OPTICAL 3-D MEASURING SYSTEM WITH NESTED CAMERA BLOCKS

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ABSTRACT:

This article describes a new photogrammetric 3-D measurement system for flat objects like plywood boards. 3-D measurement is needed to get true dimensions of the object along its possibly curved surface. The system consists of two nested camera blocks. The inner system is a movable satellite, which measures the details of the object. The outer system tracks the exact position and orientation of the satellite. The image data from different satellite positions is processed along with the satellite orientation data only after all details from different satellite positions have been measured. The measurement is controlled by a CAD file, which contains the nominal geometry of the object, the features to be measured, and their tolerances. The camera systems are calibrated into the same coordinate system using a special scale bar and an optional calibration plane. The linear motion system for the satellite is also calibrated to make measurements easier. The system relies only on analytical photogrammetry to get 3-D measurements. The accuracy of the whole system depends mainly on the measurement accuracy of the outer camera block.

1. INTRODUCTION

In plywood industry, the plywood boards coming from a machining line needs to be measured to guarantee fulfilment of the tolerances laid by the end-user customers who utilize machined plywood in their own products. The tolerances are usually about a few millimetres. Measurements are needed to detect gradual changes in the machining process, too. Conventionally, the outcome from the machining line has been measured only with a hand ruler or gauge. Only occasionally, some samples are measured using a coordinate measurement machine (CMM). Because wood is a living material, slightly curved plywood boards are allowed, too. Therefore, 3-D measurements along the curved surface are needed to get the results correctly rectified to a reference system.

Digital photogrammetry is suitable for accurate 3-D measurements. The relative accuracy of a photogrammetric system is mainly limited by the image sensor resolution. With standard video cameras, an accuracy rate of about 1:20,000 (0.2 mm in 4 metres) or higher can be obtained. The accuracy level is easily adjusted by using sufficiently many cameras and a suitable distance to the object.

2. SYSTEM GEOMETRY

In principle only two cameras are sufficient to make 3-D measurements, but more reliable and more accurate results are obtained by using more cameras. Here, the new photogrammetric 3-D measurement system consists of eight standard video cameras in two nested four-camera blocks. The smaller, inner camera system is a movable satellite that is mounted on a servo-controlled linear motion system. It can move above the object from one position to another and grab images for detailed measurements. The larger and fixed outer camera system surrounds the servo system from above. It is used to determine the exact orientation and position of the satellite system when it stands still.

The outer system measures automatically the image coordinates of certain targets in the satellite and calculates their 3-D coordinates by intersecting the corresponding projection rays. The similarity transformation between the measured targets and their calibrated reference coordinates is then determined using a closed form solution (Horn, 1987). The orientation parameters of the satellite cameras or the 3-D measurements made in the satellite system are then transformed to the outer system to get the final measurement results.

2.1 Measurement cabin

The entire system is inside a closed cabin, protecting the cameras from dust and extra light, and preventing people to enter the measurement area. Two robots can use the measurement system in turn. There are openings in both ends of the cabin, and a carriage on a railway is used to bring the object into the cabin through either of the openings. The frame of the measuring system is shown in Figure 1.

The controlling computer, a standard PC with several digitising cards installed in it, and the necessary power units are located in a separate control room near the cabin.

The system controls the illumination inside the cabin. Some light is needed when satellite cover targets are measured with the outer cameras. There are adjustable extra lights mounted below the satellite, too. They illuminate only the object area just below the satellite. They make the inner system less sensitive to the shadows due to the fixed cabin lights and a
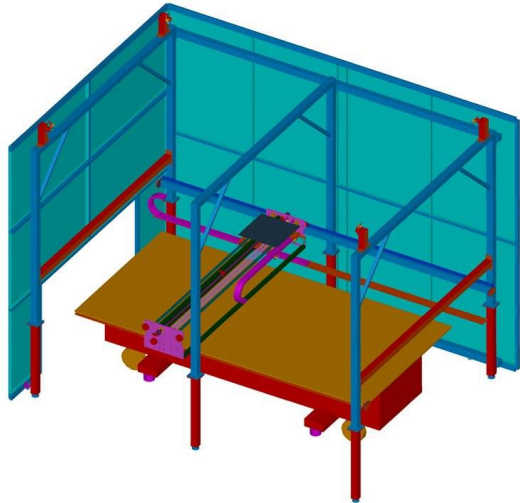
Figure 1. The frame of the measuring system.

moving satellite. The light level can be adjusted to get the best conditions for the detailed measurements using the satellite.

