EXAMINATION OF DIFFERENT DOUBLE-PLANE CAMERA CALIBRATION STRATEGIES FOR UNDERWATER MOTION ANALYSIS

Young-Hoo Kwon, Amy Ables, and Priscilla G. Pope
Texas Woman's University, Denton, Texas, USA

The purpose of this study was to evaluate five different double-plane calibration strategies with various localized control area sizes and degrees of overlapping to identify the best strategy to minimize the object-space reconstruction error in underwater motion analysis. The object-space reconstruction errors (RMS and maximum) and the RMS-to-max ratios were computed from a simulated underwater calibration trial. An imaginary experimental setup based on a theoretical refraction model was used for a series of camera calibrations. Different double-plane calibration strategies based on the same experimental setup generated very different RMS and maximum reconstruction errors. It was concluded from the analysis that large overlapping localized control areas can substantially reduce the reconstruction error in the double-plane method.

KEY WORDS: double-plane method, localized calibration, localized DLT, object-space reconstruction, underwater motion analysis, localized control areas.

INTRODUCTION: Refraction at the water-glass-air interface is the main source of the calibration errors in the underwater motion analysis. By causing non-linear deformation of the image, refraction violates the collinearity condition that is the essence of the DLT method (Kwon, 2000). Various studies have examined different methods to reduce the underwater camera calibration errors (Drenk, Hildebrand, Kindler, & Kliche, 1999; Kwon, 2001 & 1999; Kwon & Lindley, 2000). Kwon and Lindley (2000) examined 4 different 3-dimensional localization strategies (3-D LDLT and the double-plane method with/without control volume/area overlapping) based on the so-called LDLT (localized DLT) algorithms and reported that the double-plane method with overlapping localized control areas provided the best results in terms of the reconstruction error (RMS error and max error) and the discontinuity error. The key feature of the LDLT methods is the splitting of the control volume/area into smaller localized volumes/areas. The LDLT algorithms require identification of the closest localized volume/area to the marker of interest in the object-space reconstruction. Smaller control volumes/areas tend to produce smaller calibration errors (Kwon, 1999 & 2001; Kwon & Lindley, 2000) while the overlapping of the localized control volumes/areas reduces the discontinuity error due to switching of the closest localized volume/area from one area to the next area (Kwon & Lindley, 2000). Although the double-plane method with overlapping localized control areas provided the best calibration/reconstruction accuracy (Kwon & Lindley, 2000), it is important to examine the trade-off between the size of the localized control areas and the degree of overlapping among the localized areas. In an effort to reduce the reconstruction error in the underwater motion analysis, the purpose of this study was to evaluate, through simulation, five different double-plane calibration strategies with varying localized control area size and degree of overlapping among them.

METHODS: Reconstruction errors (RMS and maximum) were computed from a simulated underwater calibration trial. The simulated calibration frame consisted of five rectangular (3-m L by 1-m H) planes with the overall control volume being 3-m L, 1-m H, and 1-m W (Figure 1). A total of 325 control points (65 per plane) were marked on the frame with the distance between the adjacent points being 0.25 m. All 325 points were used in the object-space reconstruction to assess the reconstruction error while only 130 points from planes 1 and 5 were used for the double-plane calibration. A simulation program (UW.EXE) generated the image-plane coordinates of the control points based on the refraction model reported by Kwon (2001). Five double-plane calibration strategies were tested in this study: DP-2, DP-18, DP-40, DP-66, and DP-96 (Table 1). DP-96 utilized the smallest definable squares (0.25 m x 0.25 m) with no overlapping while DP-18 used the largest definable squares (1 m x 1 m) with the most degree of overlapping. DP-2 was a non-localized method with 1 control area (3 m x 1 m) per plane.

