A Wand Technique for Calibrating Two Cameras

Darrell Lahey, Michael Sullivan**, and Rod Byrne**
**Department of Computer Science*
Memorial University of Newfoundland
***Institute for Marine Dynamics*
National Research Council

Abstract

A technique to calibrate cameras in a two-camera optical tracking system is presented. This technique, which uses a wand to calibrate the two cameras simultaneously, is compared to a traditional technique that calibrates each camera individually. The wand calibration procedure is easier to implement and reduces setup time for extended volume measurements while producing similar results. External and internal parameters required to compute the locations of markers in three-dimensional space, using the image coordinates from both cameras, are determined during the camera calibration. For the calibration technique, a rigid rod with a marker fastened to each end is moved through the viewing volume of both cameras. The wand calibration algorithm determines the parameters by minimizing the difference between the actual and calculated length of the wand over all image frames. Test results are given comparing the two techniques.

INTRODUCTION

At the Institute for Marine Dynamics (IMD) in St. John's, optical tracking systems are used to study the motions of models in different environmental conditions. One of these systems uses two cameras to track the image locations of reflective markers attached to the model [1]. From these marker image locations, tracking software computes the marker locations in a three-dimensional coordinate system. To compute the 3-D marker locations, several parameter values must be known for both cameras.

A camera calibration determines the parameter values required to transform 2-D image coordinates from both cameras into 3-D marker locations. Currently, IMD uses a traditional technique for camera calibration, which works well when the volume within which the models are tracked is small (a few metres cubed). However, IMD is working toward tracking models over much larger volumes. While the traditional technique will still yield good results, calibration setup becomes more difficult and time consuming as the tracking volume increases.

The camera calibration technique presented in this report works well regardless of the tracking volume. This technique, called the wand calibration technique, uses the motion of a wand to calibrate both cameras simultaneously [2]. Results from a study performed to compare a wand calibration technique with a traditional technique are presented in this paper [3]. In the study of wand calibrations, eight different minimization strategies for optimizing the parameters were investigated. For this paper, the results from only the best minimization strategy are presented.

CAMERA CALIBRATION PARAMETERS

Camera calibration parameters are defined using a standard pinhole camera model, which is depicted in Figure 1. Light rays from the focal point of a camera to a marker strike the image plane at a location where an image of that marker is created [4]. The camera model defines three coordinate systems, which are also depicted in Figure 1. Marker image locations are measured in the image plane coordinate system. The camera is centered at and oriented with the camera coordinate system. Tracking measurements are reported in the world coordinate system.

For a given camera, a camera calibration defines its position and rotation with respect to a user-defined coordinate system, its focal length, and the center of its image plane in the image plane coordinate system. Camera calibration parameters can be divided into two main groups: extrinsic and intrinsic. Extrinsic parameters consist of position and rotation parameters. The position parameters are the coordinates of the focal point of the camera in the world coordinate system. Rotation parameters *yaw*, *pitch*, and *roll* define the rotation from the camera coordinate system to the world coordinate system about the focal point of the camera. The intrinsic parameters include the *x* and *y* components of the center of the image plane and the focal length. As the pinhole camera model is only an approximation, various lens distortion models can be

