DEVELOPMENT OF A TRAINING TOOL FOR ENDOTRACHEAL INTUBATION: DISTRIBUTED AUGMENTED REALITY

Jannick ROLLAND[a,b,c], Larry DAVIS[b], Felix HAMZA-LUP[b], Jason DALY[c], Yonggang HA[a], Glenn MARTIN[c], Jack NORFLEET[d], Richard THUMANN,[h] and Celina IMIELINSKA[e,f,g]

University of Central Florida and Research Park, Orlando FL
[a]ODALab at School of Optics/CREOL,
[b]School of Electrical Engineering and Computer Science,
[c]Institute of Simulation and Training, [d]STRICOM

Columbia University College of Physicians and Surgeons,
[e]Office of Scholarly Resources, [f]Department of Medical Informatics,
[g]Department of Computer Science, Columbia University, New York, NY

[h]Datascope Corp, Mahwah, NJ

Abstract. The authors introduce a tool referred to as the Ultimate Intubation Head (UIH) to train medical practitioners' hand-eye coordination in performing endotracheal intubation with the help of augmented reality methods. In this paper we describe the integration of a deployable UIH and present methods for augmented reality registration of real and virtual anatomical models. The assessment of the 52 degrees field of view optics of the custom-designed and built head-mounted display is less than 1.5 arc minutes in the amount of blur and astigmatism, the two limiting optical aberrations. Distortion is less than 2.5%. Preliminary results of the registration of a physical phantom mandible on its virtual counterpart yields less than 3mm rms. in registration. Finally we describe an approach to distributed visualization where a given training procedure may be visualized and shared at various remote locations. Basic assessments of delays within two scenarios of data distribution were conducted and reported.

1. Introduction

The development of the Ultimate Intubation Head (UIH), a training tool for endotracheal intubation (ETI) using 3D augmented reality (AR), is aimed at medical students, residents, physician assistants, pre-hospital care personnel, nurse-anesthetists, experienced physicians and any medical personnel who need to perform this common but critical procedure in a safe and rapid sequence.

Training a wide range of clinicians in safely securing the airway during cardiopulmonary resuscitation (CPR) and ensuring immediate ventilation and/or oxygenation is critical for a number of reasons. First, ETI, which consists of inserting an endotracheal tube through the mouth into the trachea and then sealing the trachea so that all air passes through the tube, is often a lifesaving procedure. Second, the need for ETI can occur in many places, in and out of the hospital. Perhaps the most important reason for training clinicians in ETI, however, is the inherent difficulty associated with the procedure.

In the case of severe trauma patients, emergency airway management is classified as a cause of pre-hospital death trauma by the American Heart Association [1]. 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 procedures [2]. Many anesthesiologists believe that the most common reason for failure of intubation is the inability to visualize the vocal cords. In fact, failed intubation is one of the leading causes of anesthesia-related morbidity and mortality [3]. Thus, there is international concern for the need to extensively train paramedics in pre-hospital emergency situations [4].

Current teaching methods lack flexibility in more than one sense. The most widely used model is a plastic or latex mannequin commonly used to teach Advanced Life Support (ACLS) techniques, including airway management. The neck and oropharynx are usually difficult to manipulate without inadvertently "breaking" the model's teeth or "dislocating" the cervical spine, because of the awkward hand motions required.

A relatively recent development is the Human Patient Simulator (HPS), a mannequin-based simulator. The HPS is similar to the existing ACLS models, but the neck and airway are often more flexible and lifelike, and can be made to deform and relax to simulate real scenarios. The HPS can simulate heart and lung sounds, provide palpable pulses and realistic chest movement. The simulator is interactive, but requires real-time programming and feedback from an instructor [5].

2. Purpose

We propose an interactive tool for training that does not involve programming or instructor feedback. Instead, by resorting to AR visualization, an immediate visual assessment can be made as to whether an intubation procedure was correctly performed. The AR visualization can be turned on at any step of the procedure when faults are detected and feedback is required. The HPS is at the base of the development of the training tool. We are in the process of solving the technical challenge to integrate 3D segmented models from the Visible Human in close collaboration with Columbia University [6].

In this paper we describe the integration of a deployable UIH. We present methods for AR visualization and registration of real and virtual anatomical models. Finally, an implementation of distributed visualization where a given training procedure can be visualized at various remote locations is described.

