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Final Report

Augmented Reality Magnifying Loupe for Surgery

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Abstract

A magnifying loupe is often used in surgical procedures such as dentistry. There are three principal reasons for adopting magnifying loupes for operative dentistry: to enhance visualization of fine detail, to compensate for the loss of near vision (presbyopia), and to ensure maintenance of correct posture. In previous work, a digital magnification system, was implemented on a video see-through head-mounted display (HMD) for surgical applications. In this work, we present an optical see-through HMD (OST-HMD) based augmented reality magnifying loupe system for surgery. We have adapted the Magic Leap One (Magic Leap, Plantation, FL, USA), a light-weight OST-HMD, to provide augmented reality guidance in the optical magnified view. In this report, we present the basic design of the modified HMD, and the method and results of the calibration of Magic Leap One displays to a real-world scene. The final calibration errors are measured both in the magnified view and regular view, respectively. The mean target augmentation error is 3.47 ± 1.03 mm in the magnified view and 2.59 ± 1.29 mm in the regular view.

Contents

Chapter 1

Introduction

1.1 Background and Related Work

Augmented reality (AR) refers to the overlay of computer-generated graphics over a real-world scene. Typically, a device such as a head-mounted display (HMD) is used for AR. HMD based AR has been used in the medical domain for treatment, education, and surgery [3] [9]. Useful information, measurements and assistive overlays can be provided to the clinician on a see-through display. The clinical benefit is the fact that the surgeon can concentrate on the operating field rather than looking at a monitor. In a recent work, an HMD-based AR system is used to help with both planning as well as providing guidance in endodontic therapy [8]. Many dental practitioners use magnifying loupes routinely for clinical work, and dental undergraduates are increasingly wearing them when training, so AR guidance in the loupe can potentially help the practitioner in navigation and operation. There are three principal reasons for adopting magnifying loupes for operative dentistry: to enhance visualization of fine detail, to compensate for the loss of near vision (presbyopia), and to ensure maintenance of correct posture. In practical terms, a magnification of x2–x2.5 would enable the dental operator see multiple quadrant areas in focus [4]. This is the magnification normally used in general dental practice. As the magnification increases, the field that can be viewed decreases. At magnifications of x3.5 the field becomes restricted to a single quadrant, while at a magnification beyond x3.5 the view becomes increasingly restricted until only a single tooth is seen.

In previous work, a digital magnification system, in other words, a virtual loupe, was implemented on a video see-through head-mounted display (VST-HMD) for surgical applications [6]. The system was evaluated by measuring the completion time of a suturing task performed by surgeons. Although it was accepted by surgeons as a useful functionality, it was limited by many disadvantages of the VST technology. Latency between the real world and the processed images and the potential to cause motion sickness make it not suitable for critical tasks such as surgery.

Birkfellner *et al.* [2] have adapted a commercial miniature head-mounted operating binocular for stereoscopic AR visualization. The modification is done by integrating an AR-display system into a well-accepted operating microscope. Two neuro surgeons report that between December 2006 and March 2008, 10 cases of micro neurosurgical spinal operations were performed using such system [5]. There were no technical failures and no intra-operative adverse events that could be attributed to the optical system and it was therefore recommended by these two surgeons.

1.2 Objectives and Significance

In this work, we propose an augmented reality magnifying loupe system for surgery. The proposed system uses an optical see-through head-mounted display (OST-HMD) for AR rendering and optical magnification with the attachment of a surgical loupe. Therefore, the objectives of the project are to:

- Design a surgical loupe mount for OST-HMD.
- Develop a calibration method to associate the field-of-magnified vision, the HMD screen space and the task workspace.
- Evaluate accuracy of the proposed AR system.

The success of the project can potentially increase the clinical acceptance of AR and the proposed system can be used to provide accurate guidance and navigation in a wide range of computer-aided surgery.

Chapter 2

Technical Approach

2.1 HMD Modification

The OST-HMD chosen for the project is a commercially available device, namely Magic Leap One (Magic Leap, Plantation, FL, USA). It is a light-weight, tethered headset with resolution of 1280×960 for each display. A cable connects the HMD to a small hip-mounted computer that handles the primary data and graphics processing. Its relatively flat surface in the front of the display and the light weight on the head make it suitable to attach a surgical loupe.

The headset is designed to have customizable elements including a forehead pad of different sizes and a prescriptions lens insert. These swappable components are magnetically attached to the headset shown in Fig. 2.1.

