

Endodontic guided treatment using augmented reality on a head-mounted display system

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Published in Healthcare Technology Letters; Received on 13th August 2018; Accepted on 20th August 2018

Endodontic treatment is performed to treat inflamed or infected root canal system of any involved teeth. It is estimated that 22.3 million endodontic procedures are performed annually in the USA. Preparing a proper access cavity before cleaning/shaping (instrumentation) of the root canal system is among the most important steps to achieve a successful treatment outcome. However, accidents such as perforation, gouging, ledge and canal transportation may occur during the procedure because of an improper or incomplete access cavity design. To reduce or prevent these errors in root canal treatments, this Letter introduces an assistive augmented reality (AR) technology on the head-mounted display (HMD). The proposed system provides audiovisual warning and correction in situ on the optical see-through HMD to assist the dentists to prepare access cavity. Interaction of the clinician with the system is via voice commands allowing the bi-manual operation. Also, dentist is able to review tooth radiographs during the procedure without the need to divert attention away from the patient and look at a separate monitor. Experiments are performed to evaluate the accuracy of the measurements. To the best of the authors' knowledge, this is the first time that an HMD-based AR prototype is introduced for an endodontic procedure.

1. Introduction: Endodontic treatment also known as root canal therapy (RCT) aims to treat inflamed or infected root canal system of any involved tooth. RCT ensures that a tooth with irreversible pulpal damage can retain its function in the oral cavity. Every year in the USA alone, about 22.3 million root canal treatments are performed. It is one of the most technically demanding and specialised procedures in dentistry requiring high level of technical skill. To achieve a successful result, an important step at the beginning is to create an access cavity to pulp chamber before the cleaning/shaping of root canal space. A proper access cavity provides advantages such as optimal instrumentation and adequate irrigation of root canal system, thereby influencing the success of endodontic therapy. Accidents may occur at this step and may lead to failure of root canal treatment. In most cases, the only way to visualise the root canal system is through taking radiographs; and most endodontic procedures are performed in a visual void where only tactile sensation is used. Although the introduction of dental operating microscopes has been very helpful in better visualisation of this complex anatomical structure, it still has many limitations and does not provide any assistance regarding the required path which is needed to have a proper access to the root canal system. The common procedural errors during this step are (i) removing too much dentin structure and predisposing the tooth to fracture under functional loads, (ii) an incomplete or small access cavity and (iii) perforation due to wrong inclination of the drill, not considering presence of a deviated or inclined tooth or deep penetration of the drill (Fig. 1). Perforations of the pulp chamber space lead to inflammatory response in periodontium that may cause irreversible destruction of the periodontal ligament or even tooth loss. This may result in tooth extraction and legal actions against the treating practitioner. Iatrogenic perforation of pulp chamber floor is an undesirable complication in dental practice that can have a negative impact (up to 20% decrease in successful outcome) on the treatment prognosis [1, 2].

To reduce or prevent errors in this procedure, more information and guidance should be given to the dentist during this step. For example, the drill entry point and outline shape would be more

accurate if the correct position of the long axis and the outline of the access cavity on the designated tooth is provided to the dentist in a useful way. It would also be helpful if the dentist can figure out the depth of drill and its distance to pulp chamber and root canal space. Having an alert and warning system when the operation might lead to an accident, like perforation, can prevent the procedural accident from happening and improve the overall treatment outcome.

The concept of guided endodontics was first introduced by Krastl G. *et al.* [3] as a novel treatment approach for teeth with pulp canal calcification and apical pathology. They concluded that the presented approach is a safe and clinically feasible method to locate root canals and prevent root perforation in teeth with pulp canal calcification. The accuracy of this static dynamic system or guided endodontics has been evaluated in two different studies. In an in-vitro study by Zehnder *et al.*, 60 extracted human teeth were placed into six maxillary jaw models. After access cavity preparation by two operators, a postoperative cone beam computed tomography (CBCT) scan was superimposed on the virtual planning and accuracy was measured by calculating angle and deviation of planned and prepared cavities in three dimensions [4, 5]. There are also some relevant works in implant placement (X-guide, X-nav technologies, LLC, Lansdale, PA) that have been designed for implant placement and use tracking components that have hundreds of distinct tracking points. In a model-based study, Emery *et al.* evaluated the accuracy of dental implants placements using this system. Virtual implants were placed into planned sites using the system. Post-implant placement CBCT scans were taken, mesh overlaid with the virtual plan and deviations from virtual plan were determined [6]. In another study by Block *et al.*, platform and angle accuracy for dental implants using the dynamic navigation was determined. They also demonstrated that the accuracy of dynamic navigation was superior to freehand implant placement [7]. The main limitation of this dynamic navigation system is that the clinician must look at the display rather than direct observing tooth and its related structures. Therefore, it needs longer learning period and there are some risks of complication since the dentist focus is not on oral

