Application of Augmented Reality to Visualizing Anatomical Airways

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ABSTRACT

Visualizing information in three dimensions provides an increased understanding of the data presented. Furthermore, the ability to manipulate or interact with data visualized in three dimensions is superior. Within the medical community, augmented reality is being used for interactive, three-dimensional (3D) visualization. This type of visualization, which enhances the real world with computer generated information, requires a display device, a computer to generate the 3D data, and a system to track the user. In addition to these requirements, however, the hardware must be properly integrated to insure correct visualization. To this end, we present components of an integrated augmented reality system consisting of a novel head-mounted projective display, a Linux-based PC, and a commercially available optical tracking system. We demonstrate the system with the visualization of anatomical airways superimposed on a human patient simulator.

Keywords: Augmented Reality, Medical Visualization, HMPD, Head-Mounted Projective Display, Human Patient Simulator.

1. INTRODUCTION

Airway management is a common practice and critical skill for paramedics. To secure the airway during CPR and ensure immediate ventilation and/or oxygenation, paramedics often perform a rapid sequence of endotracheal intubation (ETI), which consists of inserting a tube through the mouth, into the trachea, and then sealing the trachea so that all air passes through the tube.

However, there are inherent difficulties associated with ETI. In the case of severe trauma patients, emergency airway management is classified as a cause of pre-hospital (before emergency arrival at a hospital) death trauma by the American Heart Association[1]. A study by Orlando Regional Healthcare showed that out of 108 ETI patients who arrived at the Orlando Regional Medical Center emergency room from May 1 to Dec. 31, 1997, 27 had tubes that were placed mistakenly in either the esophagus or the voice box. Of the 27 patients with misplaced tubes, 13 died in the emergency room[2]. Moreover, in a 16 hospital study conducted by the National Emergency Airway Registry between August 1997 and October 1998, out of 2392 recorded ETIs, 309 complications were reported, with 132 of these difficulties resulting from intubation techniques[3]. Intubation failure rates are caused more often by a lack of training than by the choice of airway devices themselves[4].

Extensive instruction and training are required in order to ensure correct placement of the endotracheal tube within an acceptable time frame. The skills required to intubate a patient are not easily practiced, deteriorate over time, and can be costly with limited resources available. Thus, there is international concern for the need for extensive training of paramedics for pre-hospital emergency situations both in Europe and in the United States[5]. Current training methods for

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airway management procedures involve videos, printed media, classroom lectures and training on mannequins to develop the necessary skills. However, from the data presented, it appears that other efforts may be necessary to increase the rate of successful ETIs.

In an effort to improve airway management training, we present an augmented reality (AR) system that allows paramedics to practice their skills and provides them with visual feedback they could not otherwise obtain. Utilizing a human patient simulator from Medical Education Technologies, Inc. (METI) combined with three-dimensional (3D) visualization of the airway anatomy and the endotracheal tube, paramedics will be able to obtain a visual and tactile sense of proper ETI.

In the following sections, we review previous medical AR research, describe the methods used to realize the anatomical visualization for ETI, provide results of the visualization, and discuss observations made within the course of the research.

2. PREVIOUS MEDICAL AUGMENTED REALITY RESEARCH

There have been numerous AR applications developed for use in medicine. Peuchot et al. developed a system to aid surgeons in correcting scoliosis[6]. State et al. applied video and ultrasound technology to develop an AR system for ultrasound-guided biopsies of breast lesions[7]. An enhanced version of the system developed in [7] was later used by Fuchs et al. in a laparoscopic surgical application that used structured light patterns for tracking objects within the application[8].

DiGioia et al. merged CT data with real world images using a flat-paneled monitor and a half silvered mirror that was not head-mounted, tracking the head of the user to display CT data from the correct point of view[9]. As an improvement to the system presented in [9], Stetten and Chib presented a method to overlay ultrasound data that was also not head-mounted but tracked user position using an ultrasound stylus[10]. Grimson et al. presented an AR system to aid brain surgeons[11] and Edwards et al. developed a system to project features from MR and CT data in a stereo microscope to assist with visualizing complex structures during surgery[12]. A fetal visualization AR system, using a video see-through HMD, was developed by Bajura et al.[13]. There have also been efforts to use AR to overcome ambulatory difficulties associated with Parkinson's Disease[14].

Within our research group, it was suggested by Wright et al. that virtual reality could be used to teach medical practitioners about the complex motion of anatomical joints[15]. In this context, Baillot et al. created a physical model of knee motion that resulted in realistic knee joint animations at interactive speed[16]. The research in [16] lead to an augmented reality implementation of the VRDA Tool, an AR system designed to allow medical practitioners to dynamically visualize internal joint anatomy[17, 18]. The methods presented in [17] and [18] constitute a basic theoretical framework that we are further developing to create a desktop AR visualization of anatomical airways, now detailed.