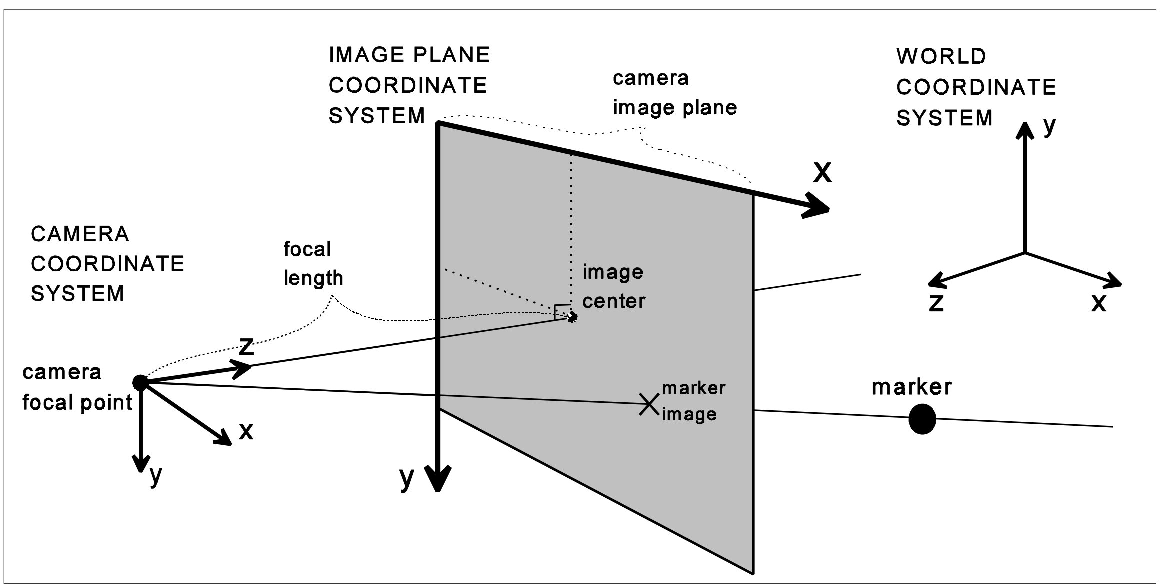

Figure 1 Pinhole Camera Model and Coordinate Systems

used to extend the model for a more accurate approximation. These models result in a higher number of camera calibration parameters whose values need to be determined during camera calibration.

TRADITIONAL CAMERA CALIBRATION TECHNIQUE

In the traditional camera calibration technique, four or more markers are placed at known locations within the viewing volume of one camera. Their corresponding 2-D locations are measured on the image plane of the camera. The calibration algorithm finds the parameter values that best transform the set of image coordinates for the markers to their corresponding world locations. Using the same marker configuration, this can be repeated for a second camera.

The traditional camera calibration technique requires markers to be positioned accurately and distributed throughout the portion of the viewing volume within which markers will be tracked. For large test volumes, this requires large and expensive calibration structures or the accurate surveying of many 3-D locations throughout the volume. Thus, calibration of large volumes with this technique requires greater skill, is more difficult, and is more time consuming.

WAND CALIBRATION TECHNIQUE

In the traditional camera calibration technique, each individual marker provides a control point for the parameter optimization. Therefore, the number of markers limits the calibration accuracy. Instead, the wand calibration technique depends on the number of image frames collected.

A wand is a rigid rod with a spherical marker fastened to each end. To calibrate two cameras together, a wand is moved throughout the their common viewing volume and the marker image locations are recorded at regular time intervals. For each wand sample, consisting of a pair of marker image locations from each camera, the calibration algorithm uses an estimate of the camera calibration parameters to compute the locations of the two markers from the wand in the world coordinate system. Figure 2 shows the wand projection onto the image planes of both cameras.

To compute the 3-D location of a marker, a vector is extended from the focal point of each camera, through the respective image location on the image plane. In theory, these vectors intersect at the location of the marker. However, uncertainties in the calibration parameters and camera noise result in vectors that do not cross. Because of this, the location of the marker is instead calculated as the closest point of intersection for the two vectors. This marker location has an associated uncertainty, which is the distance between the vectors, known as the epipolar distance.

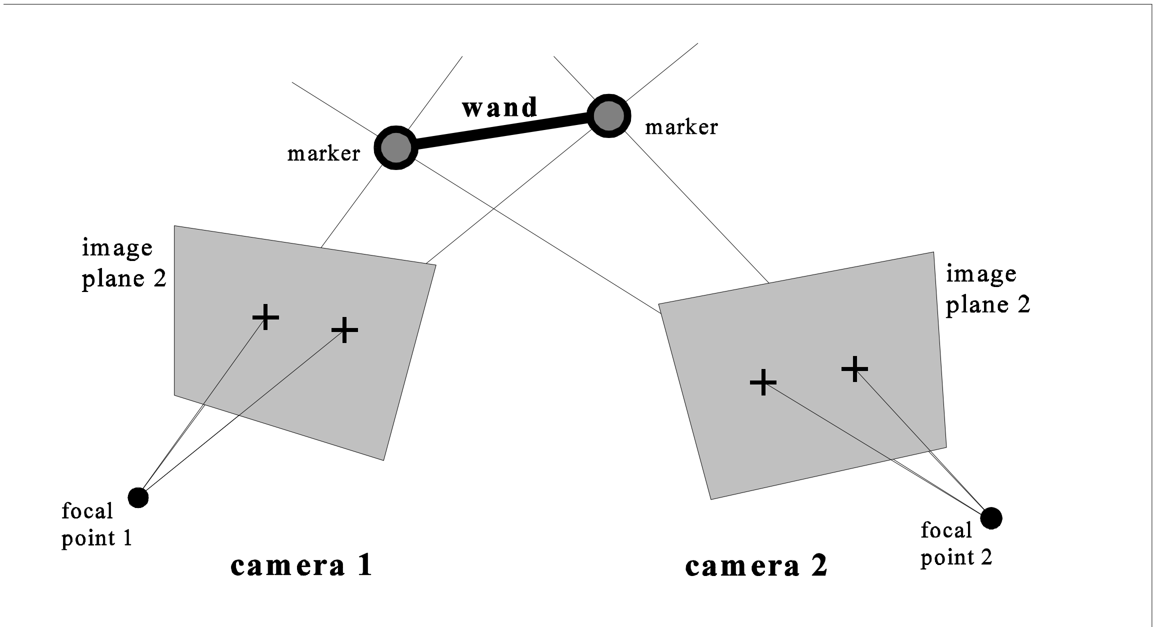

Figure 2 Projection of Wand onto the Image Planes of Two Cameras

The wand calibration algorithm computes camera calibration parameter values using a nonlinear minimization technique. In particular, it modifies the parameter values such that they minimize the following cost function:

