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Rapid Tree Diameter Computation with Terrestrial Stereoscopic Photogrammetry

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Abstract

Forest inventorying is time-consuming and expensive. Recent research involving photogrammetry promises to reduce the cost of inventorying. Existing photogrammetry methods require substantial data-processing time, however. Our aim was to reduce data-acquisition and processing times while obtaining relatively accurate diameter estimates compared to manual and other digital measurements. We developed an algorithm to identify the ground and measure diameter at breast height (dbh) or any height along a stem from the recorded video footage of trees taken with a stereo camera. Footage acquisition time, dbh root mean square error, and mean absolute error were used as comparison metrics with other methods. The time to perform three recordings for 40 trees was about 30 minutes. We recorded data at 1 m, 3 m, and 5 m from the trunk, and our dbh root mean square errors were 1.28 cm (0.50 in.), 1.47 cm (0.58 in.), and 2.57 cm (1.01 in.), respectively, using manual measures as the control. This terrestrial stereoscopic photogrammetric method is much more efficient computationally than popular terrestrial structure-from-motion photogrammetry and substantially lowers time, costs, and complexity for data acquisition and processing compared with terrestrial laser scanning.

Keywords: forest inventory, stereoscopic photogrammetry, tree diameter, depth image, TSP

Accurate, up-to-date data on individual trees in a forest are vital for proper forest management. The traditional method of analyzing forest attributes involves measuring each tree or a sample of trees by hand, which is time-consuming and expensive. Terrestrial laser scanning (TLS) provides accurate measurements of forest attributes, but the cost of the equipment is substantial (Othmani et al. 2011, Bauwens et al. 2016, Pierzchała et al. 2018). Ground-based, structure-from-motion (SfM) photogrammetric solutions have emerged in recent years as an alternative method to individual tree surveys (Liang et al. 2015). The primary advantages of SfM photogrammetry are the reduced cost of hardware compared to TLS, and a reduction in data acquisition time compared to manual methods.

Management and Policy Implications

Forest land occupies 766 million acres, or 33 percent of the total land area of the United States (USDA 2014). In 2003, there were 10.3 million family forest owners, but only 3 percent had a forest-management plan (Butler and Leatherberry 2004). Landowners require up-to-date, accurate figures describing the quantity and character of trees under their supervision. The massive amount of forest land in the United States is far too expensive to survey, and family forest landowners oversee a significant portion of this forested area. Reducing the cost of performing an inventory and analysis will lower the barrier of entry for this large population of private forest owners. Research regarding methods for efficient, scalable, and precise inventory and analysis of individual trees is crucial to meet this goal. Contemporary systems such as terrestrial laser scanning are cumbersome and expensive. In this paper, we demonstrate a low-cost, rapid photogrammetric method for estimating tree diameters that requires little operator expertise for data acquisition.

Liang et al. (2014) demonstrated the ability of a consumer camera to report a diameter at breast height (dbh) root mean square error (RMSE) of 2.39 cm (0.94 in.). Forsman et al. (2016) employed an array of cameras to report the dbh of trees with a 2.8–9.5 cm (1.1–3.7 in.) RMSE with a data acquisition time of 30 minutes for a plot 30 m (98 ft) in diameter. Fan et al. (2019) demonstrated a photogrammetric system that reported dbh with 2.08–2.54 cm (0.8–1.0 in.) RMSE and generated geo-spatial statistics. State-of-the-art solutions that are simultaneously low-cost, highly accurate, and practical are rare. We describe a method to measure tree dbh with a stereo camera that costs US$179 with similar data-acquisition times and RMSEs of SfM photogrammetric solutions.

Materials and Methods

We used an Intel RealSense D435 stereo camera to capture images of the sampled trees. The D435 camera was linked to a laptop (Microsoft Surface Pro 3) via USB and carried by hand through the plot. Microsoft Visual Studio 2017 was used as the development environment to write software in the language C++. The Intel RealSense Viewer application was used to record footage and tune parameters of the camera. The settings employed during our recordings gave us a maximum detectable depth of 6.5 m (21.3 ft) away from the camera with 1/10 mm (0.0039 in.) image resolution. All other settings were defaults. The stereo camera was calibrated using a paper target supplied by the Intel RealSense development team before recordings. All scatter plots were generated using the matplotlib module for Python 3. The functionality of our algorithm is not tied to the use of this particular camera model. Any stereo camera can be used in tandem with our method.