The measurement table is a light coloured plate. It can be covered with a dark coloured canvas, if necessary, to make measurement of light coloured objects easier.

2.1 Outer system

The outer system defines the coordinate system of the entire measurement system. It contains four or more cameras arranged into a convergent rectangular block, so that the targets in the satellite cover can be seen from at least four cameras in every possible satellite position.

Four cameras equipped with wide-angle optics are sufficient to achieve 0,25 mm measurement accuracy in the object for a system capable to measure objects of size 3,0 m × 2,0 m × 0,1 m.

2.2 Satellite

The satellite, or the inner camera system consists of four cameras, too. They are located beneath a rigid carrier plate, which is mounted on a linear motion system. The cameras form a convergent, square block, size of which is about 0,4 m × 0,4 m. The distance from the cameras to the measurement table is about 0,3 metres. The distance to the actually measured object surface is slightly shorter, depending on the thickness of the measured object. The relative orientation of the satellite system is known from camera calibration.

The upper side of the satellite carrier plate contains several circular white targets on a black background, as seen in Figure 2. Their optimal size and mutual positions depend on the resolution of the outer cameras, the geometry of the outer block, and their distance to the object surface. In Figure 2, the diameter of each target disc is about 80 mm.

The targets should be clearly visible and measurable in as many outer cameras as possible. For this purpose, coplanar targets are easiest to use. Targets distributed in 3-D may cause
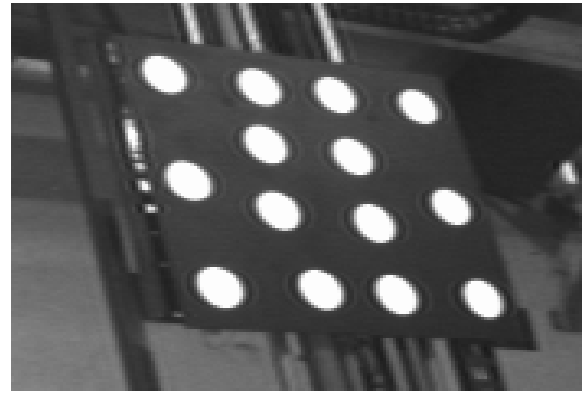

Figure 2. Targets on the satellite cover.

occlusion problems, and make the use of more sophisticated measurement algorithms necessary.

The error made in the determination of the satellite's orientation is propagated to the final measurement values the more, the larger the distance between the satellite cover targets and the object surface is. Conversely, the more targets there are in the satellite, and the wider they are distributed, the more accurate the final measurements are, too. To get approximately the same 3-D accuracy for the satellite targets and for the final measurements, the area covered by the targets should have a diameter that is at least twice as large as the distance from the satellite's target plane to the measured object surface. If the object surface is, say, 0,4 meters below the satellite cover plane, then the area covered by the target centres should be about $0,6 \times 0,6$ m^2.

2.3 Lasers

There are also two laser projectors mounted in the middle of the satellite cameras, beneath the satellite carrier. They are used to make profile measurements by projecting two mutually crossing laser lines on the measured object's surface, or in a hole like shown in Figure 3. The laser powers can be adjusted according to the measured object surface material. A dark object surface may require more power than a light coloured object. In this system, the laser light planes have fixed orientations in the local satellite coordinate system. Depending on the orientation of an edge, the profile of which has to be measured, the system can decide optimal satellite positions for the measurements.
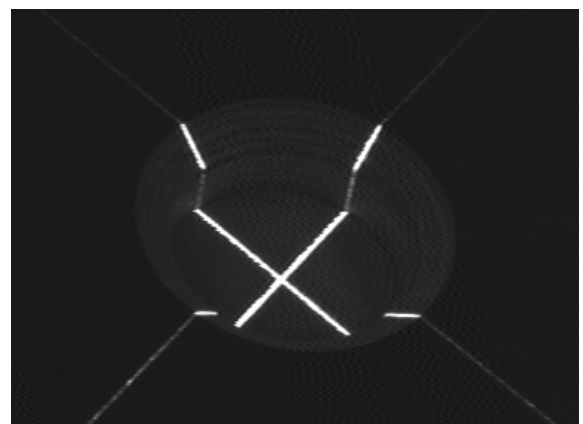

Figure 3. Two laser profiles in a machined hole.

2.4 Linear motion system

The satellite is moved in two mutually perpendicular directions using a servo-controlled linear motion system. The positioning and repeatability of the servo system needs not to be the most accurate because the satellite position and orientation are determined solely using photogrammetry. The satellite cannot be allowed to move when images are captured, so the stability of the servo system is very important. All dead motion and mechanical gaps should be eliminated in order to get reliable final results.