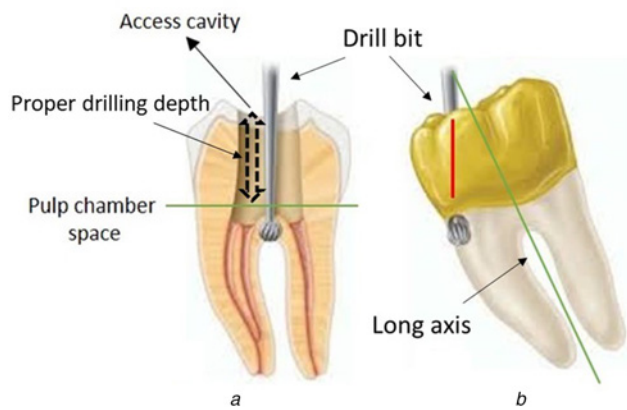


Fig. 1 Schematic view of a tooth and procedural error in RCT resulted in perforation
 a Improper depth of drilling into pulp chamber perforated chamber floor
 b Drilling misalignment

cavity. This problem can be addressed by using an head-mounted display (HMD).

HMD-based AR has been used in the medical domain for treatment, education, rehabilitation and surgery [8–13]. In another work [14], a picture-in-picture visualisation on an optical see-through HMD (OST-HMD) was proposed for navigation in neurosurgery. Useful information, measurements and assistive overlays can be provided to the clinician on a see-through display. In a recent work [15], Thoma *et al.* proposed an HMD-based AR application for intra-oral scanning, in which an OST-HMD is used to show an online overlay of the dynamic dental model onto the patient's teeth.

In the present work, we propose to use an HMD-based AR to help with both planning as well as providing guidance in endodontic therapy. We implemented a prototype using the HoloLens which contains AR instruction overlay, radiographic image and voice control and audio feedback. Preliminary experiments demonstrate that our system is capable of providing intuitive guidance in preparing the access cavity in RCT.

The remainder of this Letter is structured as follows. A detailed description of the proposed system architecture as well as key features of the developed application are given in Section 2. Preliminary experiments of the implemented system are represented in Section 3. The benefits and limitations of the system will be described in Section 4. Translation to clinical setup and future work will be discussed in Section 5 before the conclusion in Section 6.

2. System architecture: Fig. 2 represents the components and architecture of the system. Based on the configurations of the tool and tooth in endodontic therapy procedure, a warning and correction system is designed to assist the dentists, particularly endodontists, in keeping the right pose of the tool while creating the access cavity. This system provides visual and audio guides for the orientation and position of the tool and helps the clinician to avoid a dangerous tool pose. Unity 3D is the software platform for the system, and ARToolkit and Vuforia are utilised for marker tracking. Also, voice recognition is implemented as the user interface which helps the users interact with the system or control the display of the necessary radiographic images. The application can be deployed both on the Microsoft HoloLens as HMD as well as a PC with an external display.

2.1. System setup: Our system is built for the Microsoft HoloLens which has an optical see-through display. As with other single camera tracking systems, this system cannot provide the required