Stereo image recordings were performed on one tree at a time from measured distances of 1 m, 3 m, and 5 m from the trunk. We surveyed 40 trees in total in the same plot at Martell Forest, which is owned by the Department of Forestry and Natural Resources of Purdue University in West Lafayette, IN. In order to assess the computed diameters, individual trees were measured by hand with a diameter tape. The camera was held such that its two CMOS sensors were oriented vertically rather than side by side. In the side-by-side orientation, each CMOS sensor observed a region of the trunk hidden from the other sensor, a phenomenon called occlusion. The occluded areas interfered with the stereo image matching and prevented the camera from determining the depth on the sides of the trunk. A similar phenomenon is experienced by covering one eye and seeing with the other, then alternating the covered and open eye. Each eye observes a region that the covered one cannot. Vertical camera orientation caused the CMOS sensors' field of vision to encompass a greater common area of the trunk, which reduced occlusion.

The separation of the background from the foreground of the depth image was performed by enforcing a range (minimum and maximum) of valid depths, and ignoring depths outside this range. The minimum depth was set at 0.5 m (1.64 ft) for all recordings to ignore invalid depths reported by the camera as 0 m away. According to the RealSense development team, the depth RMSE error scales quadratically with distance. Since further depths will be less accurate, the depth cutoff is tuned to filter depths beyond the trunk. The maximum depth cutoff was chosen according to the distance from the tree the recording was taken. For example, the 3-m recordings used a maximum depth cutoff of 4 m to reject objects further than 4 m but include the tree trunks.

A trunk base scanning (TBS) approach was used when the bottom of a tree trunk was visible in recordings taken 3 or 5 m from the trunk. In this approach, we inferred the intersection of the ground depth and trunk depth to determine the breast height of each trunk. The boundary where the ground met the maximum depth cutoff appeared distinctly on the image. This boundary was used as a reference location to measure the average trunk depth. Then, the average trunk depth was compared to the ground depth at different distances. Starting from the boundary, the forest floor was identified as the first row of pixels for which the ground depth was within 10 percent of the average trunk depth. The pixel row corresponding to the 1.3-m mark above the calculated ground line was determined using a function provided by the Intel RealSense API to measure distances on the image.

A close-range scanning (CRS) approach was implemented at 1-m distances from the trunk, where the forest floor was not visible from the camera, and ground scanning could not be performed. We assumed that breast height was found at the middle of the image, because the camera was held level at breast height during the recordings.

Consecutive pixels that were within the depth cutoff at breast height represented partial trunk cross-sections. Directly measuring the dbh as the width of these consecutive pixels is not accurate because the entire diameter of the trunk is not visible in the image. Instead, a geometric relation between the dimensions of the consecutive pixels and the radius of the trunk was used (Figure 1).

Let C be the position of a stereo camera. Assume a tree trunk is a cylinder. Let $CD = CE = a$ be the tangent lines from the camera to the start and end of the consecutive pixels. Let $DF = EF = b$ be half the width of this row. Let $AD = AE = r$ be the radius of the tree. Since ΔCDF and ΔCAD are similar triangles, we have

$$\frac{a}{b} = \frac{AC}{r} \tag{1}$$

Applying the Pythagorean theorem, we have

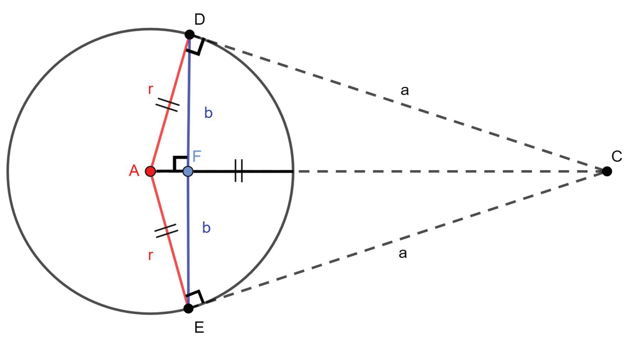

Figure 1. Geometric diagram of trunk-diameter computation.

$$r^2 + a^2 = AC^2 \tag{2}$$

We then obtain

$$r = \frac{ab}{\sqrt{a^2 - b^2}} \tag{3}$$

Each frame of the footage reported a dbh, and published it to a list of dbh values. The frame rate of the camera was 30 Hz, and the three recordings of each tree at various distances lasted a few seconds. This resulted in at least 300 frames per tree. After the footage was analyzed, the final reported dbh was the average value of the dbh list after removing outliers, which were values more than 1.5 times the interquartile range from the median (Tukey 1977).

