NEW PANNING-VIDEOGRAPHY STRATEGIES FOR THE UNDEWATER MOTION ANALYSIS

Young-Hoo Kwon
Biomechanics Laboratory, Ball State University, Muncie, Indiana, USA

The purpose of this study was to evaluate, through simulation, two new panning-videography strategies based on single continuous control volume (continuous-volume approach) in an effort to overcome the shortcomings of the previously reported method that was based on a set of discrete control volumes (discrete-volume approach). Two continuous-volume strategies were tested: the large-frame strategy and the small-frame strategy. A series of camera calibrations were performed based on a theoretical refraction model and an imaginary experimental setup. Both strategies provided continuous DLT parameter-pan angle curves and demonstrated the potential to provide more reliable calibration results than the discrete-volume approach with less discontinuity in the reconstructed object space and less chance of extrapolation.

KEY WORDS: continuous-volume approach, discrete-volume approach, refraction model, object-space discontinuity, extrapolation error

INTRODUCTION: The horizontal dimension of the volume of motion of a full swimming stroke is determined by the stroke length and the length of the swimmer's fully extended body. Covering the entire volume of motion with a single camera causes a fairly small image which makes digitizing relatively difficult. One practical solution for this problem is to increase the number of cameras employed, with each camera covering a smaller volume, but the number of cameras one can use is a function of the size and location of the underwater viewing window, or the number of the water-proof housings and periscopes available. A noble solution for this problem is the use of a panning-videography technique and Yanai et al. (1996) pioneered panning videography in the underwater motion analysis by introducing a method that utilizes multiple periscopes.

In the underwater motion analysis, light refraction introduces a non-linear image deformation that causes relatively large reconstruction errors and even larger extrapolation errors (Kwon, 1999a, 1999b; Kwon & Lindley, 2000). Kwon and Lindley (2000) also pointed out that any calibration methods based on a set of discrete control volumes would suffer from discontinuity in the reconstructed object space due to the non-linear nature of the refraction error. The panning videography method introduced by Yanai et al. (1996) intrinsically involves extrapolation and, moreover, is based on a set of discrete control volumes (discrete-volume approach). One possible solution for these problems is the so-called continuous-volume approach that employs a continuous control volume instead of a set of discrete control volumes. The core of the continuous-volume approach is a set of DLT parameter prediction equations for the entire control volume. The purpose of this study was to evaluate, through simulation, two continuous-volume panning-videography strategies in an effort to overcome the shortcomings of the method developed by Yanai et al. (1996) and to improve the reliability of the panning videography in the underwater motion analysis.

METHODS: Two continuous-volume panning-videography strategies were tested in this study: the large-frame strategy and the small-frame strategy. The large-frame strategy employed a single large calibration frame that could contain the entire space of motion. All control points that appeared within the view at a given panning position were included in the camera calibration. The small-frame strategy involved a small calibration frame that was placed at several different locations throughout the space of motion. One representative calibration was performed at each frame location.

A series of simulated calibrations were performed based on a theoretical refraction model with panning capability (Figure la). The image-plane coordinates of the control points were generated based on the refraction model. Refractive index of 1.3330 was used for the water-air interface. A hexahedral calibration frame (5-m L, 1-m H, and 1-m W) with 44 control points was used in the camera calibration (Figure Ib). It was assumed that the calibration frame was placed 10 cm below the water surface while one panning camera was set 60 cm below the water surface. The pan angle (θ_V) ranged from –28 to 28° with the increment being 2". The principal distance of the camera (D_I) was determined in such a way that the area covered by the panning camera was approximately 200 cm wide. The viewable image-plane coordinate ranges were set to –320 to 320 and –240 to 240 for the *u* and v coordinates, respectively, with the principal point being (0, 0). The 3-D DLT method (Abdel-Aziz & Karara, 1971) was used in the camera calibration and the 11 DLT parameters were computed for each panning position:

$$u = \frac{L_1 x + L_2 y + L_3 z + L_4}{L_9 x + L_{10} y + L_{11} z + 1} \quad v = \frac{L_5 x + L_6 y + L_7 z + L_8}{L_9 x + L_{10} y + L_{11} z + 1} \tag{1}$$

The entire control volume with 44 control points was used in the large-frame strategy while five control volumes (V_1, V_{12}, V_2, V_{23} & V_3) with 8 control points each were used in the small-frame strategy (Figure Ib), representing different locations of a 1-m x 1-m x 1-m calibration frame.