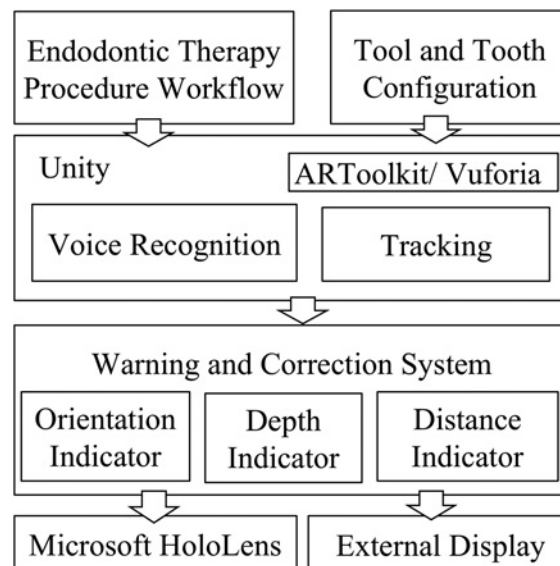


Fig. 2 Application architecture

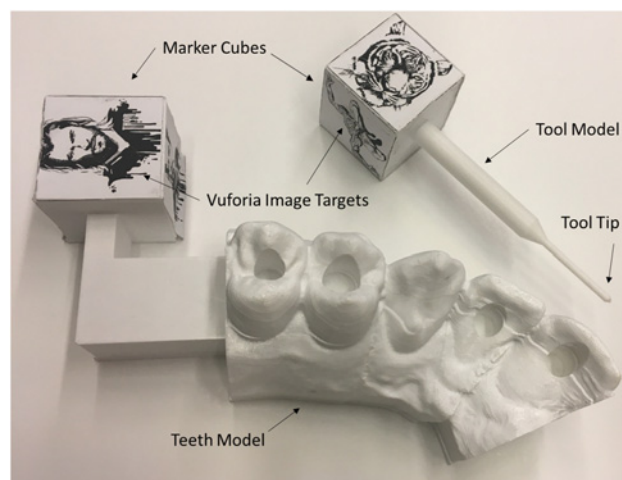


Fig. 3 System setup: 3D-printed models (3.5 times larger than the actual size)

accuracy for the real size teeth model which is in orders of sub-millimetre at the target point. Therefore, we decided to use a larger model to indicate the concept more clearly. Of course, this is not a systematic restriction and the accuracy can be substantially increased by using an external stereo tracking system. The tracking accuracy of this HMD as will be shown in 3.1 does not support measuring the relative pose between the tool tip and the patient tooth with an actual size. As a result, for this project bigger model of teeth was designed. The teeth model is 3.5 times larger the human teeth and the height of the dental crown is 3 cm. Tool which represents the handheld drill in RCT is 10 cm long and the radius of the tip is 3 mm. Both of them are designed to be able to be attached to a marker cube for tracking with an edge of 4 mm and finally 3D-printed as shown in Fig. 3.

2.2. Anatomical measurements: To measure the required geometrical properties in this procedure, the tooth and tool 3D-coordinate frames are created, respectively. The ideal access cavity is defined as a cylinder inside the tooth, where the orientation of its long axis is in the y -direction. The world frame is set to be camera coordinate frame, and the HoloLens tracks the markers relative to its front camera frame. One can see from the

above figures, the mounted cube on the designed models is for attaching the AR Tags. Since the models are designed in CAD, all geometric parameters are known. The following geometric features are represented in the homogeneous coordinates for easier computation:

p_{tip} : tool-tip position relative to the tool marker frame;
 p_c : centre position of the bottom circle of the cylinder(modelled cavity access) relative to the tooth marker frame;
 r_c : radius of the internal cylinder;
 T_{cam}^{tooth} , T_{cam}^{tool} : transformations from the camera to the tooth and from the camera to the tool. Schematic of the transformation chain among the tool, tooth and HMD is represented in Fig. 4. Additional intermediate frames are needed to build the transformation chain

$$T_{tooth}^{tool} = T_{cam}^{tool} T_{cam}^{tooth-1} = T_{cam}^{tool} T_{tooth}^{cam}$$

$$T_{tool}^{tooth} = T_{tooth}^{tool-1}$$

There are three important measurements to calculate and to provide information for the navigation in this prototype setting: depth, orientation and distance. Here are the descriptions with the mathematical expression:

- (i) *Depth*: Vertical distance from the tool tip to the bottom surface of the cylinder, which represents the depth of the drill and its distance to the pulp chamber in RCT

$$depth = (T_{tooth}^{tip} p_{tip} - p_c) \cdot (0 \ 1 \ 0 \ 0)^T$$

- (ii) *Orientation*: Angle between the tool and the central line of cylinder that shows the angular deviation of the tool from the long axis of the tooth

$$angle(\theta) = \arccos \left(\frac{T_{tooth}^{tip} (p_{tip} - (0 \ 0 \ 0 \ 1)^T) \cdot (0 \ 1 \ 0 \ 0)^T}{T_{tooth}^{tip} (p_{tip} - (0 \ 0 \ 0 \ 1)^T) \times 1} \right)$$

$$\theta \in [0, \pi]$$

- (iii) *Distance*: Distance between the tool tip and the central line of cylinder which represents the positional deviation of the tool from the tooth long axis

$$distance = T_{tooth}^{tip} p_{tip} - p_c - depth \times (0 \ 1 \ 0 \ 0)^T$$

Intuitively, *depth* controls the tool tip movements in the vertical dimension, while *orientation* and *distance* control the movements

