Immersive Analytics for Medicine: Hybrid 2D/3D Sketch-Based Interfaces for Annotating Medical Data and Designing Medical Devices

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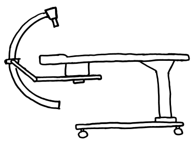
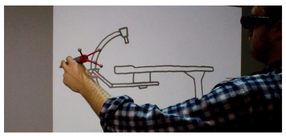
Abstract
We explore the role that immersive technologies, specifically virtual reality (VR) and hybrid 2D/3D sketch-based interfaces and visualizations, can play in analytical reasoning for medicine. Two case studies are described: (1) immersive explanations of medical procedures, and (2) immersive design of medical devices. Both tightly integrate 2D imagery and data with 3D interfaces, models, and visualizations. This is an approach we argue is likely to be particularly useful in medicine, where analytical tasks often involve relating 2D data (e.g., medical imaging) to 3D contexts (e.g., a patient's body). User feedback and observations from our interdisciplinary team indicate the utility of the approach for the current case studies as well as some shortcomings and areas for future research. This work contributes to a broader discussion of how hybrid 2D/3D interfaces may form an essential ingredient of future immersive analytics systems across a variety of domains.

Author Keywords
Immersive Analytics, Visualization, Hybrid 2D/3D User Interfaces, Immersive 3D Modeling

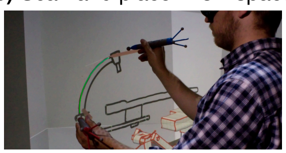
ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User Interfaces; I.3.7 [Computer graphics]: Virtual Reality



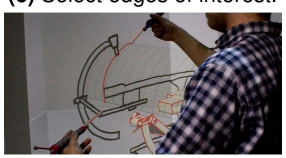
(a) Start with sketches on paper.



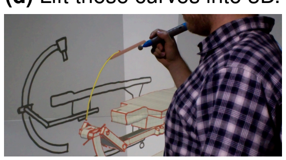
(b) Scan and place in 3D space.



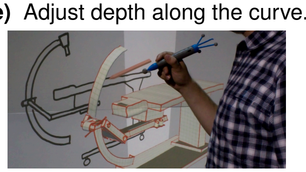
(c) Select edges of interest.



(d) Lift these curves into 3D.



(e) Adjust depth along the curve.



(f) Sweep surfaces along curves.

Figure 1: The process of designing from a sketch in Lift-Off.

Introduction

Today, society has benefited greatly from recent advances in medical imaging and innovations in medical devices. However, the ability to design, analyze, interpret, and communicate these data remains a challenge. We believe that by combining virtual reality interfaces with creative data-intensive work-flows, new immersive analytic tools can address this challenge.

In this paper, we present two application case studies showing how hybrid 2D/3D sketch-based interfaces in VR, specifically interfaces from the recent Lift-Off immersive modeling system [3], can be used to support immersive analytics in the medical domain. Lift-Off (Figure 1) allows a user to position 2D imagery within a 3D virtual environment shown in a VR Cave. The user can lift 2D contours out of the imagery into 3D space to create a wire-frame network of rails. Surfaces can then be swept along the rails creating a 3D model with precise control.

The first application using the Lift-Off system explores how immersive 3D modeling based on 2D X-ray imaging can be used to analyze and explain bone fractures to patients before receiving care. The second application explores the ways in which development of a 3D scale model of a medical device from early 2D sketches can facilitate a new style of engineering design for medical devices. Both case studies were developed by our interdisciplinary team of medical device engineers, computer scientists, and a physician. Based on these experiences, we argue that hybrid 2D/3D interfaces that support new creative output in addition to visualization are critical for the development of immersive visual analytic tools.

Our main contributions are:

- A case study of combining a hybrid 2D/3D sketch-based interface with medical imaging data to support surgical intervention for bone fractures and increase physician/patient communication.
- A case study of combining a hybrid 2D/3D sketch-based interface with hand-drawn 2D sketches on paper to support designing new medical devices in an immersive spatial context.
- A discussion of challenges and guidelines for the medical domain as a fertile application area for immersive analytics.

Related Work

Medical Analytics and Visualization in VR

Medicine has always been an important driving application area for immersive visualization and analytics. Immersive environments have been created to help scientists and physicians analyze computational simulations of blood flow [7], understand the structure of the brain and how it changes with disease [8], and plan and train for surgical procedures [6]. Now, as immersive technologies have become dramatically more accessible and affordable, there is an opportunity to do much more. For example, our first case study explores the potential of using VR not as an analytical tool for only the most complex neuroscience surgical intervention, but rather as an analytical tool for the everyday task of a physician working together with a patient, helping the patient (or perhaps a medical resident) to reason in 3D about why a medical procedure is necessary and conveying information about procedures and risks using a visual language that can be understood by non-experts. In the future, we also envision a dramatically increased role for interaction relative to prior work in immersive medical analytics. For example, our second case study explores the potential of immersive environments that are not just for interactive visualization of existing datasets but also for creating data (i.e., designing, 3D modeling).

