Exploring Mixed Reality in Specialized Surgical Environments

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Abstract
Recent technology advances in both Virtual Reality and Augmented Reality are creating an opportunity for a paradigm shift in the design of human-computer interaction systems. Delving into the Reality-Virtuality Continuum, we find Mixed Reality - systems designed to augment the physical world with virtual entities that embody characteristics of real world objects. In the medical field, Mixed Reality systems can overlay real-time and spatially accurate results onto a patient's body without the need for external screens. The complexity of these systems previously required specialized prototypes, but newly available commercial products like the Microsoft HoloLens make the technology more available. Through a combination of literature review, expert analysis, and prototyping we explore the use of Mixed Reality in healthcare. From the experience of prototyping Patiently and HoloSim, two applications for augmenting medical training, we outline considerations for the future design and development of virtual interfaces grounded in reality.

Author Keywords
Mixed Reality; HoloLens; Surgery; Augmented Reality

ACM Classification Keywords
H.5.m [Information interfaces and presentation (e.g., HCI)]; H.5.1 [Multimedia Information Systems]: Artificial, augmented, and virtual realities; J.3 [Life and medical Sciences]: Health

Introduction

Virtual reality transports the user into a new realm, in which interaction is not governed by the physical laws we experience every day. This technology allows us to peer inside computation, past flat displays, into the 'mathematical wonderland' described by Ivan Sutherland [18]. Most virtual reality devices made available over the years focused on visual and auditory experiences, however as the technology has continued to evolve, the devices began to focus more on interaction, allowing humans to interface with computation naturally with their hands. Augmented reality systems were born from the desire to provide the equivalently visceral experience of virtual reality, but by doing so within the context of the real-world. This is accomplished by understanding the real world and adding a layer of virtual information on to it which aims to augment instead of recreate the real environment through virtual mimicry. This augmentation is often characterized by an additional virtual context connected with real-world objects or by having the user engage with a virtual object given the context or real world physical laws [8].

Although the concept of VR and AR is not new, recent developments in this technology have paved the way forward creating a different kind of augmented reality, commonly referred to as Mixed Reality (MR). MR allows for the seamless integration of virtual objects into the real world. Deeply grounded in physical reality, these computer-generated entities behave and react in accordance with user actions as though they themselves were real world objects. These objects blend in with a user's own reality, enabling them to integrate with and to anchor themselves onto real objects, mixing the virtual with the physical.

Developing MR environments is a difficult endeavor and presents complex engineering challenges for both software and hardware. This is frequently due to the diverse range of technologies required to implement a system capable of accomplishing everything needed for an MR application which does not encumber its user. As discussed by Azuma [1] and more recently by Billinghurt [4], some of the key problems these devices have to solve in order to be successful are: (1) tracking user position and head orientation ("sensing"); (2) mapping the environment ("registration"); (3) mixing virtual objects with real ones while preserving important visual cues; (4) displaying the virtual data in real-time. Nevertheless, it has recently become easier to develop and build MR prototypes thanks to a new device released by Microsoft, the *HoloLens*.[1] The Microsoft Hololens is a completely self-contained wearable MR device. It consists of a transparent head-mounted display that uses an array of sensors and cameras to scan the wearer's environment and render virtual objects (which Microsoft calls 'holograms') into the user's setting. The wearer can freely move and look around their physical environment, and any virtual content being displayed will react as though they were real world objects. The wearer can also interact with the virtual environment by looking at an element and performing specific gestures with their hands or using voice commands. The HoloLens, besides tackling the problems of real world registration and user sensing, also revolves around a developer-based ecosystem, providing development kits and an application-deployment store, key features to reduce cost and lead to a more rapid evolution [16].

We are interested in exploring how MR applications made possible by HoloLens can be further developed and used in the health arena. Given the depth of possibilities for MR in the medical domain and the versatility provided by Hololens, we partnered with the surgery department at our local university hospital to perform analysis of how Mixed

[1] https://www.microsoft.com/microsoft-hololens/en-us

Reality applications could be designed to help train surgeons. In this paper we explore the design space through expert analysis in collaboration with two surgeons, and reflect on the lessons learned from the development of two prototype applications for augmenting medical training mannequins and for teaching human anatomy. We then elucidate the design requirements of building such a system.

