RECONSTRUCTION ACCURACY FOR VISUAL CALIBRATION METHOD

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INTRODUCTION: Motion analysis is a common technique in biomechanics and sport studies. Since Abdel-Aziz and Karara (1971), the direct linear transformation (DLT) is the most widely used method to analyse human movements. More recently, Drenk et al. (1999) proposed a modified DLT method, called DLT double-plane method (DLT DP), which involves two parallel control planes (rather than a whole 3D structure). With these two calibration methods, a set of coefficients is calculated. This set summarise indirectly the internal and external parameters of the camera. Kwon et al. (2002) and Elipot et al. (2008) have respectively shown that, in aerial and underwater conditions, the DLT DP method can reduce the reconstruction error.

Bouguet (1999) presented an alternative method to calibrate camera. In this method, called visual calibration (VC), camera internal and external parameters are directly calculated. Bases on the pinhole camera model, the visual calibration aim to solve the following equation:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \sim \begin{bmatrix} f_u & \alpha & U_0 \\ 0 & f_v & V_0 \\ 0 & 0 & 1 \end{bmatrix} . R . \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} + T \qquad (1)$$

where

$\sim$: up to a non zero scale factor

$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix}$: the image plane coordinate vector (pixel) of a point P ; $\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$: the space coordinate vector of the same point P

R : A 3×3 rotation matrix ; T : A 3×1 translation matrix

$\begin{bmatrix} f_u \\ f_v \end{bmatrix}$: the focal length in pixel ; $\begin{bmatrix} U_0 \\ V_0 \end{bmatrix}$: the principal point coordinates ; α : The skew coefficient defining the angle between the pixel axes x and y

Nevertheless, reconstruction accuracy of the visual calibration has never been identified. The aim of this study is to identify the reconstruction accuracy of the visual calibration and to compare this calibration method to DLT and DLT DP for the reconstruction of points placed inside (without extrapolation) or outside (with extrapolation) of the calibrated space.

METHODS: Two mini-DV cameras, with a sampling frequency of 25 Hz, have been used in this study and placed as shown in the figure 1.

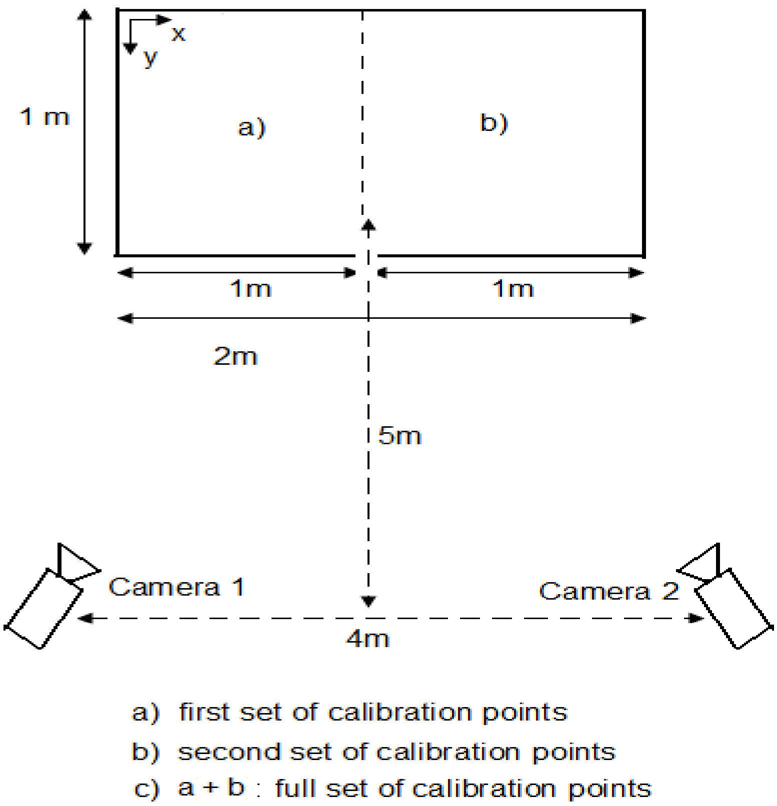

Figure 1: Experimental set up

The calibration procedure has been realised for the DLT and DLT DP methods using a calibration frame of 2×1×1 m with 69 calibration points. The calibration procedure for the VC has been realized in two steps: 1- the internal parameters of the cameras (f_u, f_v, u_0, v_0 and α) have been inferred from images of the planar calibration rig (a checker board pattern). 2- the external parameters of the cameras (R and T) have been inferred from an image of the calibration frame.

Different configurations of calibration points have been used (depending on the algorithm used). These configurations are summarised in the table 1.

