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IN-SILICO CHARACTERIZATION OF MONO-PLANAR 3D FLUOROSCOPY CALIBRATION ERROR

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SUMMARY

Mono-planar model based 3D fluoroscopy can quantify joint kinematics with 1mm–1° accuracy level. A calibration based on the acquisition of specific devices is usually applied to size the system. This study aimed at the characterization of the calibration procedure. In-silico simulations were performed to analyze a data-set obtained placing the X-ray focus and the calibration cage in known positions. Focus reference position influenced the calibration error dispersion, while the cage pose affected the bias. In the worst case scenario, the principal point can be estimated with an error lower than 1mm, while the focus distance with an error lower than 2mm.

INTRODUCTION

Several clinical [1], and methodological [2] applications are based on the accurate knowledge of in-vivo kinematics of intact and replaced joints. 3D fluoroscopy (3DF) is a technique that allows to accurately reconstruct joint kinematics, combining series of 2D X-ray fluoroscopic projections, and the knowledge of 3D geometric models of relevant bony segments or prosthetic components [3]. 3D models are obtained by CT/MRI datasets, or prostheses CAD; 2D projections are typically gathered using clinical fluoroscopes and C-arms. C-arms, however, are designed to be easily moved inside the operating room for qualitative real-time imaging of internal body moving structures, and they are not meant for quantitative studies. The X-ray image intensifier is typically used to convert X-ray to visible images, but it is affected by geometrical distortion, and the accuracy, with which the X-ray focus position is operatively set, is affected by the physical deformation of the C-arm [4] and dependent by the specific acquisition setup.

To step from qualitative to quantitative analysis, algorithms are applied to properly size a virtual model of the fluoroscope, to correct for image geometrical distortion, and to calibrate the position of the X-ray focus. The calibration is carried out with the acquisition of known geometry devices such as 2D grid and 3D cage. Once the calibration is performed, for each video frame of the acquisition, the 6 degrees of freedom (DOFs) absolute pose (3 translations and 3 rotations) of bony segments or prostheses is quantified moving the 3D model until it is best aligned to the relevant 2D image.

3DF theoretically permits to achieve a millimeter/degree accuracy level in joint motion analysis [3]. Several sources of error contribute to this accuracy and were previously characterized: local optima of the metric [3], segmentation inaccuracies [5], symmetries of the models [3], geometrical distortions [6]. Conversely, the extent to which X-ray focus calibration affects the reliability of the measurements has not been clarified yet.

A previous study [7] quantified the sensitivity of 3DF pose estimation error to calibration inaccuracies: rotations was scarcely influenced by calibration errors, while a linear trend was highlighted for translations with a sensitivity of 20%. To maintain a sub-millimeter pose estimation error, a focus calibration error lower than 5 mm is required.

The present work aimed at the in-silico investigation of the focus calibration procedure in order to identify the conditions needed to maintain a sub-millimeter pose estimation error.

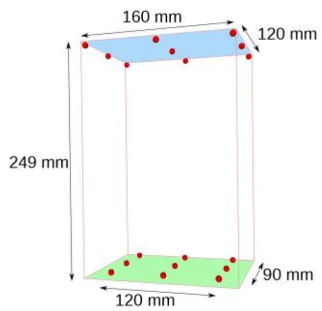

Figure 1: 3D model of the cage, fiducial plane (green) and control plane (blue) are shown together with the relevant measurements**.**

METHODS

In order to quantify the focus calibration error, the calibration procedure was repeated on a synthetic data-set of reference images, created with the focus and a 3D model of a calibration cage in known position.

The virtual fluoroscopic acquisition system was outlined defining a global reference frame with *x* and *y* axes parallel, *z*-axis perpendicular to the image plane, and with the origin in the center of the image. The Euler *zxy* convention was used for rotations. The X-ray source was virtually placed in F_{ref} = (F_x, F_y, F_z) considering all the permutations obtained with principal point coordinates F_x and F_y equal to 0 mm or 5 mm, and the focus distance F_z equal to 1000 mm or 1010 mm, as for typical fluoroscopic setups. Pixel spacing was fixed at 0.3 mm, as for 315x315 mm FOV, and 1024x1024 pixel image. No geometrical distortion was considered as already successfully investigated in a previous study [6].

A 3D cage virtual model was obtained reverse engineering the RSA cage Model 10-knee (Tilly-Medical Products AB, Sweden) composed by 2 planes of 9 spherical tantalum beads grid (diameter equal to 1 mm). The markers in the plane close to the image were denoted "fiducial markers", while the others "control markers". The fiducial markers were used to estimate the cage position, and the control markers were used to assess the position of the Roentgen focus.

