

# 3D Characterization of Apple Tree Architecture for Precision Pruning and Crop Load Management

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The sustainable growth of the apple industry relies on managing apple trees with optimal architectural traits, which significantly influence their growth, fruiting potential, and environmental interactions. For instance, tree height affects light exposure to lower branches, impacting fruit yield and quality, while trunk diameter helps determine the ideal crop load. Accurate assessment of these traits is crucial for maximizing orchard productivity and fruit quality.

Traditionally, apple tree traits have been measured manually using tools like tape measures and calipers. However, these methods are labor-intensive, subjective, and often inadequate for capturing the complex architecture essential for fruit production. Visual inspections might miss subtle differences in branch angles or lengths that affect fruit distribution and overall yield, and the intricate structure of trees can make it difficult to take accurate measurements in the field.

Optical sensing technologies, particularly imaging, are becoming increasingly popular due to their noninvasive, versatile, and cost-effective nature (Jiang et al., 2020, Jin et al., 2021, Li et al., 2014). These technologies provide detailed insights into plant architecture and physiology, driving interest in advanced imaging and machine learning (ML) methods for more precise and efficient trait characterization. Leveraging these technologies can overcome the limitations of traditional methods, leading to a better understanding of tree traits and improved orchard management.

Previous research on apple tree characterization has mostly focused on specific aspects, like branch detection (Zhang et al., 2020), fruit detection (Gené-Mola et al., 2020 and Dong et al., 2023), and leaf area analysis (Tsoulis et al., 2022), rather than providing a comprehensive view of tree architecture. A recent study explored the use of TreeQSM (Quantitative Structure Models) and Terrestrial Laser Scanning (TLS) to analyze apple tree branches, achieving high accuracy in detecting and estimating the number of primary branches (Zhang et al., 2020). However, the study also revealed limitations, such as the need for high-resolution TLS devices and the variability introduced by random seed-based tree reconstruction, which hinders consistent measurements critical for agricultural management. Furthermore, the study focused on non-trellised apple trees, which resemble natural trees and avoid some challenges related to data quality in trellised systems. Therefore, new methodologies are needed to address these challenges and improve the characterization of apple trees, particularly in modern orchards with trellised tree training.

This article is to introduce the latest development of AppleQSM (Qiu et al., 2024), a comprehensive characterization pipeline that uses TLS point cloud data to quantitatively analyze architectural traits in high-density apple orchards trained with modern practices.

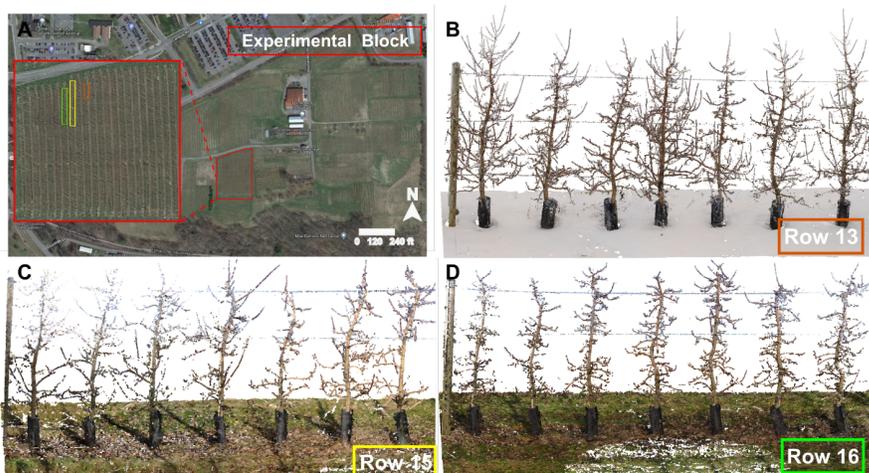
## Materials and Methods

**Field Data Acquisition.** Mature apple trees grown at Cornell Orchards (latitude: 42.445° N, longitude: 76.462° W) in Ithaca, NY, USA, were used in this study (Figure 1). Planted in 2011, these trees were spaced 3.66 meters (12 feet) by 0.91 meters (36 inches) apart and trained using the tall spindle system. The study included a total of 84 apple trees from three different rows: 9 trees from row 13 and 41 trees from row 15, both “NY1” on M.9 rootstock, and 34 trees from row 16, “NY2” on B.9 rootstock.

