3D RECONSTRUCTION OF A TREE STEM USING VIDEO IMAGES AND PULSE DISTANCES

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ABSTRACT

This paper demonstrates how a 3D tree stem model can be reconstructed using video imagery combined with laser pulse distance measurements. Perspective projection is used to place the data collected with the portable video laser-rangefinding device into a real world coordinate system. This hybrid methodology uses a relatively small number of range measurements (compared to laser scanner instruments) and convergent videogrammetry (rather than the traditional stereo approach) along with stem model assumptions to create the stem reconstruction. Multiple video frames are stitched together to increase the accuracy of and to validate the orientation parameters from the multi-sensor device's inclinometers. The 2D representation of the stem from the image data at a single viewpoint is combined with the additional range data to formulate a 2.5D model. Combining multiple vantage points aids in completing the 3D model and filling the gaps where data are absent.

INTRODUCTION

It is evident that trees have certain definitive characteristics. In fact, data structures have been named "trees" after their woody counterparts due to their hierarchical branching arrangement. Unfortunately, spatial data analysis of the crown or canopy portion of the stem is limited due to inaccessibility and difficulty of observance caused by the juxtaposition of many branches in a small volume of space.

Stem models are desired for a number of reasons including product valuation (Cost, 1979), radiative transfer models (Martens et al., 1991, Sinoquet et al., 1997) and display for architechural landscape modeling (Shlyakhter et al., 2001). The problem of existing methods for collecting stem model data is the amount of time and manual inputs needed. Even such high-tech methods such as the spatial digitizers presented by Smith and Curtis (1995) take a lot of time, and construction of scaffolding or other structures to provide physical access to the branches is impractical for many studies.

Remote sensing methods offer the most promise for rapid 3-D data collection of tree crowns. However, remote sensing also has its difficulties. One particular problem with terrestrial remote sensing and tree crowns is the location of the sensors so that the stem portion to be measured is visible, whether by optical or other electromagnetic means. Assuming the sensor height is limited to within a couple of meters of ground height, distance and direction are the only parameters that can be manipulated to obtain this visibility. A compound problem is the compromise between resolution and perspective. Precise diameter measurements require sufficient magnification (Grosenbaugh, 1963). Working against this goal, accurate height measurement based on trigonometric measurements requires distant viewpoints to avoid large perspective angles. Often dense forest conditions limit the practical distance from which a stem can be observed. An instrument such as the Barr & Stroud dendrometer (Brickell, 1976) combines well the magnification needed for diameter measurements with the ability to observe and measure from long distances. 3D stem representation requires an extraordinary number of height, diameter, and location measurements to be collected, which would render manual, individual collection of these points impractical.

Traditional parallel stereo photogrammetric methods could be employed to derive the z-axis coordinates (depth) but the difficulties would be manifold. Twice as much data would be required from each viewpoint compared with the method proposed in this paper. This would not reduce the number of viewpoints needed since there would still be many branches that would be occluded or obscured. It is unlikely that the stereo matching problem could be easily automated given the small distance to depth ratio, irregular lighting, and varying spectral responses of the same point between the left and right images. It has been noted (Byrne & Singh, 1998) that a hybrid optical and laser ranging instrument would be the most promising remote sensing solution for 3D tree measurements.

This paper presents a portable video laser-rangefinding device, having sufficient image magnification and the ability to scale these image data for the reconstruction of a tree stem into three dimensions. Details about the instrument and field data collection are briefly presented. Raw data processing methods, from data synchronization and filtering to coordinate system definition and measurement agreement, are reported. Finally, some remaining problems are identified and continuing research plans are addressed for the consummation of a 3D tree stem reconstruction tool.

TMS INSTRUMENT

The TMS instrument is a pulse laser-rangefinder with a 3-axis inclination sensor, and a charge-coupled device (CCD) video camera mounted so that the field of view (FOV) is directed through the unit's heads-up-display. This provides the spatial correspondence between the camera and the range data. The FOV of the custom lens system is 5.5 degrees high by 8.24 degrees wide, which would be equivalent to about at 250mm zoom on a 35mm camera. This results in an output pixel resolution of 0.2 mm per meter of object space distance. A portable videocassette recorder (VCR) is used to collect and store the video data. Currently the video data are transported over an analogue video cable and the range and orientation (RO) data are written to a memory card. This necessitates the synchronization of these two data streams before they can be used symbiotically. More details of this instrument can be found in Clark (2000), Clark et al. (2001), and Kee & Clark (In press).