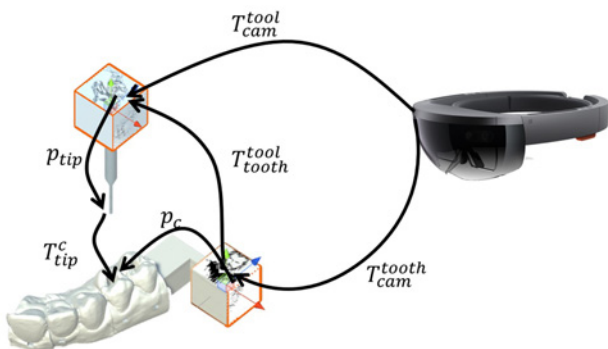


Fig. 4 Transformation chain between the HMD and the models of tooth and tool

in the plane dimension, contributing to the restriction of displacements in 3D Euclidean space and directing the manoeuvres for correction of the tool pose. In other words, the alerts and assistance given based on these measurements are able to effectively prevent the circumstances of perforation, drilling incompleteness and reducing the damage to the internal structures.

2.3. Scene configuration: There are five main objects in the designed Unity scene: Directional Light, AR Camera, Tool Target, Tooth Target and Canvas.

- (i) The ‘Directional Light’ is to determine the shading of other game objects and the shadows it casts. It is a fundamental part of graphical rendering;
- (ii) ‘AR Camera’ is created using Vuforia. It is a special camera type that supports AR apps for both handheld devices and digital eyewear. It can specify where the world frame is located, so that we are able to get the pose and calculate the transformation between game objects;
- (iii) In the scene hierarchy, ‘Tool Target’ is the parent of cube marker attached to the tool and the parent of augmented depth indicator and angle indicator on the tool;
- (iv) Similarly, the children of ‘Tooth Target’ in the scene hierarchy are the other cube markers attached to the tooth and the distance indicator on the tooth;
- (v) The ‘Canvas’ handles the displayed text on the screen or anchored to other indicators. It also handles the display of the radiographic image of the patient’s tooth along with the 2D superimposed overlays.

2.4. User interface: There are three main features in this application to provide intuitive feedback and better user experience:

- (i) Lost marker prevention. If the camera’s view is obstructed or the tracking markers are out of camera’s field of view (FOV), a pop-up text will appear on the screen telling the dentist which marker is lost and instruct the dentist to move in a way that the HoloLens can find the marker again;
- (ii) Visual cues during interaction. Indicators change colour and shape based on the relative transformation (depth, distance and orientation) between the tool and the tooth. The colour of indicators changes gradually from green to red which suggests that the tool is entering the unsafe zone. The scale of the depth, distance and orientation indicators also indicates how safe the situation is. These indicators can provide an intuitive visual cue and the dentist’s goal is to make sure the indicators stay green and small during the procedure;
- (iii) Audio cues during interaction. Audio alerts are integrated in the form of a beep sound that changes frequency and intensity based on the relative transformation (depth, distance and orientation) between the tool and the tooth. The frequency of indicators changes gradually from low to high which suggests that the tool is entering the unsafe zone. The intensity of the sound is also proportional to the level of the deviation. These indicators can provide an additional aid in case the clinician is not looking at the screen during the procedure;
- (iv) Voice integration. The application integrated voice control to display and hide radiographic images when needed as well as text on each indicator so that they would not cause distraction during procedure. This feature makes the application more intuitive and easier to use in a clinical setup without the need to touch a mouse or keyboard.

2.5. Display calibration: Since the proposed AR system has to visualise 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 [16]. 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 dentist can see the overlays in the correct location.

3. Experiments

3.1. Tool navigation and guidance: To verify the implemented system, the application was deployed on the HoloLens and a series of manoeuvres were performed using the tool and tooth model phantom which are represented here.

One should note that the change in the indicator colour from green to red shows gradually entering the unsafe zone. Indicator size is proportional to the deviation from the correct pose for the tool. In addition, real-time measurement is superimposed on the scene to further assist the dentist with adjusting the tool.

The orientation indicator changes its scale from small to large and the colour from green (Fig. 5a) to red (Fig. 5c). As shown in Fig. 5, the angle changes from 2.15° to 45.10°, which means that it is leaving the safe zone and entering the unsafe zone (note: Fig. 5a is taken with HMD and Figs. 5b and c are taken with external monitor).

The distance indicator changes its scale from small to large and the colour from green to red. As shown in Fig. 6, the distance changes from 0.36 to 3.22 cm, which means that it is entering the unsafe zone (note: Fig. 6b is taken with HMD and Figs. 6b and c are taken with external monitor).