The focus of this study was on characterizing tree architecture. To achieve this, data acquisition trials were conducted during the offseason, with three collection sessions held between February and April 2022. This period was chosen to ensure maximum visibility of tree trunks and branches. A terrestrial laser scanner (TLS) (FARO Focus S350, FARO Technologies Inc., Lake Mary, FL, USA) with a 360° horizontal and 300° vertical scanning view was used to collect colored point clouds of the apple trees (Figure 2). The scanner was mounted on a tripod approximately 1.5 meters above the ground and set to a resolution of 6.1 mm at a distance of 10 meters.

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**Computer vision coupled with a pipeline (Apple QSM) for processing the images allowed us to accurately measure trunk diameter and branch diameter and angle. These digital measurements will be essential in calculating optimum crop load for precision crop load management.**



**Figure 1. Blocks at the Cornell Orchard were used for field data acquisition and example images of the point clouds for the collected blocks.**

Scanning of row 13 was performed with the goal of optimizing data quality by maximizing the overlap between neighboring scans. This trial aimed to understand the balance between the number of scans required and the resulting data quality. For rows 15 and 16, the scanning positions were adjusted to maximize both efficiency and data quality, with the distance between neighboring scans set at approximately 10 meters (33 feet). Additionally, reference points were strategically placed in the field to further enhance the quality of the point clouds.

**AppleQSM Analysis.** AppleQSM was developed to characterize apple tree architecture using full-view point clouds. It consists of four key modules: data preprocessing, tree instance segmentation, tree structure segmentation, and architectural trait extraction.

**Data Preprocessing Module:** In this module, extraneous data from the registered point clouds were removed. Due to the laser scanner’s wide field of view (360° by 300°) and multiple scanning locations, the data often included irrelevant objects like neighboring trees, trellis wires, and covers. To focus on the desired row, a region of interest (ROI) was manually selected to include only the relevant point clouds. The data was then denoised using Statistical Outlier Removal (SOR) with default parameters in CloudCompare (version 2.11.3), and any remaining non-tree data, such as tree covers and trellis wires, was manually removed.

**Tree Instance Segmentation Module:** Individual apple trees in each row were automatically segmented using a computationally efficient algorithm based on geometric features. This algorithm iteratively searched for linear units—connected point clusters that exceed a cluster-level linearity threshold—representing stems or branch segments. These linear units were then assembled into individual trees based on connectivity and topology, offering a more robust identification of small stems and thin branches compared to existing methods.

**Tree Structure Segmentation Module:** For each segmented tree, a customized algorithm was developed to identify the trunk and branches of different orders.

**Architectural Trait Extraction Module:** This module extracted architectural traits important for tree crop load management using the input point clouds and refined tree skeletons. Tree-level traits included height and trunk diameter, while branch-level traits focused on diameter and inclination angle relative to the trunk.

**Manual Measurements and Evaluation.** To evaluate the performance of the developed pipeline, reference measurements for all traits were obtained using protocols established by the apple research community and industry (Figure 3). Tree height and trunk diameter were measured for all 84 apple trees in this study. Additionally, branch diameter and inclination angle were measured for 106 branches from 9 trees in row 13. The number of branches was also manually counted from the collected point clouds using CloudCompare (version 2.11.3).

Robust linear regression analyses were performed to compare pipeline-extracted measure-