3. Methods and Results

3.1 The Ultimate Intubation Head (UIH)

In an effort to improve airway management training, the UIH system illustrated in Fig. 1a is being developed. The system will allow paramedics to practice their skills and provide them with the visual feedback they could not otherwise obtain.

Utilizing a HPS from Medical Education Technologies, Inc. (METI) combined with 3D AR visualization of the airway anatomy and the endotracheal tube, paramedics will be able to obtain a visual and tactile sense of proper ETI. Intubation on the HPS is shown in Fig. 1b. The location of the HPS, the trainee, and the endotracheal tube are tracked during the visualization.

The AR system integrates a head-mounted projective display (HMPD) and an optical tracker with a Linux-based PC to visualize internal airway anatomy optically superimposed on a HPS. 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 CPU running Red Hat Linux 7.2 OS.

The locations of the user, the HPS, and the endotracheal tube are tracked using a Polaris^{TM} hybrid optical tracker from Northern Digital Inc. and custom designed probes. The tracker maximum data rate is 115kBaud through an RS-232 interface having a maximum update rate of 60Hz. Based on a total of three custom tracking probes, the first on the HMPD, the second on the chin of the HPS to compute its location, and the third on the intubation tube, the tracking data obtained is currently updated at 20 Hz. The tracker working volume is a cone with the height of about 1.5 meters and a base radius of 0.5 m.

Fig.1 (a) Illustration of the UIH for training paramedics on endotracheal intubation, Graphics by Steve Johnson -ODALab. **(b)** The system setup, consisting of a HPS dressed with retroreflective material, an optical Polaris tracker, a desktop computer, a HMPD worn by a trainee, and the intubation tools.

3.2 *See-Through Head-Mounted Display*

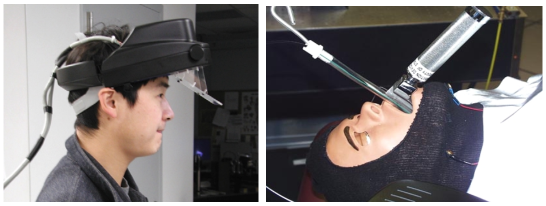

Fig. 2 (a) The head-mounted projective display prototype. **(b)** Integration of retroreflective material as clothing to the HPS and endotracheal tube with curvature measurement device and intubation tool.

HMPDs are a novel type of head-mounted displays [7-8]. They differ from conventional head-mounted displays in that the images are formed using projection optics [9]. Similar to a LCD projector, a HMPD projects computer-generated images into the environment. Contrary to conventional projection systems, a HMPD (shown in Fig.2a) uses a retro-reflective screen instead of a diffusing projection screen. For each eye, an image from the LCD is projected towards a beam splitter that directs the image towards the retro-reflective screen. The light is reflected back by the retro-reflective screen, and passes through the beam splitter to reach the eye of the user. The advantages of using a HMPD as opposed to a conventional eyepiece HMD, are the lightweight optics of 8g per eye and the high quality images obtained from projection optics as opposed to eyepiece optics. A discussion of engineering and perceptual issues and the assessment of the optics in visual space can be found in [10] and [16], respectively.

The HMPD has a diagonal, binocular field of view of 52 degrees, and for the UIH, retro-reflective material is placed on the neck and chest of the HPS as shown in Fig. 1b and 2b. The retroreflective clothing is necessary on the HPS to see the computer models superimposed on the HPS from the HMPD. The HMPD currently displays images at a resolution of 640x480 and the models are rendered at a distance of 1m from the user.

3.3 *Anatomically Correct Models for AR: A Challenge*

With respect to the airway, the HPS is anatomically correct. The trainee wears the HMPD and is able to see graphic models of the internal airway anatomy accurately superimposed on the HPS as illustrated in Fig. 1a. Ideally and ultimately, the training tool will utilize virtual 3D models of anatomy that correspond exactly to the HPS on which the procedure is performed. The models will also include the capability to deform or add tracheal structures to create difficult intubation events. Such matching between the real and virtual models is critical for the accuracy of registration.

Furthermore, for the UIH, a 3D model of the mandible in correct relation to the trachea will prove to be useful in facilitating the registration of the real and virtual models since we can most easily measure the position of the mandible at all times. Once the head is correctly positioned for intubation, we anticipate little motion of the trachea with respect to the mandible. The trachea will then be in correct relationship with respect to the mandible, and the elongation as well as the motion of the trachea during intubation can be modeled. Finally, the integration of a physiological model of the breathing lungs will complete the first requirements for the UIH.