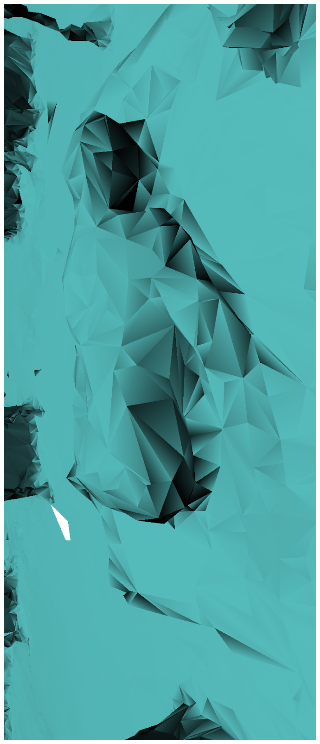

Figure 1: 3D mesh of a mannequin on a table as generated by HoloLens' spatial-mapping algorithm and rendered through its web interface.

Related Work

The interest for augmenting the real-world to provide useful virtual information within the context of our senses is not new. AR has been applied to provide a user with in-place instructions on how to maintain equipment [7], an interface to communicate spatial information for robot path planning [13], and as a virtual board for annotations ("attaching windows onto specific locations in the world") [6]. AR is also seen often as an alluring visualization tool for medical training and surgery. In 2004, Sielhorst et al. surveyed papers that applied AR to visualization of ultrasound, visualization of CT scans, simulation for training, surgery, rehabilitation, and education [17]. Moreover, prior work has combined a real-time incremental volume visualization algorithm with a video-see-through head-mounted display to render ultrasound imagery on the patient body [2]. Using a similar setup, other researchers have managed to build a collaborative system focused on augmenting ultrasound-guided biopsy of the breast [12].

Although these prototypes showed that AR has a "promising potential to be used in medical applications" [3], we concur with Sielhorst [17] that there was still a need to overcome technological limitations, having specific interest in the development of smaller and lighter head-worn displays with larger field of view and improved resolutions. Most of these systems used specialized hardware and cumbersome devices [3]. This fact combined with how the systems were built to demonstrate feasibility, contributed to why most of the discussed work did not develop widespread adoption and usage. For the medical applications discussed, none reached actual usage in the operating room [10]. This can be partially attributed to the lack of evaluation performed with target end-users[19], demonstrating that the clinical need for these systems was met in a successful and useful manner. The focus must begin to extend beyond simply developing new methods and technology, but also on the human factors and suitability of design pertaining to the domains these systems hope to be deployed into.

We believe that HoloLens and other consumer-facing MR technologies will help in taking MR out of the laboratory and in to the wild. We look forward to seeing these technologies contributing to a growing body of research, evaluating and validating the ecological usefulness of novel visualization and interaction systems.

Mixed reality in surgery

In order to better understand the design space of MR in the health space, and in particular within surgery, we employed expert analysis, working with two surgeons (S1: senior attending surgeon, and S2: surgery fellow) with the goal of surveying the need for MR from the physician's perspective and experience. Analysis was based on a series of interviews and brainstorming sessions over the course of 6 months. After mapping possible applications and their requirements, we embarked in a comparative research exercise looking for previous similar works. We integrated results from our expert analysis with existing literature, outlining prior failures and success stories of VR and AR deployments within surgery and medicine. The remainder of this section outlines a division of the design space devised by our experts: pre-clinical, clinical, and post-operative.

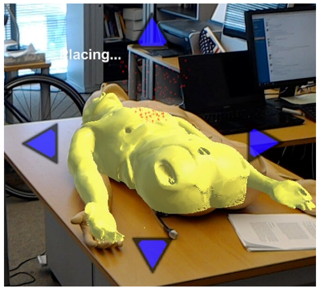

Figure 2: HoloSim first iteration: The user had to place a virtual version of the mannequin overlaying with the real one by gazing around and using floating markers to move the virtual representation of the mannequin around as to align it with the real one.

Figure 3: HoloSim second iteration: The user only had to look at the Vuforia™ marker on top of the virtual mannequin to calibrate the app.

Pre-clinical utilities
Our expert analysis first assessed how MR can be exploited before interactions with real patients. This space is mainly characterized by training and simulation.

Medical Student Teaching and Anatomy – Teaching medical students was one of the main applications where MR promised to have impact. An example that arose from our investigation was augmenting dissection. In this setting an MR application could provide a virtual 1:1 real-world scaled model of the body, which would teach students the size and location of individual organs with accurate context. This approach can extend to blend a perfect 3D model with a real body, providing richer anatomy training through MR augmentation of a cadaver.

Augmented simulation mannequins – Simulation-based learning is critical to high-stake industries such as health care. It promotes development of experience before performance on real patients. Learners can then be taught and assessed without risk to patients [11]. MR mannequins can provide additional feedback to increase the realism of a simulation through addition of bleeding, vomiting or noises. Moreover, students benefit from a virtual 3D view of the inside of the mannequin to help build spatial understanding of the body during particular situations. Since MR devices, such as the HoloLens, track the wearer's position and gaze, teachers can assess a student's performance based on attention and behavior.