$$\frac{\sum_{1}^{M} [\alpha(l_a - l_c)^2 + \beta(e_1^2 + e_2^2)]}{M}$$

This function computes the sum of three mean-of-squares errors over a set of M wand samples. The first error accounts for the difference in the actual distance between the two markers, l_a, and the computed distance, l_c. The remaining two errors are given by the uncertainties, e_1 and e_2, in computing the locations of the two markers in the world coordinate system. Weighting factors α and β account for the two error types not having the same effect on calibration accuracy.

TEST PROCEDURE

A volume of approximately four metres cubed was defined in which the calibration and tracking was performed. Two cameras were positioned such that they were nearly perpendicular to each other and their fields of view covered the entire test volume. The same setup was used for all tests. Four experiments were carried out. Two used a 252.5 mm wand (short wand) and the remaining two used a 552.5 mm wand (long wand). For each experiment, three sets of marker image data were acquired using the optical tracking system. The first set was for the motion of the wand inside the test volume. Over thirty seconds, a total of 1,500 image frames was collected for each camera, from which a subset of approximately one hundred pairs of marker image locations for each camera was used for the wand calibration procedure. The second set of data was for a calibration frame consisting of eight markers, which was placed near the center of the test volume. This data set was used for the traditional calibration technique. The final set of data was for a rigid test frame of eight markers that was moved inside the test volume for thirty seconds. This data set, which consisted of 1,500 frames of marker image data for each camera, was used in determining the accuracy of each calibration. Thus, for each experiment, two data sets were collected for camera calibration, and one set was collected for evaluating the calibrations.

In each experiment, the wand and traditional calibration techniques were each used to calibrate the two cameras. After each calibration, the resulting calibration parameters and test marker image data were used to evaluate the accuracy of the calibration technique. The motion tracking software computed the 3-D locations of each of the markers attached to the test frame. For each time interval, a least squares technique was used to calculate the six degree-of-freedom motion of the test frame by minimizing an RMS error [5]. This RMS error is the square root of the average distance errors between each calibrated marker, rotated and translated by the calculated six degrees of freedom, and its measured marker location. A low error value indicates that the solution has a high accuracy.

TEST RESULTS

The data output from the motion tracking software for each new calibration included the 3-D position and rotation of the model being tracked, as well as the average distance RMS error and the number of markers tracked. The mean and standard deviation of the average distance error from the 1,500 frames of test data were used to evaluate the results from the four experiments and are shown in Table 1. For the short wand experiments, the traditional calibration technique produced results with an average mean distance error of half that of the wand technique. Comparing the longer wand results to those of the traditional technique shows little or no difference. The standard deviations were similar for all for experiments.

	252.5 mm Wand		**552.5 mm Wand**	
	Test 1	**Test 2**	**Test 3**	**Test 4**
Wand	2.87 ± 0.77	2.76 ± 0.68	1.59 ± 0.72	1.60 ± 0.71
Traditional	1.66 ± 0.65	1.51 ± 0.66	1.44 ± 0.66	1.40 ± 0.64

Table 1 Experiment Results

CONCLUSIONS

Results from the limited experiment described in this paperreport show that the wand calibration technique produces results similar to those of the traditional technique, although more work needs to be done to determine the effects of wand length on accuracy. These experiments were performed over a small test volume, but similar results would be expected over a much larger volume. However, the setup for the traditional technique requires greater skill, effort and time over that of the wand technique.

REFERENCES

[1] M. Sullivan, *Optical Tracking at the Institute for Marine Dynamics*, Presented at the 4th Canadian Marine Hydrodynamics and Structures Conference, Ottawa, 1997.

[2] N.A. Borghese and P. Cerveri, *A New Method for Calibrating a Video Camera Pair with a Rigid Bar: Comparison with Bundle-Adjustment*, submitted to ISPRS, 1998.

[3] Darrell Lahey, *Calibrating a Camera Pair Using the Motion of a Wand*, Department of Computer Science, Memorial University of Newfoundland, 1999.

[4] D. C. Brown, *Close-range Camera Calibration, Photogrammetric Engineering: Journal of the American society of Photogrammetry*, Vol. 37, 1971, pp. 855-866.

[5] T.S. Huang, S.D. Blostein and E.A. Margerum, *Least-squares Estimation of Motion Parameters From 3-D Point Correspondences*, Presented at the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Miami Beach, Florida, June 22-26, 1986.