FIELD SAMPLING

Proper field data collection is integral for a successful automated measurement system. Most standard methods of field data collection output real-time measurements which can be screened for blunder errors by the forester on the spot. In its current state, the TMS measurements are not calculated until processing back at the office. This poses difficulties if the data are not collected properly in the field. The automated data processing functionality is cued by various conditions of field data collection. The definition of the stem base, determination of tree height, and the guidance of the stem segmentation procedures are reliant upon a methodical field sampling procedure.

Subsequent to locating a suitable stem viewpoint at a distance approximately equal to the highest desired point to be measured, data collection begins by aiming the instrument at the lowest unobstructed location on the stem. The instrument is then declined until the ranging point is directed at the point representing the stem's base. As with most hypsometers, a base angle and sometimes distance is required to be measured at either ground or stump height. In this study, ground height on the uphill side will be used as the base angle. It is crucial that the TMS instrument operator does not decline the instrument below this position as the current software uses this point as the base angle.

The instrument is then slowly scanned up the stem to the point representing the highest desired point (i.e., total tree height). When branch data are needed, as in this study, start with the lowest branch extruding from the right of the stem and trace each branch out to the end. Return to the stem axis and trace the next branch in the counter-clockwise direction. Branches that have directions that closely coincide with the direction of the camera axis are omitted. Tracing each branch is important, as the motion vector is an important parameter used to drive the segmentation algorithm. Following each adjacent branch in the counter-clockwise direction also eases the computational complexity, as well as, prevents the field worker from omitting branches. Figure 1 shows sequential data collection from a single viewpoint. Notice the pitch (inclination) value drops to the lowest point then steadily rises to the highest point. Subsequently the branches are traced, as indicated by increasing azimuth values followed by a sharp decrease back to the stem axis value.

ALGORITHM DEVELOPMENT

Shlyakhter et al. (2001) present a method of constructing 3D tree models by backprojecting multiple polygonal tree silhouettes into cones. Then from multiple camera poses, the intersections of these cones are determined and used to form a visual hull. A closed polygonal mesh is derived from the visual hull and Voronoi nodes are automatically assigned to points representing major branch tips. "Interesting vertices" are determined by tracing rays from the branch tip nodes back through the medial of the convex hull toward the base of the stem. A hierarchy of convex hulls is formulated using additional vertices. Tree skeletons (branching structure) are formed from this hierarchical nodal structure. L-systems (Prusinkiewicz 2002) were then used to “grow the tree” model smaller branches and leaf structure for the graphic rendering. The result is a semi-realistic rendering of an actual tree. This method was used on foliated stems, and the authors indicated that the skeleton model often differed quite a bit from the actual stem. As of the time of the publication of this paper, no work had been done on nonfoliated stems.

