Development of a Hand-Eye Calibration Method for Augmented Reality Applied to Computer-Assisted Orthopedic Surgery

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Purpose

Recent technology advances in Augmented Reality (AR) is creating an opportunity for a paradigm shift in the field of Computer Assisted Surgery (CAS). In March 2007, Microsoft released the Microsoft HoloLens Development Edition. This platform is a wearable high-definition stereoscopic 3D optical head-mounted system (OHMDs) equipped with near-eye multifocus dichromated-gelatin holographic lenses (AR headset, Microsoft HoloLens). Despite having the potential of being a promising technology in clinical applications, its accuracy, robustness, and performances under specific environmental conditions have not been fully investigated and evaluated. In an attempt to address the limitations and uncertainties that arise from using computer vision in SLAM based algorithms [1] due to the dynamism of clinical environments, we propose a Hand-Eye (HE) based approach to determine an invariant mapping between the HoloLens headset (i.e., rigid body defined by a unique set of passive markers) and the OHMDs virtual camera.

Methods

In order to achieve the required precision for using the Microsoft HoloLens in a surgical application, an invariant mapping was estimated. First, a set of non-collinear retroreflective markers were rigidly attached to the Microsoft HoloLens headset (Fig. 1). Consequently, the OHMDs's intrinsic parameters, as well as their radial and tangential lenses distortion coefficients, were determined by solving simultaneously a set of homogeneous system of equations by using nonlinear optimization techniques. Posteriorly, the extrinsic OHMDs parameters were determined with respect to checkboard pattern by solving a linear homogeneous system of equation [2], and then an invariant transformation was determined by solving the following matrix equation: $\mathrm{T}_{\mathrm{h}}^{\mathrm{c}} = \mathrm{T}_{\mathrm{p}}^{\mathrm{c}}\mathrm{T}_{\mathrm{w}}^{\mathrm{p}}\mathrm{T}_{\mathrm{h}}^{\mathrm{w}}$, as graphically represented in Fig. 1.

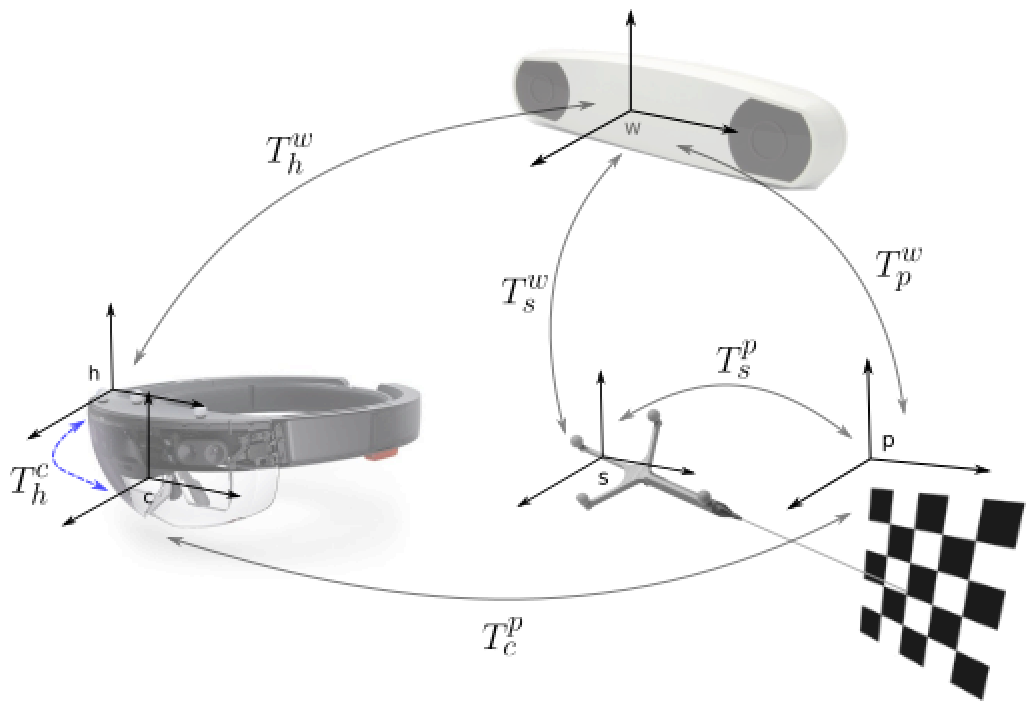

Fig. 1. T_c^p: Transformation from the chessboard-pattern to the OHMDs (user's visual system). T_p^w: Mapping the physical chessboard-pattern with respect to the physical world. T_h^w: Mapping the HoloLens headset with respect to the physical world. T_s^w: Mapping between the surgical pointer and world reference frames. T_s^p: Mapping between the surgical pointer and the chessboard-pattern reference frames. $T_h^c = T_p^c T_w^p T_h^w$.

The accuracy of the proposed HE based method has been evaluated by using a retro-projection error estimation method. Finally, a full male pelvis model with acetabulum and cancellous inner structures (SKU #1301-1, Sawbones, Pacific Research Laboratories, Vashon, Washington, USA) was used to validate and test the proposed calibration method.