The depth indicator changes its scale from small to large and the colour from green to red. As depicted in Fig. 7, the depth changes

from 2.03 to -0.72 cm, which means that it is entering an unsafe zone (note: Fig. 7c is taken with HMD and Figs. 7a and b are taken with external monitor).

3.2. Accuracy evaluation: In order to verify the accuracy of our measurement, we conducted the measurements for distances and angles using digital caliper and goniometer. The experiment setup for measuring distances and angles are shown in Figs. 8 and 9, respectively. As one can see, we used a digital caliper and goniometer as our ground truth and recorded it along with each measurement reported by our AR system. It should be noted that since the digital goniometer only operates in vertical plane, the angles were first aligned with the manual goniometer and as shown in Fig. 8 (right) we recorded the readings of the more accurate digital meter that corresponds to the measured angle.

Measurements are performed on nine random distances and angles. The plots for average and maximum error for these observations are depicted in Figs. 10 and 11, for distances and angles, respectively.

These reported values for errors are in the marker centre, however the actual error that we care about and affects the procedure is at the tool tip where drilling occurs. Therefore, we need to calculate propagation of the error from the marker to the tool tip

$$E_{tip} = E_{distances} + \sin(E_{angles}) \times L$$

where E and L represent the measured errors and length from the marker centre to the tool tip, respectively, E_{angles} is converted in rad. In our experiment setting, $L = 119.31$ mm, and we calculate

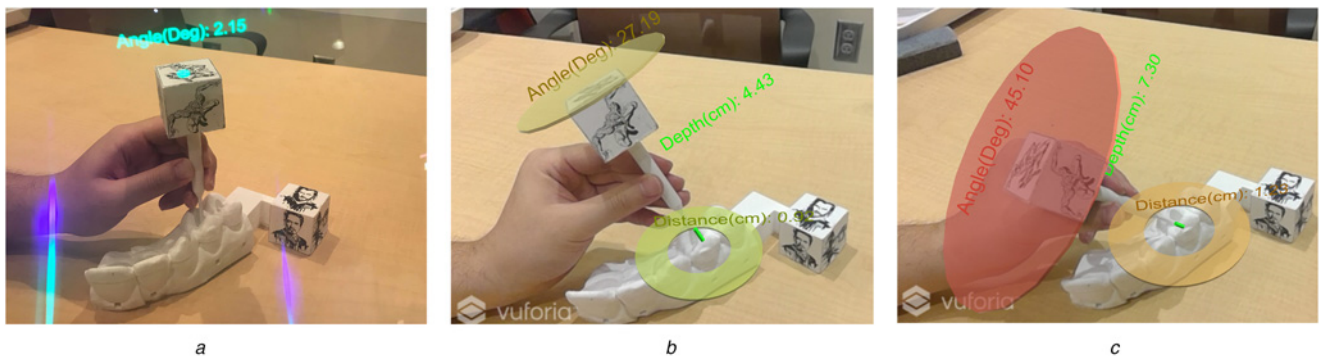


Fig. 5 Warning and assistive augmented overlays for tool angle relative to the tooth long axis warning and guidance
a Tool orientation in safe zone
b Tool orientation in warning zone
c Tool orientation in danger zone

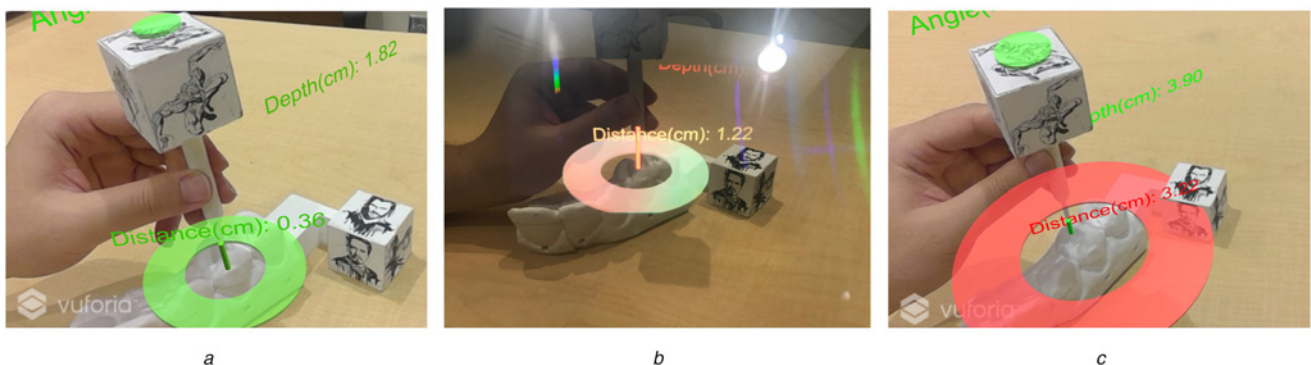


Fig. 6 Warning and assistive augmented overlays for tool distance from the tooth long axis
a Tool distance from axis in safe zone
b Tool distance from axis in warning zone
c Tool distance from axis in danger zone

