A Structured Light Sensor System for Tree Inventory

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ABSTRACT

Tree Inventory is referred to measurement and estimation of marketable wood volume in a piece of land or forest for purposes such as investment or for loan applications. Exist techniques rely on trained surveyor conducting measurements manually using simple optical or mechanical devices, and hence are time consuming, subjective and error prone. The advance of computer vision techniques makes it possible to conduct automatic measurements that are more efficient, objective and reliable. This paper describes 3D measurements of tree diameters using a uniquely designed ensemble of two line laser emitters rigidly mounted on a video camera. The proposed laser camera system relies on a fixed distance between two parallel laser planes and projections of laser lines to calculate tree diameters. Performance of the laser camera system is further enhanced by fusion of information induced from structured lighting and that contained in video images. Comparison will be made between the laser camera sensor system and a stereo vision system previously developed for measurements of tree diameters.

Keywords: structured light, laser emitters, stereo vision, sensor fusion, tree measurement

1. Introduction

Tree Inventory is referred to measurements and estimation of marketable wood volume in a piece of land or forest for purposes such as investment or for loan applications. Typical measurements including tree diameters, tree heights, and profiles of canopy. Existing techniques rely on trained surveyors conducting measurements manually using simple optical or mechanical devices, and hence are time consuming, subjective and error prone. Estimates from experts suggest that due to the subjective nature of these methods, inventory on a per-area basis can vary up to 25% from the true value [1]. The advance in computer vision makes it an excellent substitute for labor intensive repetitive work such as measurements of tree diameters. Vision techniques are being extensively used in industries for inspection, measurements, guidance for robotic vehicles, visual enhancement for microsurgery, and virtual environment generation. Structured lighting and stereo vision are two of the most widely used techniques in robotics vision. Single light stripe sensors are frequently used for either obstacle detection or self-localization on mobile robots [2]. Kemmotsu and Kanade [3] proposed to use a three light-stripe range sensor for estimating poses of polyhedral objects. Khadraoui et. al. [4] used two laser stripes fixed rigidly to a camera, with mutually orthogonal light planes, to derive kinematics relation between the sensor and the scene as basis for visual servoing. Structured light coding has also been used to develop a system for measurement of 3D surface of human back [5]. Wang and Cheng [6] proposed an approach to 3D reconstruction and recognition by fusing intensity images and structured light coded images. Researches have also been conducted in exploiting structured light coding to solve correspondence problems in stereo vision [7].

Vision based measurements of tree diameters was first reported in [1]. In their work, tree diameters were calculated based on range measured by a spot laser range finder, and angular sizes of tree trunks extracted from video images. Co-occurrence matrix of texture, combined with the concept of Mahalanobis difference, is used as the basis for locating edges of tree trunks. No timing is reported in [1]. However, texture analysis has been known to be computation demanding and time consuming.

This paper describes 3D measurements of tree diameters using a uniquely designed ensemble of two line laser emitters rigidly mounted on a video camera, with the two laser planes parallel to each other. The proposed laser camera system relies on a fixed distance between two laser planes and projections of laser lines to calculate tree diameters. Performance of the laser camera system is further enhanced by fusion of information induced from structured lighting and that contained in video images.

The remaining of the paper is organized as follows. Section 2 gives a brief description of 3D measurements using another structured light sensor system with a single emitter. The weakness of the system motivated us to design the proposed laser camera system, the design of which will be detailed in section 3. A basic algorithm for calculating tree diameters based on laser projections (only) is described in sections 4. The proposed approach is enhanced by fusion of information induced from laser projects and that contained in video images as described in section 5. Section 6 gives a brief overview of another approach to measurements of tree diameters using a stereo vision system previously developed in house, and comparison between the two approaches. Concluding remarks and future work are presented in section 7.