A calibrated servo system, with an accuracy of a few millimetres, makes it possible to automatically measure the satellite targets from their predicted positions in images.

3. CALIBRATION

The measurement system requires careful system calibration to get final measurements in a correctly scaled, orthogonal 3-D coordinate system. Calibration of the whole system consists of the camera calibration, laser calibration, and the calibration of the servo system.

3.1 Camera calibration

The outer and inner camera systems can be calibrated simultaneously using a free-network bundle adjustment (Haggrén and Heikkilä, 1989). Approximate values for the unknown parameters can be obtained using the projective adjustment method developed by I. Niini (2000). Normally, the absolute scale of the coordinate system is fixed by observing the end-points of a known scale bar and by using the known distance as a constraint in the adjustment. More information about the calibration method can be found in (Niini, 2002).

Here, due to the scale difference between the two systems (the inner system size is less than one tenth of the outer system) only one scale bar or distance cannot be used easily. A calibration tool containing targets for both systems is appropriate. A scale bar with four collinear targets can be used. It contains two larger targets in the ends of the bar, and two smaller ones close to each others in the middle of the bar. The first large target and the first small target are made recognisable by adding a smaller index target close to them. All targets are white circles in a black background, and they can be searched and measured automatically from the images.

Since the mutual distances of the calibration targets are known precisely, e.g., from a coordinate measurement machine, the bar can be used to get the systems into a common coordinate system and scale. During this part of calibration, the satellite is kept at a fixed position, preferably in the middle of the measurement area. The targets in the calibration tool are then observed from the images so that both systems can see their corresponding targets simultaneously. This is made in several different positions and orientations. The image coordinates of the satellite cover targets are also measured in this fixed position, and taken in the adjustment, so that the satellite base position also becomes calibrated and can be used later as a reference.

To strengthen the calibration of the outer system, additional observations (say 50-100) of the calibration bar are made well distributed in the entire measurement volume. The calibration of the inner space is also strengthened using another small calibration tool, scale of which may be known but needs not to be known. It is then only constrained to have a constant, but unknown length.

The overall calibration can be further strengthened with a precise calibration plane that contains several unknown circular targets for both systems. This plane can be placed in several different positions and orientations below the satellite, and both systems can observe their dedicated targets. Corresponding points can be determined using the epipolar geometry obtained from previously determined calibration parameters. The image observations of the plane points enter the adjustment, and the corresponding 3-D points are constrained to lie on the same plane. The calibration also gives the relative positions of the plane targets. Then this calibration plane can be used to recover an accidentally lost calibration between the two systems.

3.2 Satellite reference position

The calibration volume has to include the area where the satellite targets can move. Additional calibration points are generated easily by moving the satellite over the entire linear motion area, simultaneously registering the image coordinates of the satellite targets. These image coordinates are added into the adjustment, along with the constraints that keep the relative geometry of the satellite targets constant in all measured satellite positions. Thus, the relative geometry of the satellite targets will be adjusted using image observations over the entire calibration space.

3.3 Laser calibration

The laser light planes are calibrated in a simple manner after the satellite camera system has been calibrated. It is only required that the visible 3-D laser lines are measured from at least two distinct object planes. The laser planes are then obtained from these 3-D lines. The intersection of the two laser planes is the 3-D line that is projected down as the laser cross in the object surface.

After the laser calibration, it is possible to calculate where the laser cross locates in any known plane in the satellite coordinate system. Using the similarity transformation between the satellite base position and current position, the position of the laser cross is also known in the outer coordinate system.

Optionally, the information from the laser planes can be used to constrain the measurements, because the visible laser line segments have to lie on the same known plane of the corresponding laser.

3.4 Servo system calibration

The servo system has its own coordinate system and scale. The axes may not be exactly straight, or may not have the same scale. There may also be minor discontinuities in certain positions along the axes, especially when the axes are made from several racks. The calibration of the servo system is based on a polynomial model for the servo coordinates.

The servo calibration data consists of pairs of recorded servo coordinates and corresponding, photogrammetrically measured 3-D points obtained from the laser cross in the object surface. The units and scales of the servo coordinates are chosen and fixed before the calibration using a separate control program for the servo system.