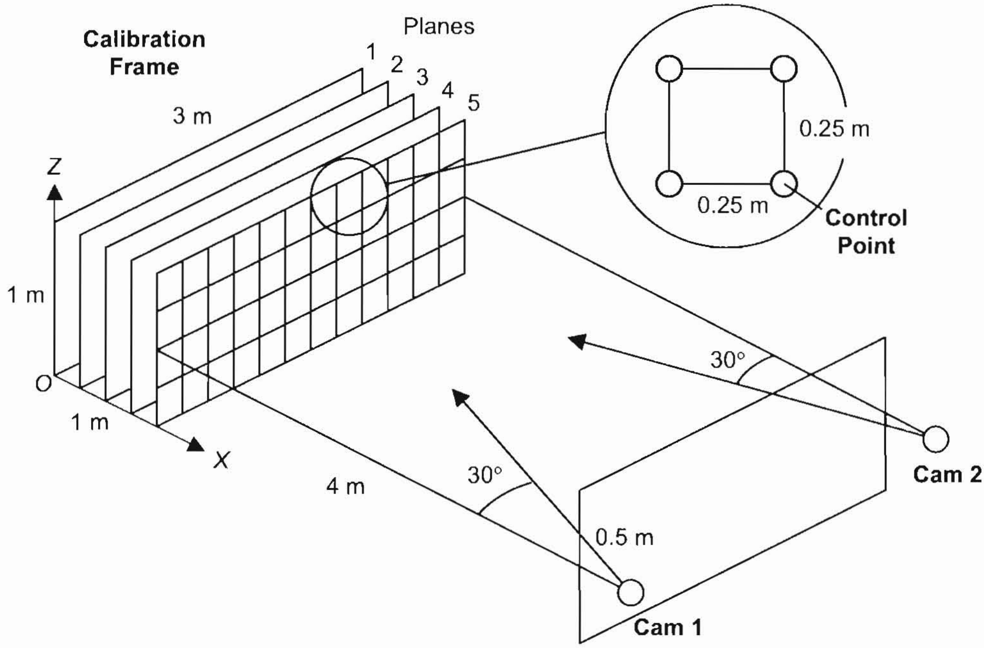

Figure 1. Calibration frame and the camera setup used in the simulated calibration trial. Calibration frame was placed 4 m away from the water-air interface, parallel to the interface plane. The cameras were set at 0.5 m behind the interface plane, 3 m apart from each other, with the angle between them being 60 degrees. A total of 65 control points were marked on each control plane.

Table 1. Double-Plane Calibration Strategies Used.

	Localized Area Size	Areas/Plane	Points/Area	Overlapping	Localization
DP-2	3 m x 1 m	1	5 x 13 = 65	No	No
DP-18	1 m x 1 m	1 x 9 = 9	5 x 5 = 25	Yes	Yes
DP-40	0.75 m x 0.75 m	2 x 10 = 20	4 x 4 = 16	Yes	Yes
DP-66	0.5 m x 0.5 m	3 x 11 = 33	3 x 3 = 9	Yes	Yes
DP-96	0.25 m x 0.25 m	4 x 12 = 48	2 x 2 = 4	No	Yes

The reconstruction errors (RMS and maximum) of the double-plane calibration methods were also compared with the 3-D DLT method. All 130 points from planes 1 and 5 (Figure 1) were included in the 3-D DLT calibration. Kwon3D Motion Analysis Software Version 3.0 (Visol, Inc., Seoul, Korea) was used in the camera calibration and subsequent object-space reconstruction.

RESULTS AND DISCUSSION: All double-plane calibration methods except DP-96 scored smaller calibration errors than the 3-D DLT method (Table 2). DP-96 revealed the largest RMS and maximum reconstruction errors among the calibration strategies used in this study. Its maximum error was similar to that of the 3-D DLT calibration but the RMS error was much larger. DP-18 scored the smallest RMS and maximum reconstruction errors and the smallest max-to-RMS error ratio as well. It is clear from these results that different double-plane calibration strategies based on the same calibration frame can generate very different reconstruction results. It is, therefore, important to use the right size-overlapping combination to minimize the reconstruction errors for given experimental conditions.

Table 2. Calibration Results (Unit: cm).

	RMS Error	Max Error	Max-to-RMS Ratio
3-D DLT	1.53	5.57	364.1%
DP-2	1.30	3.08	236.9%
DP-96	1.71	5.60	327.5%
DP-66	1.10	3.98	361.8%
DP-40	0.94	3.61	384.0%
DP-18	0.76	1.78	234.2%

