Touching the Future: AR and VR in Surgical Training

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ABSTRACT

This paper reviews the history and state of augmented and virtual reality (AR and VR), with a focus on surgical training. The medical profession as been an early adopter of these technologies, and this turns out to be an informative filter to examine how the issues of human-computer interaction in the have been addressed with respect to the development and adoption of this technology. Concepts of technology evolution, user value and training value are repeatedly expressed in the paper sample.

Evidence from the review shows that although virtual reality is generally effective in the training of minimally invasive procedures, the need for richer tactile interaction, such as with tools like dental mirrors, has constrained the further development of VR-based simulation. As a result, trainers that were once fully virtual are now incorporating AR in conjunction with physical models.

This development appears poised to support much richer forms of training, as the ability for 3D printing promises to be able to physically "render" tactile representations of a surgical site. This has the possibility of opening up simulation from its focus on fully-machine mediated procedures to a much larger field of training that requires less structured interaction with the patient.

Author Keywords

Augmented Reality; Virtual Reality, Mixed Reality, history; human perception;

ACM Classification Keywords

I.3.0 [Computer Graphics]: General. H.5.0 [Information Interfaces and Presentation]: General. H.5.2 [Interaction Styles]: General. J.0 [Computer Applications]: General.

INTRODUCTION

Surgeons have long been obsessed with augmenting their view of the patient. As early as 1938, Steinhaus developed a method that used fluoroscopy to position a marker with a partially silvered mirror between the doctor and the patient that could position a marker that appeared to float within the patient at the exact position that a solid object such as a bullet might lie[1]. More recently, computers have allowed the technology of visualizing information within the patient during surgery to be much more manageable, but the goal has remained the same - "I need to see the bullet".

But surgery is more than knowing where the bullet lies. It is both a cognitive and a motor skill. For a surgeon to master a particular procedure, several stages need to occur[2]:

1. The cognitive phase - The initial learning process
2. The associative phase - Learning the skill
3. The autonomous phase - proficiency

This is embodied somewhat in the trope of "see one, do one, teach one" that is still dominant in the medical community. In this case, the "See one" is the cognitive phase, where the learner is exposed sufficiently to a procedure to "understand" it. The "Do one" stage is where the learner develops the psychomotor skills to perform the procedure, while being monitored by a more experienced peer or teacher. The final "Teach one" phase assumes sufficient proficiency to not only perform the procedure but to also judge how another learner is comprehending the task. Needless to say, the room for error in such a paradigm is minimal. There is no point in this process where the person who is performing the procedure can make a mistake.

Lam, et al[3] describe simulation as an imitation of real world phenomenon in a controlled environment. As such, the ability to explore, even repeatedly, the rare or dangerous event without negative consequences is greatly enhanced. Perfectly realized, this would be the end of "see one do one teach one". Instead, learners would learn a procedure using simulation to iterate over the cognitive and associative phase until proficiency was achieved, without the risk of harming a patient.

The adoption of medical simulators has been increasing, and is now at the point that the Food and Drug Administration advocates the use of simulators as part of the approval of new devices and that several medical organizations are using simulation as part of the certification process[4].

However, this adoption has been restricted almost exclusively to minimally invasive procedures that are mediated by mechanisms such as endoscopes, laparoscopes, and catheters. "Open" types of surgery, because of the much deeper level of physical interaction with the patient and the use of a broad set of simpler, direct tools have been extremely difficult to effectively simulate in a virtual environment. Recently however, augmented reality techniques have begun to be incorporated into research simulators[5][6], where virtual components are integrated with physical models. This may allow the learner to interact more directly with the "patient", using standard tools.

This paper examines a set of HCI papers to determine the elements that have been common among simulator and augmented surgical systems over time to determine possible implications for simulator design that would lead to user acceptance and institutional adoption.

METHODOLOGY

The literature review was accomplished by performing initial searches in hcibib.org and Google Scholar[1] for representative articles over the span of years that the following terms produced results:

Surgical training (1999-), medical training (1990-), virtual reality (1983-), augmented reality (1986-), mixed reality (1994-), mediated reality (1997-) and 3D printing(2006-).