Results

In total, 120 recordings were performed on 40 trees in about 30 minutes. About 10 seconds of footage, or 300 frames, were recorded and processed for a tree. About 12,000 frames in total were processed for all the 40 trees. It took 3 minutes and 18 seconds to process all footage using CRS approach, and 2 minutes and 40 seconds to process the 3 and 5-m footage with TBS approach. Estimated dbhs using both the TBS and CRS approaches were virtually identical to hand-measured dbhs for a range of tree diameters (Table 1; Figure 2). Footage taken 1 m from the trunk with the TBS approach was not processed because the forest floor was not present in images taken at that distance. Our algorithm estimated breast height on images close enough to 1.3 m to permit accurate dbh estimates (Figure 3).

Table 1. Errors in computed dbh using two different scanning settings.

Distance (m)	Algorithm	dbh RMSE (cm)	dbh MAE (cm)
1	CRS	1.28	1.01
3	CRS	1.33	1.13
5	CRS	3.1	2.32
3	TBS	1.47	1.23
5	TBS	2.57	2.25

Note: The error in computed dbh across all 40 trees at different distances was calculated using either the CRS approach or the trunk base scanning approach. CRS, close-range scanning; dbh, diameter at breast height; dbh MAE, mean absolute error of the computed dbh; dbh RMSE, root mean square error of the computed dbh; TBS, trunk base scanning.