Sketch-Based Modeling and Annotation in VR

There is an exciting history of sketch-based modeling tools for VR. Early work in this area includes the 3DM system [1] which supported the creation of 3D surfaces by sweeping a tracked six degrees-of-freedom stylus through space. This was followed by Holosketch [2] and many others. In general, 3D sketching in VR has been embraced for its immediacy and the ease with which even novice users are able to create complex models. However, user feedback shows that unconstrained 3D input is difficult to control. The Lift-Off modeling system [3] avoids much of this issue by introducing constraints from hand-drawn 2D sketches (Figure 1). In addition to modeling, freehand sketch-based systems have been used to annotate and describe scientific data. Keefe et al. explored how to prototype scientific visualizations using sketched 3D input [4]. Miller et al. studied surgeons' ability to annotate vasculature structures in VR for surgical planning [5]. We believe incorporating engaging, full-body, gestural interfaces in these styles into immersive data visualizations is the thing that is needed to create a next generation of successful immersive data analytics tools.

Application 1: Immersive Annotation of Medical Imaging Data

While brainstorming possible roles for immersive analytics in medicine, our team arrived at an application that was surprising to the team members not directly involved in medicine. There is a great need right now to better facilitate communication about medical data. Although patients are often engaged in their treatment process, their lack of training to read medical images hinders their ability to link their condition to the knowledge they have gained with on-line resources. Physicians need to quickly and reliably translate medical information to patients and their family members, and this often involves translating concepts captured in 2D imagery or other data to the 3D context of a patients body.

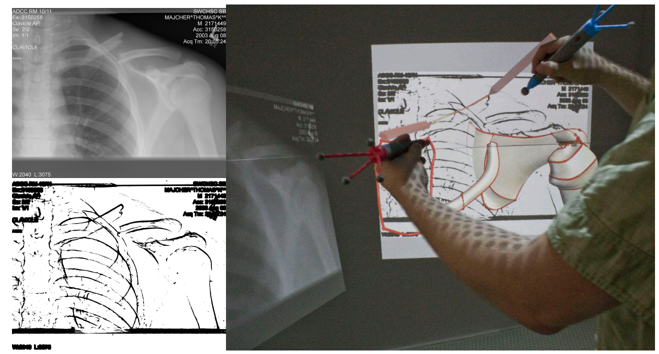


Figure 2: Starting with a standard X-ray image (top-left) and applying an edge-detection filter (bottom-left), users place these data images as slides in 3D space and then "Lift-Off" curves to construct 3D models and annotations (right). Data credit: X-ray image

Prior work with Lift-Off has focused on translating artist-defined 2D line-sketches into 3D virtual models for architecture and sculpture art, but we reasoned that a similar hybrid 2D/3D interface might also be useful for physicians to facilitate patients' comprehension of medical imaging data.

Methods and Results

To test this potential, we developed an example use case based on the concept of translating the 2D medical data captured in a patient's X-ray to a 3D context that might be more easily understandable to the patient. We considered the case of a broken clavicle bone. Figure 2 (top-left) shows the original digital X-ray image, and Figure 2 (bottom-left)

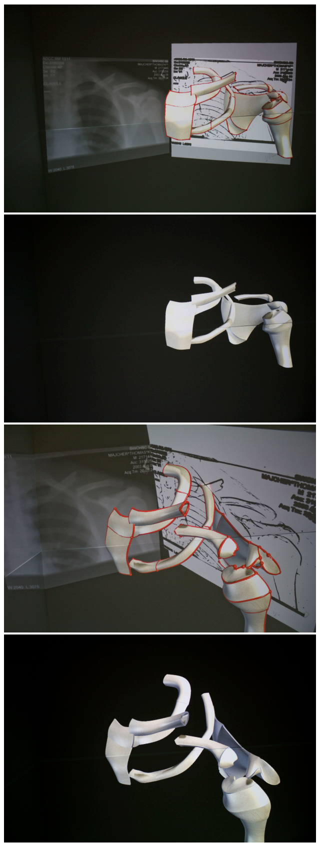


Figure 3: A complete 3D model of the broken clavicle from two angles. Shown both with and without the design scaffolding.

shows the same image after applying the simple edge-detection filter built into the Lift-Off tool. Together these images are placed (like floating slides) in 3D space within VR, and they serve as the data context for 3D illustrations and annotations. Figure 2 (right) shows how construction lines were selected from the edge data and pulled out from the image to a user-defined depth to construct the anatomy relevant to the discussion.

To illustrate this specific medical example, we lifted out geometry for a section of the sternum, the first and second rib, the broken clavicle, a section of the scapula, and a section of the humerus. Several views of the 3D scene this process generated are shown in Figure 3.

