Fast and Automatic Optical 3D Cameras Calibration for Contactless Surface Registration in Computer Assisted Surgery

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INTRODUCTION

Computer Assisted Surgery (CAS) has expended over the years and is now commonly used in orthopedic surgery. It was shown that CAS improves functional outcomes compared to conventional non-assisted surgeries [1]. However, to implement such assistance, a precise registration between the patient's preoperative CT-scan data and the patient's intraoperative data in the operating room (OR) is required.

Artificial markers are the gold standard for this registration but imply a lot of drawbacks such as patient discomfort, hospital flow complications, etc. Surface-based registration methods are preferred and are usually implemented in the OR. The goal is to register the preoperative patient's bone surface data extracted from a CT-scan volume with the corresponding intraoperative surface data digitized with a navigated tracked stylus. However the use of tracked stylus for surface digitization is not always accurate due to its calibration precision and tissue deformation upon contact. Moreover, for large surface acquisition, it is time consuming and user-dependent.

Camera-based solutions (laser range scanner, time-of-flight cameras, structured-light cameras, etc.) for patient's bone surface digitization have become quite common nowadays in CAS since they are faster, contactless and have less sterilisation constraints than tracked stylus [2]. They allow to acquire thousands of points in a few seconds without any contact. For example, these advantages inspired the application of structured light [2] in spinal surgery. However, precise camera calibration, namely "Hand-Eye" (H-E) calibration, is necessary to localize the camera's acquired data in the physical OR space. This calibration consists in finding the transformation between the camera and the robot end-effector that handles it or between the camera and a tracked marker fixed to it: the problem remains the same.

For 3D cameras, it has been shown in [3], [4] that exploiting the depth information gives better H-E calibration results than exploiting only the RGB information. In this context, different methods based on the use of camera depth information have been proposed in the literature. Khan *et al.* [3] proposed an iterative method based on the palpation, with a probe handled by a robot, of a complex calibrated wavy 3D object to digitize and register its surface in the robot frame. The surface of this 3D object is also digitized with the optical 3D camera. The desired H-E calibration has been thus obtained by registering the obtained two sets of points. Nevertheless, the obtained results depend on the probe calibration precision, the quality of palpation and the quality of 3D-printing of the calibrated object. Yang *et al.* [4] proposed to use a simpler 3D object (namely a sphere) for the H-E calibration. In this method, thanks to the depth information, the 3D object has been digitized and its center has been computed using a RAndom SAmple Consensus (RANSAC) algorithm. This allows to estimate the translation between the camera and the 3D object and compute the H-E transformation thanks to a non linear optimization. Their method gave non-satisfying results (2.864 mm) in accordance with surgical application.

In our study, a fast and automatic method adapted to optical 3D cameras and based on a 3D printed phantom is presented. This phantom is separated from the camera to reduce printing errors and deformation. It was thought to be as simple as possible to ease printing and registration. The proposed method is easy to implement and does not require any experience from the user. It also gives precision compatible with surgical application.

MATERIALS AND METHODS

The proposed camera calibration method is represented in Fig.1 where ${}^{\mathrm{b}}\mathbf{T}_{\mathrm{a}}$ is the transformation from the coordinate system a to coordinate system b, and W, P, C, M_p, and M_c, represent respectively the frames attached to the world (localizer), the phantom, the camera, the marker on the phantom, and the marker on the camera. The marker was fixed on the camera with a 3D-printed support adapted to the camera and to the marker. Our objective is to compute the transformation ${}^{\mathrm{C}}\mathbf{T}_{\mathrm{M_c}}$ and thus perform the 3D camera H-E calibration. The proposed approach is based on the digitization and registration of a tracked 3D-printed phantom equipped with a marker. The tracked phantom was designed as one compact single piece to be as simple as possible to be produced: a cube with a marker fused to it to minimize deformations and cubic shapes on its faces to facilitate their digitization and allow precise registration. The requested H-E transformation can thus be computed with the following equation:

$$ {}^{\mathrm{C}}\mathbf{T}_{\mathrm{M_c}} = {}^{\mathrm{C}}\mathbf{T}_{\mathrm{P}} \, {}^{\mathrm{P}}\mathbf{T}_{\mathrm{M_p}} \, {}^{\mathrm{M_p}}\mathbf{T}_{\mathrm{W}} \, {}^{\mathrm{W}}\mathbf{T}_{\mathrm{M_c}} $$

In accordance with Fig.1, the transformations of this equation can be obtained separately:

- ${}^{\mathrm{C}}\mathbf{T}_{\mathrm{P}}$ is computed with an Iterative Closest Point (ICP) registration of the phantom CAD (Computer Aided Design) model expressed in P with the phantom point cloud generated by the camera expressed in C.
- ${}^{\mathrm{P}}\mathbf{T}_{\mathrm{M_p}}$ is known by CAD model of the calibration phantom.
- ${}^{\mathrm{M_p}}\mathbf{T}_{\mathrm{W}}$ and ${}^{\mathrm{W}}\mathbf{T}_{\mathrm{M_c}}$ are given by the optical tracking system.

This method has the advantage to be simple (it only requires the design and printing of the phantom), fast and does not necessitate any experience from the user. It is easy to use as the user intervention is requested only for ICP initialization: he/she has only to click on three characteristic corresponding points on the phantom CAD model and on the camera's point cloud to perform a first coarse registration. Those points are usually the cube corners that are easy to find.