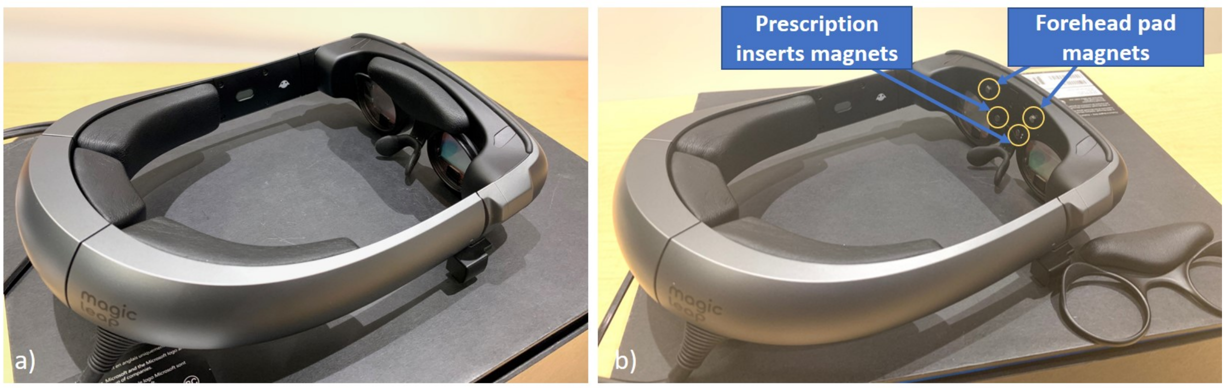

Figure 2.1: a) Magic Leap One headset with forehead pad and an empty prescription insert that comes with the box. b) 4 magnets that connect the customizable components to the headset

Based on the shape and dimension of the device, we design a mount that serves as both

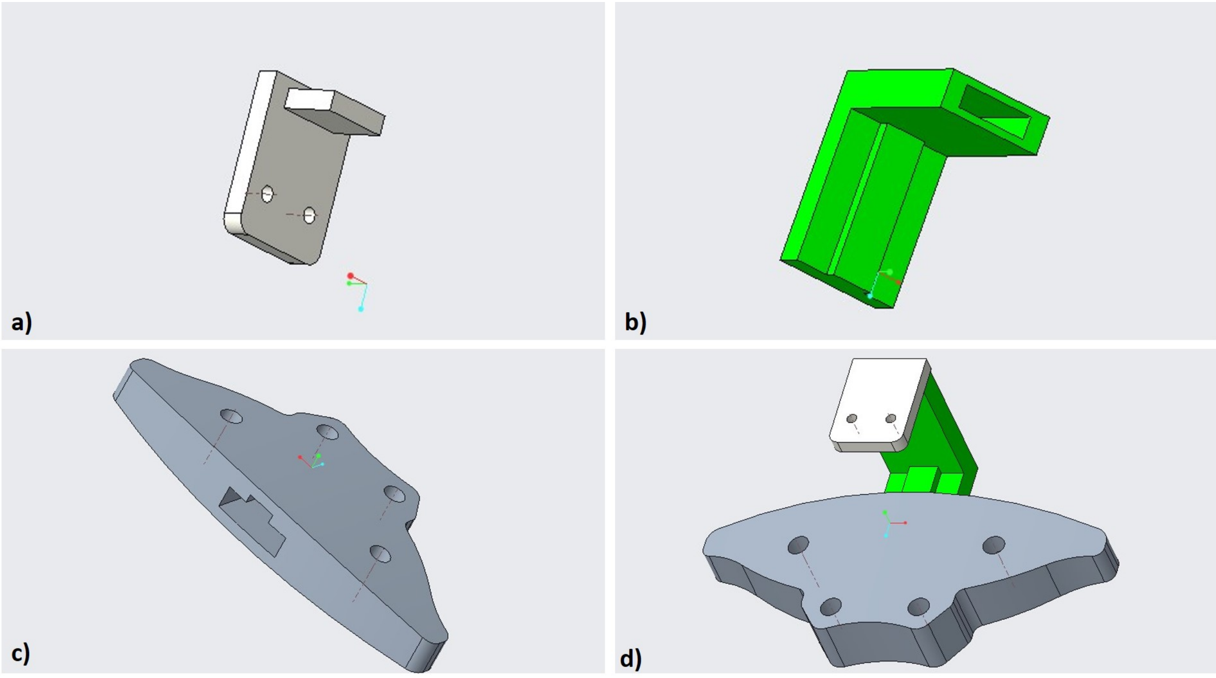

Figure 2.2: CAD design of the mount. The individual parts of the mount are shown in a) - c). d) shows the assembly of the mount.

a forehead pad and a muti-purpose platform to attach the surgical loupe. The CAD design (Fig. 2.2) are done by PTC Creo Parametric (version 4.0, PTC, Boston, MA, USA).

The mount is then 3D-printed and 4 strong magnets are placed and glued inside the holes of the mount so that it is rigid enough to be used to attach a 260-gram weight Galilean loupe. The surgical loupe chosen has a working distance ranging from 280 - 380 mm and a magnification of 3.5x. We refer to the prototype as the AR magnifying loupe. The prototype of the system is shown in Fig. 2.3. With the loupe attached, the user is able to adjust the angle and distance just like the normal surgical loupe without compromise.