2. A structured light system with a single emitter

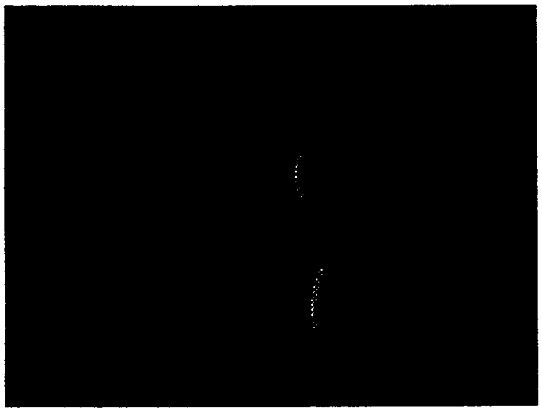

Figure 1: An image taken with a laser light stripe sensor (Sensus 500) with peaks detected

The first structured light sensor system used in our work is Sensus 500, made by Nomadic Technologies Inc. It includes a single-beam laser source emitting a plane of laser light, and a camera to observe projection patterns of the laser light on target objects. Shown in Figure 1 is an image of two targets taken with Sensus 500. The two targets are a tropical plant and a section of PVC pipe of about 2 and 4 inches in diameters, respectively. Bright curves are laser projections observed from the camera, with black

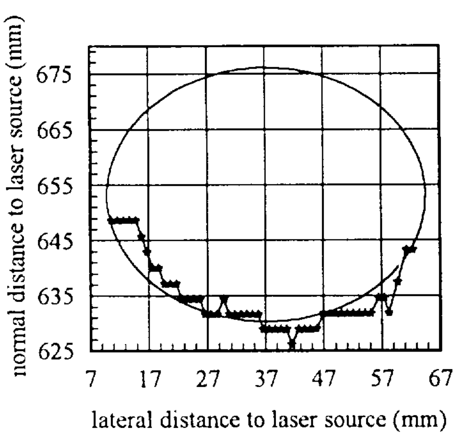

Figure 2: Fitting an elliptic curve on computed 3D data

dots inside marking detected peaks

Given a configuration of the laser source and the camera, a relationship between 3D coordinates and illuminated pixel locations in images can be established as described in [8]. An elliptic curve is then fitted on computed 3D data points to yield the tree diameter as illustrated in Figure 2.

Initial experiments indicate that the number of data points provided by one plane of laser beam is not be enough to provide accurate and robust measurements of tree diameters. It may not be able to handle cases where the trees are tilted with respective to grounds or the sensor system is tilted due to rough terrain. This weakness motivated us to look for alternative structured light sensors emitting more than single laser planes as described below.

3. A structured light system with dual emitters

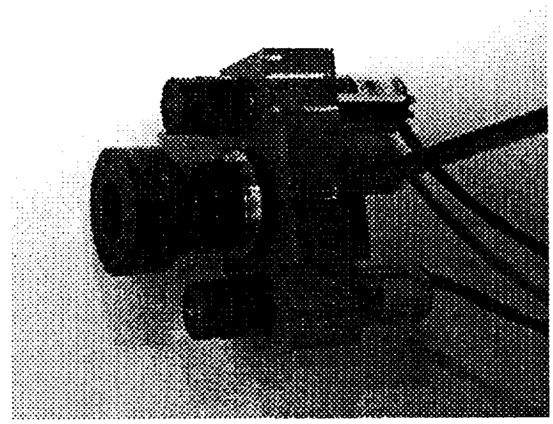

Figure 3: The proposed sensor head with a camera mounted in-between two line laser emitters

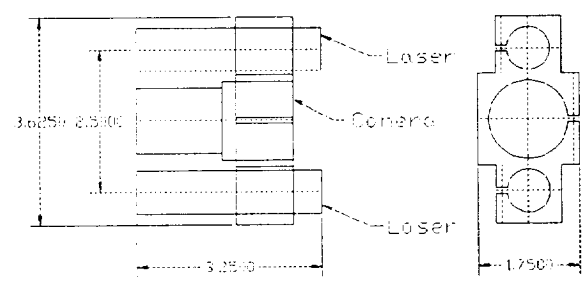

Figure 4: Drawing of laser camera head assembly

The proposed system consists of a CCD camera (along with a Matrox Pulsa frame grabber) and two line generating laser emitters as shown in Figure 3, with the drawing illustrated in Figure 4. The camera and lasers are rigidly mounted as an assembly such that the laser line planes are parallel, and the camera is positioned at the center between the laser line planes. A 25 or 50 mm focal length lens is used. The lasers line generators are Lasiris SNF-670-10 lasers with 30-line generator optics attached. The lasers are powered from a 5-volt external power supply. The lasers are strobed using a HEXFET transistor driven by a digital output from a Matrox Pulsar frame grabber. A band-pass filter is used to allow only the light from the laser line emitters to be detected by the camera. The laser line emitters have a wavelength of 670 nm. The band-pass filter has a bandwidth of 40 nm centered at 670 nm.

