CAMERA CALIBRATION FOR UNDERWATER APPLICATIONS: EFFECTS OF OBJECT POSITION ON THE 3D ACCURACY

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The purpose of this study was to investigate the effects of object position in the working volume on the accuracy of 3D reconstruction, using four different camera calibration approaches: 1) the classical DLT, 2) the nonlinear DLT, 3) the 2D plate and 4) the wand calibration. The DVideo kinematic analysis system was used for underwater data acquisition. The system consisted of two gen-locked Basler cameras (100 Hz) enclosed in housings. A dynamic rigid bar test (acquisition volume - $4.5\times1\times1.5$ m^3) was used to obtain the accuracy of the 3D reconstruction. Larger errors were found using the classical and nonlinear DLT methods. Furthermore, these approaches were affected by the rigid body position in the working volume. In conclusion, 2D plate and wand calibration methods provided more accurate results and were not affected by object position in the volume.

KEY WORDS: Camera calibration, accuracy evaluation, 3D underwater analysis.

INTRODUCTION: A linear camera model (DLT - Direct Linear Transform) is commonly used for underwater applications (Gourgoulis, Aggeloussis, Kasimatis, Vezos, Boli, & Mavromatis, 2008; Machtsiras & Sanders, 2009). This approach requires a calibration structure, with known geometry, and it becomes cumbersome if a large acquisition volume is considered. Moreover, this camera model disregards the lenses optical distortions that strongly impact the reconstruction accuracy. Better results were obtained when the optical distortion was modeled in the DLT method as shown in Kwon (2008). However, this implies in more control points on this cumbersome calibration structure (Kwon, 2008). Two alternative approaches that presented highly accurate results in underwater applications were wand and 2D plate-based methods (Silvatti, Dias, Cerveri, & Barros, 2012). Both approaches make use of simpler calibration objects and include nonlinear models for the camera calibration (Cerveri, Borghese & Pedotti, 1998; Zhang, 2000). The aim of the present study was to investigate the effects of the object's position, inside the working volume, on the accuracy of 3D reconstruction, using four calibration approaches.

METHODS: A kinematic analysis system, the DVideo, was used (Figueroa, Leite & Barros, 2003; Silvatti Telles, Rossi, Dias, Leite & Barros, 2010; Silvatti, Telles, Dias, Cerveri, & Barros, 2011; Silvatti et al. 2012) for underwater online data acquisition. The system consisted of two gen-locked Basler cameras working at 100 Hz, with wide angle lenses (8mm focal length) enclosed in waterproof housings. In order to perform the classical DLT, a graduated rod, with four black markers, was acquired in four different underwater positions which defined the working volume ($4.5\times1\times1.5$ m^3). The water levels were measured in each graduated rod position to build the coordinate system on the water plane. The distances between the four rods and two arbitrary points, located on the swim pool border, were measured, allowing the computation of the 3D coordinates of the control points using a triangulation method. Sixteen control points (CP) were used to calculate the closed-form solution (DLT) for the camera parameters. In order to perform the nonlinear DLT (as implemented in http://metrovisionlab.unizar.es) we used the same sixteen CP acquired for DLT calibration. The distortion was taken into account in the camera model, adopting a radial and tangential model with 5 parameters. In order to perform the 2D plate calibration (Zhang,

2000), a waterproof chessboard (7×8 squares of 100×100 mm), with 42 corners, was used (Silvatti et al. 2011, Silvatti et al. 2012). In order to refine the intrinsic and distortion parameters of each camera, the chessboard was moved in the working volume and two hundred sequential frames were acquired (10 Hz) and each corner was automatically detected and tracked. The distortion was taken into account in the camera model, adopting the same distortion parameters of the nonlinear DLT camera model; however in this approach the distortion correction exploited the straight lines of the chessboard. In order to perform the wand calibration, an orthogonal waterproof triad, with nine spherical black markers, was used to determine initial extrinsic and intrinsic parameters using the DLT (Silvatti et al. 2011, Silvatti et al. 2012). The moving wand, carrying one marker at its end, was acquired in the whole working volume, during 15 s. In order to refine the initial parameters, two hundred and fifty useful frames were opportunely extracted from the sequence and used in a nonlinear bundle adjustment optimization. The distortion was taken into account in the camera model by adopting a radial model with 2 parameters.
The accuracy of each calibration method was assessed considering the same sequence, containing 700 frames, of a rigid bar with two black markers. The rigid bar was moved in the working volume and their markers were automatically tracked. The distance between markers (nominal value D: 291.89 mm) was obtained as a function of time. The accuracy was defined by the norm of the difference between the real and obtained value (error). This error was evaluated as a function of the rigid bar 3D position in the working volume, in terms of their coordinates (swimming pool longitudinal (X), transversal (Y) and vertical (Z) directions).

RESULTS: Figure 1 shows the error as function of the rigid bar's position in the working volume for each camera calibration approach.