2.2 System Calibration

The surgical loupe has an obvious radial distortion effect, to be more specific, a barrel distortion. The effect of barrel distortion is that straight lines are bent as curves and points are moved from their correct position towards the centre of the image. In order to merge the augmented content with the real world more realistically, the same distortion and zoom effect needs to be provided in the magnified view.

In order to determine the distortion parameters of the loupe and the intrinsic parameters of the system, a system calibration process is needed. A mini USB camera module with

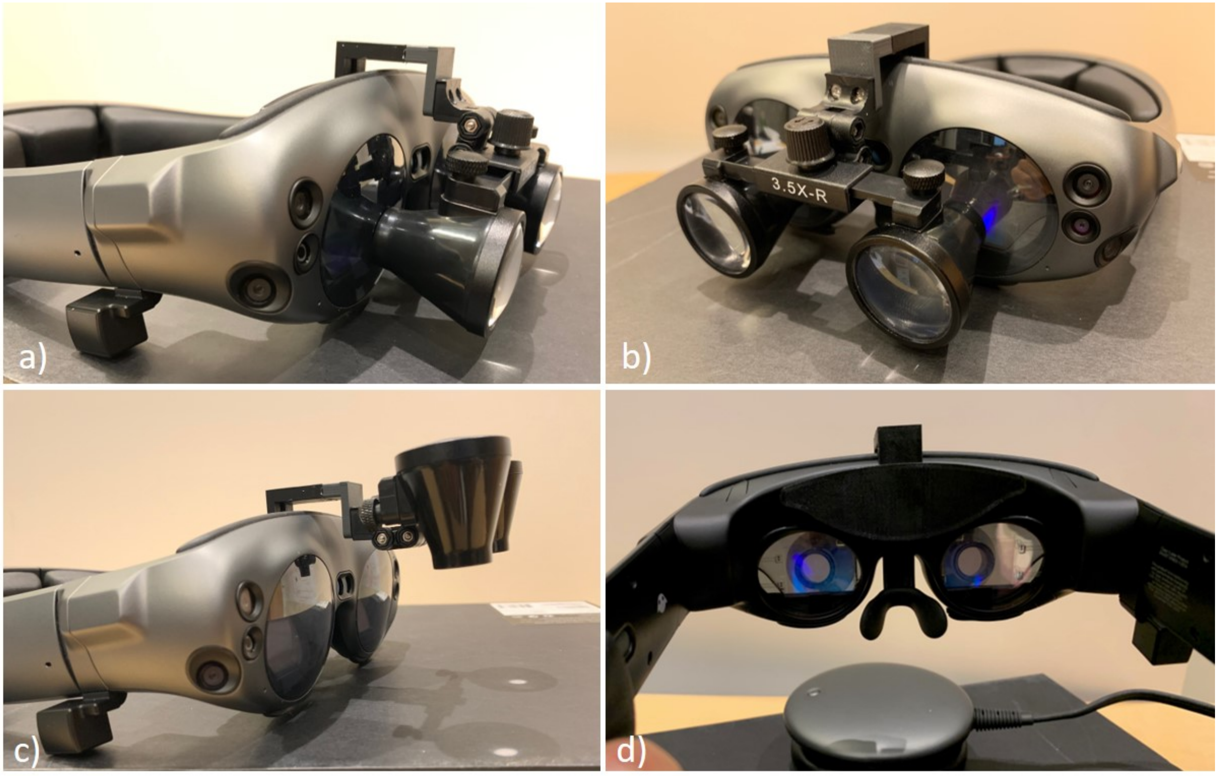

Figure 2.3: Photographs show the prototype of the AR magnifying loupe from different views. a) - b) show the loupe attached close to the displays of the headset. c) shows the capability of flipping the loupe up and down to allow surgeons to switch from normal view and a magnified view. d) shows the circle-shaped view of the loupe in the rectangle display of the headset.

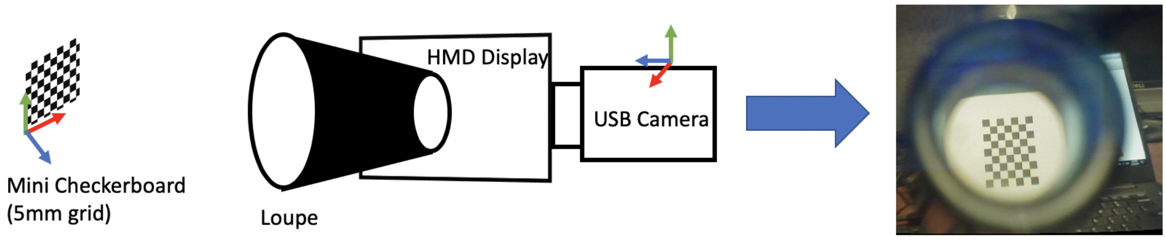

Figure 2.4: The system calibration setup and the acquired image of a 5mm checkerboard which is displayed on a laptop screen in actual size.