Observations and Feedback

Our interdisciplinary team generated several observations from this experience, and we recorded feedback from the physician on the team as he engaged with the tool to demonstrate how he might use it to better communicate with a patient or resident (Figure 4).

One of our first observations was a surprise. The physician's first step was not to discuss the break in the bone specifically; rather, he began decisively sketching areas of concern near the fracture such as blood vessels, explaining that the bone fragments could cause further internal damage if not treated, a danger he indicated was critically important for the patient to understand in order to pursue appropriate treatment. Interestingly, this is precisely the type of 3D context that is not visible on the 2D X-ray image; here, it was only made visible with the new ability to sketch in 3D around the data-driven context provided by the X-ray image positioned in space.

We also noted the feedback that this clavicle fracture case is perhaps a bit too simplistic to convey the real need for

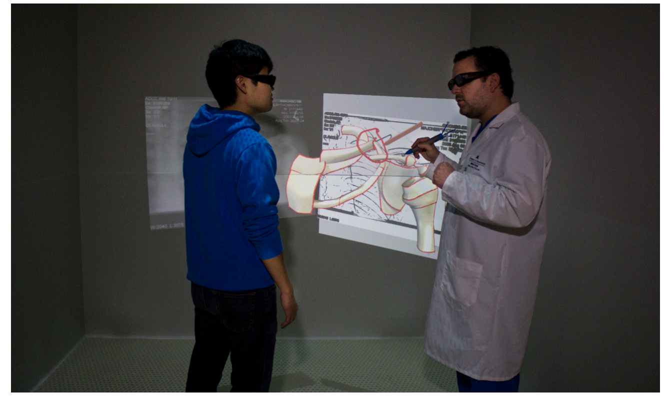


Figure 4: Using immersive data-driven 3D annotations to explain treatment options.

a tool in this style. For example, a more compelling example of the need for communication might involve broken ribs in elderly patients – here, it can be difficult to convey to the patient the need for additional supervision in a setting where the patient can remain still, breathing deeply for a consistent period of time so as to avoid developing pneumonia. He then went on to demonstrate how he would describe an even more complicated condition, pancreatic cancer, using freehand 3D sketching to create a diagram in the air showing the pancreas and surrounding organs and adding arrows as annotations while describing the treatment process.

The primary conclusion from our observations is that these situations would benefit from a virtual 3D white-board that allows physicians to draw as they talk in the context of both 2D images and 3D anatomy. This would enable physicians to annotate the 3D reconstruction, describing procedural and securement methods and identifying implant locations.

The current case study succeeded to a degree in making this possible. However, there were also some shortcomings. The physician noted that while physicians would likely not want to take the time to actually model the contextual bones and anatomy in practice, they would make extensive use of the ability to sketch 3D diagrams in the context of generic 3D anatomy and 2D medical images. We interpret this as a need to extend the data visualization supported in our prototype, which is currently limited to just 2D medical imagery, to 3D visualizations that include surface and perhaps even volumetric models for organs and other structures. Imagine, for example, an ability to perform the type of annotation and modeling described here within the context of a state of the art 3D visualization of neural fiber tracks visualized in VR.

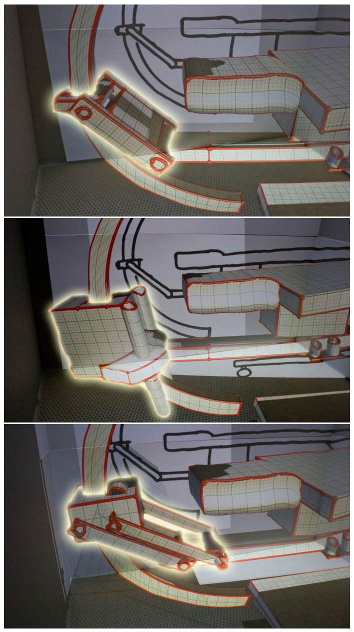


Figure 5: Three variants of the robotic mechanism, sketched in the 3D immersive environment.

Application 2: Immersive Medical Device Design

Medical device design is a collaborative process. Designers need to conceptualize ideas for new medical devices and relay those concepts to engineers for further refinement and prototyping. This process often starts on paper, but because the 3D complexity of these models can be so high, the process then often quickly moves to computer-aided design (CAD). One of the limitations of this quick transition to CAD tools is that once we move to a CAD model, with precise geometry, constraints, etc., we lose much of the quick, creative, and exploratory benefits of sketching. On the other hand, it is clear that traditional 2D sketching can only go so far, particularly when we consider designing medical devices with complex geometries that might be inserted within complex 3D human anatomy.

