JOHNS HOPKINS
UNIVERSITY

Display Calibration for Holographic OST-HMD

Paper Review

Group 15:

Yiwei Jiang

Mentors:

Ehsan Azimi

Dr. Peter Kazanzides

April 22, 2019

Reviewed Literature

Qian, Long, et al. "Comprehensive tracker based display calibration for holographic optical see-through head-mounted display." *arXiv preprint arXiv:1703.05834* (2017).

Introduction and Relevancy

With the rapid development of augmented reality technology, OST-HMD has been utilized in more and more applications in many fields, including medical field. However, the display calibration part, which is aiming to overlay the virtual object with correct pose and shape at correct location in reality, is still challenging for most of the OST-HMD systems. It is especially crucial for surgical navigation systems since millimeters error could lead to trauma and put patients into risk. Therefore, an accurate, robust, user-friendly, widely-compatible method is demanded by most of the surgical applications based on OST-HMD.

Although there were already many methods [1, 2, 3] for display calibration before this reviewed paper, few of them works for holographic head-mounted displays because it is conceptually different between stereoscopic and holographic scene generation [4], these existed methods cannot fully capture the optical characteristics of holographic display systems. This paper proposed a novel approach to properly register rendered holographic with tracked object in reality. Additionally, not only the internal(head-mounted) tracking systems but also external (world anchored) tracking systems were studied and they did experiments, which made this method be more general and theoretically support a quite wide range of potential applications. They also designed two evaluation approaches that make these subjective results more objective to some degree.

Our project, Navigation System for Ventriculostomy, is to develop a medical application provides guidance for surgeons when doing external ventricular drain. According to background research, we found that usually 30% of the trials fail [5]. It will be significant if our application can improve the success rate by letting the surgeon see where the ventricle is and even providing specific guidance like where to inject the catheter using AR technology. Therefore, the accuracy of overlay the virtual object model to its real counterpart in our system will directly affects the correctness of guidance it provides.

Same as their application, our navigation system is also based on Microsoft HoloLens, and our situation is quite similar to their head-mounted tracker case, one thing different is that for this case they used the embedded camera on HoloLens rather than we use an external ZED camera mounted to HoloLens, but they are still mathematically the same, so their method should surely work in our case. Furthermore, since we are developing a medical application, the expected users are surgeons and they might do not have much background in AR, so it also demands us to choose a relatively intuitive and uncomplicated way to calibration the system meanwhile can give us a high accurate calibration result, as our surgeon collaborators require an ideal target accuracy within

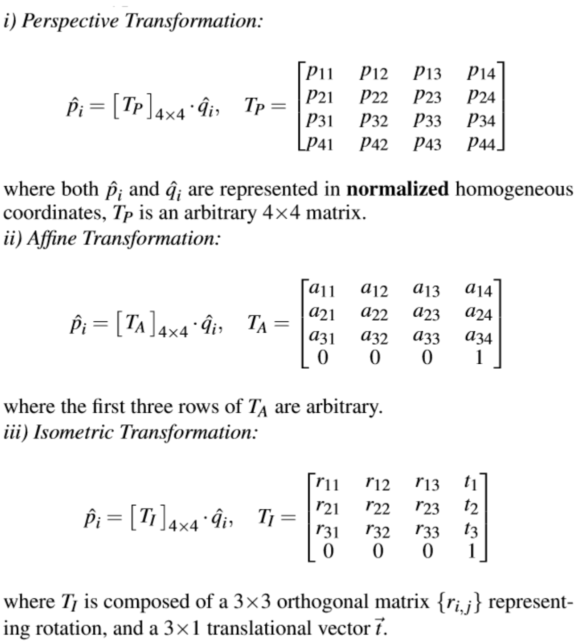
3mm, which is very challenging. This blackbox approach they offered enables surgeons to use the application on any HMD without worrying about the technical details of each individual system.