1080P resolution and field-of-view of 100° is used. The camera module was first calibrated using Zhang's method [10] with a 30mm checkerboard consisting of 8x6 vertices and 9x7 squares. We then attach the camera module to the back of the HMD display to capture 30 images from different poses of a 5mm checkerboard consisting of 8x6 vertices and 9x7 squares. During the photo capturing process, the checkerboard is placed in the range of the working distance of the loupe, and the whole checkerboard is visible in the magnified view (Fig. 2.4). These 30 images are then processed based on the intrinsic parameters of the USB camera module to rectify the images, therefore, the distortion effect due to the USB camera are removed. Next, the 30 processed images are fed into the same algorithm to get the intrinsic parameters of the system. The whole calibration process is illustrated in Fig. 2.5.

2.3 AR Rendering

In order to achieve the same distortion effect of AR content as the surgical loupe in the magnified view, we follow the hybrid magnification approach [6] to perform real-time distortion of any AR content in the constraint domain.

We model the distortion in the following:

$$\begin{aligned} x_d &= x_u(1 + k_1\dot{r}^2 + k_2\dot{r}^4 + k_3\dot{r}^6) \\ y_d &= y_u(1 + k_1\dot{r}^2 + k_2\dot{r}^4 + k_3\dot{r}^6) \end{aligned} \tag{2.1}$$

where x_u and y_u undistorted pixel locations. x_u and y_u are in normalized image coordinates. Normalized image coordinates are calculated from pixel coordinates by translating to the optical center and dividing by the focal length in pixels. Thus, x_u and y_u are dimensionless. $r = x_u^2 + y_u^2$ and k_1, k_2, k_3 are the distortion parameters, which are determined by the calibration process in Sec. 2.2. The implementation of the model is done in Unity (version Unity 2018.1.9$f2 - MLTP10$ (64-bit), Unity Technologies, San Francisco, CA, USA)

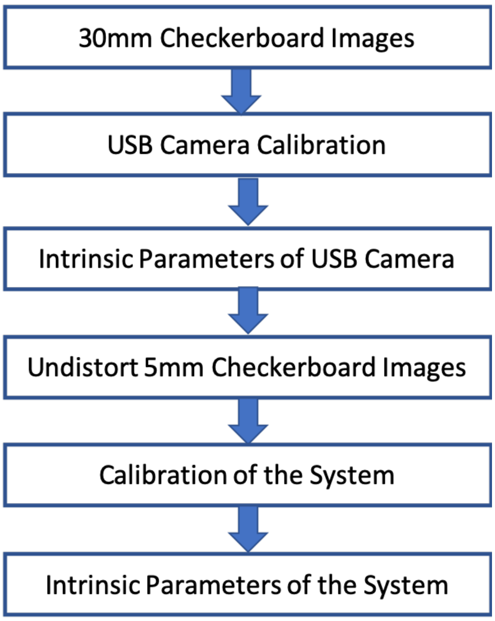

Figure 2.5: System calibration steps

and Microsoft Visual Studio (version Community 2017, Microsoft Corporation, Redmond, WA, USA). In the Unity scene, each eye is assigned with two cameras for rendering. The regular camera is used to render a non-magnified view of the augmented content directly to the display and the other camera is used to render the distorted magnified view of any AR content to a texture. The texture is then displayed to the 2D screen in a constrained domain. The exact 2D location will be determined by a user-dependent calibration procedure later introduced in Sec. 3.1.1. Fig. 2.6 represents the components and architecture of the system and the simulated eye view result.

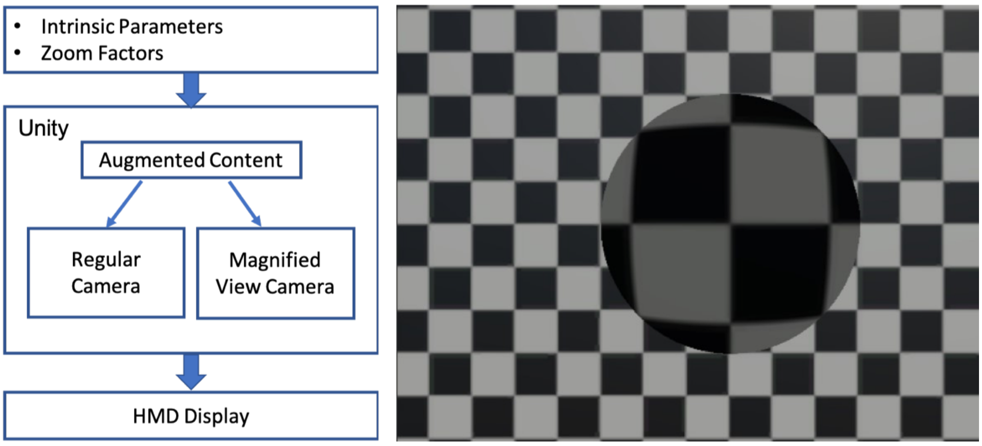

Figure 2.6: Software architecture of the system and simulated HMD view.