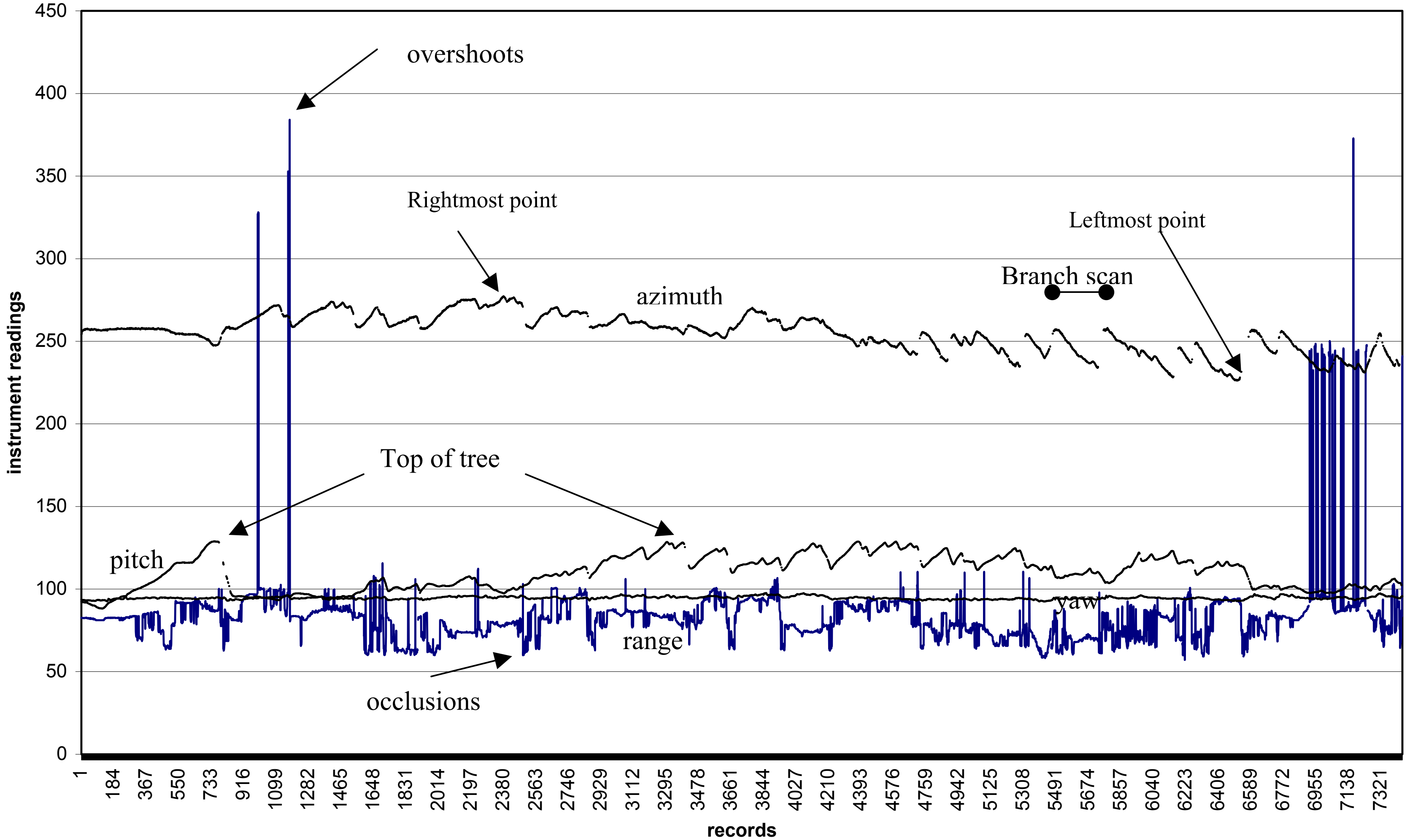


Figure 1. Graph of seqential range, azimuth, pitch, and yaw. These 7500 points collected in 7.5 minutes

Multiple overlapping layers, when visualized from a single viewpoint, would present multiple solutions that would be difficult to solve using backprojection intersection. This is one of the problems using nonfoliated stems. With the convex hull model as used by Shlyakhter et al.(2001), only the outer extremities are used with no consideration given to overlap. The motion field information combined with range data are used in this study to determine the location of each branch in x, y, and z coordinates, eliminating or making easier the task of point correspondence from different viewpoints.

Once data have been collected, quite a few procedures are used to process the data intelligently. First, the instrument RO data are synchronized with the video sequence and the appropriate frames are captured as still frames. Overshoots and occlusions (Figure 1) are filtered from the range data. There is error in the orientation data as well. Inclination or pitch (rotation about the x axis, ω) is probably the most important place this error will affect the output, especially at the extremes. Previous studies (Clark et al., 2001) using TMS data have often used individual frames with manually correlated RO data. There is the potential that a one degree error in ω combined with tree lean, can result in an error in tree height estimation that would be beyond acceptable limits. Inclination data are used in a reciprocal process with image mosaicking to increase the accuracy and precision for ω for each frame. Next, the stem sections are segmented from the background and edges are found. This provides us with dimensional information along the defined stem. Range data are then applied to truncate the conical area of the perspectively projected space. This provides enough information for a 2.5D representation. However additional viewpoints at sufficiently disparate azimuths (i.e., perpendicular to first view) provide the ability to observe branches which may have be obscured or occluded from other viewpoints or just to provide verification and increase precision of the other estimates.

Data synchronization

Currently, data are collected simultaneously in two streams with the TMS instrument. Ranging data are subsampled from 238 pulse measurements per second down to 10 output records per second with associated orientation information. These data are written to a removable static random access memory (SRAM) card inserted into the unit. The video data are sent to the miniDV portable videocassette recorder (VCR) via a video cable. Current software uses time to synchronize the data streams. RO data are uploaded from the SRAM card to the processing computer. The software program filters the range data for noise and instability and flags capture time (CapT) records. These times are used in the frame capture procedure. Because of the defined data collection protocol, the frame capture procedure can be automated. RO data capture begins concurrently with the powering on of the camera in the field. Thus the two data streams share a common starting point in time. So when the synchronization process begins, the software program searches for the beginning of the video collection and initializes a time counter. Using data streaming rates of 10 records per second for the RO data and 30 frames per second for the video capture, the frame capturing algorithm then captures the frames every (CapT record number divided by 3) seconds. This occurs in a loop for all of the capture times until a viewpoint delimiter is encountered. This is the reason that uninterrupted field data collection must occur for each viewpoint. This nested loop process begins again for each viewpoint within each tree until all files have been processed. The captured frames are saved as 24 bit RGB bitmaps to a hard drive and an associated ASCII text file is saved which links the RO records to the captured frames for later processing.