Technical Approach

The goal of a calibration process is to find a transform T (·) which maps 3D points from the world coordinates to a 3D virtual holographic environment. Basically, if we are given the points q1,···, qn, through the transform we observe p1,···, pn, such that:

$$p_i = T(q_i) \quad i = 1, \cdots, n.$$

They assumed that the transformation T (·) is linear, and based on the linearity assumption, they solved for a general case where the transformation T is a perspective transformation, however an affine as well as an isometric transformation are also calculated for comparison.



i) Perspective Transformation:

$$\hat{p}_i = \left[T_P\right]_{4\times4} \cdot \hat{q}_i, \quad T_P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix}$$

where both $\hat{p}_i$ and $\hat{q}_i$ are represented in **normalized** homogeneous coordinates, T_P is an arbitrary 4×4 matrix.

ii) Affine Transformation:

$$\hat{p}_i = \left[T_A\right]_{4\times4} \cdot \hat{q}_i, \quad T_A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where the first three rows of T_A are arbitrary.

iii) Isometric Transformation:

$$\hat{p}_i = \left[T_I\right]_{4\times4} \cdot \hat{q}_i, \quad T_I = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where T_I is composed of a 3×3 orthogonal matrix $\{r_{i,j}\}$ representing rotation, and a 3×1 translational vector $\vec{t}$.

Calibration with Head-Anchored Tracking System

In this case, they used the built-in camera on HoloLens as the head-anchored tracker, and a cube with five fiducial markers as the object to track. The coordinate systems of the tracker, object and holographic display are represented as {C}, {O} and {H} respectively (Fig. 1).

$\overrightarrow{p_H}$ is pre-defined, G_{CO} is obtained by HoloLensARToolKit and used to compute $\overrightarrow{q_C}$ where $\overrightarrow{q_C}$= G_{CO}* $\overrightarrow{q_o}$. So that we can find G_{HC}, since $\overrightarrow{p_H}$ = G_{HC}* $\overrightarrow{q_C}$.

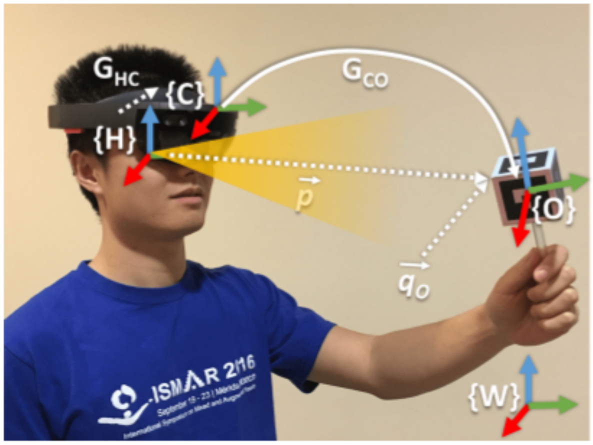


Fig. 1

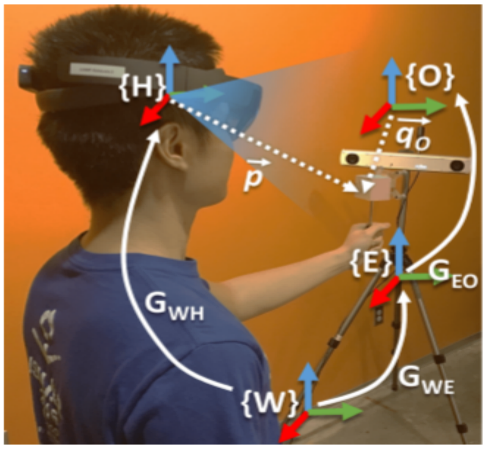


Fig.2

Calibration with World-Anchored Tracking System

In this case, they used an external world-anchored FusionTrack 500 as the tracker, and a frame with four passive spherical markers that is attached to the colored cube for tracking. The coordinate systems of the tracker, object, holographic display and world are represented as{E}, {O}, {H} and {W} respectively (Fig. 2).