Chapter 3

Experimental Results and Evaluation

3.1 User-Dependent Calibration

Since each user has different interpupillary distance (IPD) and each user adjust the headset and the surgical loupe differently, we propose a 2-step user-dependent calibration procedure for accurate registration of the rendered graphics with tracked objects in the real world.

3.1.1 Eye-tracking Based Calibration

In order to associate the field-of-magnified-vision with the HMD screen space, the user is first asked to adjust the loupe such that the user is able to read comfortably any text or graphics that is within the working distance of the system through the magnified view of the surgical loupe. During this process, the fixation point of the user's eyes in 3D space can be retrieved from Lumin SDK (version 0.19.0) in real-time. Therefore, the lines connecting the fixation point and the user's eyes will be intersecting with the left and right HMD display respectively. The intersection point on the 2D HMD screen space can be recovered by the camera matrix P with:

$$x = PX \tag{3.1}$$

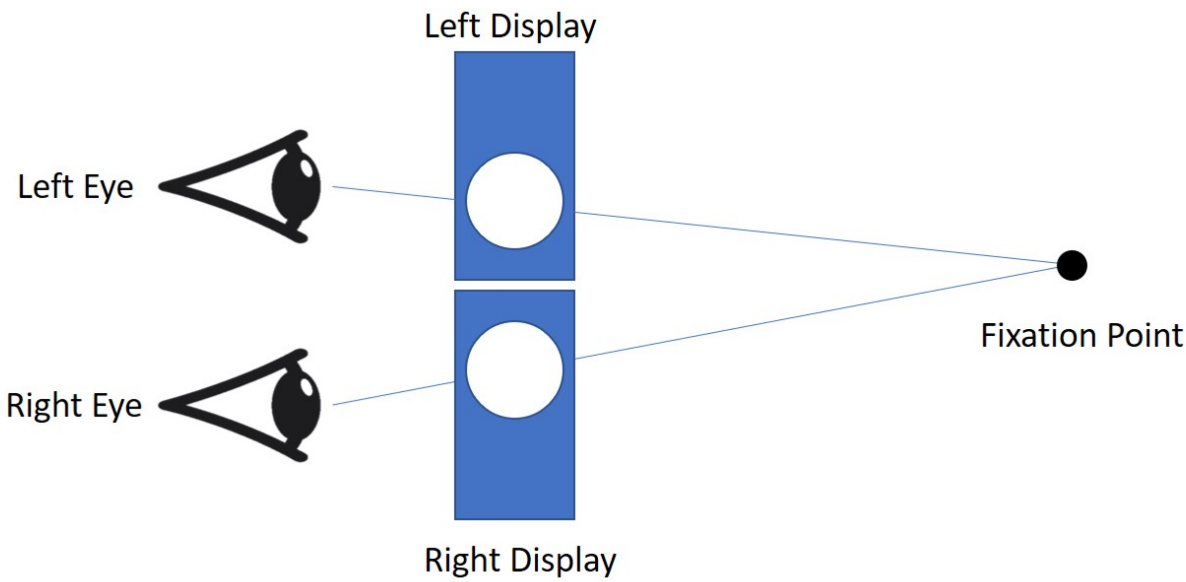

Figure 3.1: Illustration of process to determine field-of-magnified-vision on the 2D HMD screen space.

where x is the 2D screen coordinates of the corresponding point X in 3D world space. The camera matrix P can be further decomposed into the following:

$$\begin{aligned} P &= \overbrace{K}^{\text{Intrinsic Matrix}} \times \overbrace{[R \mid \mathbf{t}]}^{\text{Extrinsic Matrix}} \\ &= \overbrace{\underbrace{\begin{pmatrix} 1 & 0 & x_0 \\ 0 & 1 & y_0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{2D Translation}} \times \underbrace{\begin{pmatrix} f_x & 0 & 0 \\ 0 & f_y & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{2D Scaling}} \times \underbrace{\begin{pmatrix} 1 & s/f_x & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{2D Shear}}}^{\text{Intrinsic Matrix}} \times \overbrace{\underbrace{\left(I \mid \mathbf{t} \right)}_{\text{3D Translation}} \times \underbrace{\left(\begin{array}{c|c} R & 0 \\ \hline 0 & 1 \end{array} \right)}_{\text{3D Rotation}}}^{\text{Extrinsic Matrix}} \end{aligned} \tag{3.2}$$

where the intrinsic matrix K is computed with the properties of the regular Unity camera for non-magnified view rendering mentioned in Sec. 2.3 and $[R \mid \mathbf{t}]$ are determined in Unity world coordinate frame in real-time. Fig. 3.1 illustrates the eye-tracking based calibration method.