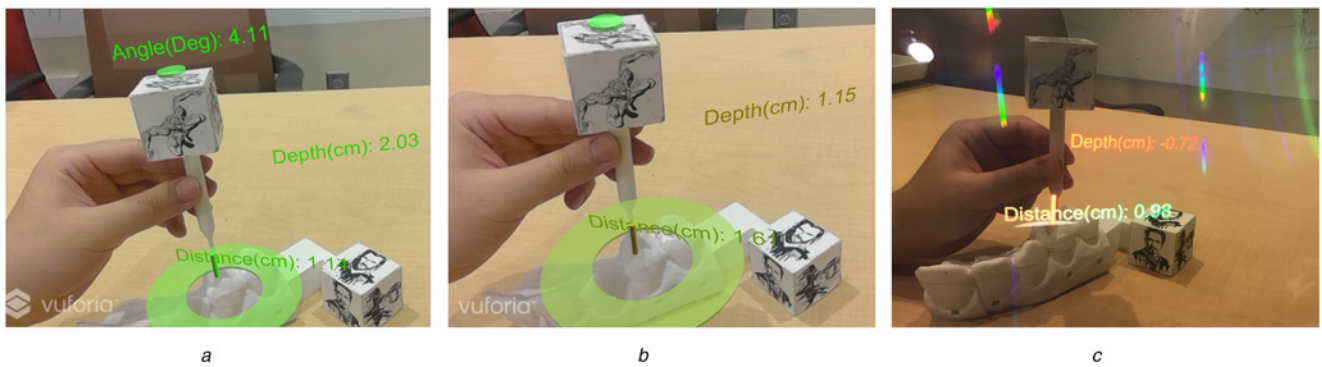


Fig. 7 Assistance and warning for tool-tip depth to indicate the proper depth of drilling for access
 a Tool depth in safe zone for drilling
 b Tool depth is in warning zone
 c Tool depth is in danger zone

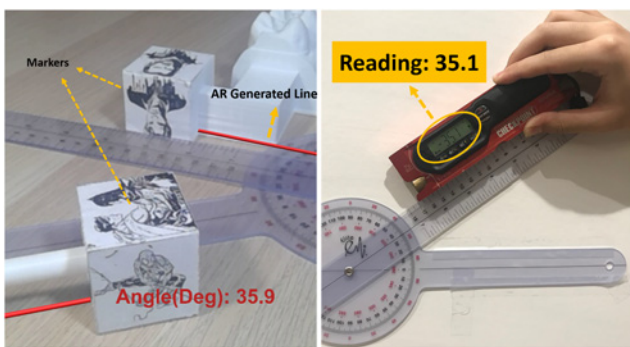


Fig. 8 Experiment setup for accuracy evaluation of the angles

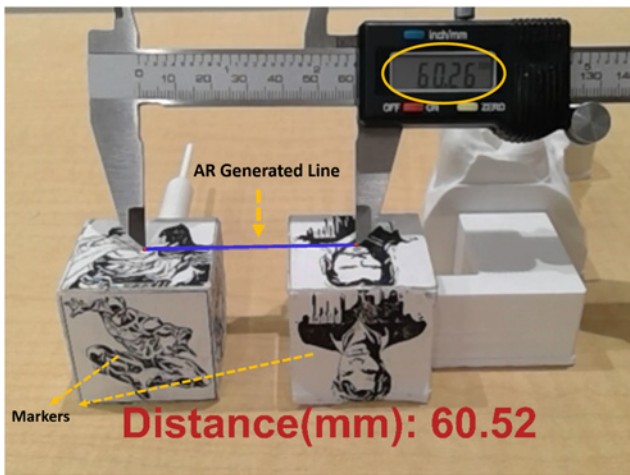


Fig. 9 Experiment setup for accuracy evaluation of the length

the average and maximum errors in the tool tip: $E_{tip}^{average} = 2.8$ mm and $E_{tip}^{maximum} = 5.2$ mm. With this magnitude of error it was not possible to use a real-size teeth model and as discussed we used an enlarged model.