$\overrightarrow{p_H}$ is also pre-defined, $\overrightarrow{q_E} = G_{EO} * \overrightarrow{q_O}$, G_{EO} is obtained SDK of FusionTrack 500, and similar with the first case: $\overrightarrow{p_H} = G_{HE} * \overrightarrow{q_E}$. The difference is we cannot obtain G_{HE} directly, $G_{HE} = {G_{WH}}^{-1} * G_{WE}$, where G_{WH} is obtained by SLAM-based spatial mapping function by HoloLens, G_{WE} is fixed. So, finding G_{HE} is actually a process of finding G_{WE} and computing G_{HE}.

Experiments and Evaluation

Their designed two types of experiments for both cases described above. As the calibration begins, the user is instructed to align one corner of the cube to the virtual counterpart s/he sees in the HMD, once is satisfied, s/he click a button for confirmation. Then the virtual corner appears in another position waiting for another alignment. The process continues until 20 successfully alignments are done. After that, the user can choose one of the three different geometrical models to compute the results.

In terms of evaluation, they designed two approaches to address the challenge of subjectivity in evaluation of OST-HMDs.

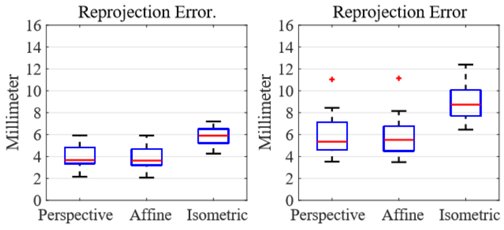
1, Train-and-Test: In the first method, the user is asked to collect 8 additional samples, and these samples are tested against the calibration calculated with the training data sets consisting of the 20 alignments. Reprojection error of the test data is computed based on each of the three transformation matrices (perspective, affine, isometric).

2, Double-Cube-Match: In the second evaluation analysis, a second cube marker is used as an auxiliary reference for objective measurement of the calibration error. Using the computed transformation from the calibration phase, a virtual cube is displayed in the holographic scene with a predetermined offset of 150mm with respect to the first marker cube at four different equidistant positions. The user is asked to align the second real marker cube with the displayed virtual cube as precisely as possible by moving it relative to the other.

Results

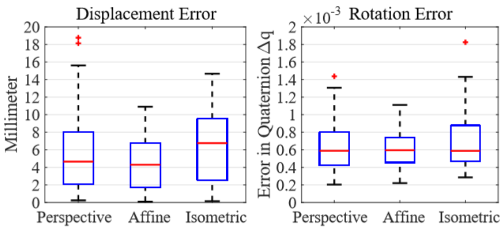
Fig. 3a represents the reprojection error of the testing data using perspective, affine and isometric transformation matrices. The mean and standard deviation of the reprojection error are: perspective (4.04±1.04mm), affine (3.96±1.06mm), and isometric (5.86±0.81mm).

Fig.3b shows the same matric for world-anchored tracker case, the mean and standard deviation of reprojection error is 5.88±1.81mm, while affine transformation yields an error of 5.83±1.78mm, and isometric transformation yields an error of 8.92±1.60mm.



(a) Calib. with head-anchored tracker (b) Calib. with world-anchored tracker

Fig. 3



(a) Displacement error $E_{\Delta P}$ (b) Rotational error $E_{|\Delta q|}$

Fig.4

Table 1 shows the mean and standard deviation of the reprojection error along different axes with different geometrical models. Here, the x-y plane is perpendicular to the user's view, and the z axis is parallel with the user's line of sight, indicating the depth of alignment.

Table 2 demonstrates the distribution of error along different axes. However, in the case of calibration with the world-anchored tracker, the x, y, and z axis are parallel to the world coordinate system {W}. The user is able to move around and make alignments from different viewing perspectives. Therefore, no axis is associated with the depth direction in this case, as indicated from the error values.