3.1.2 Real-to-Virtual Alignment Calibration

Since the proposed AR magnifying loupe system has to visualize virtual objects in reality, the correct pose and alignment of the displayed objects are of critical importance for the proper user experience using such systems. The calibration procedure is therefore performed with the "blackbox" approach [1] implemented on the headset. We designed a marker with rich texture (Fig. 3.2) so that if only part of the marker in visible in the magnified view, we are still able to determine the complete 6 degree-of-freedom pose of the marker. In this step, a virtual marker with the same size and texture is displayed in the magnified view in 4 different poses. The user is asked to align and confirm the real marker to the virtual marker in the magnified view sequentially. The real marker is also being tracked with the built-in RGB camera on the headset, so that the 3D coordinates of the real and virtual marker can be obtained at the same time. The mathematical 3D to 3D transformation is represented by the following equation:

$$P_i = [T]_{4\times4} Q_i \tag{3.3}$$

where P_i and Q_i are real and virtual 3D coordinates of the marker. From these 4 poses, we seek to compute the mean rotation and translation. The mean rotation matrix $\overline{R}$ is computed on the Special Orthogonal group $SO(3)$ by minimizing:

$$\underset{\overline{R}\in SO(3)}{\operatorname{argmin}} \sum_{i=1}^{N} d(R_i, \overline{R})^2 \tag{3.4}$$

where $d(.)$ denotes a distance function on the Riemannian manifold. To establish $d(.)$, the rotation matrix is expressed in the Lie algebra (tangent space) of the Lie group as $R = e^{\hat{w}}$. The tangent space $\hat{w}$ is then obtained as $log(R) = \hat{w}$, such that $\hat{w}$ is the skew-symmetric matrix constructed from the vector w. Consequently, the mean rotation is estimated as ([7])

$$\underset{\overline{R}\in SO(3)}{\operatorname{argmin}} \sum_{i=1}^{N} \|log(R_i^T \overline{R})\|_F^2 \tag{3.5}$$

where $\|.\|_F^2$ is the Frobenius norm. The mean translation $\bar{t}$ is computed in Euclidean space as:

$$\bar{t} = \frac{1}{N} \sum_{i=1}^{N} t_i \tag{3.6}$$

We calibrated our system to enable the augmented virtual objects to be represented in the same coordinate system as the real-world objects. As a result, the user can see the overlays in the correct location.

3.2 Target Augmentation Error

To evaluate the proposed system, we designed a 15 cm planar marker with 8 pre-defined locations on the marker (Fig. 3.3). We measured the target augmentation error (TAE) by using the built-in RGB camera to track and locate the marker 3D position and augmenting

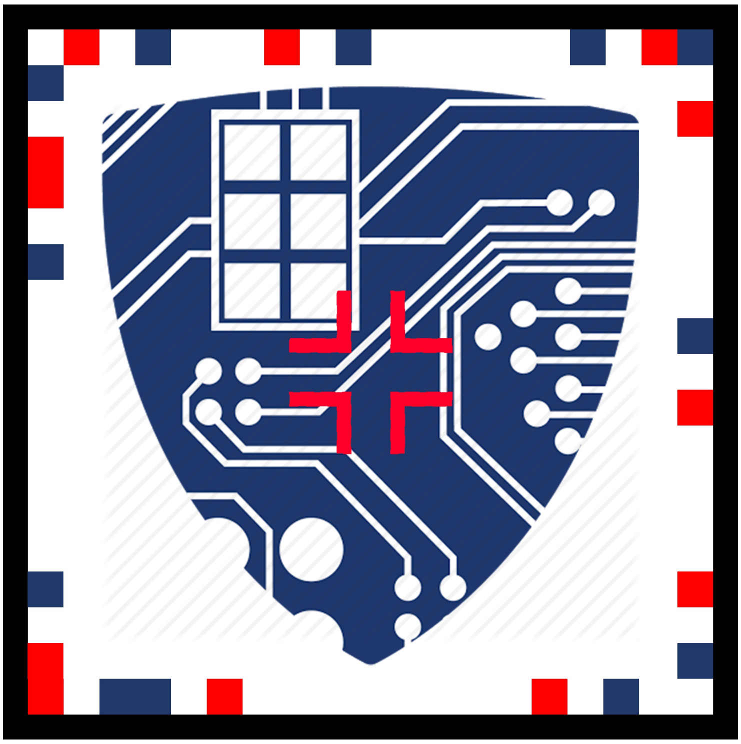

Figure 3.2: Marker used for tracking

Table 3.1: TAE measurements in regular view.