Surgical guidance to aid resident training – Attending surgeons can augment the environment around a patient's body in order to visually and spatially guide residents in terms of *where* to operate. Using a system similar to [5], the guiding surgeons might not even need to be physically co-located nor using MR directly. We envision remote surgeons using teleconferencing clients (e.g.: Skype[2]) to share a view from the resident's point-of-view and mark the body accordingly.

Clinical utilities
When surgeons are operating, MR can help perform better operations, collecting records of the procedures performed or providing better real-time visualizations.

Remote surgical guidance – Similar to remote teaching with medical residents, remotely located surgeons that have a specialization in certain types of operations can guide novice surgeons during an operation at another location. Guidance would be achieved through annotations on the shared 3D space, allowing the physically present surgeon to focus, operate, and act based on the locations marked in the virtual space. We envision this interaction to be supported by a remote VR system connected to a local MR environment (e.g. using HoloLens).

Surgery recording –MR devices, more specifically the HoloLens, are built around depth-sensing technologies and cameras. These resources could be used to record a surgery from the perspective of the surgeon, creating a 3D video of the operation that could be later used for teaching or evaluation. This could also be used in training to guide a novice surgeon, *following the example* previously recorded by a experienced surgeon.

Real-time imaging visualization – In the literature, one of the most explored applications of augmented reality is an in-place display for imaging scans. The source can be sonograms [12, 9], CT scans, MRI, or the infrared light reflected by indocyanine green [15]. MR would allow the surgeon to focus on the patient with the images directly

[2]https://www.skype.com

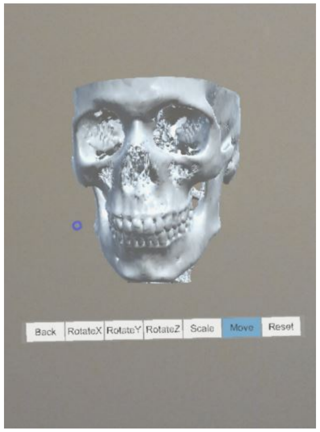

Figure 4: Patiently displaying a CT scan with anatomic precision along with controllers to change its orientation, size and location.

Figure 5: Patiently displaying the muscular system. The virtual body can be scaled to match a real human-body, giving students a clear, anatomically correct view of individual muscles

displayed onto his/her body, avoiding the artificial interaction with a separate display. Ultimately this could help support better visualization of important structures - such as organs, vessels or tumors - or enable a greater accuracy in dissection or resection.

Post-operative
Finally, MR can also be used after specific surgical procedures. We envision MR to support remote patient-centered care based on games that make use of the patient's spaces (e.g.: living room) to stimulate, guide, and monitor them through exercises. For instance, a MR game could instruct the patient to move to a nearby wall in order to perform wall squats, or it could mark the floor with a route to be followed, exactly as specified by the clinician. Other examples include breathing exercise games and specific rehab routines following orthopedic or spine operations.

Prototyping Mixed Reality Applications

Based on our experiences with MR we believe that having accurate mapping of the real-world while being able to anchor virtual objects to it are the most important features of MR that find great appreciation in medical applications. In particular MR can provide the real-world as a frame of reference to virtual objects. Virtual objects benefit from a cognitive sense of volume and depth because they share context with real objects from all possible angles. This allows for in-place visualizations to become more real since synthetic imagery can be anchored to physical objects.

In order to evaluate the extent to which MR and HoloLens implement these two features, and in order to suggest possible solutions to the limitations of this first generation device, we focused two different applications: (1) HoloSim and (2) Patiently.

HoloSim and Patiently
HoloSim was our first experiment and aimed to extend a real and physically present surgery simulator mannequin to provide more realistic situations to students interacting with it (e.g: skin bleeding or the patient vomiting during intubation). The core motivation for its development was the nature of this application: interaction in a mixed environment of real and virtual, which heavily relies on the headset's abilities to track the room and sense the user's head position and orientation.

Patiently, on the other hand, focused on the natural display of 3D data, such as scans of the skeleton and the muscular system (Fig. 5) from the BodyParts3D database [14] or CT scans of the user, after properly converted to a format accepted by Unity3D[3]. Its use cases cover medical students and patients alike to learn about the pathology than can affect the human body (Fig. 6), through interactive 3D visualizations. Users can explore different bodily systems, and see the course of various diseases, while having the real-world as a context for these holograms.