Papers were selected based on the proportion of the paper that was devoted to research regarding the above terms. In other words, if a paper on medical training only mentioned simulation or augmented reality in passing, it was not selected. These papers are included in the references as [3,5,6,8,9,10,11,12,14,15,17]. One source of bias was that if papers were not freely available online, the ACM Digital Library or through the UMBC Albin O. Kuhn Library databases, they were not examined.

The papers were then open coded using emergent descriptive terms methodology[7] using MSExcel. Primary and secondary themes were associated with elements of the articles. These themes were then counted to determine the ordering of themes across the corpus.

RESULTS

Before going into the specifics of the papers, it is worth looking at the overall trends of Virtual Reality and Augmented Reality in the HCI community. Figure 1 shows the number of papers returned by year when the terms "virtual reality" and "augmented reality" were used as search terms on hcibib.org. As can be seen, VR is recognized in the community first, though both VR and AR follow similar publication trends with AR publication numbers offset by a few years.

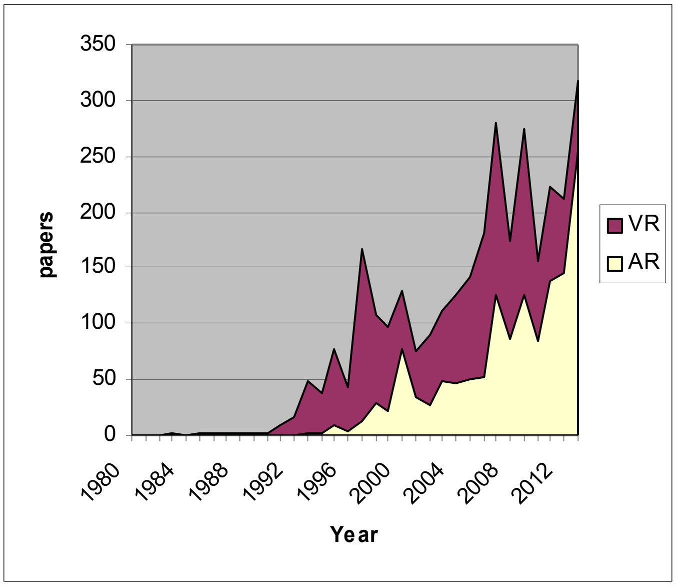

Figure 1: hcibib search results for "augmented reality" and "virtual reality"

This collection of papers paints a picture of the HCI community embracing the new innovations of augmented and virtual reality. At the same time, there is significant concern that these new technologies are not just adopted because they are shiny and new but because they can provide real value to the individual user and to communities of practice. The coding shows this clearly. Roughly three quarters of the emergent descriptive terms are split between discussions about these technologies directly, versus discussions about the value these technologies can provide to the users and institutions incorporating them. The actual percentages are broken out in the following list:

Technology Evolution	16%
User Value	16%
Training Value	13%
Need for Validation	8%
Novel Technology	8%
Added Realism	5%
Helpful Technology	5%
Safety	5%
other	24%

Technology Evolution / Novel Technology

When the papers discuss virtual and augmented reality, they are often describing it as an inevitable improvement on current systems. For example, VR systems will inevitably be better training systems This discussion starts in the HCI community in the 1990s as an enumeration of benefits in [8].

- *Geographic and Situational Flexibility/Variability*
- *Throughput of Trainees*
- *Cost per Trainee and Standardization*

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[1] Searches occurred during September-December 2013.