Target Augmentation Error (TAE) in Regular View	Mean	RMS	Median	Standard Deviation
	2.59 mm	1.21 mm	2.63 mm	1.29 mm

8 corresponding spheres to the pre-defined location on the marker. A digital caliper was used to measure the absolute distance between the augmented points and the actual points. We evaluate the TAE in both regular view and magnified view and Table 3.1 and 3.2 show the TAE results.

3.3 Surgical Use Cases

Finally, we demonstrate the application of the AR magnifying loupe with a high volume clinical procedure called endodontic guided treatment. Following the method implemented

Table 3.2: TAE measurements in magnified view.

Target Augmentation Error (TAE) in Magnified View	Mean	RMS	Median	Standard Deviation
	3.47 mm	0.96 mm	3.22 mm	1.03 mm

Figure 3.3: Marker for TAE measurements.

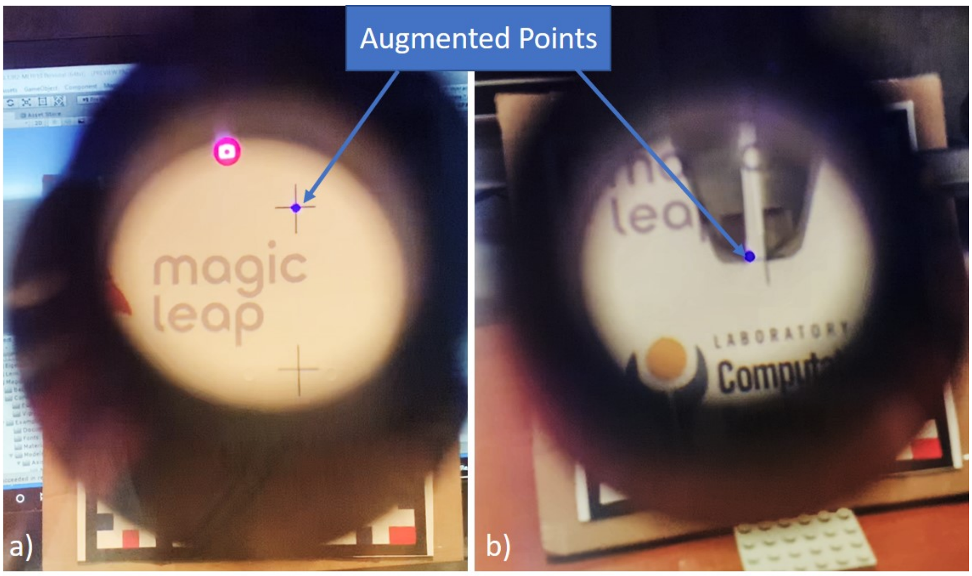

Figure 3.4: Experiment setup for TAE measurements.

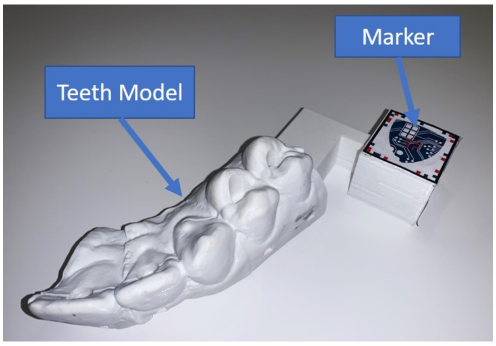

Figure 3.5: 3D-printed models

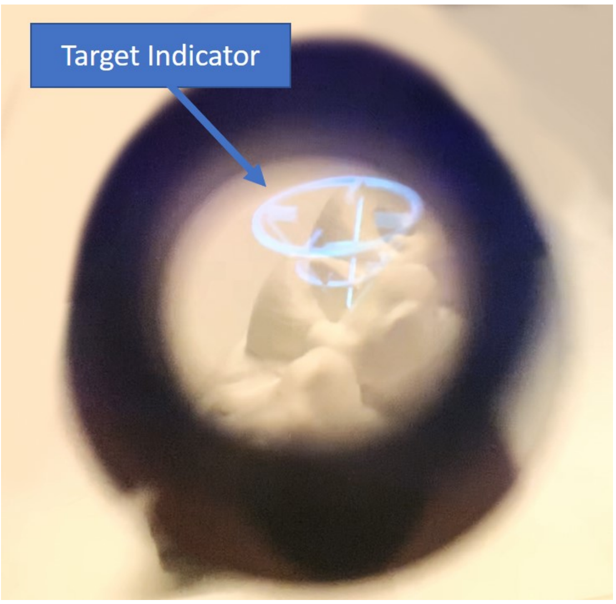

Figure 3.6: An AR target indicator is shown in the optical magnified view.

by Song *et al.* [8], we 3D-printed a teeth model with a marker motioned in Sec. 3.1.2 attached to the model (Fig. 3.5). The proposed AR system is able to track and augment useful guidance information to assist the dentists to prepare an access cavity in the magnified view. We show an exemplary scene of the aforementioned case in Fig. 3.6.