These two applications, besides solving problems inherent to simulation and learning, were developed to assess HoloLens's support for important MR features pointed out in the literature [4, 1, 16]: (1) portability, (2) accurate tracking of user position and head orientation (sensing), (3) fine-grained mapping of the real-world (registration), (4) stable reproduction of the virtual imagery, (5) non-delayed rendering, (6) a developer based ecosystem.

HoloLens and its developer based ecosystem
From the development perspective, a HoloLens application is nothing but a game that has access to a mesh representation of the real world. The inconvenience of sensing

[3] https://unity3d.com

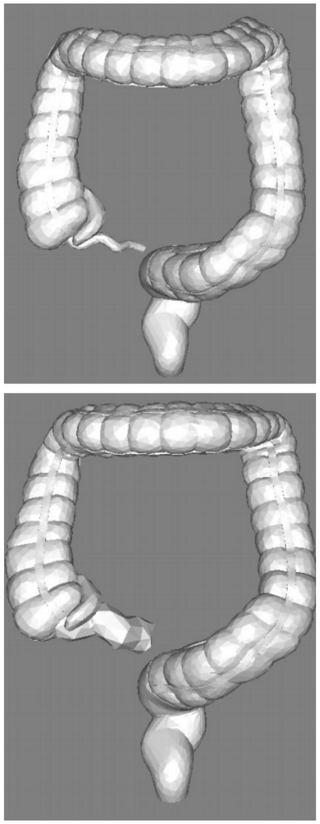

Figure 6: Patiently displaying a healthy appendix (top) and a diseased appendix (bottom)

user movement and timely refreshing the display is totally transparent to the developer. The developer can then focus on creating a 3D experience, knowing that a virtual representation of the room will be provided. HoloLens supports development both with a game-engine Unity3D and directly through Direct-X calls. In addition, to aid rapid development on Unity3D, Microsoft provides a dedicated toolkit.[4] Both Patiently and HoloSim were developed using Unity3D, almost totally agnostic to the MR nature of the application. In agreement with Rankin et al. [16], we believe that this development ecosystem can lead to a more rapid evolution while decreasing costs at many levels.

Registration

HoloLens's generates a real-time 3D mapping of the real environment without the need for calibration or fiducials. Applications can then use this 3D mesh representation of the real world to create the illusion that virtual objects are sitting on top of real tables or occluded by large real objects. Nonetheless, the 3D mesh does not provide semantic understanding of objects in a room. As seen in Fig. 1, the mesh merges the mannequin with the table, not having knowledge of their distinction.

The latter was an essential feature for the proper functioning of HoloSim since it aimed at displaying virtual information on it. To overcome this constraint, we first introduced a calibration step, requiring the user to place a virtual version of the mannequin on top of the real one (Fig. 2). To release users from this calibration burden, we then proceeded to integrate the application with Vuforia's SDK [5] for augmented reality. This required the user to look at the mannequin once, as a calibration step (Fig. 4). A third iteration might rely on visual cues aided by the 3D mesh. In short, albeit having a general purpose registration system, there is still a need for further development from the app design perspective.

[4]https://github.com/Microsoft/HoloToolkit-Unity

[5]https://www.vuforia.com/

Sensing, stable reproduction of the virtual imagery and non-delayed rendering

Both applications relied heavily on HoloLen's inherent capabilities for sensing the user's head orientation and movement, while timely selecting and displaying the right part of the 3D scene. The stable reproduction of virtual imagery only becomes a concern to developers when the application uses more processing power than is available for rendering 60 frames per second. Both HoloSim's and Patiently's 3D models had to be simplified and use fast shaders to achieve this desired performance.

Conclusion

In this paper we started to explore the opportunities and the feasibility to exploit latest advances in Mixed Reality to advance surgery. With the help of expert surgeons we discussed possible applications of MR in the pre-clinical, clinical and post-opearative phases. While in our future work we want to explore more of those scenarios, in order to evaluate HoloLens, we focused on two of them and developed HoloSim, a prototype MR mannequin to augment surgical training, and Patiently, a prototype MR application focused on teaching anatomy. While developing these applications, we assessed HoloLens as a prototyping environment for MR applications and established that current HoloLens hardware is able to roughly support these applications, requiring however extra processing power and development. Nonetheless, through these initial experiences with HoloLens in surgery we believe that MR can be an effective tool to augment and enrich surgical experiences in the near future and HoloLens opens up an unprecedented opportunity for user-centered research on Mixed Reality.

References

[1] Ronald T Azuma. 1997. A survey of augmented reality. *Presence: Teleoperators and virtual environments* 6, 4 (1997), 355–385.