- *Clinical Risks*
- *Immediate Feedback and Review*
- *Trainee Evaluation*

By 2008, surgical simulation had become enough of a presence that Eric Seibel[9] could state:

> *Virtual reality is alive and well in medicine, and is rapidly integrating into common medical practice. Dialog about VR has become a mainstream topic at ... conferences.*

Five years later, these capabilities have become completely integrated into certain types of surgery[3]

> *Computer simulation, which is able to cover every procedure involved in cataract surgery along with surgical safety and complications, will be favored in training curricula in the future.*

At roughly the same time Augmented Reality is going through it's own technological evolution, from the groundbreaking work of Sutherland's "Head mounted three dimensional display"[10] where the

> *objective in this project has been to surround the user with displayed three-dimensional information.*

to Feiner's initial efforts to overlay knowledge on the world[11][12] by

> *presenting a virtual world that enriches rather than replaces the real world. Instead of blocking out the real world, this approach annotates reality to provide valuable information, such as descriptions of important features or instructions for performing physical tasks.*

By the mid 2000's medical augmented reality is vigorously being researched with conferences (MIAR, MMVR) and practical systems finding their way into the operating room. In one of the earlier versions of AR visualization to find its way into a clinical setting, a semitransparent mirror was mounted to an ultrasonic probe[1], in a setup recalling Steinhaus' original device, providing:

> *in situ visualization without tracking. In addition to real-time images, it allows for arbitrary slice views, as the ultrasound probe can be freely moved.*

Interestingly, even as virtual reality systems have become accepted as training systems, augmented reality is still uncommon in the operating room, and as late as 2012, authors still feel a need to justify its use[13]:

> *The emerging Augmented Reality (AR) technology has the potential to bring the direct visualization advantages of open surgery back to minimally invasive surgery and can increase the physician's view with information gathered from the patient's medical images.*

This may simply be the result that AR is a younger technology than VR, as shown in figure 1, or it may change as AR technologies such as Google Glass become more socialized[13]. however, this is too recent a phenomenon to be within the scope of this paper.

Added Realism

An issue with virtual reality is that every additional channel of interaction has to be explicitly added. Collisions have to be calculated from complex models. Every tool has to be able to appear and behave correctly. A classic example of this problem is how to include the user's hands in a simulation. This issue explains how virtually all surgical simulators are for minimally invasive procedures, where all activities are mediated through mechanisms such as endoscopes and laparoscopes. The virtual scene is rendered on a monitor, with the user separated from the experience. This barrier - where the user is situated in one space, interacting through an indirect mechanism to a simulated space greatly constrains the types of simulations that can be used for training. To address this, and to provide deeper and richer interactions such as tactile, training simulators are being researched that use a physical frame into which virtual elements are added.

An example of using augmented reality to increase the realism of a virtual reality simulator is the work of Rhienmora, et al[4]. The system began as a pure VR-based simulator for training dental surgeons. Initially developed using a full head-mounted display, the simulator suffered from a variety of usability issues, including the hand-tracking issues mentioned above.

> *some evaluators found it difficult to navigate and control the dental tool in the simulator. We attribute this problem to the difficulty of hand-eye coordination in non-co-located VR systems.*

When reconfigured for augmented reality, the trainer could take advantage of using standard dental tools. For example the dental mirror was a commercial tool with a registration pattern where the actual mirror was. This simple modification to include, direct manipulation of tangible objects within the simulation contributes greatly to the sensation of realism with the user community. Based on their interaction with the mirror, the desire was stated by their expert user for a system where

> *the virtual tooth is overlaid on a traditional mannequin along with other tangible real teeth.*

Another example where the addition of tangibility and visualization increases realism is in the work of Gillet at the HIT lab on teaching structural biology[9]. In this example, a molecule model is 3D printed with registration marks. An augmented reality overlay dynamically animates the electrostatic characteristics of the molecule. This completely frees the user of any mediation by mechanism and allows for direct, tangible interaction with the subject matter:

> *Since the underlying physical model is intimately related to and registered with both the graphical and haptic models, this approach provides a uniquely integrated tool for learning molecular biology.*

User/Training Value

All the systems in these papers, whether standalone simulators or augmentation systems implicitly need to be evaluated with respect to how effective they are in improving the ability of the learner above the baseline of what "see one do one teach one" can provide. Within the context of this study, the descriptive terms that pertained to value were associated with meeting the direct needs of the user (user value) and delivering (or not) effective training (Training value/Need for validation).