Range Filtering

The streaming range data collected by the TMS instrument are the most variable of the RO data elements collected (Figure 1). This is the result of capturing ranges to non-target-tree objects either in the foreground or background. Unless a completely unobstructed viewpoint can be selected in a forest, range measurements of understory vegetation and other objects in the foreground are unavoidable. Overshoots are more rare, but occasionally the operator may misdirect the instrument, especially near the top of the tree where the stem is thin. Most of the image capture and mosaicking functionality is conditioned upon the inclination and azimuth data, however the range data are critical to the dimensional calculations. For 3D reconstruction, the range data are also required to determine the direction of branches.

As previously mentioned in the field data collection section, an unobstructed initial range to a point on the main bole is essential to use as a basis for the validation of other ranges. Horizontal distances are calculated by

$$HD_p = R_p \cos(\omega_p) \tag{1}$$

where HD_p is the horizontal distance, R_p is the instrument measured range, and ω_p is the instrument measured ω rotation from level of a instrument recorded point p. Horizontal distances, of points on the main bole near the same height of the original range point, that differ by less than 1.8 meters from the horizontal distance of the original range point are kept and considered "good". Missing or noisy values that lie between "good" ranges are replaced by interpolated values. Noisy values below the lowest "good" range and above the highest "good" range are extrapolated based on overall stem lean from their nearest "good" range. In this way, most occlusion and overshoot outliers are eliminated while allowing for some reasonable stem form anomalies.

Mosaicking and Inclination adjustment

It was determined that some corrections needed to be made after examining measurement bias from previous studies (Clark et al. 2001) indicating possible instrument ω reading or synchronization errors. At nearly perpendicular angles to the stem axis, this error does not pose a great problem, however as angle between the stem and optical axes becomes more acute (this is also usually coupled with increased range, i.e., near the tops of the trees) the effects can become quite severe. A 1 degree error can result in a height estimation error of several feet and consequently a mismatched diameter estimate.

Mosaicking is used with the TMS system to increase the precision of individual video frame position and for a user-friendly graphical user interface (GUI). As each video frame has the potential to be 0.4 to 1.0 degree off from it's true location, combining adjacent spatial data of these highly magnified scenes would be noisy in regards to the assumption of a topologically continuous structure. The mosaicking procedure uses the inexact measurements from the instrument to provide initial estimates for image matching. When the image matching is accomplished, the parameters are used to adjust the coordinates to a reference frame. This process is described more in depth by Kee & Clark (In press) in this same publication. Successfully mosaicked frames reduce the relative error between frames to ±0.023 degrees in each direction, which is visually undetectable and mensurationally insignificant at the distances considered for a typical stem sampling situation. Figure 2 shows an example mosaic.

Stem image segmentation

To get to the stage where actual measurements can be automatically determined, the computer has to be taught what it needs to measure. Stem dimensions, heights and diameters, are the primary informational outputs desired at this stage. Therefore, image segmentation has to be implemented for the determination of image coordinates of interest that will later be used for calculations of stem dimensions. After segmentation is performed, additional analysis must be performed to filter out occlusion and background noise.

The typical subcanopy video frame consists of only four classes: stem, leaves, ground, and sky. Characteristics that are known about each of these classes provide us with knowledge of how to create a segmentation algorithm. The sky is always bright, with blue hue if any present, and has a high probability of being present in the frames of the upper portion of the stem. Texture is normally very low or absent for sky regions. Leaves are always green, except when they are white due to direct reflectance caused by their orientation or when they are blue around the edges. The ground is difficult to define at times, but it is the default background in the lower images. Spectral separation is easy for many of these classes. However, all bright pixels may not be sky or leaf reflections. If the stem is in a position to reflect sunlight, bright pixels may be in the stem class. In the lower inclined frames, often the brightest pixels are of the leaf or stem class since sky is absent. Consequently, a single segmentation algorithm with fixed classifications and thresholds may not function well for subcanopy video data.

Many tools are available for image segmentation based on fundamental image characteristics such as intensity, color, and texture. The methods for digital image segmentation published in the literature are typically very generalized and designed for global image segmentation, frequently only considering each characteristic independent of the others. Human image analysis is more complex, being able to use these fundamental characteristics adaptively and in tandem with other characteristics such as topology and contextual information. Often many assumptions and correction factors are made on-the-fly and applied and verified with a large database of complex model templates. To eventually arrive at an automated robust digital image segmentation algorithm, an intelligent combination and order of these characteristics needs to be determined.

Whether in a single image frame or over the entire mosaicked sequence, separations are based on HLS (hue, lightness, saturation)(Chien and Cheng, 2002), texture (Byrne & Singh 1998), topological and contextual information (Juujärvi et al. 1998), or some combination of these characteristics. These features do not all have to be considered for every segmentation decision. Knowledge from the image characteristics and ancillary data can be used to formulate an intelligent segmentation strategy.