Contrary to the common observation that larger control area causes larger reconstruction errors (Kwon, 1999; Kwon & Lindley, 2000), the reconstruction errors decreased substantially as the size of the localized control areas increased with increased degree of overlapping: DP-96 ⇒ DP-66 ⇒ DP-40 ⇒ DP-18. In the double-plane calibration strategies with overlapping, the whole area of a given localized control area is used in calibration to obtain the DLT parameters. Only the central portion of the control area, however, will be used in the reconstruction because the closest localized control area changes to the next localized control area before the projected marker actually reaches the border of the current control area. The reconstruction error in the central portion of a given localized control area is much smaller than that near the border (Kwon, 1999) and this explains the trend observed in this study. Both strategies DP-66 and DP-40 revealed smaller RMS but larger maximum errors than DP-2, thus resulting in much larger max-to-RMS error ratios. This appeared to be a result of extrapolation problem intrinsic to the double-plane method. As shown in the Figure 2, all the control points in the gray region will be projected to outside of plane 1 in camera 2. In other words, extrapolation occurs in these points based on the closest localized control area during reconstruction. The size ratio of the extrapolated region to the closest localized control area will determine the magnitude of the reconstruction error in this region. DP-66 and DP-40 have larger size ratios of the extrapolation region to the localized control area than DP-2. DP-18 was considered as the optimal size-overlapping combination since it resulted in the smallest reconstruction errors. DP-18 had the advantage of the localized camera calibration approach over DP-2. It was characterized by more overlapping of the localized control areas than DP-66 and DP-40. Its size ratio of the extrapolated region (Figure 2) to the localized control area was the smallest among the double-plane calibration strategies with overlapping, thus providing advantages in terms of extrapolation. Therefore, the best double-plane calibration strategy is to define as large localized control areas as possible with as much overlapping among them as possible for a given calibration frame. One problem observed in DP-96 (the smallest localized control areas + no overlapping) is that this method could not generate the reconstructed coordinates of some control points. This was due to the alternation of the closest localized control area back and forth between two adjacent localized control areas during the iterative computation of the converged object-space coordinates, as explained previously by Kwon and Lindley (2000). Overlapping of the localized control areas can reduce this problem to a certain extent since only the central portion of the control areas will be actually used in the reconstruction with less reconstruction error. Throughout all methods used in this study including the 3-D DLT method, the *X*-component of the reconstruction error was much larger than those of the *Y*- and *Z*-components. This appears to be due to the angle between the two cameras (60°). Since the control points were projected to the *YZ*-plane (Figure 1) and the inter-camera angle was smaller than 90°, any errors in the image coordinates of the projections of the points in the *YZ*-plane due to the deformation of the image could cause larger error in the X-coordinate than in the other coordinates. Smaller reconstruction error in the X-coordinate was expected with a larger inter-camera angle.

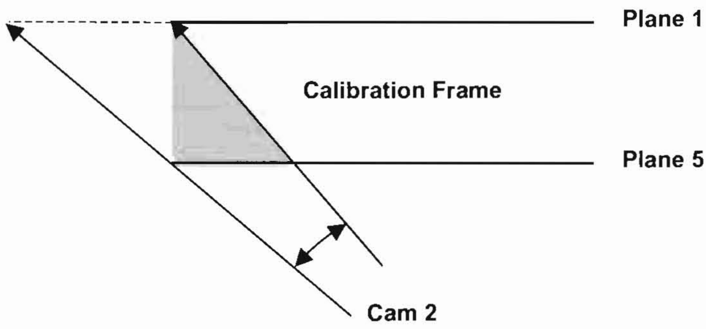

Figure 2. Extrapolation on plane 1 in camera 2 (overhead view). Control points in the gray area will be projected to outside of plane 1 (broken line) in the double-plane method although they are within the control volume.

CONCLUSION: It was demonstrated through simulation that different double-plane calibration strategies based on the same calibration frame generated very different reconstruction results. It is, therefore, important to identify the optimal size-overlapping combination to minimize the reconstruction errors for given experimental conditions. It was concluded that larger overlapping control areas could improve the quality of double-plane camera calibration for underwater motion analysis.

REFERENCES:

Drenk, V., Hildebrand, F., Kindler, M., & Kliche, D. (1999). A 3D video technique for analysis of swimming in a flume. In R.H. Sanders & B.J. Gibson (Eds.), *Scientific Proceedings of the XVII International Symposium on Biomechanics in Sports*, 361-364. Perth, Western Australia: Edith Cowen University.

Kwon, Y.-H., (2001). New panning-videography strategies for the underwater motion analysis. In J. R. Blackwell & R. H. Sanders (Eds.), *Proceedings of Swim Sessions, XIX International Symposium on Biomechanics in Sports*,109-112. San Francisco, CA: University of San Francisco.

Kwon, Y.-H., (1999). Object plane deformation due to refraction in two-dimensional underwater motion analysis. *Journal of Applied Biomechanics*, **15**, 396-403.

Kwon, Y.-H., & Lindley, S.L. (2000). Applicability of four localized-calibration methods in underwater motion analysis. R. Sanders & Y. Hong (Eds.), *Proceedings of the XVIII International Symposium on Biomechanics in Sports*, 48-55. Hong Kong, China: The Chinese University of Hong Kong.