3. METHOD OVERVIEW

The AR system presented integrates a head-mounted projective display (HMPD) with a Linux-based PC to visualize internal airway anatomy on a human patient simulator (HPS). The concept of the HMPD will be reviewed in Section 4. The advantages of using a HMPD in this application are the lightweight optics (8g per eye) and the high quality images obtained from projection optics as opposed to the eyepiece optics employed in conventional, optical see-through HMDs[19]. The location of the HPS, the trainee, and the endotracheal tube are obtained with a tracking system. The HPS is a mannequin with several simulated human functions, including respiration, heart beat, and eye movements. Moreover, with respect to the airway, the HPS is anatomically correct. The trainee wears the HMPD and is able to see the internal airway anatomy due to retro-reflective material that has been placed on the throat and chest of the HPS. Thus, the trainee can see the airway anatomy, see the endotracheal tube, and feel normal bodily functions while practicing an intubation. A conceptual diagram of the application setting is shown in Figure 1.

To correctly visualize the internal airway anatomy, the computer-generated airway model must be properly registered. This requires a correspondence between features on the HPS and the airway model, as well as rendering the model from the correct viewpoint. The procedure for registering the airway model assumes the use of a marker-based tracking system that is capable of tracking at least three objects and able to provide 3D location data for each object. The procedure also assumes that the tracker coordinate system is the global coordinate system for the application.

To provide correspondence between features or landmarks on the HPS and the model, we use an anatomical landmark calibration procedure. The procedure begins with placing a collection of markers, or tracking probe, on the HPS. The placement of these markers depends upon the tracker configuration. In our case, the markers were placed in a rigid configuration on the chin of the HPS and secured to a cloth mask placed on the head of the HPS, as shown in Figure 2. The cloth mask was incorporated to allow removal of the markers during other uses of the HPS.

Figure 1: Conceptual intubation of a HPS with superimposed anatomy – Courtesy of Stephen Johnson, ODALab-UCF

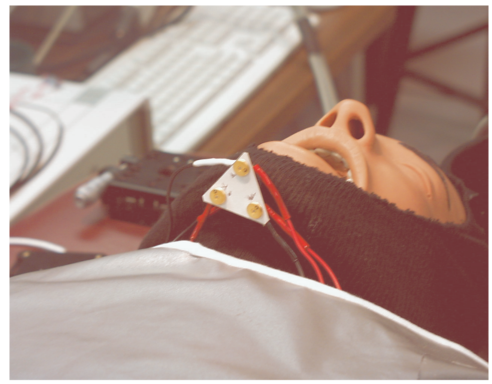

Figure 2: Tracking probe on the chin of the HPS

The local coordinate system of the tracking probe is first defined during an off-line procedure. Knowing the mask local coordinate frame (as defined by the tracking probe placed on the chin), the tracking system can determine the transformation matrix from the mask to the global frame, M_{g_m}. Inverting this matrix gives the transformation from the global frame to the mask frame, M_{m_g}. We then measure the global location of anatomical landmarks on the mandible of the HPS with a digitizing probe. Since M_{m_g} is known, we can express the landmark locations in terms of their relative positions with respect to the tracking probe placed on the mask. Furthermore, the origin of the computer-graphics airway model (which contains a mandible) is at tip of the chin. Thus, using the correspondence between the anatomical landmarks on the HPS and the corresponding points within the airway model, we determine a transformation, M_{m_c}, to specify the correct position for the computer model relative to the mask on the HPS. M_{m_c} is determined by an optimization procedure described by [17]. M_{m_c} does not change during the rendering process and only needs to be computed once.

To render the airway model from the correct viewpoint, we place a collection of markers on the HMPD. This rigid collection of markers provides the global head position and orientation of the trainee in a transformation matrix, M_{g_h}, . Using this data, we compute a viewpoint transformation from the trainee head position to the left and right eye respectively, M_{le_h} and M_{re_h}. We use the center of rotation of the eye as the eyepoint for rendering[20, 21]. Finally, for each frame we calculate the transformation from the computer model to the eyepoints, and render the airway model appropriately. The operation to transform a point in the computer-generated airway model, P_c , to a point that coincides with the HPS (with the correct viewpoint) is

$$P_{HPS} = M_{le\_h} \cdot M_{h\_g} \cdot M_{g\_m} \cdot M_{m\_c} \cdot P_c \qquad (1)$$

The endotracheal tube is also tracked using a three marker tracking probe, whose local coordinate system is defined and whose transformation is given by the tracking system. To transform a point in the computer-generated tube model to a point that coincides with the actual endotracheal tube, we replace $M_{g\_m} * M_{m\_c} * P_c$ in Equation (1) with $M_{g\_t} * M_{t\_c} * P_t$, where P_t is the point in the model of the tube, M_{t_c} is the transformation from the computer model to the real tube (calculated directly), and M_{g_t}. is the transformation from the tube to the global coordinate system. We have found that during intubation, the torsion and flexion of the trachea with respect to the intubation tube is negligible[22], thus we do not have to account for changes in the shape of the tube.