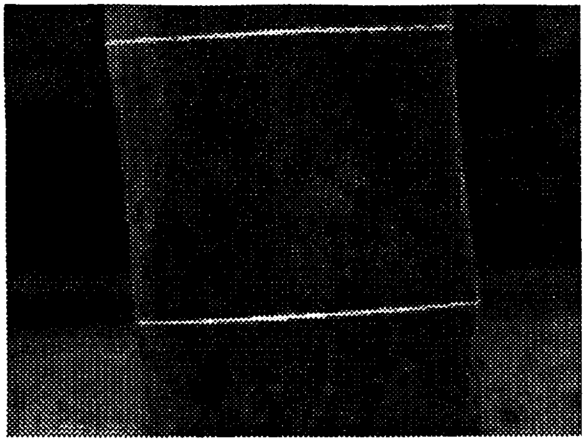

Figure 5: An example shown two laser lines projected on a tree trunk

The two parallel line planes project a pair of lines on the trunk of the tree. The camera images the two lines (as shown in Figure 5). Since the aperture is set as small as possible, the lines are the most prominent structure in the resulting image. The perpendicular distance between the two lines is known, and the lines are parallel, therefore the scale factor of the image is determined by the perpendicular distance in inches divided by the perpendicular distance in pixels between the two lines. The actual physical distance between the lines remains the same at any angle.

4. Calculation of tree diameters

Given an image, the projections of the two parallel laser planes in the image can be detected by any edge operator, and extracted by fitting lines to two sets of edge points. In practice, there may be leaves and other objects such as stakes in the field of view. The line extraction software has to be robust enough to eliminate the spurious lines. Our line extraction software locates all lines in the field of view and attempts to locate a valid pair based on the following criteria.

- Angle of lines with respect to each other: The lines should be parallel to each other within a reasonable tolerance. They should also be parallel to the camera x-axis.
- Positions of lines with respect to each other: The positions of the two lines should not be offset too much from each other. Otherwise, it would imply an extreme angle of the tree or an extreme angle of the camera to the normal y-axis.
- Length of lines with respect to each other: The diameter of the tree should not vary drastically over the distance between the two laser lines, (this criterion will be removed to handle occlusion as to be discussed).
- Continuous line segment. Overall intensity of lines with respect to each other: There should not be a discontinuous line of greater than a certain tolerance based upon the type of bark of the tree.

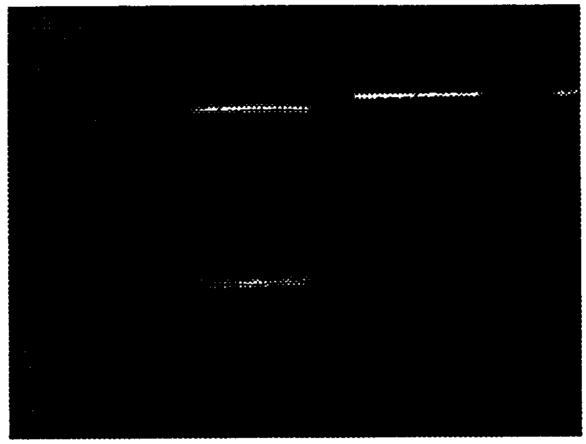

Figure 6: An image with a pair of valid lines (marked by black dots) and spurious lines caused by leaves

Figure 6 shows an image with spurious lines, and an extracted valid line pair marked with black dots. The pair of lines on the left is deemed valid. With a pair of (nearly) parallel lines detected, the perpendicular distance between the lines is calculated. Using the known perpendicular distance between the lines, the scale factor is calculated. The length of the lines is determined by the end points of the lines. The lengths are averaged and multiplied by the scale factor. The derivation of the tree diameter D is as follows (referring to Figure 7)

$$D = \cos[Tan^{-1}(\frac{x3 - x1 + x2 - x0}{y3 - y1 + y2 - y0}) \bullet (\frac{x3 - x2 + x1 - x0}{2})$$