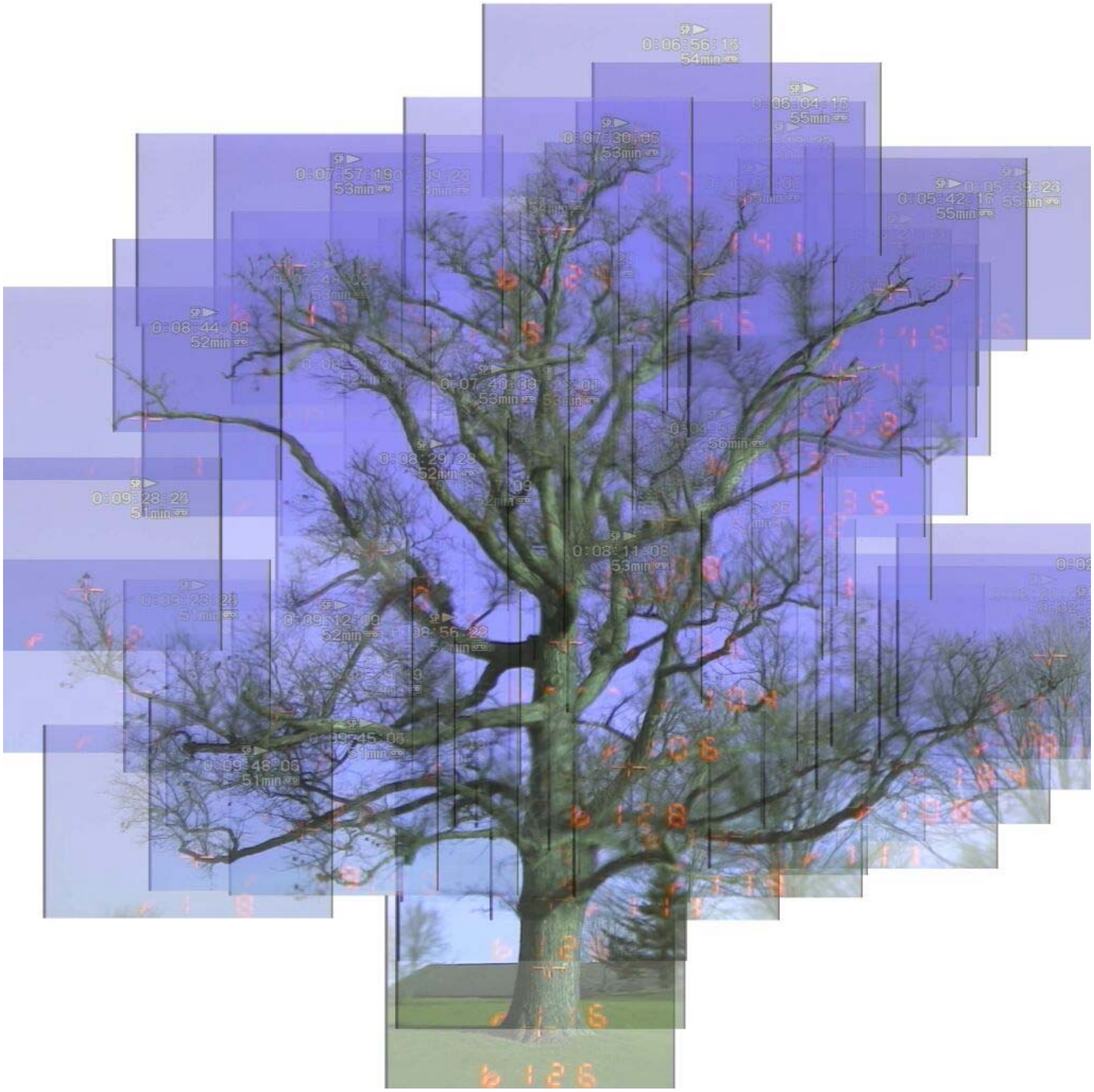


Figure 2. Image from one viewpoint created from 68 video frames. Final resolution is 2700 x 2700 pixels.