4. Discussion

4.1. Advantages: The prototype system presented here has a number of advantages when compared with the existing methods in RCT and to the best of our knowledge this is the first time HMD-based AR system is introduced for RCT.

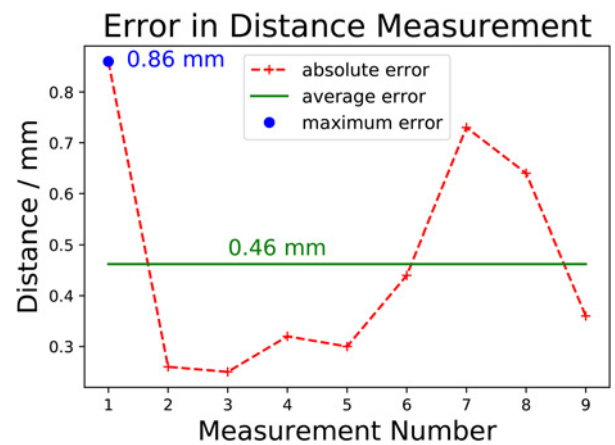


Fig. 10 Error values for distance observations at different points, average, maximum

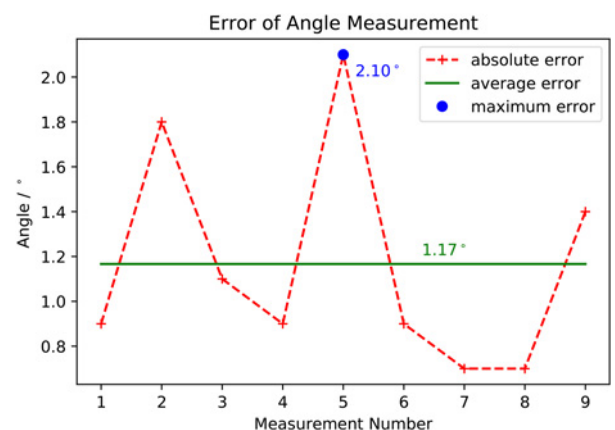


Fig. 11 Error values for angle observations at different points, average, maximum

In the existing setups microscopes are often used for this procedure which is considered an static system and any movement of the patient or microscope leads to misalignment [7]. Current available dynamic systems use optical technologies to provide guidance on a separate monitor. Our proposed HMD-based AR-assisted dynamic guidance allows direct views of the tooth and provides real-time visualisation and movement of the patient or tool is updated online and does not need any readjustment. The ease of application

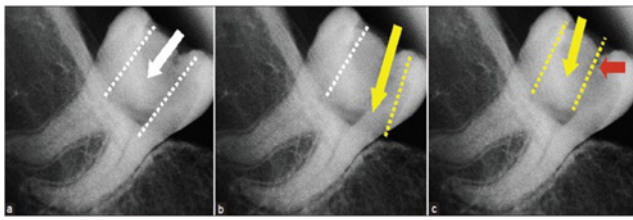


Fig. 12 Superimposed guidance on the radiographic images; white arrow is the correct path for the tool while yellow arrow shows the actual incorrect pose direction and red arrow guides the dentist to reorient the tool

also reduces the required learning curve and it is more natural and user friendly.

More recently, microguided endodontic methods [3, 5] have been developed to achieve minimally access cavity preparation in cases with calcified canal using a novel computer-guided technique. With the help of special software, alignment with 3D radiographs (CBCT) and surface scan, virtual planning of an ideal access cavity was done and then a template was fabricated by means of a 3D printer that guided a minimally invasive drill to the calcified root canal system. However, there are some limitations associated with this technique. Due to the space needed for the template and the bur, treatment might not be feasible in the posterior region. Additionally, a considerable time and technical efforts are needed for microguided endodontics application.

The developed application in the present study is more user friendly, feasible to use for posterior teeth and also free of any need for template fabrication unlike the microguided method. In addition, voice control enables the clinician to perform bi-manual procedure without the need to touch a mouse or keyboard which can affect the sterility as well as the user's focus.

As it was mentioned, the proposed system is capable of visualising the radiographic images of the patient tooth along with the superimposed assistive guidance. This feature is illustrated in Fig. 12. Using voice command, the dentist can hide or show this radiographic image of the tooth based on the situation. Another indicator on the screen also informs the user if both tracking AR markers were found and detected in the camera view. Incorporating radiograph in the scene eliminates the need for the dentist to look at another screen and deviate from the patient and procedure. However, the system is also capable of showing the graphical content on an external display in case the patient or trainees need to also see that.