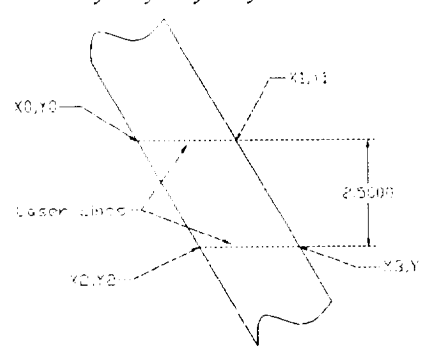

Figure 7: Geometry of the laser camera sensor system

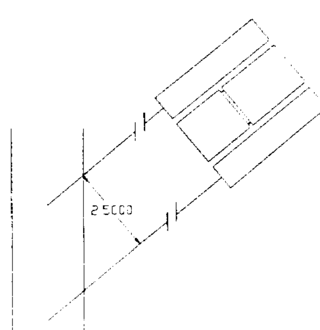

Figure 8: An example showing the sensor system aiming at a pitch angle at a tree trunk

Note that the above equation is equally applicable to cases where the sensor system aims at non-zero pitch angles at tree trunks as shown in Figure 8. The scale factor is determined by the number of pixels (in the vertical direction) associated with the tree trunk and actual distance between the two laser planes, as in a case when the laser planes are perpendicular to the tree trunk.

It should be pointed out that the above equation usually underestimates tree diameters since its calculation is based on visible part of tree trunks being measured. The estimation may be refined as follows (see Figure 9).

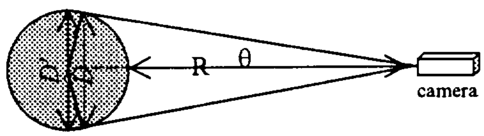

Figure 9: Geometric illustration of deriving D' (tree diameter) from D (width measured from visible part)

$D' = 2 \bullet (R + \frac{D}{2}) \bullet Sin\theta$, where $\theta \approx Tan^{-1}(\frac{D/2}{R + D/2})$, and R is the range of the tree trunk measured from the sensor system. R can be estimated based on the scaling factor and camera parameters. In this work, the angle is θ fairly small in most of the cases, and the difference between D and D' is negligible.

Table 1: Sampled results from measurement of tree diameters using the proposed sensor system

Tree ID	Reported	Actual	Data	%
1	0.85	0.84	0.01	1.2
2	1.04	1.06	-0.02	-1.9
3	1.37	1.36	0.01	0.7
4	1.70	1.75	-0.05	-2.9
5	1.41	1.45	-0.04	-2.8
6	3.47	3.45	0.02	0.6
7	3.38	3.40	-0.02	-0.6
8	3.31	3.35	-0.04	-1.2
9	3.50	3.45	0.05	1.5
10	3.35	3.40	-0.05	-1.5
11	3.24	3.25	0.01	0.3
12	3.53	3.45	0.08	2.3
13	3.75	3.75	0.00	0.0
14	4.13	4.22	-0.09	-2.1

Results of measurement of tree diameters using the structured light sensor system are listed in Table 1 (with errors). It can be seem that all the error are under 3%, and no significant systematic error can be observed. The laser-camera structured light system has multiple advantages. It is self-calibrating and immune to camera image position. The laser-camera head is small enough to be handheld or trailer mounted. The power consumption is low and the accuracy is high.

5. Measuring tree diameters with occlusion

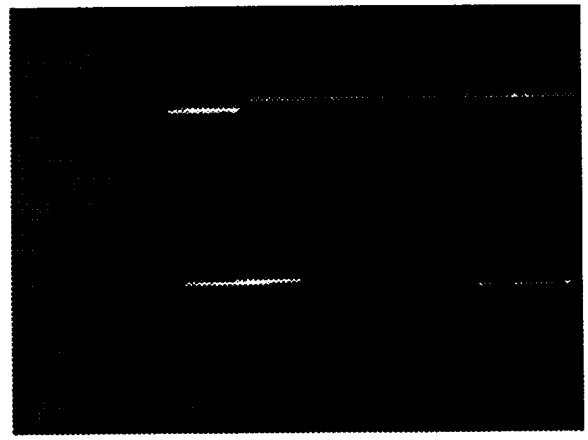

Figure 10: An example showing that part of laser projection is missing due to occlusion