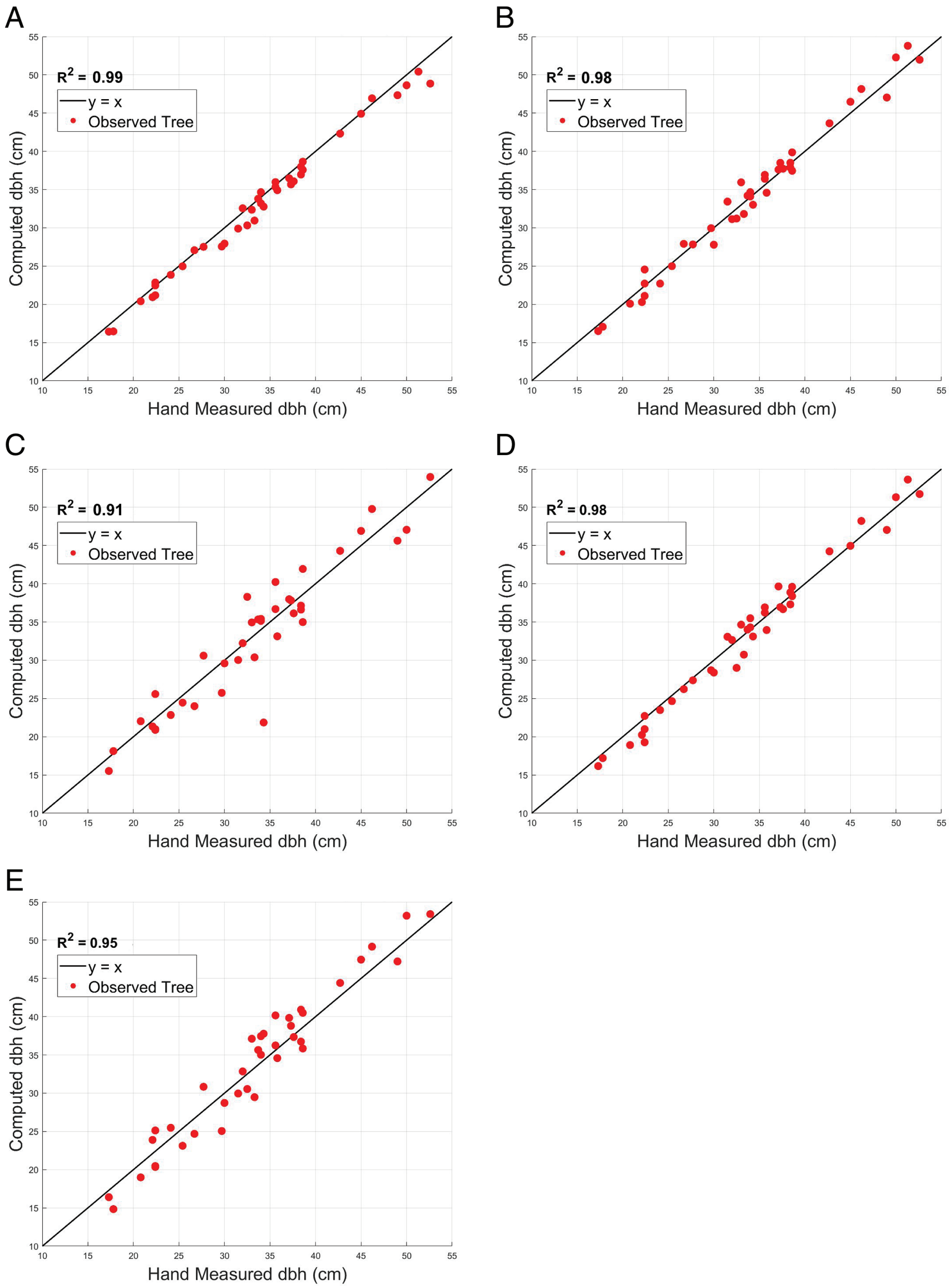

Figure 2. Scatter plots of measured dbh versus computed dbh using different methods. The dbh values were estimated using the close range scanning (CRS) approach at 1 m (a), 3 m (b), and 5 m (c), or the trunk base scanning (TBS) approach at 3 m (d) and 5 m (e).

Discussion

The dbh estimates we obtained using the TBS and CRS approaches on video images taken with the Intel RealSense D435 stereo camera were reasonably accurate (Table 1). Terrestrial stereoscopic photogrammetric (TSP) estimation of dbh is subject to several types of systemic error, however, including the error caused by misalignment of the camera. If the camera is not held perpendicular to the ground, it causes elliptical cross-sections, rather than circular ones, to be used for estimating dbh. The resulting error is equivalent to that encountered with hand-made measurements where the plane of the d-tape is not entirely perpendicular to the axis of the tree stem. The tilt error can be reduced by using a gimbal mount for the camera. It is also possible to design an algorithm that detects and corrects tilt encountered because of misalignment while performing recordings. At 3 m, the CRS approach obtained a

Figure 3. Visual comparison of computed and measured breast heights. A composite color and stereo image that illustrates the actual breast height of the trunk (orange paint) and the computed breast height marked with a stippled white line. Occluded regions appear black because of the inability to cross-reference the stereo images in those locations.

smaller RMSE than the TBS approach. The use of CRS should be limited to 3 m, however. The middle row of pixels from the depth image cannot produce a reliable estimation of dbh at distances greater than 3 m because tilt or misalignment during recording results in an estimation of dbh that is not at breast height. At distances greater than 3 m, stabilization of the camera is required to ensure that dbh estimates using the CRS approach are accurate.

The TSP method we have developed to calculate the dbh of trees in the forest seems more efficient and effective than the existing digital methods, although an unbiased comparison is difficult (Figure 4). The times reported by each author were scaled to the time to process 60 trees for comparison. Many methods using TLS require long data-acquisition times because equipment must be moved to different areas of the plot to obtain a complete map of the plot. One major benefit of our method is that the data-acquisition time is limited to around 3 seconds for a single scan of an individual tree.

In terms of accuracy, we demonstrated a 1.28-cm dbh RMSE and 1.47-cm dbh RMSE 1 and 3 m from each trunk, respectively. The lowest dbh RMSE reported by recent research papers using SfM photogrammetry was 1.80 cm (Mikita et al. 2016) and 2.08 cm (Fan et al. 2019). A limitation of our current algorithms is that they can calculate the dbh of only one tree at a time, and that the recorded images contain only a single tree in the frame at a time. This is not a limitation of SfM photogrammetry, but a shortcoming of our algorithm that we intend to address in the future. In order to analyze multiple trees in the same frame, each tree must be identified across multiple frames in which it appears. An object-detection method is required to ensure that the dbh of each tree is reported correctly. Our algorithm, even with this restriction, is able to consistently and efficiently report relatively accurate dbhs.