[2] Michael Bajura, Henry Fuchs, and Ryutarou Ohbuchi. Merging Virtual Objects with the Real World: Seeing Ultrasound Imagery Within the Patient. In *Proceedings SIGGRAPH '92, the 19th Annual Conference on Computer Graphics and Interactive Techniques* (1992). ACM, 203–210.

[3] Reinhold Behringer, Johannes Christian, Andreas Holzinger, and Steve Wilkinson. Some usability issues of augmented and mixed reality for e-health applications in the medical domain. In *Symposium of the Austrian HCI and Usability Engineering Group* (2007). Springer, 255–266.

[4] Mark Billinghurst, Adrian Clark, and Gun Lee. 2015. A survey of augmented reality. *Foundations and Trends in Human-Computer Interaction* 8, 2-3 (2015), 73–272.

[5] Henry Chen, Austin S Lee, Mark Swift, and John C Tang. 2015. 3D Collaboration Method over HoloLens and Skype End Points. In *Proceedings of the 3rd International Workshop on Immersive Media Experiences*. ACM, 27–30.

[6] Steven Feiner, Blair MacIntyre, Marcus Haupt, and Eliot Solomon. 1993b. Windows on the world: 2D windows for 3D augmented reality. In *Proceedings of UIST'93, the 6th annual ACM symposium on User interface software and technology*. ACM, 145–155.

[7] Steven Feiner, Blair Macintyre, and Dorée Seligmann. 1993a. Knowledge-based Augmented Reality. *Commun. ACM* 36, 7 (July 1993), 53–62.

[8] Denis Kalkofen, Erick Mendez, and Dieter Schmalstieg. 2009. Comprehensible visualization for augmented reality. *IEEE transactions on visualization and computer graphics* 15, 2 (2009), 193–204.

[9] Xin Kang, Mahdi Azizian, Emmanuel Wilson, Kyle Wu, Aaron D Martin, Timothy D Kane, Craig A Peters, Kevin Cleary, and Raj Shekhar. 2014. Stereoscopic augmented reality for laparoscopic surgery. *Surgical endoscopy* 28, 7 (2014), 2227–2235.

[10] Marta Kersten-Oertel, Pierre Jannin, and D Louis Collins. 2012. DVV: a taxonomy for mixed reality visualization in image guided surgery. *IEEE Transactions on Visualization and Computer Graphics* 18, 2 (2012), 332–352.

[11] Fatimah Lateef and others. 2010. Simulation-based learning: Just like the real thing. *Journal of emergencies, trauma, and shock* 3, 4 (2010), 348.

[12] Mark A Livingston, William F Garrett, Gentaro Hirota, Mary C Whitton, Etta D Pisano, Henry Fuchs, and others. 1996. Technologies for augmented reality systems: realizing ultrasound-guided needle biopsies. In *Proceedings of SIGGRAPH '96, 23rd annual conference on computer graphics and interactive techniques*. ACM, 439–446.

[13] Paul Milgram, Shumin Zhai, David Drascic, and Julius Grodski. 1993. Applications of augmented reality for human-robot communication. In *Intelligent Robots and Systems' 93, IROS'93. Proceedings of the 1993 IEEE/RSJ International Conference on*, Vol. 3. IEEE, 1467–1472.

[14] Nobutaka Mitsuhashi, Kaori Fujieda, Takuro Tamura, Shoko Kawamoto, Toshihisa Takagi, and Kousaku Okubo. 2009. BodyParts3D: 3D structure database for anatomical concepts. *Nucleic acids research* 37, suppl 1 (2009), D782–D785.

[15] Soh Nishimoto, Maki Tonooka, Kazutoshi Fujita, Yohei Sotsuka, Toshihiro Fujiwara, Kenichiro Kawai, and Masao Kakibuchi. 2016. An augmented reality system in lymphatico-venous anastomosis surgery. *Journal of surgical case reports* 2016, 5 (2016).

[16] Timothy M Rankin, Marvin J Slepian, and David G Armstrong. 2015. Augmented Reality in Surgery. In *Technological Advances in Surgery, Trauma and Critical Care*. Springer, 59–71.

[17] Tobias Sielhorst, Tobias Obst, Rainer Burgkart, Robert Riener, and Nassir Navab. 2004. An augmented reality delivery simulator for medical training. In *International Workshop on Augmented Environments for Medical Imaging-MICCAI Satellite Workshop*, Vol. 141. 11–20.

[18] Ivan E. Sutherland. The Ultimate Display. In *Proceedings of the IFIP Congress* (1965). 506–508.

[19] J Edward Swan and Joseph L Gabbard. 2005. Survey of user-based experimentation in augmented reality. In *Proceedings of 1st International Conference on Virtual Reality*. 1–9.