4.2. Limitations: There are, however, some challenges associated with this project as with other systems using HMDs. The tracking accuracy for dental procedures needs to be in sub-millimetre order, and tracking accuracy of the mono-camera of the HoloLens is not enough for this purpose. To alleviate the limited tracking accuracy, we can incorporate external tracking systems with sub-millimetre accuracy. In this work in order to show the general concept and use a simple standalone setup, we only used the front camera of the HoloLens, however we have planned to integrate a stereo tracking system with the HoloLens. It satisfies the sub-millimetre accuracy condition of the application and it can alleviate the tracking accuracy issue. In addition to the tracking accuracy, it also suffers from a limited FOV of around 35° diagonally. However, we believe that with the continuous advancement of the design of OST-HMDs, the FOV would be enhanced. Also, when the marker is outside the tracking volume, the system is not able to provide any further estimate. Increasing the tracking volume by adding additional trackers will resolve this issue as well. Moreover, detecting the markers highly varies based on the lighting condition.

5.. Clinical translation and future work: In order to incorporate the proposed guidance and navigation system in a clinical setup,

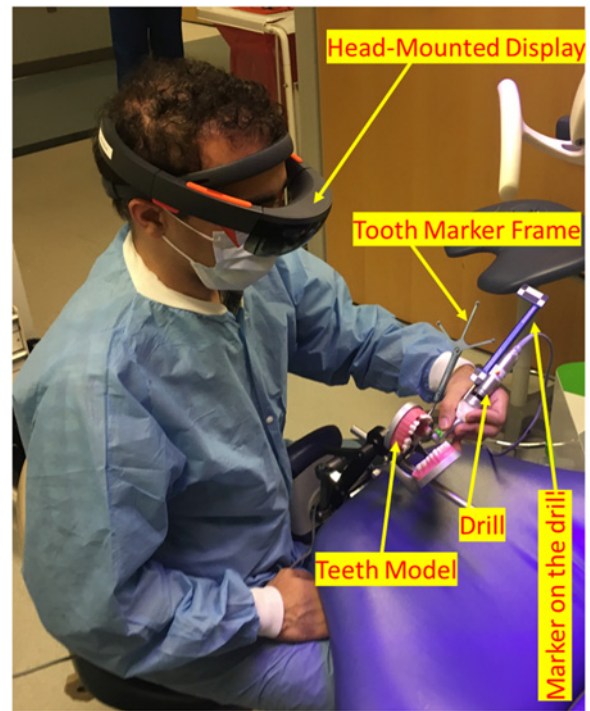


Fig. 13 Dentist is wearing the HoloLens to perform the procedure on the real-size tooth model, marker is mounted on the handpiece (drill) that can easily be tracked. Another marker frame is mounted on an adapter that is fixed inside the mouth on the teeth

some modifications are necessary. To illustrate our plan we have presented the mock setup in Fig. 13 as our next step in this project. As it is indicated the dentist is wearing the HoloLens and is performing a root canal treatment on the real-size teeth model. A marker is used for tracking the tooth which is mounted on an adapter that is fixated on the teeth. A second marker is mounted on the handpiece (tool) that the dentist is using for drilling. As one can see both markers are clearly out of the mouth and are visible for tracking purposes.

Our next plan once we completed this setup is to do a multi-user study and compare the performance of the users in the procedure using HMD and without HMD. We are also planning to use stereoscopic trackers with high accuracy so we can use the application on the true human size tooth. We will also replace 2D radiographic images by 3D radiographic scans (CT scans) to perform preoperative planning based on 3D view.

6. Conclusion: This project investigated a potential AR assistance for preparing a proper cavity access in the endodontic therapy. An HMD-based application was introduced that provides AR feedback to the dentist to reduce or prevent accidental errors in root canal treatment. The developed audiovisual warning and correction system which is overlaid on the real anatomy assists the dentists in tool pose adjustments when creating the cavity access. Results show that this designed AR guidance is able to provide clear and useful information to the dentist to correct wrong poses of the tool. It shortens the decision time for the dentist to apply the correction. Integration of radiographic images and voice interaction makes this application more intuitive and easier to use in a clinical setup.

7. Acknowledgment: The initial implementation of this work was done as part of the AR course taught by Professor Nassir Navab. The authors particularly thank Sing Chun Lee for his help, coordination and support during the course. The authors would also like to thank LCSR for the support.

8. Funding and declaration of interests: A patent of title Systems and Methods for Endodontic Guided Treatment and Dental Implant Surgery Using Augmented Reality on a Head-Mounted Display has been disclosed to the Johns Hopkins University Technology Transfer Office.

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