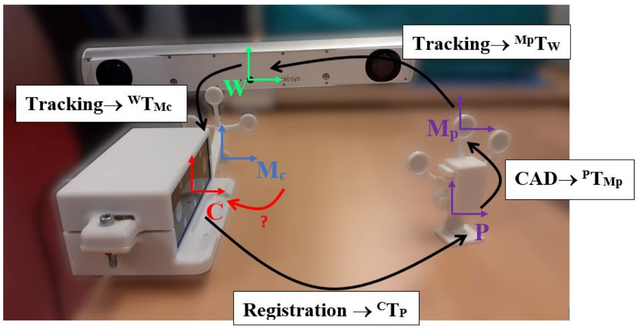

Fig. 1: Set up for camera calibration using a 3D-printed phantom and a localizer

RESULTS

To evaluate the camera calibration precision, another tracked 3D-printed phantom was designed and used as a validation geometry. This validation phantom consists in a marker and a cube designed as one single piece with three validation points on its faces. Each validation point corresponds to the center coordinate of a holes (a half-sphere of ∅ 1 mm) engraved at the surface of the phantom.

The position of each hole in the camera frame, noted $\{{}^{C}P_i\}_{i=1:3}$, is obtained using the CloudCompare software (www.cloudcompare.org) by a mouse click on the center of hole as it is clearly visible in the screen. The position of each hole in the marker frame, noted $\{{}^{M_p}P_i\}_{i=1:3}$, is known by CAD model design. The ${}^{M_p}P_i$ points are reprojected in the camera coordinate system through the localizer information and the found H-E transformation using ${}^{C}\mathbf{T}_{M_c}{}^{\mathrm{M_c}}\mathbf{T}_{\mathrm{W}}{}^{\mathrm{W}}\mathbf{T}_{\mathrm{M_p}}{}^{M_p}P_i$.

To evaluate the calibration precision, we thus compute the euclidean distance between the reprojected and observed holes:

$$||{}^{C}P_i - {}^{C}\mathbf{T}_{M_c}{}^{\mathrm{M_c}}\mathbf{T}_{\mathrm{W}}{}^{\mathrm{W}}\mathbf{T}_{\mathrm{M_p}}{}^{M_p}P_i||$$

We performed 25 calibrations followed by a systematic validation step after each calibration process. The global mean distance between the observed and reprojected points was 0.324 mm with a standard deviation of 0.206 mm. More detailed results for each validation point are given on Fig.2. Distances between the observed and reprojected points were 0.388 ± 0.234 mm, 0.279 ± 0.199 mm, 0.303 ± 0.169 mm for point 1, 2 and 3 respectively. It is important to notice that all the values are inferior to 1 mm. Moreover, the calibration method is fast: the whole procedure, including point cloud generation, user clicks for ICP initialization, and ICP registration, takes on average 37.5 ± 2.8 s.

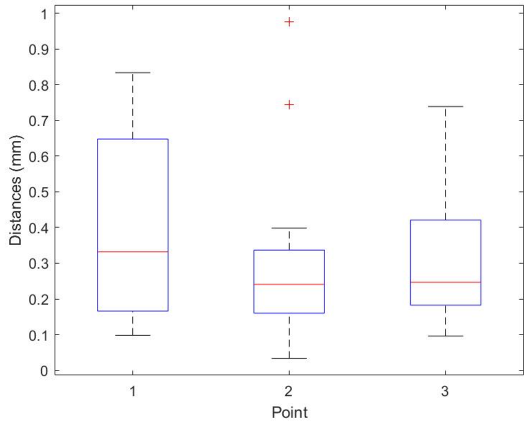

Fig. 2: Distances between detected and registered points on 25 calibrations

CONCLUSIONS AND DISCUSSION

Using a 3D-printed phantom for 3D camera calibration proved successful to reduce calibration time and ease the process while being precise. The proposed approach gives precision compatible with surgical applications (less than 1 mm). As a future work, even if it is fast, the process could be sped up by more automatization. Indeed, the manual ICP initialization by point picking could be replaced by Principal Component Analysis (PCA) or other coarse automatic registration method. Besides, the validation procedure could also be improved to make it independent from the user because manual clicking could introduce a bias in the error evaluation. Finally a quantitative comparative study with other methods should be done.

REFERENCES

[1] W. Fan, Y. Dai, and G. Giordano, "CAOS TKA Provides Improved Functional Outcomes Compared to Conventional TKA," pp. 74–69. [Online]. Available: https://easychair.org/publications/paper/QNfl

[2] Jakubovic and Raphael, "High Speed, High Density Intraoperative 3D Optical Topographical Imaging with Efficient Registration to MRI and CT for Craniospinal Surgical Navigation," *Scientific Reports*, vol. 8, no. 1, p. 14894, Dec. 2018. [Online]. Available: http://www.nature.com/articles/s41598-018-32424-z

[3] S. Kahn, D. Haumann, and V. Willert, "Hand-eye calibration with a depth camera: 2D or 3D?" p. 10.

[4] L. Yang, Q. Cao, M. Lin, H. Zhang, and Z. Ma, "Robotic hand-eye calibration with depth camera: A sphere model approach," in *2018 4th International Conference on Control, Automation and Robotics (ICCAR)*. Auckland: IEEE, Apr. 2018, pp. 104–110. [Online]. Available: https://ieeexplore.ieee.org/document/8384652/