A NON-LINEAR CAMERA CALIBRATION ALGORITHM: DIRECT SOLUTION METHOD

Young-Hoo Kwon
Biomechanics Laboratory, Texas Woman's University, Denton, TX, USA

INTRODUCTION: Direct Linear Transformation (DLT) method suffers from an intrinsic shortcoming: non-orthogonal camera calibration and object space reconstruction. This is due to the fact that the eleven DLT parameters are basically derived from a set of ten independent camera parameters and thus are mutually dependent. Alternative algorithms such as MDLT have failed to gain popularity due to the complexity and inconsistency in performance. The purpose of this study is to develop a non-linear orthogonal camera calibration algorithm with the capability to correct the optical distortion errors.

METHODS: A 15-parameter non-linear camera calibration method, Direct Solution Method (DSM), was developed based on the following relationships between the object space coordinates and the image plane coordinates of a given control point:

$$u-u_o-\Delta u=-d_u\cdot\frac{t_{21}(x-x_o)+t_{22}(y-y_o)+t_{23}(z-z_o)}{t_{11}(x-x_o)+t_{12}(y-y_o)+t_{13}(z-z_o)} \quad [1]$$

$$v-v_o-\Delta v=-d_v\cdot\frac{t_{31}(x-x_o)+t_{32}(y-y_o)+t_{33}(z-z_o)}{t_{11}(x-x_o)+t_{12}(y-y_o)+t_{13}(z-z_o)}, \quad [2]$$

where (u, v) = image coordinates of the control point, (u_o, v_o) = image coordinates of the principal point of the camera, (Δu, Δv) = optical errors in the image coordinates, (x, y, z) = object space coordinates of the control point, (x_o, y_o, z_o) = position of the camera, (d_u, d_v) = scaling/unit conversion factors, and t_{11}, ..., t_{33} = elements of the transformation matrix from the object space reference frame to the image plane frame. The transformation matrix is a function of three Eulerian orientation angles:

$$\mathbf{T}(\phi,\theta,\psi)=\begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix}. \quad [3]$$

The optical error terms add 5 additional parameters (k_1 ... k_5) to the system, yielding a total of 15 independent internal and external camera parameters: u_o, v_o, x_o, y_o, z_o, d_u, d_v, ϕ, θ, ψ, and k_1 - k_5. A minimum of 8 non-coplanar control points (2*8 = 16 equations) makes the system sufficiently determined. The Newton method, commonly used in solving a system of non-linear equations, was used in the proposed calibration algorithm. A complete set of partial differential equations were developed in this study to build the Jacobin matrix.
A series of 9 single-camera calibrations (1-4: camera fixed with varying zoom settings; 5-9: zoom fixed with panning) were performed using the new algorithm and results were compared with those of the 16-parameter DLT method. A separate 6-camera calibration was also performed to assess the reconstruction error.

RESULTS AND DISCUSSION: In all calibration trials, the DSM successfully generated orthogonal calibrations, while the 16-parameter DLT method exhibited non-orthogonality. The mean calibration error was similar between DSM (0.38 ± 0.11 pixels) and the DLT method (0.38 ± 0.10 pixels). The new algorithm provided stable solutions for all 16 parameters in all trials. Trials 1-4 revealed consistent camera angles while trials 5-9 generated consistent principal point coordinates, and scaling factors. The optical error correction terms ($\leq 10^{-6}$) improved the calibration accuracy significantly. A relatively large variability was observed in the optical error correction parameters when compared with other internal camera parameters. A slightly larger reconstruction error was observed in the DSM (0.25 cm) than in the 16-parameter DLT method (0.22 cm) from the 6-camera calibration trial.