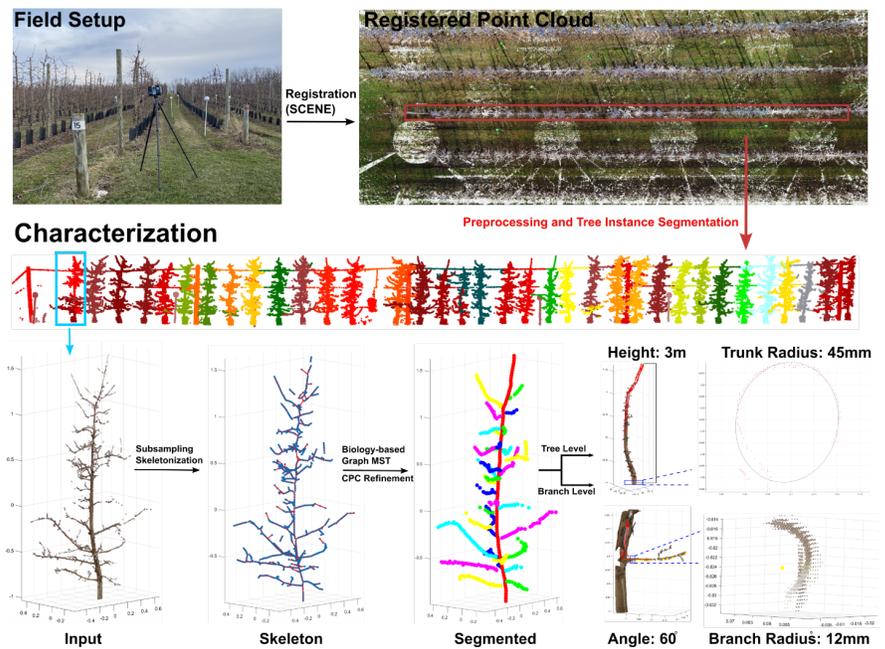
ments with reference values. Metrics used included root mean square error (RMSE) and the coefficient of determination ( $R^2$ ). Additionally, mean absolute error (MAE) and mean absolute percentage error (MAPE) were calculated to thoroughly assess the pipeline’s accuracy. All analyses and calculations were conducted using MATLAB (version R2022a). The pipeline was developed on a laptop with an Intel Core i7-10870H CPU running at 2.20 GHz, but it is compatible with any laptop that supports the specified MATLAB version.

## Results

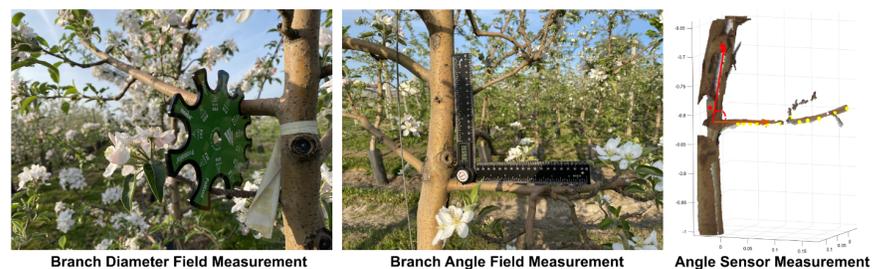
The developed characterization pipeline was evaluated at both the tree and branch levels (Figure 4). Tree height and trunk diameter calculated using the pipeline showed high correlation with manual measurements, with  $R^2$  values of 0.92 and 0.83, MAEs of 6.1 cm and 4.71 mm, and MAPEs of 1.94% and 8.3%, respectively, indicating high accuracy in measuring architectural traits at the tree level. A few outliers were noted in trunk diameter measurements due to factors such as interference from the tree rootstock’s black cover and variations in raw point cloud quality. These challenges highlighted the difficulty in developing a universal solution to address all potential edge cases

At the branch level, the pipeline achieved reasonable accuracy in measuring branch inclination angles, with an  $R^2$  of 0.69,

### Data Acquisition



**Figure 2. Flowchart of AppleQSM-based 3D characterization of apple tree architecture: from field data acquisition using terrestrial laser scanner, to individual tree segmentation, and to architectural trait extraction.**