Methods and Results

To demonstrate how Lift-Off can be used in the medical device development process, we made several sketches on paper to capture ideas for a table-based robotic surgery device that our interdisciplinary team had been discussing for several weeks as part of another project. Working from one of the sketches, we created a full 3D model (i.e., a virtual 3D sketch) of the device in VR. (Figure 1 documents this process.)

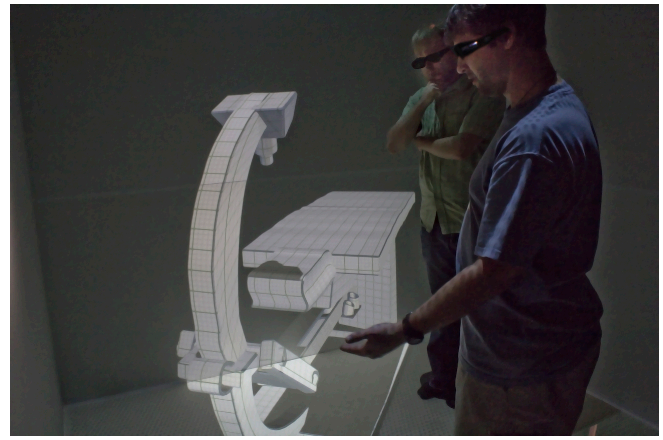


Figure 6: Critique of the robotic surgery device sketches can occur directly in the immersive environment.

In this specific example, a successful design must be able to robotically control the position and orientation of a laser relative to the patient's head while the patient lies on an operating table. Precise and stable positioning is required, and the design must also address several spatial constraints, such as room for the medical staff to work, room to transfer the patient on and off the table, and room for the surrounding equipment in the operating room. The design can be modified at real-life scale inside VR, and variations can be explored. For example, Figure 5 shows three variations for the hinging mechanism. All three of these designs were creating based on the same 2D sketch by using freehand 3D sketching and brainstorming.

Observations and Feedback

The medical device engineers on our team evaluated this process and provided insights as the process moved from conference room ideation and sketching on whiteboards and paper to VR, where critique focused on the 1:1 scale 3D model shown in Figure 6.

An observation we made was how the approach to discussing the device changed when one of our medical device engineers encountered the virtual prototype. First, upon entering the immersive environment, the engineer appeared energized as compared to the conference room discussion. When another member of our team noticed that our system did not actually allow the different parts to move relative to each other, she took the opportunity to draw arrows in the air around the virtual prototype to indicate the degrees of rotational freedom of the multiple moving parts. Interestingly, these 3D arrows showed movement in several planes that would be difficult to visualize together on a 2D sketch.

When asked to reflect on the design variations of a particular hinging mechanism (Figure 5), one engineer commented on possible implementations involving four-bar linkages and sliding systems with clamps that could be powered by hydraulics. Before the sketch and virtual prototype were developed, this hinging mechanism hadn't even been discussed. While in the cave, members of our team tried standing at various positions around the virtual prototype to see how the various components might get in the way of potential surgical operations.

Our conclusion from our observations is that putting people in a 3D space with a life-size and life-like virtual prototype facilitates discussion and allows for considerations of implementation and spatial constraints. All design decisions can be made with a perspective to scale and functionality within the surrounding environment with an immersive application like Lift-Off. Without a hybrid 2D/3D VR tool, these sorts of discussions and considerations would be inhibited until a physical prototype could be produced. However, there are also shortcomings to using Lift-Off over physically prototyping, such as the inability to physically interact with the virtual prototype or to move individual parts.

Although this particular case study focused on a large-scale medical device, our team members also work regularly with smaller scale and implantable devices (e.g., replacement heart valves, cardiac leads, drug delivery systems). This is an area where we think the interfaces described here can be combined with data-rich immersive visualizations to create immersive analytics systems that are powerful. Imagine, for example, the style of collaborative 3D design and sketching described here coupled with the style of immersive visualizations of blood flow through the heart mentioned earlier when discussing related work.

Conclusion

In the paper, we explored the potential of using a 2D/3D hybrid user interface to sketch on top of medical imaging data, not just as a way to plan a high-end surgery (although this could certainly be useful) but as a way to even perform the much more common task of explaining a complex medical procedure to a patient. Similarly, we explored the potential of using a VR system as a 3D sketchpad for medical device engineers to create new device prototypes in immersive environments. In the end, we believe the two most successful elements of our case studies that others may learn from as they implement additional immersive analytics tools are: (1) the freedom to to sketch and create new 3D data with reference to a data visualization rather than simply providing interactive techniques to explore a preexisting dataset, and (2) the ability to link one's prior experience with 2D data (or even physical sketches on paper prepared outside of VR) to the new immersive 3D environments in which people will work in the future. We look forward to continued discussion of how these two concepts, often embodied in expressive hybrid 2D/3D interfaces, might facilitate the success and adoption of future immersive analytics tools, both in a medical context and beyond.

Acknowledgements

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