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UNDERWATER COMPARISON OF WAND AND 2D PLANE NONLINEAR CAMERA CALIBRATION METHODS

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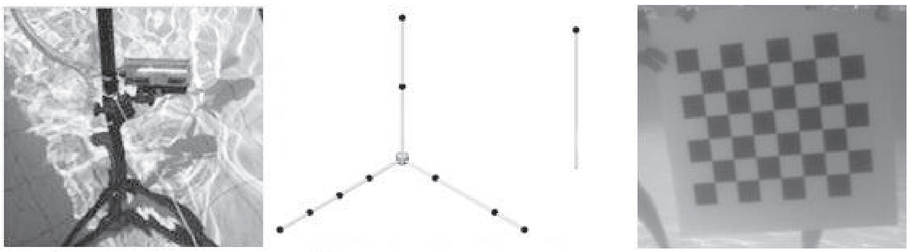
The purpose of this study was to compare two nonlinear camera calibration methods for 3D underwater motion analysis. The DVideo kinematic analysis system was used for underwater online data acquisition. The system consisted of two gen-locked Basler cameras working at 100Hz, with wide angle lenses that were enclosed in housings. The accuracy of both methods was compared in a dynamic rigid bar test. The mean absolute errors were 1.16mm for wand calibration, 1.20mm for 2D plane calibration using 8 control points and 0.73mm for 2D plane calibration using 16 control points. The results of both nonlinear camera calibration methods provided better underwater accuracy than all previous papers reported in literature. Both methods provided similar and highly accurate results, providing promising alternatives for underwater 3D motion analysis.

KEY WORDS: nonlinear camera calibration, 3D underwater analysis.

INTRODUCTION: Nowadays, the accuracy of 3D kinematic systems is greatly improved using nonlinear camera calibration methods. The wand calibration method is offered by the vast majority of 3D system manufacturers. This method is based on the DLT equations to determine the initial camera calibration parameters and on the bundle adjustment, a nonlinear optimization, to compute all camera calibration parameters (Cerveri et al., 1998). Another alternative for an accurate camera calibration is the 2D plane calibration method. This method uses the closed-form solution to determine the initial intrinsic and extrinsic parameters. A nonlinear optimization technique, the maximum likelihood criterion is used to refine all the parameters including lens distortion (Zhang, 2000). In previous works, accurate results were found out of the water (Silvatti et al., 2009) and underwater (Silvatti et al., 2010) using the 2D plane non-linear camera calibration method. The aim of the present study was to investigate the accuracy of wand and 2D plane non-linear camera calibration methods for 3D underwater analysis.

METHODS: The DVideo kinematic analysis system (Figueroa et al., 2003; Silvatti et al. 2010) was used for underwater online data acquisition. The system consisted of two gen-locked Basler cameras working at 100Hz, with wide angle lenses (8mm focal length) enclosed in waterproof housings (figure 1a). In order to perform the wand calibration (table 1), an orthogonal waterproof triad (1m×1m×1m) was built to determine initial extrinsic and intrinsic parameters using DLT equations. Nine spherical black markers (35mm) were screwed onto it (figure 1b). All the holes were obtained by a computer numerical control machine (CNC). The 3D coordinates of the markers were known with accuracy of about 10μm. The moving wand, carrying one marker at its end (figure 1b), was acquired in the whole working volume (4.5×1×1.5m^3) during 15 seconds. Two hundred and fifty useful frames were opportunely extracted from the whole sequence to refine the initial parameters into a bundle adjustment nonlinear optimization, which uses control points with both known (triad markers) and unknown (wand marker) 3D coordinates. The bundle adjustment iteratively estimates the parameters of all the cameras along with the unknown 3D coordinates by minimizing the 2D projection error (measured vs. predicted by the camera model) on the image. In our method, just one marker was utilized because of the simplification of the tracking during the acquisition sequence. Commonly, commercial systems (Smart, BTS. SpA, Italy) utilize two markers at the ends of the rigid bar including the

marker distance as an additional constraint in the optimization. The distortion was taken into account in the camera model adopting a radial model with 2 parameters.
In order to perform the 2D plate calibration (table 1, Zhang, 2000), a waterproof chessboard (5×6 squares, 100×100mm with 42 corners, figure 1) was used (Silvatti et al., 2010). A graduated rod, with four black markers, was acquired in 4 different underwater positions. The water levels were measured in each graduated rod position to build the coordinate system on the water plane. The distances between the 4 positions of the graduated rod and the two points located on the swim pool border were measured to perform the triangulation and to obtain the control points 3D coordinates. Two different amounts of control points (8 and 16) were used to provide the closed-form solution (DLT) for the camera parameters. The chessboard was moved in the working volume and was automatically tracked. The 100Hz frame rate was resampled to 10Hz to acquire two hundred sequential frames in order to refine the intrinsic and distortion parameters for each camera. The distortion was taken into account in the camera model, adopting a radial and tangential model with 5 parameters. The distortion correction exploited the virtual straight lines of the chessboard.



a) b) c)

Figura 1: a) Cameras enclosed in housings fix on tripods for underwater aquisition. b) Triad and wand built with black markers to contraste in underwater used to wand calibration. c) Chessboard used for 2D plate calibration.