Table 1: Reprojection error along different axes for the calibration with head-anchored tracking system

	Axis X (mm)		Axis Y (mm)		Axis Z (mm)	
Model	mean	std	mean	std	mean	std
Perspective	1.00	0.81	0.91	0.68	3.55	2.62
Affine	0.94	0.74	0.83	0.63	3.51	2.67
Isometric	1.82	1.08	2.05	1.36	4.58	3.31

Table 2: Reprojection error along different axes for the calibration with world-anchored tracking system

	Axis X (mm)		Axis Y (mm)		Axis Z (mm)	
Model	mean	std	mean	std	mean	std
Perspective	2.47	2.04	3.01	2.49	3.20	3.01
Affine	2.44	1.98	2.98	2.52	3.21	3.01
Isometric	3.64	2.75	6.14	3.88	3.43	2.93

Fig. 4 depicts the evaluation results of the Double-Cube-Match metric. Fig. 4a shows the distribution of displacement with the three different models. More specifically, for perspective transformation, the displacement erroris5.47±4.26mm; for affine transformation, the displacement error is 4.45±3.00mm, and for isometric transformation, the displacement error is 6.44±4.15mm.

The average error in quaternion for the affine transformation EΔq is given by (0.999, 0.005, 0.002, 0.007) where q follows q = (w, x, y, z) representation. Similarly, for the perspective transformation, the quaternion error is (0.999, 0.001, 0.001, 0.001) and (0.999, 0.009, 0.002, 0.003) for the isometric transformation.

Strength, Limitation and Future Work

Strength

1. They proposed a blackbox approach for solving the transformation between the tracking coordinate system and the virtual scene coordinate system, regardless of the internal features of a specific HMD.
2. Two mathematic model are studied, head-mounted tracker and world anchored tracker, make this method more general and widely compatible.
3. Evaluating an OST-HMD calibration has always been challenging since only the user wearing it can observe the superimposed objects that resulted from the calibration. However, they designed two approaches which can eliminate the subjectivity to some degree.
4. Accuracy around 4mm is good for most applications.

Limitation:

1. The tracked object, cube, has one marker on each of its five surfaces but they only used three of them, and the poses of corners are almost the same, maybe it is better to align different corners with more poses.
2. These experiments were performed by two experienced HoloLens users, actually were the joint first authors of this paper. When I first do the calibration process, my errors are around a couple of centimeters. So their accuracy results may not representative for common users. The results would be more convinced if they did the tests among non-experts.
3. The symmetry of the cube might be a little bit confusing and it is unfriendly for color blind, an asymmetrical object can be used to improve this.
4. Their assumption of linear transformation. When I was doing the test, at somewhere the alignment is almost perfect but if I move the cube somewhere else, I could see the discrepancy between the real object and its holographic. So maybe the transformation is somewhat related to the position.

Future Work:

1. This calibration method depends on an external object with markers attached to it. It would be better if the process can be markerless, it would be great if application could detect an object that is there, and then let user move that in different locations for calibrate.
2. Integrate head-anchored and world anchored tracking systems in the holographic OST-HMD using sensor fusion, thereby overcoming issues such as occlusion or limited field of view.
3. Use a stereo camera instead of human behind the HMD, perform the alignments automatically.

Conclusion

In conclusion, the chosen paper provided me with a handful of knowledge in display calibration of OST-HMD. We are indeed using their method to calibration our navigation system, and the results are quite good for current stage. However, there still many things need to be improved if we want to use this on real patients.

Reference

[1] C. B. Owen, J. Zhou, A. Tang, and F. Xiao. Display-relative calibration for optical see-through head-mounted displays. In Third IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR), pages 70–78. IEEE, 2004.

[2] M. Tuceryan, Y. Genc, and N. Navab. Single-point active alignment method (SPAAM) for optical see-through HMD calibration for augmented reality. Presence: Teleoperators and Virtual Environments, 11(3):259–276, 2002.

[3] E. Azimi, L. Qian, P. Kazanzides, and N. Navab. Robust optical seethrough head-mounted display calibration: Taking anisotropic nature of user interaction errors into account. In Virtual Reality (VR). IEEE, 2017.

[4] S. Reichelt, A. Schwerdtner, G. Futterer, H. Stolle, N. Leister, and R. Haussler. Holographic 3-D displays-electro-holography within the grasp of commercialization. INTECH Open Access Publisher, 2010.

[5] Lee, C. K., Tay, L. L., Ng, W. H., Ng, I., & Ang, B. T. Optimization of ventricular catheter placement via posterior approaches: a virtual reality simulation study. Surgical neurology, 70(3), 274-277.2008