User Value

In this category, user value could range from the issues of head-mounted displays [10]:

> *The image presented by the three-dimensional display must change in exactly the way that the image of a real object would change for similar motions of the user's head.*

to the effects of psychological pressure and stress [8]:

> *Supervised surgery, the traditional method of training. is highly expensive in terms of operating theatre scheduling and the time of the supervising surgeon. Consequently, surgeons may Feel pressured to perform operative arthroscopy before they are ready.*

to the nature of interaction[15]:

> *The real world allows intuitive manipulation of elements (interaction and navigation), haptic feedback, a natural environment for collaborative activities and perceptual possibilities that are not artificially limited by the capabilities of a computer. A system for modifying the real world can benefit from the advantages of both domains and therefore has enhanced expressive potential.*

To human factors [16]:

> *From our current implementation we can conclude, that for high-fidelity augmented reality, precise registration of the real world with augmented reality is crucial, and that our current static registration is barely sufficient. Nevertheless, our experiences show that users feel comfortable and working in the environment is pleasant.*

It can be seen from these and other papers in the sample that the issues that pertain to user value have been part of the discussion with respect to virtual and augmented reality since the beginning. They also point to the factors that contribute to an effective experience: The mechanism should be transparent as possible to the user, both in terms of comfort and how it integrates with the environment. The environment should not add to the stress of the user, and should ideally provide ways to reduce or eliminate it. Lastly, the computer interference in actions and perceptions should be minimized.

Training Value/Need for Validation

Where user value is how effectively a system interacts with an individual, training value is a good indicator of how the system interacts with an organization. A device may be wonderful to use, but if it does not promote learning, then it has no value to a teaching organization. To know if a system has training value, it needs to be validated. Unfortunately, this is not a straightforward question to answer. Is the system that trains the best the system that is best for training? Waxberg, in [14] finds that

> *it appears that the physical box trainer may be more representative of real motor tasks with the expected kinesthetic and haptic feedback from the task space, and thus was able to better reflect the skill level of the subject.*

And yet, in the conclusions of the same article, she also states

> *However, as virtual reality technology becomes more popular and better developed, we may see a change in its value and usefulness.*

This is in line with the conclusions that Arthur made in 1999[8] that:

> *Systems can be used repeatedly when trainees are available. Changes to the training environment. such as pathologies and camera specifications. can be made in software rather than requiring physical changes. Numerous surgical situations can be modeled using virtual surgical environment. With feedback. surgeons can learn from their errors at a level that is simply not possible in the operating theater. Random error potential can also be built into the simulated scenarios very easily.*

These statements did in fact turn out to be reasonable. The simulator described in [8] was reworked in 2007[17], to be a mixed-reality simulator, with good results:

> *The differentiation of expert and novice performance demonstrated through Sect. 3 suggests that the tactile augmentation SKATS carries a basic level of construct validity. This, along with the feedback received from the participants rationalizes continued development and validation of the mixed reality-training environment. Following initial acquisition on a VR simulator, skills should be readily transferable into the operating theater without the trainee having false confidence in their ability.*

This trend continues with Lam's review[3] of cataract surgical simulators. By 2013 the discussion is entirely focused on how best to use simulation to train, even when compared to cadaver/animal (wet) practice:

> *The current stage of a VR cataract surgery simulator on surgical training and assessment is encouraging, as statistical validation from different articles showed significant improvement compared with traditional wet-lab practice.*

Based on these papers then, it appears that the HCI community finds that simulation is effective, and mixed reality adds richness and flexibility to interaction. Would the added richness of mixed reality simulation enable greater training capability, particularly in the area of open surgery? This is our research question.

RESEARCH PROBLEM

Open surgery is still is and will continue to be a significant portion of all procedures performed, and yet the amount of time spent practicing is reduced because of a lack of access to effective simulation[19].

Minimally invasive surgery can be simulated more easily because the users actions are constrained by having to be mediated by the device. Open surgery on the other hand is direct and at-hand. Tools are simple, and feedback is a massive variety of visual, touch, sound and smell as the surgeon interacts intimately with the body of the patient. Forces are proportional to effort – suturing the pancreas is a light, delicate procedure. Hip replacement is more like carpentry.