A variety of spatial and contextual elements are being employed to guide the stem segmentation system. Stratification of a leaf-on or leaf-off condition is the first node in the decision tree. Inclination information combined with a histogram analysis is used to determine whether textural segmentation is required or whether intensity or color segmentation is adequate. Region growing is a useful technique using location within the frame along with scale and spectral clues to determine the seed areas. This intrinsically offers some spatial constraints. In some cases, points that have a high probability of being stem edges, are used to restrict the search space and weighting for spatial location while relaxing the spectral and textural constraints. Knowing that a stem is opaque allows for further spatial constraints that assist in separating the portion of stem of interest from overlapping or background stem sections with similar characteristics. Trunk form models, have been shown to be useful for stem segmentation (Juujärvi et al. 1998). The model need not be overly exacting for this particular application. Simply a geometric constraint resembling a tapered form will suffice to eliminate errors caused by background and occlusions (Figure 3). Flow direction, determined by orientation data from the TMS instrument, is also another helpful “known” that can be used to guide the algorithm. This is particularly useful as the branches get smaller and curve away from the principal stem axis.

Figure 3. Segmentation of a stem segment demonstrating occlusions and background obfuscation. Red crosshairs from bottom to top represent sequential laser range readings. Yellow outline represents segmentation results from image analysis alone. The green area represents segmentation filtered by stem form model constraints.

Defining Measurement Coordinates

Once the stem is segmented from the background the edge finding is easily attained. As with other portions of this project, more work could be done here to find subpixel edges and compensate for varying edge strengths, but the attainment of pixel level edges from which to select measurement coordinates is accomplished. Although edges are defined from the segmentation, only a few sections of these edges truly represent the tree stem edges. Areas where the segmentation method failed due to occlusions and background obfuscation are still present. Tree stem models, which quantify the allometric growth pattern of typical trees, are used to assess the validity of these segmented edges.

The establishment of an origin is the first step in the process of putting the image measurements into real world coordinates to obtain real world measurements. A logical object space coordinate origin for an individual tree stem would correspond to the central stem axis (pith) at the highest ground level. Since the mechanical sensors within the instrument are gravitational, the y-axis would be a plumb line through this origin point. The x and z axes would naturally be perpendicular to the y axis and each other, however the direction can be somewhat arbitrary. The easiest method for application is to treat each viewpoint as if it were aligned with the z axis, then transform the coordinates using a sequential rotation matrix (Equation 2). In this way, the points determined by all viewpoints are aligned within the same coordinate system.

$$R = \begin{bmatrix} \cos\phi\cos\kappa & \sin\omega\sin\phi\cos\kappa + \cos\omega\sin\kappa & -\cos\omega\sin\phi\cos\kappa + \sin\omega\sin\kappa \\ -\cos\phi\sin\kappa & -\sin\omega\sin\phi\sin\kappa + \cos\omega\cos\kappa & \cos\omega\cos\phi\sin\kappa + \sin\omega\cos\kappa \\ \sin\phi & -\sin\omega\cos\phi & \cos\omega\cos\phi \end{bmatrix} \quad (2)$$

Using a cylindrical stem model, or some other model, each pixel could be assigned an object space coordinate value. For realistic spectral rendering, this would be the case and the spectral values of the corresponding object space would be mapped to the model. For now, no rendering is being performed and only dimensional information is of interest assuming a cylindrical stem model. This allows a simplified data structure to be applied recording only the stem center object space coordinates, a radius value calculated by equation 3, and an angular rotation of the stem or branch axis from the original stem axis.

$$radius = \sin(\sigma / 2) * r_p \quad (3)$$

where σ is the angle between edgepoints perpendicular to the stem axis corrected for perspective and r_p is the range from camera perspective center to stem axis.

3D reconstruction

Using the dimensional information from the imagery and the orientation information provided by the RO data a 3D reconstruction of the stem is now possible. Theoretically, a 3D model could be formed from these edges, a cylindrical stem model, and the RO information. However, due to potentially missing information resulting from perspective projection, a single viewpoint will really only result in a 2.5D representation. Using multiple viewpoints from sufficiently disparate azimuths, a much better model can be formulated as multiple estimates can be averaged together to increase precision, or gaps in the data can be filled for branches which may have be obscured or occluded from other viewpoints (Figure 4).

Each tree consists of a number of segments (branches). These segments each contain a series of nodes which may be predefined, or determined by some rule (e.g., extreme diameter change, direction change). The first segment for each tree is the main bole, with the first node being the "stump" and last node being the top (Figure 5). Additional nodes are inserted as needed. Smaller distances between nodes make the output more continuous (and perhaps more accurate). This can be done iteratively as the data are recorded and can easily be revisited.

The coordinate measurements obtained by the methods above need to be put in some sort of structure in order for the algorithm to keep track of all elements. Further refinement may be accomplished using image processing methods for finer branches, but this task may prove difficult due to overlap of many branches from the perspective views. The data collection method is crucial for lending rigor to the branch segmentation algorithm. Since the branches are traced from the stem central axis to their tip, the sequential data can be traced. The height where the branch connects to the stem is recorded into the data structure. The branch tip, represented by the farthest Euclidean distance from the stem axis prior to a sharp return to the central axis, coordinates are calculated. From its terminal location, the main direction of the branch can be calculated and recorded into the data structure. This process continues for every branch traced during data collection. When the tree is ready to be processed the images corresponding to each branch can then be segmented for diameter determination. Nodes can then be added to denote smaller branches and major diameter changes. Lengths between nodes are also calculated and written to the data structure.