Conclusion

We demonstrated the use of a TSP algorithm to report dbh in a plantation environment. This algorithm involved ground-based optical scanning with a stereo camera to generate depth images that provided distances from the camera to locations in the plot. Either videos or still photos can be taken with the camera. The algorithm consists of depth image generation, stem base identification, and diameter determination along the stem. This TSP method is more efficient computationally than popular terrestrial

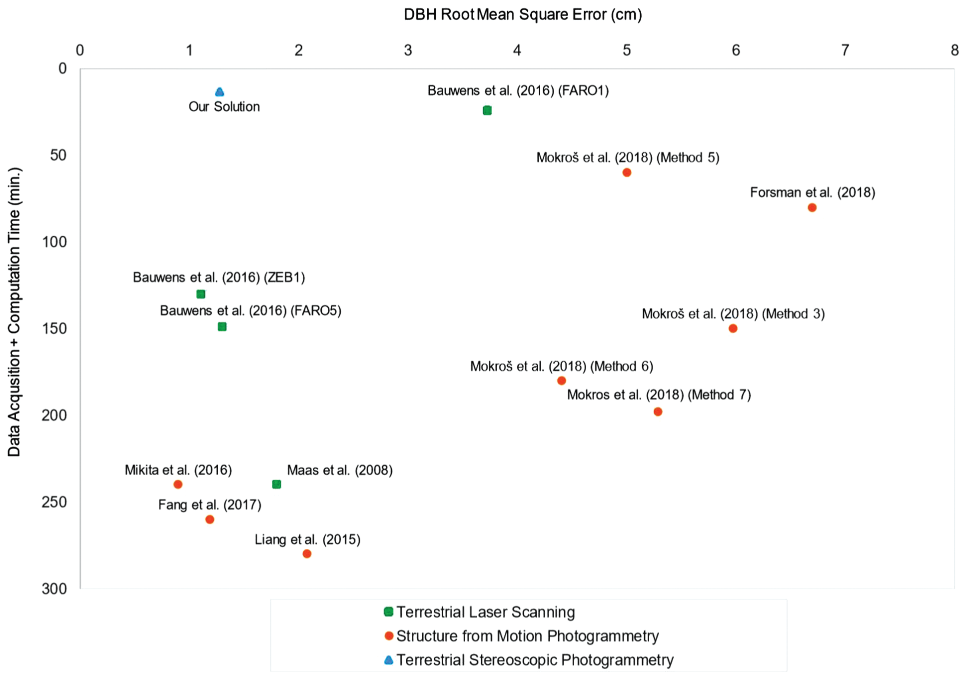

Figure 4. Data acquisition and computation time for 60 trees versus diameter at breast height (dbh) accuracy: time (seconds) to acquire data and compute dbh versus dbh root mean squared error for several recently published results. The vertical axis was calculated from published data adjusted to 60 trees, including setup time for each tree. We downloaded the software mentioned by authors that generated photogrammetry point clouds, and computed the time to align 400 images. Visual structure from motion was used to approximate point cloud computation time for Liang et al. (2015), Fang et al. (2017) and Mokroš et al. (2018), because the software they used was not listed. In all cases, the time required for data acquisition and subsequent computation was scaled linearly with the number of trees for which data were reported. For authors who implemented laser scanning (Maas et al. 2008, Bauwens et al. 2016), we assumed that it took no time to align each scan, and the run time purely depended on the number of data points and our machine's computing speed. Authors who demonstrated multiple methods are listed on the scatter plot with the name of the method mentioned in their respective papers.

SfM photogrammetry and lowers time, costs, and complexity for data acquisition and processing comparing with TLS. The accuracy of tree-diameter measurements with TSP algorithm is comparable with, if not better than, that of sophisticated SfM and TLS methods. The stereo camera, purchased in August 2019, used in our methods cost only US$179, which is more affordable than laser scanning systems. The software runs on a laptop computer, making it possible to realize real-time extractions of tree parameters on the ground. The next step of this research is to pair geo-spatial information for each tree with its parameters.

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