As we started this project in the Spring 2001, having no access to segmented 3D anatomical models of the trachea or lungs, we started by creating a simple 3D anatomical model of the trachea and lungs from 2D models and anatomical statistics. The first model is shown in Fig. 3a.

We are currently working towards integrating 3D anatomical models segmented from the male Visible Human data sets [12][13]. The first challenge in using these models is their large sizes (295,276 polygons for the mandible and 1,063,178 polygons for the trachea and mandible together). Based on methods developed for registration of internal anatomy on the HPS, we expanded the 3D models to include the mandible in correct anatomical relationship with the trachea. 3D visualizations of the hand-segmented trachea and mandible from the Visible Human male data sets, generated for this project, are shown in Fig. 3b-c. Interestingly, the understanding of the 3D spatial relationships between the anatomical structures, e.g. mandible and trachea, is crucial for planning and understanding the virtual endotracheal intubation procedure as well.

Fig. 3 (a) Open Inventor created model of the internal anatomy of the airway. (b-c) 3D visualization of bronchial tree. 3D relationship between the trachea and mandible from the Visible Human Male dataset using 3D Vesalius^{TM} Visualizer. Two different viewpoints are

Future work will also include segmentation of patient specific data sets from CT and MR images to create patient-specific visualizations and to perform a study of the variation of human anatomy relevant to this procedure.

3.4 Dynamic Registration

The overall approach includes a calibration method and a dynamic superimposition method. Both methods assume the use of a marker based tracking system. The procedures further assume the use of a stereoscopic display device with markers attached to it for determining the location and orientation of the head of the user. A description of these optimization-based methods for calibration and superimposition are found in [14][15].

We choose to develop our applications using the Virtual Environment Software Sandbox (VESS). VESS is a freely available library (http://vess.ist.ucf.edu) developed by the UCF Institute for Simulation and Training, which runs on top of OpenGL Performer.

The methods were implemented and tested using first a simple planar head-tracking probe facing the tracker. The head position was known within 0.35mm in positional accuracy and precision, and 0.6 degree in rotational accuracy. A single view capture behind the HMPD is shown in Fig. 4.

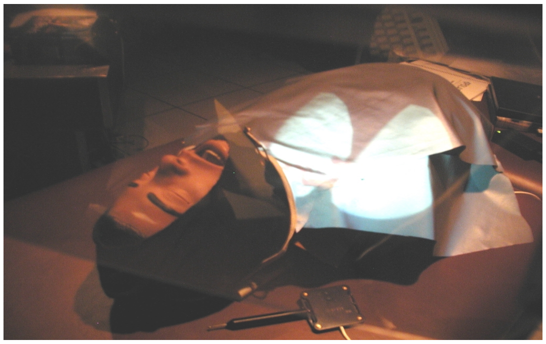

Fig. 4 In a first implementation of the methods, an approximate model of the trachea and the lungs shown in Fig. 3a were employed to demonstrate the optical superimposition.

While the implementation allows us to get a subjective assessment of the dynamic superimposition in 3D on the HPS, rigorous assessments may also be obtained by conducting a separate experiment that eliminates the challenges we still need to overcome for accurately scaling the anatomical models to the HPS.

Fig. 5 Physical phantom of the virtual jaw model.

Based on the high-resolution anatomical models from the Visible Human data sets, a physical phantom of the mandible from the male Visible Human was fabricated using Rapid Prototyping (RP). RP is the technology of producing physical models, layer by layer, directly from a 3D CAD-model. For RP, a Stereo Lithography Apparatus (SLA) builds the model layer by layer out of a liquid photosensitive polymer, solidifying each layer through the use of a laser. Such physical phantoms allow an exact correspondence between the real and virtual model. After fabrication, a procedure was established to coat the physical model with retroreflective powder donated by 3M Inc. The resulting phantom is shown in Fig.5.

The painted mandible was positioned on the table, in the same orientation of the HPS mandible. Next, simple anatomical landmarks were selected as “markers” on the phantom. The methods for AR described in [14][15] were then implemented and applied. Visual assessment yields an estimate of registration within 3mm rms error. To quantitatively assess the registration, four landmarks were digitized on the real mandible, with known corresponding landmarks on the virtual model. A set of 10 camera views, acquired within +/- 20 degrees with respect to the tracker, were simultaneously captured of the real and the virtual mandible. The acquisition camera was located at the eyepoint of the HMPD. The transformation between the plane of the camera and the 3D space was previously established according to fundamentals of computer vision camera calibration. Preliminary results yield an rms error in registration of less than 3mm. We are in the process of collecting extensive data on registration and results will be consequently published.