One drawback of multiple observations is that a strategy must be put in place to formulate agreement. Measurements are made by range differences and angular measurements on the image. Perspective can often cause difficulties. One approach would be to use the mean of the measurements from each viewpoint for each

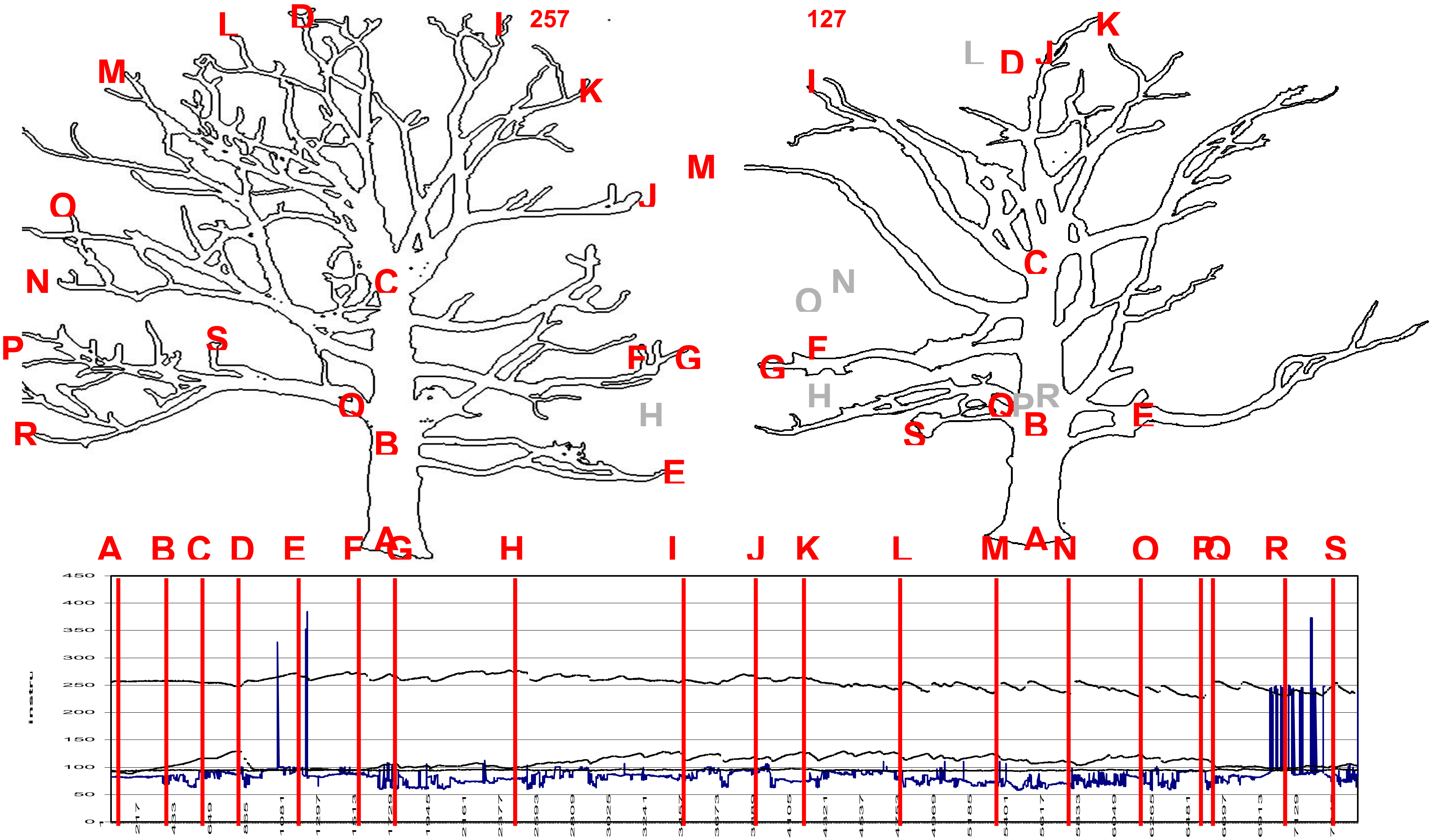
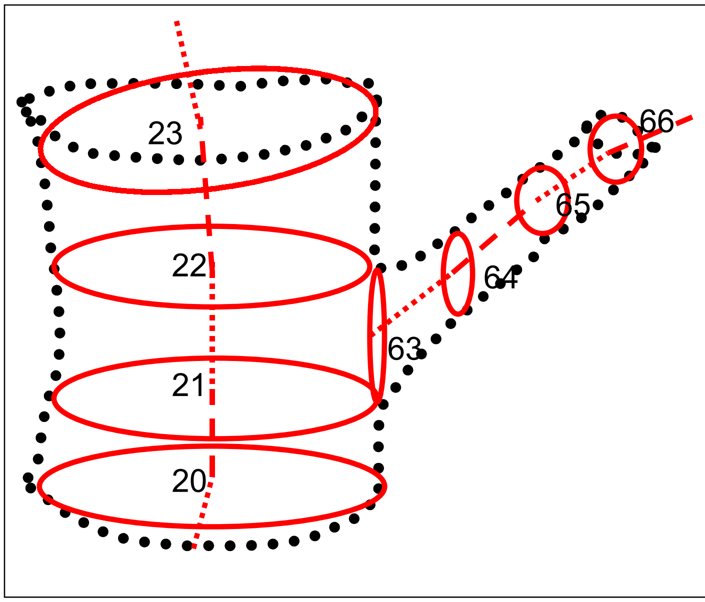