Chapter 4

Discussion and Conclusion

This work presents a work flow from modification of the existing HMD, calibration of the system to error evaluation. The proposed system associates the field-of-magnified-vision, the HMD screen space and the task work space. The customizable forehead pad, and adjustable surgical loupe make the system flexible to different users. The TAE results show that the modification of the HMD does not introduce a large alignment error in the magnified view compared to the regular view. The alignment accuracy between virtual and real is sufficient for a wide range of computer-aided surgery.

However, there are many limitations of the system. In the user-dependent calibration process, it is hard for the user to perceive depth from one direction, therefore, the user may have trouble aligning the real to virtual object, which eventually affects the final accuracy of the alignment. In addition to the real-to-virtual alignment issue, the system also suffers from limited field of view (FOV) of 20 degrees diagonally in the magnified view of the loupe. The additional rendered graphics can make the scene in the magnified view too crowded. A more efficient way to provide AR guidance is needed.

In the future, we aim to improve the tracking accuracy of the system by attaching a zoom lens to the tracking camera. With a zoom lens attached, markers used for tracking can be minimized. Besides the further development of the system, preclinical and clinical evaluation at various surgical tasks as well as a multi-user study are needed.

Chapter 5

Appendix

5.1 Deliverables

- Minimum: A hardware prototype to integrate Magic Leap One with magnifying loupe, a calibration process for single eye. (Complete)
- Expected: A user-friendly stereo calibration process to associate the field-of-magnified-vision, the HMD screen space and the task workspace. (Complete)
- Maximum: Minimized AR marker tracking ability, evaluation results of proposed system with a comparative phantom study. (Not finished)

5.2 Dependencies

Please see the table below.

5.3 Schedule

Please see Fig. 5.1.

5.4 Key dates and milestones

- Mar 4th: Finish Hardware prototype, begin calibration
- Mar 25th: Finish calibration for single eye

Dependencies	Solution	Alternative	Estimated Date
Access to Magic Leap One	Ask Dr. Navab for access	Ask Ehsan for Epson BT-300	Resolved (Mar 1)
Access to surgical loupe	Ask Long for access		Resolved (Feb 11)
Access to CAD Software (SolidWorks or PTC Creo)	Download from JHU software catalog		Resolved (Feb 18)
Access to 3D printer	Access to LCSR 3D printer	Use DMC 3D printer	Resolved (Mar 15)
USB Camera with wide FOV	Ask Long for access	Buy one from Amazon	Resolved (Apr 11)

Activities	**Start Date**	**End Date**	**Status**
Literature review on previous work and technical solutions	2/11/2019	2/18/2019	**Complete**
Plan proposal and presentation	2/11/2019	2/18/2019	**Complete**
Written project plan	3/4/2019	3/7/2019	**Complete**
Design HMD mount for loupes	2/18/2019	3/5/2019	**Complete**
3D print and manufacture mount	3/4/2019	3/11/2019	**Complete**
Develop HMD calibration methods for single eye	3/11/2019	3/25/2019	**Complete**
Develop stereo HMD calibration methods	3/20/2019	4/15/2019	**Complete**
Identify a practical sub-task in dental procedure	4/15/2019	4/20/2019	**Complete**
Evaluate the accuracy of the system	5/1/2019	5/4/2019	**Complete**
Implement minimized marker tracking	4/20/2019	5/1/2019	**Not Startec**
Conduct a comparative phantom study	4/15/2019	5/6/2019	**Not Startec**
Prepare for final report and poster	5/1/2019	5/9/2019	**Complete**

Figure 5.1: Yellow items represent the minimum deliverable, green items reprent the expected deliverables and blue items represent the maximum deliverables

- Apr 15th: Finish stereo calibration, begin evaluation implementing minimized AR marker tracking
- May 6th: Finish evaluation and minimized AR marker tracking (Only evaluation is finished)
- May 9th: Finish project report

5.5 Management Summary

- I have weekly meetings with my project mentors Long and Mathias to discuss our progress and obtain advice and direction on the project. Presentations slides and reports were sent to all my mentors to get feedback several days before due date.
- All the source code is stored on a GitHub private repository.
- Design document, project report and additional project files are stored on JH Box Click here for access
- Task distribution: I have completed the expected deliverables by my own and guidance from mentors.
- Challenge: One of the big challenges in the project is the limited range of the working distance of the surgical loupe making the system calibration process painful.
- Lessons learned: The minimum clipping plane of the Magic Leap can not be changed in the Unity to any other value than 0.371m. Any virtual object will not be rendered within this distance.

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