The calibration accuracy of both calibration methods was assessed on a 10s acquisition of a rigid bar (two black markers) moved within the working volume. The distance between markers (nominal value D: 291.89mm) was obtained as a function of time. The following variables were calculated: a) the mean absolute errors (MAE) b) the standard deviation, c) the minimum and d) maximum error, e) the root mean squared error (RMSE) and f) the RMSE relative to reconstruction expressed as a percentage of the real length of the rigid bar movement.

Table 1
Comparison of the procedure to calibrate the camera parameters in both methods

	Type of calibration	
Issues	**Wand Calibration**	**2D Plate Calibration**
Calibration support	Triad + wand	Graduated rod + Chessboard
Points to track	Spherical - Black Markers	Planar - Corners
Acquisition protocol	Static triad + Moving wand	Graduated rod in 4 positions + Moving chessboard
Calibration approach	Closed-form for initial estimation Refinement by bundle adjustment	Closed-form for extrinsic parameters Refinement of the intrinsic parameters
	Camera network	Single camera calibration
Distortion model	Radial	Radial e Tangential

RESULTS: Table 2 shows the mean, standard deviation, minimum error, mean absolute errors, maximum error, RMSE of the distance curves between markers and the %RMSE for the wand calibration and for both tests using the 2D plate calibration in the rigid bar test. The results of the three approaches were comparable in terms of MAE (1.16mm, 1.20mm, 0.73mm). The mean values of the bar length and the mean absolute error for the 2D plate calibration with sixteen control points were better than those obtained in the configuration with eight control points and with the wand calibration. However, the standard deviation (0.69mm, 1.07mm and 0.89mm) and the maximum error (3.99mm, 8.03mmand 6.90mm) were smaller in the wand calibration than in both 2D plate calibration configurations.

Table 2
Results of the wand calibration, of the 2D plate calibration using 8 points and the 2D plate calibration using 16 points in the dynamic test. D: 291.89 mm. Values in millimeter (mm).

	Mean	Standard Deviation	Minimum Error	Mean Absolute Error	Maximum Error	RMSE	%RMSE
Wand Calibration	290.77	0.69	0.20	1.16	3.99	1.31	0.45
2D plate Calibration (8 control points)	292.87	1.07	0.19	1.20	8.03	1.45	0.50
2D plate Calibration (16 control points)	291.67	0.89	0.07	0.73	6.90	0.92	0.31

DISCUSSION: According to the results, we can assert that the wand calibration allows reduction of the error spread in the calibration volume with respect to the 2D plate calibration. This is well justified by the bundle adjustment approach which intrinsically makes homogeneous the reconstruction error across all the calibration volume. As far as 2D plate calibration is concerned, the accuracy results were slightly worse than those values previously found (Silvatti et al. 2010). This fact might be due to the water transparency that was better in the previous experiment. This suggests that the water transparency should be taken into account when highly accurate results are required. Both methods led to underwater accuracy better than previously reported in the literature (Yanai et al., 1996; Kwon et al., 2000; Gourgoulis et al., 2008 and Machtsiras,G. & Sanders R. H. 2009). Pribanic et al., 2008 compared the same camera calibration methods, but out of the water, and found values ranging from 0.66mm to 0.75mm for the wand calibration and 0.69mm to 0.84mm for the 2D plate calibration. Our results were comparable to these values with the accuracy of commercial systems used for dry land 3D analysis (Chiari et al. 2005). The advantages and disadvantages of each method were synthesized in Table 3.

Table 3
Synthesis of the advantages and disadvantages of both methods.

Type of calibration	Advantages	Disadvantages
Triad + wand Calibration	• Equalization of the reconstruction error across the calibration volume • Only one point to track • Calibration structures are light and easy to setup • High portability	• The wand must be moved opportunely to cover all the calibration volume • Accuracy strictly depending of the construction of the triad • High sensibility of wand marker tracking to water quality • Assumes the vertical axis based on the swim pool floor
Graduated rod + 2D Plate Calibration	• Each camera can be calibrated separately • Better corner visibility • More accurate distortion correction • Lower sensibility of corner detection to water • Allows to correct the vertical axis based on the water plane	• Unbalanced camera network • High number of corners to track • Chessboard are cumbersome • Accuracy strictly depending of the construction of the chessboard

CONCLUSION: The results of both nonlinear camera calibration methods provided better underwater accuracy than all previous papers reported in literature. Both methods tested in this study provided similar and highly accurate results, providing promising alternatives for underwater 3D motion analysis.

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