Figure 4. RO data showing readings from left tree representation and corresponding locations on both outlines. The right outline is from a viewpoint 130 counter-clockwise to the left outline. Collection is sequential starting at A (stem bottom center) scanning to the top (point D) then tracing each bronch in a counterclockwise direction based on branches junction with main stem. Grayed letters represent RO points not segmented. Note the lack of identified points on the right side of the right outline indicating branches occluded from the left viewpoint. Also the grayed points L,N,O,P,and R which are occluded in the right viewpoint. Point H is in the foreground of both viewpoints and not segmented due to perspective effects and background interference.

modeled dimension. Alternatively, other methods could be used such as random selection from one viewpoint or selecting the measurement of the most perpendicular viewpoint. For this reason, length measurements for branches that are the most perpendicular to the line of sight should be weighted more heavily than estimates from more acute viewing angles. Diameters should be weighted more for the closer viewpoints unless the range measurement is suspect, or the edges are not clear.

Once the multiple estimate agreements have been made and the gaps filled by all of the viewpoints, a final output data structure can be created. This output can then be sent to a 3D graphics rendering module for customized viewing.



branch	start point	end point	node[0]	node[1]	node[2]
0	0	62	0	1	2
1	63	89	63	64	65
2	90	110	90	91	92
3	111	134	111	112	113
4	135	148	135	136	137
5	149	188	149	150	151

node	x	y	z	radius	dec-ang	az-ang
0	0.00	0.00	0.00	38.50	0.00	0.00
1	-0.02	0.50	-0.04	27.40	4.60	-2.30
2	-0.10	1.00	-0.03	23.20	1.20	-11.60
20	0.44	12.80	-1.24	22.10	11.77	36.87
21	0.52	13.28	-1.30	23.40	3.90	90.00
22	0.52	13.72	-1.33	23.80	19.79	149.93
23	0.41	14.33	-1.52	20.50	22.19	160.70
62	5.20	102.30	-15.20	0.10	2.70	45.20
63	24.12	13.50	-1.20	2.20	49.68	-45.00
64	24.27	13.68	-1.35	1.52	56.31	-67.38
65	24.42	13.94	-1.71	1.50	77.38	-52.28
66	24.83	14.09	-2.24	1.48	77.90	-40.03

Figure 5. Stem section outline and cylindrical representations of nodal structures linked by axial directions.

SUMMARY

A framework has been presented for the 3D reconstruction of a tree stem using field data collected with an instrument that collects streaming range, orientation, and image data. Details have been presented about the instrument, field collection procedures, and data processing methods. TMS offers several advantages over alternative strategies for rapid collection of rough branch structure. The magnified lens system provides for greater precision for diameter measurements, while allowing distant observation points in order to minimize perspective effects. For a complex stem with many branches, such as that shown in Figure 2, the data collection time from a single viewpoint was from 5-12 minutes. This is only a short time given the amount of data that is collected. And while video may be somewhat spectrally inferior to still image collection with a smaller aperture and longer exposure time, it's speed and automated adjustment for varying light conditions allow data to be collected rapidly. The large number of images captured allows increased optical zoom (magnification) and instrument motion. The motion permits the collection of directionally controlled pulse ranges. These ranges create the ability to calculate the spatial arrangement of the branches and provide scale for diameter calculation. The stitching of small central areas of the video frames simulates a hemispherical "fisheye" camera with a spherical film platen minimizing the effects of perspective distortion.

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