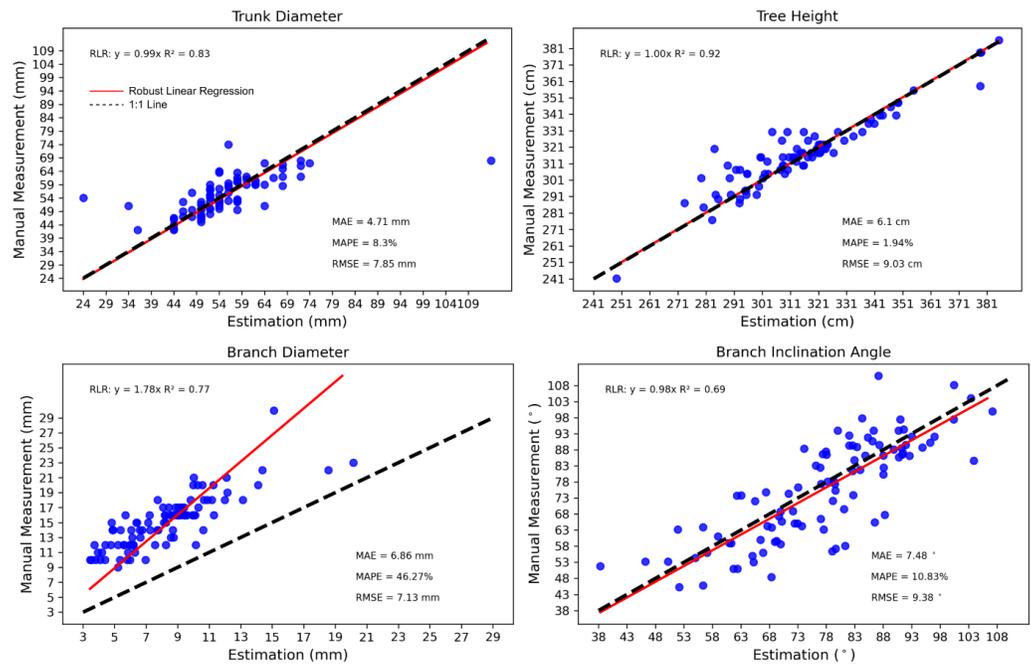
**Figure 3. Methods used to measure important architectural traits for apple trees.**

an MAE of 7.48°, and a MAPE of 10.83%. The lower correlation was primarily due to challenges in the field measurement protocol as consistent angle measurements were difficult to obtain. Field measurements with a digital angle finder were less accurate because the exact 2D projection angle between branches and trunks was hard to define and access. In contrast, the pipeline calculated angles in 3D space using point clouds, which differed from the 2D field measurement protocol, potentially increasing quantitative error.

The pipeline exhibited significant errors in branch diameter estimation, primarily due to incomplete branch point clouds. The accuracy of diameter measurements relies on fitting circles or ellipses, which requires a complete set of geometric points. When point clouds are incomplete, these fitting algorithms often perform poorly, leading to underestimation of branch diameters and resulting in large MAE and MAPE values. Even human operators may struggle to estimate diameters accurately using CloudCompare (a computer program allows manual measurements in the collected 3D images) when working with highly incomplete point clouds. Despite these challenges, the pipeline demonstrated a correlation of  $R^2 = 0.77$ , showing that the AppleQSM-based method could effectively address incomplete point clouds for branch diameter measurement to some extent.

## Discussion

The developed 3D characterization pipeline offers significant potential for utilizing TLS and geometry-based methods to assess fruit tree architectural traits at both tree and branch levels, thanks to its enhanced measurement accuracy, objectivity, and throughput. In the context of apple research and production, this pipeline could greatly improve the prediction of crop load potential, providing the accuracy and efficiency necessary for precision crop load management. Estimating crop load potential during the off-season is crucial for guiding tree pruning and crop thinning during the growing season. Traditional mechanical pruning, which relies heavily on human experience without quantitative data, often results in imprecise cuts and potential profit loss. By enabling accurate estimation of apple crop potential, this pipeline allows for precise mechanical pruning, optimizing the selection and quantity of branches to prune, thereby maximizing profits and ensuring high-quality apple production. Moreover, understanding apple crop load potential helps in determining the correct chemical spray applications for crop thinning, achieving effective load reduction while minimizing environmental impact. Additionally, the pipeline proved to be an effective tool for accurately and efficiently measuring branch inclination angles, which could be valuable for large-scale genetic studies of tree architecture.



**Figure 4. Regression analysis results for four architectural traits measured using the AppleQSM-based method and field manual methods.**

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