Results

A checkerboard pattern was digitized by using a surgical navigation pointer and therefore, the position of each individual pattern (i.e., internal corners of the checkerboard pattern) was determined with respect to the world reference frame. Based on the estimated invariant transformation $\mathrm{T}_\mathrm{h}^\mathrm{c}$ shown in Fig. 1, holograms representing these internal edges were created and represented into the physical space. Since these holograms representing the internal edges of the used checkerboard calibration object have their counterparts in the real world, the root mean square error (RMSE) of the 2D representations of these holograms were compared with the acquired OHMDs checkerboard images. RMSEs for ten randomly selected poses and at different radial distances ranging from 0.5 to 1.5 meters from the calibration object were considered. A RMSE of 3.2 ± 1.6 mm for a total of 150 different patterns were considered in this analysis (3x5 grid size and 10 poses).

Initially, a surgical frame has been anchored to the organ of interest as shown in Fig. 2. After loading the patient-specific dataset, a hologram of the organ of interest appears in front of the user's initial position. Correspondences between the hologram and the fiducial markers can then be established by using the tracked surgical pointer and then be mapped with respect to the surgical frame. After finishing this process, an orthonormal basis is created in the physical space, which has its counterpart in the image space and, therefore, a transformation can be determined to map the hologram with respect to the surgical frame as shown in Fig. 2.

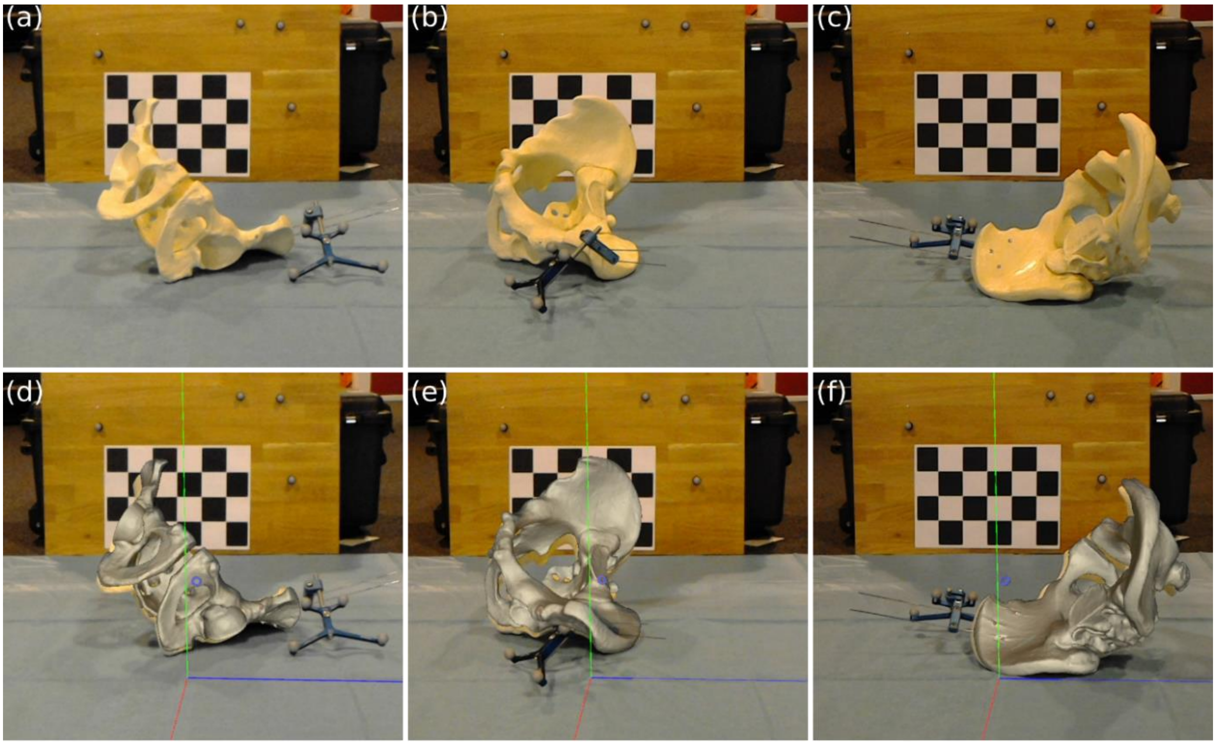

Fig. 2. (a)-(c): Three randomly selected poses from the full male pelvis model with acetabulum and cancellous inner structures (Sawbones, Pacific Research Laboratories, Vashon, Washington, USA). (d)-(f): Superposition between the physical specimen and its corresponding isosurface mesh represented with respect to the surgical frame.

Conclusions

Preoperative planning may be an extremely complex and cumbersome task, involving different qualitative and quantitative aspects, such as patient's physical and mental health conditions and records, different image-acquisition protocols, different clinical laboratory results, multiple surgical choices for the same case, and optimal surgical sequences and maneuvers that should ideally be performed during a surgical intervention. It is important to note that surgeons may have several competing responsibilities and multiple patients and surgical procedures to be carried out on the same day and on pre-specified time windows. For these reasons, OHMDs may be able to create an opportunity for a paradigm shift in the field of CAS, since all this detailed information could easily be displayed on virtual and interactive screens in the operating room on the same time and in real time. A very important aspect of using such OHMDs is that it can be very intuitive, especially among inexperienced surgeon, since surgical instruments and maneuvers motions are represented with respect to the surgeon's visual system and, therefore, attention disruptions are more likely to be reduced in terms of the surgeon's gaze, considering that the surgeon would not need to be searching for a conventional display located at static location in the operating room.

References

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