Space reconstruction accuracy has been calculated from equations 2 and 3 given by Kwon and Casebolt (2006):

$$\varepsilon = \sqrt{(Xk - Xr)^2 + (Yk - Yr)^2 + (Zk - Zr)^2} \quad (2)$$

$$\varepsilon_{RMS} = \sqrt{\frac{1}{n}\sum \varepsilon^2} \quad (3)$$

where (X_k, Y_k, Z_k) are the known object-space coordinates, and (X_r, Y_r, Z_r) are the reconstructed object-space coordinates, ε is the reconstruction error for a given control point, and ε_{RMS} is the overall reconstruction error. As shown in the table 1, for the condition without extrapolation (i.e. 0% extrapolation), reconstructed points are inside the calibrated space. For the condition with extrapolation, reconstruction accuracy is checked with points placed 25, 50, 75, 100 cm (on the x axis) outside of the calibrated space (i.e. from 25% extrapolation to 100% extrapolation).

Table 1: Configuration of the calibration points used

	Algorithm	Configuration of calibration points
Without extrapolated points	DLT	full set of points (c.)
	DLT DP	set c. split in two planes (front and back plane)
	VC	set c.
	VC DP	set c. split in two planes (front and back plane)
With extrapolated points	DLT	points in a. are used to calibrate points in b. (outside of the calibrated space) are used to check the reconstruction accuracy
	DLT DP	points in a. are used to calibrate (split in two planes) points in b. (outside of the calibrated space) are used to check the reconstruction accuracy
	VC	points in a. are used to calibrate points in b. (outside of the calibrated space) are used to check the reconstruction accuracy
	VC DP	points in a. are used to calibrate (split in two planes) points in b. (outside of the calibrated space) are used to check the reconstruction accuracy

RESULTS: All the results are summarised in the table 2.

Table 2: RMS and maximum reconstruction errors for the four algorithms

Algorithm	Extrapolation	RMS Error (mm)	Max Error (mm)	Max-to-RMS-ratio (%)
DLT standard	***0%***	***9***	***26***	***290.2***
	25%	9.8	12.5	128
	50%	14.1	20.5	145.3
	75%	18	20.6	114
	100%	19.9	28.8	144.5
DLT double-plane	***0%***	***5***	***10.9***	***214.6***
	25%	12.5	17.7	141.7
	50%	12.3	18	146.6
	75%	14.8	17	114
	100%	14.3	18	144.5
VC standard	***0%***	***9.7***	***18.9***	***193.8***
	25%	9.2	11.4	123.6
	50%	10.9	13.9	128.2
	75%	12.1	15.2	125.5
	100%	16	21.9	136.6
VC double-plane	***0%***	***6***	***10.7***	***179.3***
	25%	5.6	7.0	126
	50%	8.4	11.4	135.6
	75%	11.1	15.5	139.9
	100%	19.2	19.2	134.6

For the condition without extrapolation: The results show that, for the two algorithms and for the condition without extrapolation, the double plane method (DLT DP and VC DP) score smaller calibration errors for the RMS values and for the maximum errors values. Results also show that, without extrapolation, RMS errors for the DLT DP and DLT are respectively slightly smaller than the RMS errors for the VC DP and the VC. Nevertheless, maximum error observed for the VC and the VC DP are respectively smaller than those observed for the DLT and DLT DP. The max-to-RMS ratios are also smaller for the VC and VC DP.

For the condition with extrapolation: The results of the conditions with extrapolation show that, for every level of extrapolation, except for 100%, the RMS and maximum values are smaller for the VC DP than for the VC. Also, the RMS and maximum values are respectively smaller for the VC DP and the VC than the values observed for the DLT and the DLT DP.

DISCUSSION: The present data (Table 2) supports the conclusion that double plane methods provide more accurate reconstruction of points within the calibration space (0% extrapolation). The VC DP and the DLT DP allow an improvement of the reconstruction accuracy of respectively 41% and 43%. These results agree with those of Kwon et al. (2002) and Elipot et al. (2008).

Reconstruction errors increase for the DLT and DLT DP method if the reconstructed points are placed outside of the calibrated space. More especially, the DLT DP appears to be much more inaccurate (191% more inaccurate) when the extrapolation is fixed at 75%. These results agree with those of Kwon et al. (2002) and Kwon and Lindley (2000).

The VC DP may have slightly improved RMS reconstruction accuracy compared to the other methods, but it also create a more homogeneous space calibration. VC DP also improves reconstruction accuracy for points placed outside of the calibrated space. So the VC method is particularly convenient to study large movements or when it is impractical to build a calibration frame large enough to prevent any extrapolation.

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