RESULTS AND DISCUSSION: The parameter-angle curves of selected DLT parameters obtained from the large-frame strategy are presented in Figure 2: L_4 (2a) and L_{10} (2b). Since panning occurred about the V axis of the image-plane reference frame, parameters related to the *u* and y coordinates were more sensitive to the pan angle than others. L_4 serves as the representative of the parameters involved in the computation of the *u* coordinate while L_{10} is for those related to the y coordinate of the control point (Equation 1).
The large-frame strategy generated continuous parameter-angle curves with fluctuations. The shape and dimension of the actual control volume formed by the control points vary as the pan angle changes and this appears to be the main cause of the fluctuation in the parameter-angle curve. One may perform either polynomial or spline-function fitting of the parameters to reduce the fluctuation in the parameter-angle curve and/or to generate a single set of parameter prediction equations. By nature, the large-frame strategy also guarantees less extrapolation than the discrete-volume approach. On the other hand, the discrete-volume approach generated discontinuous curves with each control volume providing a close-to-linear parameter-angle curves. The discrete-volume strategy thus would likely cause discontinuity in the reconstructed object space (Kwon & Lindley, 2000).
The small-frame strategy generally demonstrated a good agreement with the results from the large-frame strategy, providing a more consistent parameter-angle curve for parameter L_{10} with less fluctuation (Figure 3). The small calibration frame used in this study was much smaller than the area covered by the camera and a better agreement between the two strategies could have been achieved if the size of the small calibration frame was increased to that of the actual control volume involved in the large-frame strategy. Again, one may perform either polynomial or spline-function fitting of the parameters to generate a single set of DLT parameter prediction equations for the entire control volume. The chance of extrapolation depends on the relative size of the small calibration frame to the area included in the camera view.

CONCLUSION: It was demonstrated through simulation that the continuous-volume strategies proposed in this study could potentially improve the camera calibration quality and subsequently the reconstruction accuracy by reducing discontinuity in the reconstructed object space. The large-frame strategy discards the need to place the calibration frame at multiple locations, thus simplifying the overall calibration process. The small-frame strategy can be used when a large calibration frame that can contain the entire volume of motion is not available. The small-frame strategy is in fact much simpler than the discrete-volume approach, originally introduced by Yanai et ai. (1996), but can provide a more reliable reconstruction of the object space. In the small-frame strategy, the best results are expected when the calibration frame is large enough to contain a fully extended swimmer's body since it eliminates the chance of extrapolation.

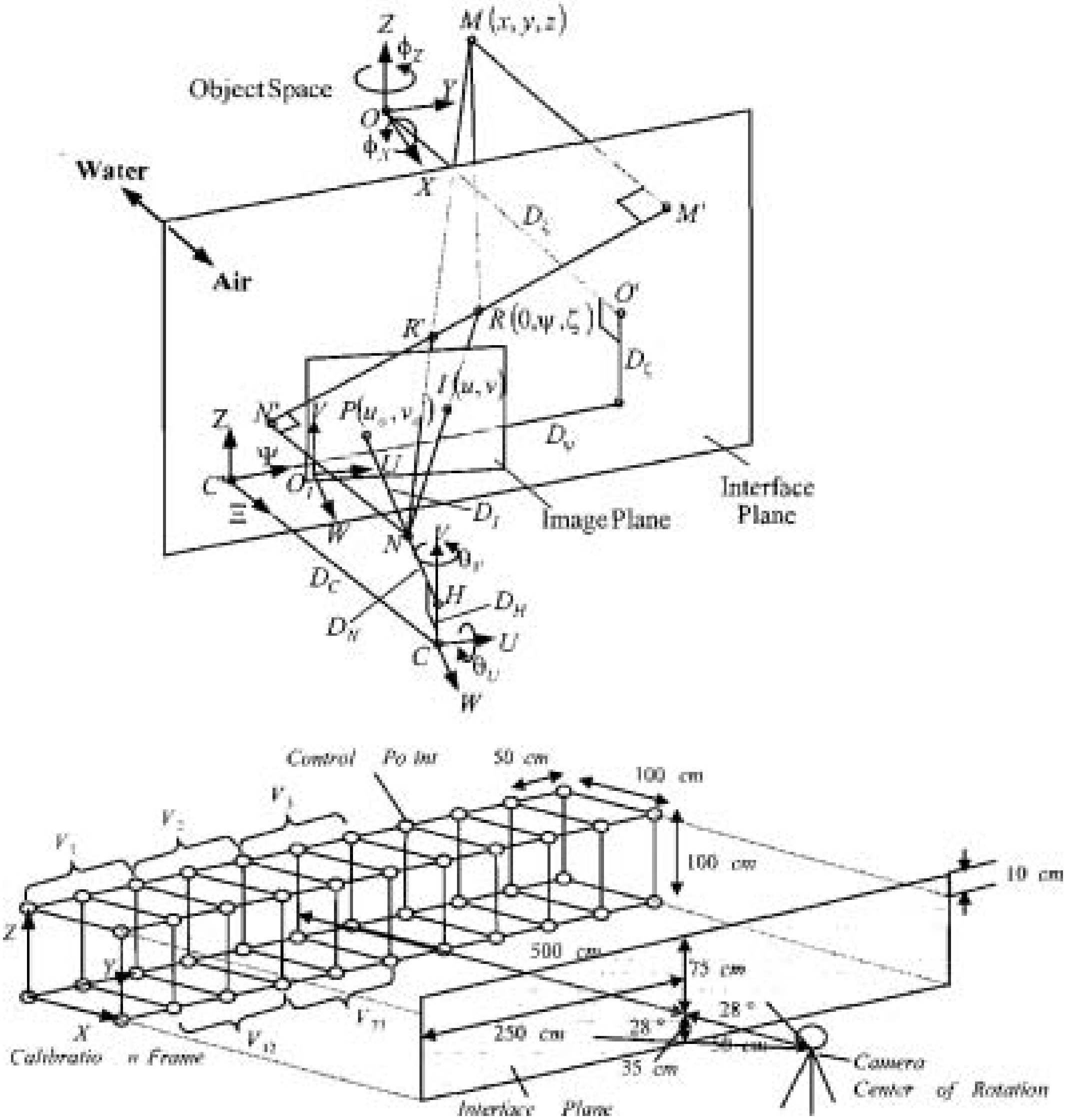
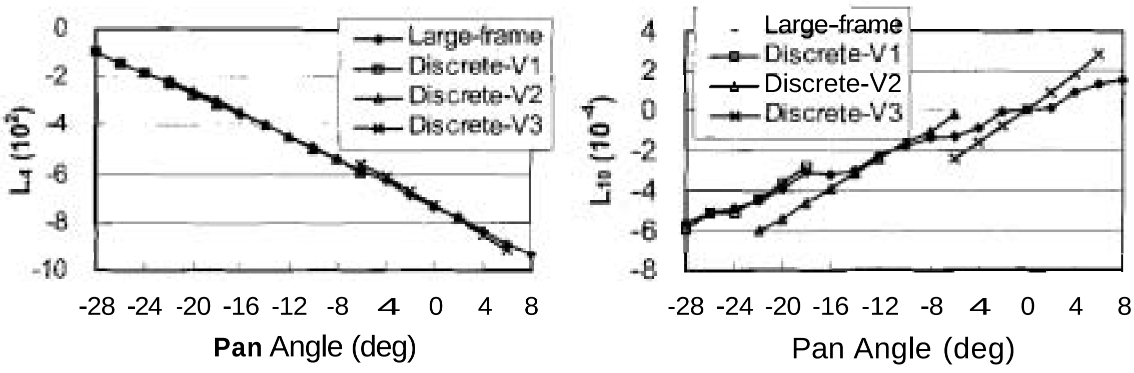