It seems that one inherent limitation of most of structure light sensor systems (with either single or dual laser emitters) is that information can only be extracted from laser projections in images. The problem is worse if part of laser projections is missing due to occlusion (as illustrated in Figure 10). It is not the case, however, with our proposed sensor system. Unlike the system used in acquiring the image in Figure 1, our proposed sensor system does retain large portion of all the visible light. As can be seen in Figure 10, the tree trunk is clearly visible. It is possible to have this additional information extracted to increase accuracy in measurements of tree diameters. This observation suggests a need for modification of algorithms for measuring tree diameters. The modified algorithm is as follows.

1. Extract line segments from a given image.
2. Check the criteria (except the one on nearly equal line lengths) listed in section 4 on each pair of parallel lines for valid line pairs.
3. For each invalid line pair, connect their left end points with a straight-line segment. Search in the neighborhood of the line segment to see if a section of left trunk edges can be located.
   (a) If the whole section (between the two line laser projections) of the left trunk edge is located, than the line pair is valid. Select the right end point of the longer of the two lines, and search for a section of the right trunk edge along the direction parallel to the left one.
   (b) If no section of the left trunk edge is detected, no valid tree diameter will be reported.
4. If a significant portion of the left trunk edge (between the two laser projections) is extracted, then connecting the right ends of the two lines with a straight-line segment and conduct similar search of trunk edges.

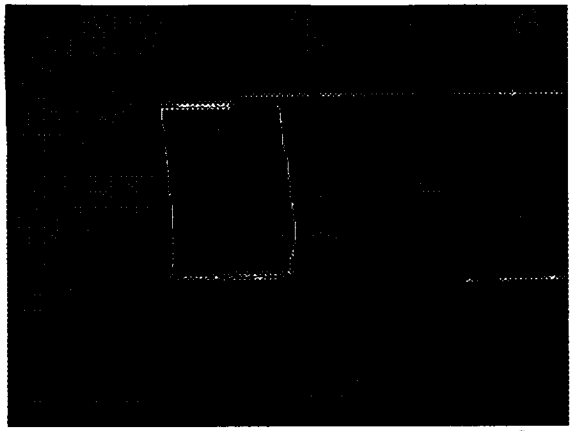

Figure 11: An example showing measurement of tree diameter based on two types of information

The modified algorithm integrates two types of information to conduct measurements of tree diameters. The laser projections are used to guide search of trunk edges, and the extracted trunk edges are in turn used to either verify the validity of laser projection pairs or to recover occluded information. The two types of information are complementary to each other. As shown in Figure 11, the two laser projections guided the extraction of the left edge, that in turn was used to extract the right trunk edge including the occluded portion.

6. Tree diameters from stereo

Previously, a stereo vision system has been developed for measurements of tree diameters [9]. The system consists of two Sony CCD cameras, with a basis line of 2.6 inches. For each pair of images from the two cameras, image matching based area correlation is employed to generate a disparity map. A segmentation algorithm is used to extract a blob containing the tree trunk closest to the cameras. The extracted blob is then used to guide detection of edges of tree trunks. The 3D locations of the edges of the tree trunk, and the tree diameter are then computed.

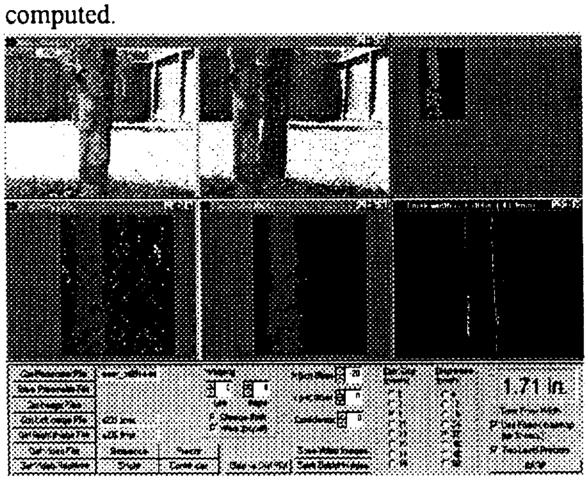

Figure 12: Results of stereo-based measurements of the diameter of a tree standing in front of bush

Shown in Figure 12 is the graphic display of one of the test runs. In the Figure, the image from the left camera is on the upper left corner, and that from the right camera is at upper center. The image on the upper right corner shows intermediate results from coarse level processing (at a reduced resolution). The disparity map and the extracted tree trunk are shown in the lower left and center. The extracted outline of the tree trunk is shown on the lower right, with the measured tree diameter displayed right below it.