What would an open-surgery simulator look like? What would it need to do? Based on the descriptors that emerged in the study of our corpus, Let's look at this problem from three perspectives; User value, institutional (training) value, and community acceptance.

User Value

To achieve a high level of expertise, individuals need to practice. Combining practice with additional information, such as multiple scenarios and complications provide a blend of physical and cognitive learning which can improve the quality of the learning experience and make it more entertaining and motivating. Ideally, a level of assessment should be available so that the learner can judge achievement and progress. Lastly, all this should be delivered conveniently and at low cost, reducing the barriers to training and increasing the frequencies of opportunity, so that expertise can be attained.

The current range of simulations that are available for surgical training range from inexpensive, low-fidelity “bench models” to expensive VR simulators such as discussed earlier in this paper. Bench models are cheap and simple because they are purely physical. VR systems are expensive primarily because they are essentially robots for producing force feedback.

A reasonable possibility for this study is to assume that 3D printers will progress sufficiently to be able to render anatomical models. Visual characteristics of living tissue could be rendered onto the model using a variety of augmented reality techniques, ranging from projection to overlay[15]. Moody[17][18] shows that direct tactile responses are effective for learning knee surgery in mixed reality systems. Printing and augmenting a bench model, then comparing performance to the actual bench models could provide the basis for an initial study.

Training/Institutional Value

Currently, open surgery is evaluated using observer-based criteria such as the Objective Structured Clinical Examination (OSCE) or the Objective Structured Assessment of Technical Skills (OSATS)[19]. Computer-based evaluation for minimally invasive surgeries can be achieved using the simulator's built in assessment software[14], or by tracking the user's hands, looking for motion cues that are indicative of autonomy, such as the Imperial College Surgical Assessment Device, (ICSAD) [19]. In the case of an augmented 3D printed model, tracking cameras such as the Kinect could provide this same capability[20]. In a user context, such hand tracking could allow the simulator to track skill development and provide assessment in a non-evaluation context, providing for additional value to the user, while also providing already established assessment capability to the institution. To study this capability, an option would be to evaluate the effectiveness of a low-cost device such as a Kinect against the ICSAD system. Additional, more sophisticated assessment that involves cognitive assessments of pathologies that the simulator could provide along the lines of full VR systems could also be developed and evaluated with expert evaluations and user studies.

Community Acceptance

Based on the papers in this survey, the medical community is quite open to novel simulators. The need for training and evaluation of surgical personnel is high, and the acceptance of “technological evolution” appears to be well integrated into the community. Nonetheless, determining the best way to integrate a new potentially low-cost training and evaluation technology into the community might be to begin with unstructured interviews of known early adopters of previous technologies in the field. This could indicate what the adoption issues were when they were involved. The outputs of these interviews could be used as the basis of a participatory design study that determines a good baseline for the initial systems, and the types of procedures they should support initially.

CONCLUSION AND INSIGHT

In this paper, we have reviewed the history and state of augmented and virtual reality as it pertains to the HCI community. Using open coding techniques, we analyzed a sample of papers retrieved from the HCIbib.org website using search terms for surgical training, medical training, virtual reality, augmented reality, mixed reality, mediated reality and 3D printing. The descriptive terms that emerged from this sample were then ordered by frequency to determine the dominant themes in the HCI community discussion that these papers represent.

Based on these themes, the insight of combining low-cost tactile “bench-like” open surgery trainers with computer simulation emerged as an interesting and achievable option. The idea of combining these two technologies has been touched on with devices like the Sheffield Knee Arthroscopy Trainer[8][17][18], but there does not seem to be any examples in the literature of using custom bench models that are enhanced using augmented reality for open surgery training and evaluation.

Lastly, the research problem of what such an open surgery simulator should consist of was addressed. A potential study was presented that addressed the major themes from the corpus of papers – User Value, Training/Institutional Value, and technological evolution as part of Community Acceptance.

This looks to be an exciting time for medical simulation. The barriers that have existed in the past that prevented computer simulation to be an effective part of open surgery training appear to be disintegrating. Now is a good time to begin to determine what the potential of this new class of simulators can be.

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