. Try to move as little as possible for a few seconds and then press “v”. This will change the color of points to red letting you know you have started the verification step. During the verification step, the potential detected trees will be outlined on the map. The map will one-by-one turn each potential tree pink. You can push ‘k’ to tell the device that it is a valid tree turning the outline green or you can push ‘t’ to tell the device that it is not a valid tree, such as a rock or stump or tall bush. Alternatively, to cancel taking the sample you can press ‘r’. Once each potential tree has been marked, the map will go back to its normal display. You can press ‘p’ to save the sample plot. If you change your mind or make a mistake and do not wish to save the sample plot, you can press ‘m’ to start a new sample without saving. Do this for as many samples as desired. Once finished you can press ctrl C in the terminal running scanVis.py to shut the program down and export OUTPUT_FILENAME.txt to the laptop computer using a flash drive, cloud storage service or Filezilla and move it to the AutoTSI/TestData directory.

Halt the running mission on Mission Planner and move the telemetry log to the AutoTSI/telemLogs directory. The saved samples can now be processed into a data frame, exported as a spreadsheet, and mapped onto a plot. The GitHub page with the software shows an example of a simple pipeline to process the data for the stationary sampling method a dynamic sampling method. The shape file for your region can be found online from services like Google Street Maps. If not provided, it will default to the Gainesville Florida map which will show a white background for other regions. The final output will be the map of measured trees and a spreadsheet detailing the DBH, basal area, and basal area per hectare.

Validation and characterization

The device accuracy in a controlled setting was tested on objects with a perfectly circular cross-section. In this controlled setting 5 objects of known diameter (Fig. 10) were measured and tested against the outputs from the LiDAR based system using the operation detailed above. Hand-measured diameters were obtained using calipers to the nearest 1/10 of an inch. The results of the test are shown in Table 1. It was found that the percent error was low, with a maximum absolute percent
error of 4.5%. While this test proved the concept of the device worked as intended, it was necessary to do further testing to demonstrate performance on real trees, whose cross-section are more irregular than manufactured objects.

A second test was conducted in the intended environment, on the intended objects designed to be measured, trees. The result of this test is shown in Table 2. A plot showing the bias tendency of the device is shown in Fig. 11. Hand-measured diameters were obtained by measuring the trees circumference 4.5 ft (1.37 m) from the ground with measuring tape and recording to the nearest graduation mark which were in 1/16 of an inch.

The tested forest environment was a managed tree farm which undergoes prescribed burns approximately every-two years and is reflective of typical tree farms in the Southeastern US. Overgrown environments with tall brush would be expected to reduce measurement accuracy, however, this is not a use case this sensor is aimed at. We also expect adventi-
tious roots, stem galls and other epicormic growth to cause variations in the measurements. However, as this is a manually operated instrument, we expect the operator to make minor adjustments to the LiDAR FOV as the survey progresses.

Note that the variation in percent error, absolute error, and absolute percent error in the controlled environment test (Table 1) is not strongly correlated with diameter or distance from the LiDAR. The fit \( R^2 \) ranges from 0.038 for absolute error versus DBH to 0.322 for percent error versus distance which logically indicates bigger trees are slightly more easily estimated. The two objects with the largest absolute percent error are both metallic and non-white in color. We believe that the metallic surface finish and dark color contribute to specular scattering off the surface which reduces accuracy. These issues are not expected to be present on trees (as demonstrated in field tests). In the intended forest environment, the fit \( R^2 \) is 0.906 for percent error versus DBH showing that measurement error predictably increases as tree sizes approach higher and lower extrema. The linear relationship shown in Fig. 11 means that this error can be corrected post hoc using a linear debiasing calibration with high accuracy \( R^2 > 0.9 \).

| Hand Measured Diameter [cm] | AutoTSI Measured Diameter [cm] | Percent Error [%] |
|-----------------------------|-------------------------------|------------------|
| 3.9                         | 4.0                           | 0.8              |
| 6.8                         | 7.1                           | 4.5              |
| 10.8                        | 10.5                          | −3.2             |
| 18.3                        | 18.4                          | 0.8              |
| 23.4                        | 23.1                          | −1.0             |

| Hand Measured Diameter [cm] | AutoTSI Measured Diameter [cm] | Percent Error [%] |
|-----------------------------|-------------------------------|------------------|
| 44.5                        | 42.3                          | 4.8              |
| 40.4                        | 38.9                          | 3.7              |
| 59.9                        | 64.6                          | −7.7             |
| 43.4                        | 40.8                          | 6.1              |
| 24.1                        | 21.5                          | 10.7             |
| 29.0                        | 26.6                          | 8.1              |
| 51.1                        | 52.2                          | −2.2             |
| 61.5                        | 66.1                          | −7.5             |
| 27.4                        | 23.4                          | 14.8             |

**Fig. 11.** Bias plot of hand-measured versus LiDAR measured values.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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