3.5 Distributed Visualization

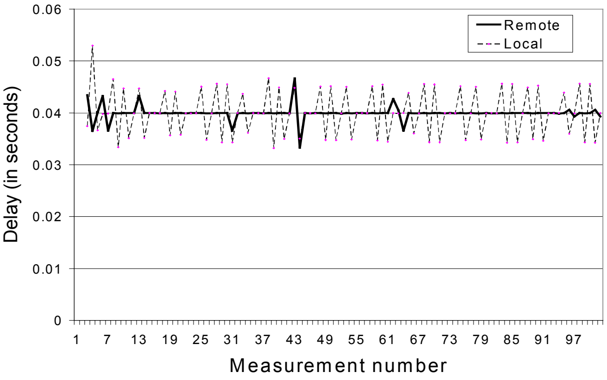

Fig. 6 System delays for the remote and local configurations

An important function of the UIH is its capability for operating across collaborative distributed virtual environments. Such environments will transform the computer networks into navigable and populated 3D spaces. A realistic approach is to augment the distributed environments with computer generated 3D images. Furthermore, by providing an infrastructure for the distribution of these objects inside interested communities of users, the communication capacity will exponentially increase, adding new dimensions to collaborative environments.

DARE (Distributed Augmented Reality Environment) is a computer supported collaborative environment under development at ODALab (UCF). Based on augmented reality built on a distributed system infrastructure, this system offers distributed access to electronic data and enhanced three-dimensional visualization. DARE will allow real-time remote demonstrations in different fields and disciplines.

The system will be first tested for remote medical procedure demonstration, therefore the real time constraints are stringent. In support of this interactive speed system development we have performed preliminary tests using C/C++.

The system consists of the Polaris tracking system, a Client machine (i.e. a 1.7GHz PC running Linux RedHat 7.2 OS with 1GB of RAM), and a Server machine (i.e. a 1 GHz PC running RedHat 7.2 OS with 512MB of RAM linked to the optical tracking system).
For data distribution, an implementation of the Client-Server architecture using C sockets was first tested. Two kinds of tests were performed and graphed in Fig.6 ; a) **local tests**: the server and the client processes are running on the same machine and b) **remote tests**: the server process is running on the server machine while the client process is running on the client machine

Results show that an average delay of 40ms occurs in both the remote and the local test on a 0.2 ms average round trip delay network connection without Quality of Service. Both tests suffer from a minimum of 16ms in tracking delays. The fact that the average delays are the same for the local and remote tests prove that the application is suited for real-time distribution which constitute a milestone in our development of a distributed AR environment.

4 Conclusion

In this paper we presented the integration of a deployable UIH. The system comprises an innovative head-mounted display with ultra compact and light weight optics and custom designed tracking probes. The optics is shown to perform at basically human visual acuity. Moreover, the system uses an HPS as well as a deployable tracker. Methods for assessment of the AR registration are presented using high-resolution physical phantoms fabricated using rapid prototyping. Such approach allows rigorous assessment methods. Registration within 3mm rms. error has been achieved. Finally, we presented results to show that the application can be run across distributed platforms.

Future work will include creating different scenarios for training and qualitatively measuring the process for cost-effectiveness, safety, enjoyment of using the system, level of physical comfort, and reliability. However, before such initiative is started, we must overcome the current challenges we are facing with anatomical models (i.e. scale, complexity, and patient specific). Various approaches are under investigation.

5 Acknowledgements

We thank Seth Frolich for creating the first model of the trachea and lungs shown in Fig.3a, Catherine Meyer for her research into difficult intubation procedures, and Kurt Lin for his stimulating discussions about this project. We also thank Karen Kerner for stimulating discussions on clinical intubation procedures. We also thank Jay Anton from METI Corporation for stimulating discussions about the UIH and his loaning of the HPS. This work is supported by the U.S. Army Simulation, Training, and Instrumentation Command (STRICOM), the Florida Education Fund, the NSF/EIA-99-86051 and NSF/ITR IIS-00-82016, and NLM contracts 1-R29-LM06322-01A1 and the "VHP Segmentation and Registration Toolkit" - NLM99-103/DJH.

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