4. VISUALIZATION OF THE AIRWAY

With the exception of the HMPD, the airway visualization is realized using commercially available hardware components. The computer used for computations and stereoscopic rendering has a 1GHz AMD Thunderbird CPU running Red Hat Linux 7.2. The graphics card used is a dual-head, Asus GeForce2MX. The tracking system used is a Polaris hybrid optical tracker, capable of tracking up to three objects simultaneously. The tracking data obtained is updated at 20 Hz. The current system configuration is shown in Figure 3.

Figure: 3 The system setup, consisting of an optical tracker, desktop computer, HMPD, and curvature measurement device

The computer-generated models are displayed to the user with a Head-mounted projective display. HMPDs are a novel type of head-mounted display. They differ from conventional HMDs in that the images are formed using projection optics. Similar to a LCD projector, a HMPD projects computer-generated images into the environment. However, a HMPD uses a retro-reflective screen instead of a diffusing projection screen. In a HMPD, the image from the LCD is projected to a beam splitter, directed by the beam splitter toward the retro-reflective screen, reflected back in the same direction by the retro-reflective screen, and passes through the beam splitter to the eye of the user. The concept and design of a HMPD as well as a discussion of engineering and perceptual issues can be found in[23].

The HMPD used in this application has a diagonal, binocular field of view of 52 degrees. Retro-reflective material is placed on the neck and chest of the HPS to see the computer models. The HMPD displays images at a resolution of 640x480 and the models are rendered at a distance of 1m from the eyepoints.

The application is currently implemented in Open Inventor 2.0 and Open Performer 2.4. We initially chose Open Inventor because of its low-level functionality and made an additional Open Performer version to take advantage of virtual environment optimizations that are built into the API. The preliminary airway model, shown in Figure 4, is 665 kB with 1.4 MB of texture and transparency enabled. The endotracheal tube model is 80 kB. But, the preliminary model of the airway is not anatomically accurate. To overcome this issue, we have obtained an accurate computer graphics model of the airway through collaborators at Columbia University. The model was created with data taken from the Visible Human project and segmented by medical researchers. A view of the airway visualization shown from behind the HMPD is shown in Figure 6.

5. OBSERVATIONS AND FUTURE WORK

In the course of this research, we made several observations. The first was that the quality and speed of rendering was excellent, considering the consumer-level pricing of the system. Moreover, we were able to use an operating system and software, which, aside from the expenditure of time, was free and available to the general public. These two events lead us to believe that high-fidelity desktop stereoscopic rendering is possible. We also observed that a side benefit of using a HMPD is that some of the occlusion effects are preserved[23]. Specifically, objects passing between the user and the retro-reflective material occlude the computer-generated objects, as opposed to other see-through head-mounted displays.

Figure 4: Preliminary Open Inventor model of the internal anatomy of the airway

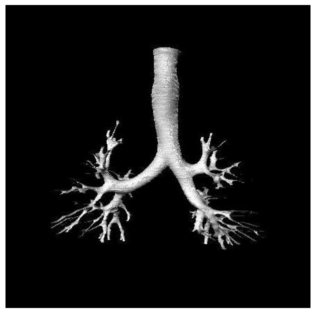

Figure 5: Open Inventor airway model from visible human

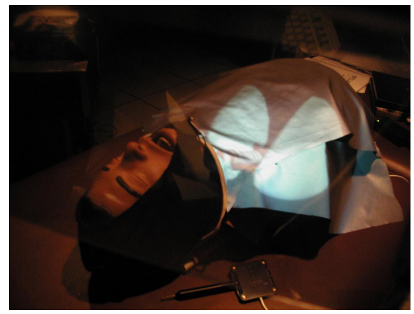

Figure 6: Visualization of the airway anatomy using the model shown in Fig. 4.

In addition to the observations made, we gained valuable knowledge. We learned that there are substantial amounts of time and resourcefulness required for AR development on the Linux PC platform. We had to overcome hardware driver incompatibility issues. Specifically, to interface with the curvature measurement device and the tracking system, we had to write a Linux driver and API, respectively. Furthermore, the display parameters had to be adjusted to specify the resolution of the system, the color depth, the use of OpenGL rendering, and the locations of the stereoscopic windows within the frame buffer. However, these issues will likely improve as more Linux development occurs.

As part of future research, we plan to make various enhancements to the airway management training system. Visual comparison of the two airway models shown in Figures 4 and 5 produce a strong preference for the realistic airway model in Figure 5. However, this model is very large (51 MB) and complex (many thousands of polygons) and dynamic simulation using this model will be computationally expensive. A solution that will be implemented in future versions of the system is significant decimation of the airway model. Also, we plan to improve the HMPD illumination via enhanced materials, with the end goal of full daylight visualization capability. In addition, the HMPD will become wireless, adding to the overall deployability of the system. Finally, we shall begin perception and performance studies with combat medics to gauge the effectiveness of AR airway management training.

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