The cage was placed in known reference poses $P_{ref} = (T_x, T_y, T_z, O_x, O_y, O_z)$ with T_x and T_y equal to 0 mm or 10 mm and O_z equal to 0° or 30°, T_z equal to 0 mm, O_x and O_y equal to 0°. The fiducial plane resulted adjacent to the image plane.

For every combination of F_{ref} and P_{ref} a reference image was obtained projecting the shadow of the tantalum beads. To better simulate real fluoroscopic images, Poisson noise was added to the images [8].

The digitally reconstructed radiography of the cage was processed with a Hough transform in order to find the centers of the projected tantalum beads. The beads were then manually labelled in order to associate the projection with the correspondent 3D bead. A well known calibration procedure was applied to estimate the focus position [9]. Briefly, fiducial markers were used to estimate the translations ($T_{x,est}$, $T_{y,est}$) and the rotation around the projection axis ($O_{z,est}$) of the 3D cage. The control markers were then used to estimate the focus position ($F_{x,est}$, $F_{y,est}$, $F_{z,est}$). In both cases, singular value decomposition (SVD) was used to minimize the root mean square distance between the beads and their projections with respect to the cage pose or F_{est}, respectively.

The focus calibration error was computed as:

$$F_{err} = F_{est} - F_{ref} = (F_{x,err}, F_{y,err}, F_{z,err}) \qquad (1)$$

The effect of F_{ref} and of P_{ref} on F_{err} were investigated using an 6 way ANOVA (α=0.05). Data were clustered represented using box and whiskers plots to visualize the effects.

Table 1: Minimum median and maximum focus calibration error.

F_{err}	Minimum	Median	Maximum
$F_{x,err}$ [mm]	-0.9	~0	0.8
$F_{y,err}$ [mm]	-0.9	~0	0.7
$F_{z,err}$ [mm]	-1.75	~0	2.0

RESULTS AND DISCUSSION

The calibration procedure proved to be effective in quantifying the three coordinate of the focus. The median value of the error was nearly 0 mm. As expected given the symmetry of the problem no difference were found between $F_{x,err}$ and $F_{y,err}$ with a maximum absolute error lower than 0.9 mm. $F_{z,err}$ showed a slightly larger maximum absolute error of 2.0 mm, but this was also expected due to the nearly parallel projection setup. Median, maximum, and minimum error are reported in Table 1.

ANOVA highlighted that the focus reference position had no effect on F_{err} bias (P-value>0.05), but $F_{x,ref}$ and $F_{y,ref}$ contributed to increase the measurement dispersion of the $F_{x,err}$ and $F_{y,err}$ respectively (Figure 2). On the other hand, the cage reference position P_{ref} influenced the measurement bias (P-value<0.05) but not its dispersion. This uncertainty was due to cage central fiducial and control beads projection overlapping that introduced an error in the estimation of the cage pose. This situation can be easily avoided in real acquisition setup, and can be corrected introducing a manual correction of the Hough estimation of the bead centers. $F_{z,err}$ was not related to either F_{ref} or P_{ref}.

CONCLUSIONS

The 3DF calibration procedure proved to be effective with any combination of the tested parameters. Considering the correlation between pose estimation error and calibration error (20%, [7]), in the worst case scenario the mis-calibration will affect the pose estimation for 0.2 mm for in-plane translations and 0.4 mm (order of magnitude of pixel spacing) for out-of-plane translation, but this can be improved operatively avoiding the overlapping of bead projections.

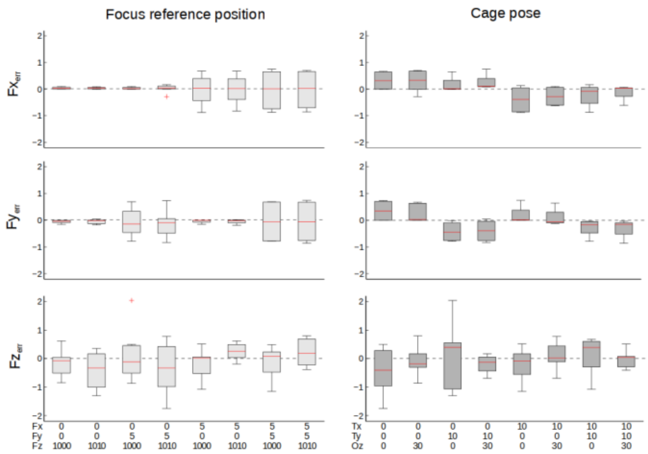

Figure 2: Box and whiskers plot of the calibration error grouped by focus reference position and cage pose

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