Figure 1 – The refraction model used in this study (top) and the calibration setup (bottom). Three reference frames were identified (a): the object-space frame (***XYZ*-**system), the interface-plane frame (**ΞΨZ-system**), and the image-plane frame (***WUV*-**system). Points **O'** and ***C'*** are the projections of points ***O*** and C (center of rotation), respectively, on the interface plane. Point P is the projection center of the camera while points M, R and **I** are the marker, the refraction point and the image point, respectively. A total of 4 angle factors (ϕ_X, ϕ_Z, θ_U & θ_V) and 7 distance factors (D_ξ, D_ψ, D_ζ, D_C, D_H, D_N & D_I) were defined to simulate the underwater recording with a panning camera. The following conditions were used in the camera calibration (b): $\phi_X = \phi_Z = \theta_U = 0°$, $\theta_V = -28$ to $28°$, $D_\xi = 500$ cm, $D_\psi = -250$ cm, $D_\zeta = -35$ cm, $D_C = 50$ cm, $D_H = 15$ cm, $D_N = 10$ cm, and $D_I = 1200$ cm. Discrete control volumes (V_1, V_2, V_3, V_{12} & V_{23}) were also defined (bottom).



(a) (b)

Figure **2** – The parameter-angle curves of selected DLT parameters: L_4 (a) and L_{10} (b). Due to the symmetric experimental setup, the results of panning range 10 **- 28"** were omitted. The DLT parameters obtained through the discrete-volume approach with volumes V_1, V_2 **&** V_3 shown in Figure I b are also included for comparison.

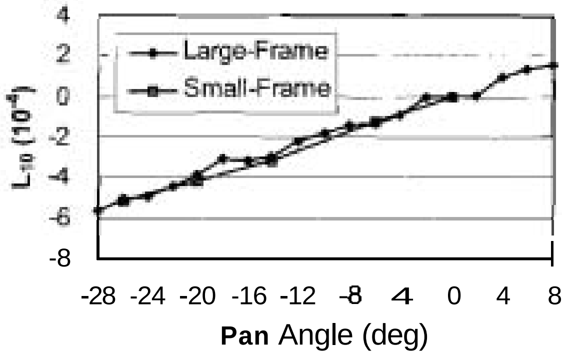


Figure 3 – Comparison of the parameter-angle curve between the small-frame and the large-frame strategies.

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