The mathematical model between the servo coordinates and the corresponding 3-D laser point can be put in form:

$$\overline{x}' + v + f^{\,p}(\overline{x}) = A(\overline{X} + V)\,, \qquad (1)$$

where $\overline{x}$ is the 2×1 vector of the servo coordinates, v contains their residuals, $f^{\,p}(\overline{x})$ is the polynomial function of degree p for the servo coordinates, A is a 2×4 parallel projection matrix for the 3-D laser cross coordinates, $\overline{X}$ is the homogeneous 4×1 vector containing the 3-D coordinates of the laser cross in the object surface, V is their residual vector. Currently, up to a fourth degree polynomial can be used. The adjustment model corresponds to the generalized least squares model. Either of the residual vectors can also be ignored to simplify computations.

Due to the underlying parallel projection, the 3-D points used in the calibration cannot lie on a plane. They have to come from at least two different 3-D planes, to avoid a singular system.

The laser crosses are measured from an object surface using a grid covering the entire movement area. To get all non-linear effects calibrated, the grid is measured several times, each time placing the object at different height level. After the servo calibration, the laser cross can be driven accurately to a desired 3-D point on a known surface. Similarly, the required servo coordinates, and the predicted 3-D coordinates of the satellite cover targets can be computed for a given 3-D object point.

4. MEASUREMENT ALGORITHM

A robot always puts the object to be measured in a certain position and orientation in the measurement table. The accuracy of this positioning is typically about one millimetre.

A CAD file controls the measurement. The CAD file contains the nominal geometry of the object, the features to be measured, and their tolerances. There can also be additional information about the object type or colour, which may be used to adjust certain measurement parameters. Only the features marked in the CAD file are measured and reported. Each different object type requires its own CAD file, and the system has to be told which CAD file to be used when a new measurement task begins.

At first, the system checks the position of the object and determines the similarity transformation between the measurement coordinate system and the CAD system. Further measurements can then be made directly in the predicted CAD nominal positions.

The satellite can see only a certain fraction of the object area in one measurement position. Measurement of larger features, like long sides of a rectangular object, has to be measured in several satellite positions, and join the results only later.

The measurement time depend mostly on the number of satellite positions needed and the total length of the satellite movements. It can take several minutes to measure a complex object. To save time consumed in the satellite movements, the satellite positions should be optimised, and their number should be minimized. A simple algorithm is developed for that purpose. It decides optimal satellite positions, the number of needed satellite positions, and the parts of features measured in each position.

First, the entire object area is divided into areas, sizes of which correspond to the area seen by the satellite. The features are then converted into 2-D points, and it is checked which features or parts of them fall into which areas. Empty areas can then be ignored. If possible, the remaining areas are centred with respect to the desired data in their area. Finally the optimal path between the areas is determined.

For most geometric features, like edges and holes, the image measurements can be made using edge search in a window whose direction is normal to the edge of the feature. The sub-pixel position corresponding to the largest gradient is searched using interpolation. The image data is first verified or filtered in the image domain, by fitting it robustly to a line or ellipse. Only the filtered data is stored for later, final 3-D fit which is made only after all satellite positions are measured. Certain geometric features, like angles, parallelity of lines, side lengths, etc., can be computed only after the final 3-D data is first computed and possibly rectified to a plane.

The curvature of the object surface can be determined coarsely, by measuring the laser cross on several positions on the object surface, and fit the data to a cylinder surface, for example. This way, the influence of the curvature on the predicted positions of the features can be taken into account. After all features have been measured, a better estimate for the curvature can be computed using all gathered 3-D data.

5. CONCLUSIONS

This article describes a new photogrammetric 3-D measurement system designed to measure flat objects, like plywood boards, in an industrial production line. The system consists of two nested four-camera systems, the inner system being a moving satellite. The inner system measures the details in the object space, while the outer system measures the position of the satellite. The accuracy of the outer system describes also the final accuracy of the system. The functionality of the system relies entirely on photogrammetry, not on high precision machinery.

The moving satellite makes the system slow compared to the fastest real-time systems. It is therefore best suited for on-line quality control and measurement purposes where a few minutes wait per a measured object can be tolerated.

References

Haggrén, H. and Heikkilä, J., 1989. Calibration of Close-Range Photogrammetric Stations Using a Free Network Bundle Adjustment. *The Photogrammetric Journal of Finland*, 11(2), pp. 21-31.

Horn, B. 1987. Closed-form solution of absolute orientation using unit quaternions. *Journal of the Optical Society of America A*, Vol. 7, pp. 629-642.

Niini, I. 2000. Photogrammetric Block Adjustment Based on Singular Correlation. Dissertation, *Acta Polytechnica Scandinavica Ci* 120, Helsinki University of Technology, Finland.

Niini, I., 2002. On the Calibration of Mapvision 4D System. *The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences,* Vol. 34, Part 3A, pp. 225-227. Graz, Austria.