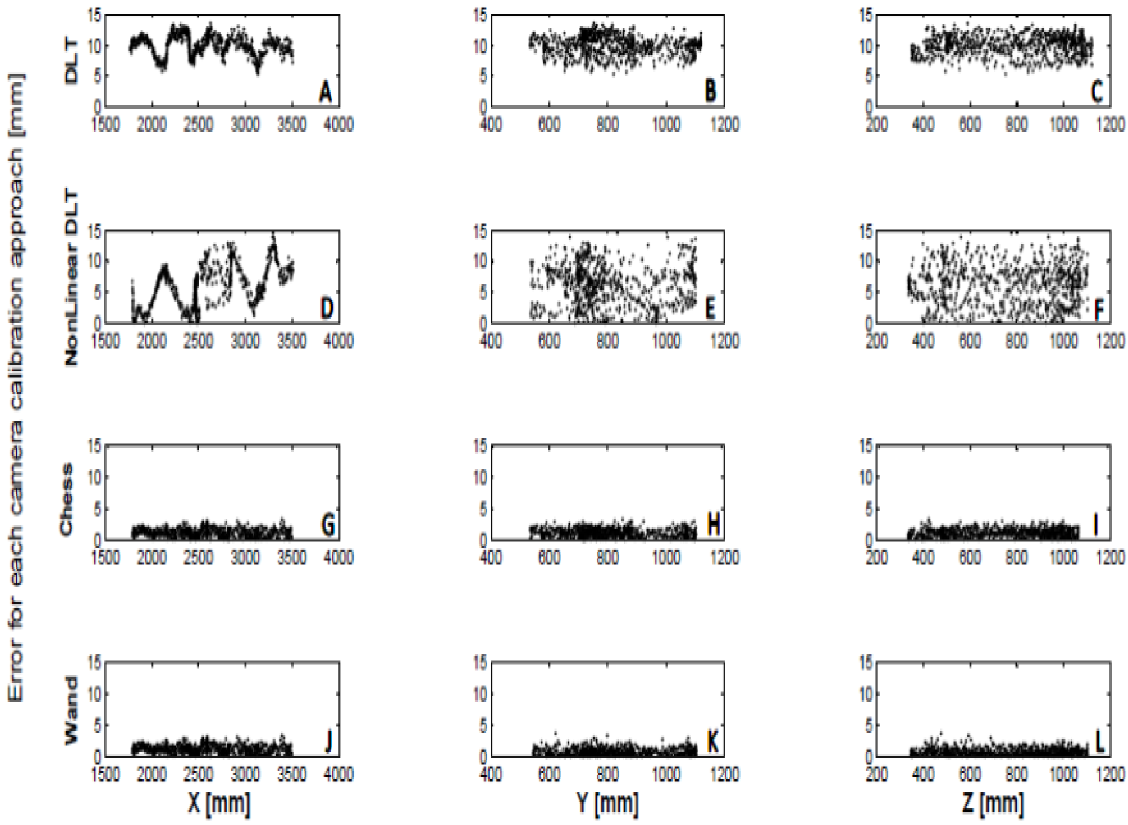

Figure 1. 3D reconstruction error as function of the rigid bar position in the working volume (swimming pool longitudinal (X), transversal (Y) and vertical (Z) directions) in each camera

calibration approach (DLT, Figure 1A, 1B, 1C; nonlinear DLT, Figure 1D, 1E, 1F; 2D plate calibration Figure 1H, 1I, 1J and wand calibration Figure 1K, 1L, 1M).

The DLT (values ranging from 5.36 to 13.42 mm) and the nonlinear DLT (0.05 to 14.56 mm) approaches present increased errors compared to 2D plate (0.002 to 3.65 mm) and wand (0.01 to 3.29 mm) methods. In the X axis, both DLT based methods showed a clear signal varying in function of the rigid bar position in the working volume. This relation between error and position is not identifiable in the results of 2D plate and wand calibration. In the Y and Z axes, the DLT based methods present more spread errors than 2D plate and wand calibration, however none of four methods present association with the test bar movement.

DISCUSSION: The first remarkable effect revealed by the results was the increased error in the DLT based methods. As expected, the linear DLT camera model presented the worst result, since it does not include the distortion parameters. Otherwise, the nonlinear DLT performance was expected to provide better results since the nonlinear effects were modeled. According to Kwon (2008), the use of a small number of control points in the working volume or their poor distribution can affect negatively the accuracy. In this study, sixteen control points were assumed to be enough to calibrate the cameras using nonlinear DLT, considering the minimum of eight points requested by the method. The point's distribution might be another explanation, but no further experiment was predicted to allow this evaluation. The 2D plate and the wand calibration approaches provided very accurate results, as already reported in previous papers (Silvatti et al. 2011, Silvatti et al. 2012).
The second effect was the relation between the object position in the working volume and the 3D reconstruction accuracy. The results pointed out that 2D plate and wand calibrations were not affected by object position contrarily to both DLT based calibrations. Miks and Novak (2005) demonstrated the theoretical relation between the object position and accuracy, showing that when the distortion is properly modeled there is no effect of object position on accuracy.
For sporting underwater applications large acquisition volumes are frequently involved. Large calibration structures with a great number of well distributed control points are needed in order to apply the DLT and nonlinear DLT. This kind of structure is difficult to handle with the required accuracy. On the other hand, the 2D plate and wand calibration devices showed to be easier to build and manipulate, presenting better accuracy values (Silvatti et al. 2011, Silvatti et al. 2012) than other methods found in the literature (Yanai, Hay & Gerot, 1996; Kwon & Lindley, 2000; Gourgoulis et al., 2008; Machtsiras & Sanders, 2009)

CONCLUSION: In conclusion, 2D plate and wand calibration methods provided more accurate results and were not affected by object position in the working volume contrarily to the classical DLT and nonlinear DLT.

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Acknowledgement: Research supported by FAPESP (00/01293-1, 2006/02403-1 and 2009/09359-6), CNPq (473729/2008-3, 304975/2009-5) and CAPES (2011/10-7).