Table 2: Results from measurements of tree diameter of artificial tree using stereo vision

Tree ID	Reported	Actual	Delta	%
1	1.65	1.58	0.07	4.4
2	1.72	1.63	0.09	5.5
3	1.83	1.72	0.11	6.4
4	1.72	1.68	0.04	2.4
5	1.79	1.70	0.09	5.3
6	1.68	1.64	0.04	2.4
7	1.69	1.64	0.05	3.0
8	1.68	1.63	0.05	3.1
9	1.71	1.64	0.07	4.3
10	1.69	1.65	0.04	2.4
11	1.68	1.72	-0.04	-2.3
12	1.73	1.66	0.07	4.2

Results of measurement of tree diameters using the structured light sensor system are listed in Table 2 (with errors). In comparison with the laser camera sensor system described earlier, measurements errors from the stereo system, though all are under 5%, seem to be larger than those incurred using the laser camera sensor system described earlier, partially due to imperfect alignment of the two cameras. Imperfect alignment is also evident by systematic overestimation. A quick comparison between the two types sensor systems suggests that some of advantages of the proposed laser camera system over a typical stereo vision system are as follows:

- It is more compact than a typical stereo vision system, and can be relatively easily made into a portable sensor system for field operations. (Note that a stereo vision system can be made much more compact by using CMOS based imagers with micro lens).
- It does not require sophisticated geometric calibration as long as the two laser planes are nearly parallel to each other. It yields more accurate results, and its measurements are relatively insensitive to minor misalignment.
- It requires less processing power, as the laser projections suggest where tree trunks may be.
- Its ability in segmenting targets of interest from background is weaker.

7. Concluding remarks and future work

A laser camera sensor system has been proposed and field tests conducted for 3D measurements of tree diameters. The proposed system is an ensemble of two line laser emitters rigidly mounted on a video camera, with the two emitted laser planes parallel to each other. The proposed laser camera system relies on a fixed distance between two parallel laser planes and projections of laser lines to calculate tree diameters. Experimental results indicate its ability to provide fairly accurate 3D measurements. Its weakness in handling occlusion has been overcome by fusion of information incurred by the laser projections and that contained in video images.

Figure 13: An example illustrating dim laser light under strong solar illumination

One limitation of the current system is that the laser power is not strong enough to compete with strong solar illumination as evident in Figure 13. Measures to be taken to alleviate the problem include the following:

- Increase laser power: Existing lasers are 7mw. It is possible to use higher power lasers. The safety of the system would not be jeopardized because the lasers are pulsed and are spread into a fan beam.
- Decrease fan angle: A decrease of the fan angle from 30° to 15° would increase the light incidence by a factor of two. A 25mm lens would have an angular field of approximately 15°.
- Increase filter transmittance: Present filter transmittance is 60%. A search will be made for more efficient filters.
- Decrease band-width: Present bandwidth is 80nm centered at 650nm. Lasers emit at ~676nm. Use of a 10nm narrow band-pass filter centered at 676nm would decrease non-informational light. Discrimination would increase by 80% assuming no reduction in transmittance at laser wavelength.
- Camera / Laser synchronization: The camera and lasers can be synchronized to the frame grabber. In the present system the camera free runs. The lasers are turned on and the system waits for a complete camera frame to be stored. The frame grabber has control signals for starting the camera capture and pulsing of the lasers which would improve the consistency of the light captured.
- Increase camera / frame grabber gain: AGC was used in the initial tests. A fixed gain can be set in the camera and the frame grabber.
- Decrease aperture size: A decrease in the aperture size would decrease the light incident on the imager and improve the depth of focus. This would have to be done in conjunction with an increase in the camera/frame grabber gain.

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