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Brown University

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* EAGER - EArly-concept Grants for Exploratory Research
** RAPID - Grants for Rapid Response Research

Project Summary

HCC: Small: Collaborative Research: Immersive Visualization and 3D Interaction for Volume Data Analysis

Visualization of volume data is critical in a variety of application domains, such as medicine, geophysical exploration, and biomechanics. For effective analysis of a 3D volume, scientists and other users need to integrate various views and to peer inside the volume. However, despite many advances in volume rendering algorithms, neither traditional *displays* nor traditional *interaction techniques* are sufficient for efficient and accurate analysis of complex volume datasets.

Desktop computer monitors lack more realistic visual stimuli such as stereoscopic 3D graphics and motion parallax due to head tracking. Thus, it may be difficult for the user to judge the size, shape, or depth of the structures in the volume data. Current interaction techniques include slicing, importance-driven rendering, and focus+context views, but all of these have significant limitations, such as removing or distorting some of the spatial context, or requiring users to specify the ROI precisely before analysis. In addition, interaction is typically performed via 2D input devices; it is difficult for users to understand the mapping of this 2D input to 3D actions.

Intellectual Merit

We propose to study the use of **displays with higher levels of fidelity**, as well as **natural and innovative 3D interaction techniques**, to allow scientists to view and analyze volume datasets easily without prior segmentation. Our work will address the following questions:

1. *How do various display characteristics or components of display fidelity impact the effectiveness of volume visualization?* We plan to run controlled experiments using our MR simulation methodology to determine how high fidelity display features affect user performance and preference with volume data analysis tasks.
2. *How can we design 3D interaction techniques to improve the effectiveness of volume visualization as compared to traditional desktop interaction techniques?* Starting with our recent technique called *Volume Cracker*, which allows inspection of the interior of volume datasets without distortion or loss of context, we will design a suite of tools based on 3D interaction to improve interactive analysis and to allow rough interactive segmentation of volume data.
3. *How can we describe volume data analysis tasks in a generic and comprehensive way?* Addressing both of the questions above requires that we understand the types of tasks performed by scientists when analyzing volume datasets. Based on surveys and interviews, we will generate a task taxonomy for volume data analysis so that our results will be generalizable across domains.

Based on the findings related to these research questions, we propose to design, prototype, and evaluate a next-generation interactive volume data analysis system with best-practice display characteristics and interaction techniques.

Broader Impacts

The proposed work will provide a deep understanding of ways to innovate in the realm of volume data analysis. Easier, more accurate, and faster analysis can lead to improvements in healthcare, breakthroughs in science, and advances in education.

We will also use our research program to provide benefits to underrepresented groups, through recruitment of women and minorities, and through demonstrations and presentations to organizations such as the Association for Women in Computing and the Center for Enhancement of Engineering Diversity.

Keywords: Immersive visualization; display fidelity; 3D interaction; interaction fidelity; volume data analysis; spatial understanding

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For font size and page formatting specifications, see PAPPG section II.B.2.

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Table of Contents	1	
Project Description (Including Results from Prior NSF Support) (not to exceed 15 pages) **(Exceed only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**	15	
References Cited	5	
Biographical Sketches (Not to exceed 2 pages each)	4	
Budget (Plus up to 3 pages of budget justification)	6	
Current and Pending Support	3	
Facilities, Equipment and Other Resources	2	
Special Information/Supplementary Documents (Data Management Plan, Mentoring Plan and Other Supplementary Documents)	5	
Appendix (List below.) **(Include only if allowed by a specific program announcement/ solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**		

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HCC: Small: Collaborative Research: Immersive Visualization and 3D Interaction for Volume Data Analysis

Doug A. Bowman and John Socha (Virginia Tech); David Laidlaw (Brown University)

1. Vision and Goals

Visualization of volume data is critical in a variety of application domains, such as medicine, geophysical exploration, and biomechanics. For effective analysis of a 3D volume, scientists and other users often need to integrate various views and to peer inside the volume. However, despite many advances in volume rendering algorithms, neither traditional *displays* nor traditional *interaction techniques* are sufficient for efficient and accurate analysis of complex volume datasets. We propose to gather empirical evidence for the effects of *high-fidelity display features*, and to design innovative *natural 3D interaction techniques*, for volume data analysis tasks. Our findings will lead to the design of a powerful but affordable interactive visual analysis workstation for scientists working with volume data.

1.1 Problem statement

Volume data is generated through processes such as computed tomography, magnetic resonance imaging, ultrasound, and confocal microscopy (Kaufman 1990; Kaufman 1996). Volume data, in its raw form, is composed of voxels (x, y, z, v) on a 3D grid instead of 2D pixels. Each voxel has a numeric value based on some property of the object it is representing. These properties may include color, density, refractive index, or other material properties, mapped in the rendering using some transfer function (Kaufman 1996) (We use the term *transfer function* to refer to any method of determining the visual representation of the voxels in a volume rendering). There are many techniques for voxel rendering such as decomposition, isosurface rendering, maximum intensity projection, semi-transparency, and x-ray rendering (Marmitt 2006).

Visualization of volume data is critical to a variety of application domains, such as medicine, biology, geophysical exploration, engineering, and paleontology (Kaufman 1996). Scientists, engineers, physicians, and technicians need to be able to view, analyze, and interpret the features of volume data samples produced by the various 3D scanning technologies in order to gain scientific insight, diagnose medical problems, find new deposits of natural resources, and so on. For example, co-PI Socha examines insects to understand how form relates to function, particularly in regard to how insects create internal fluid flows. Because the internal morphology is extremely diverse across species, it is critical to gain an understanding of the 3D relationships among parts of the body, and to make quantitative measurements for description, comparison, and model making for physical and computational experiments.

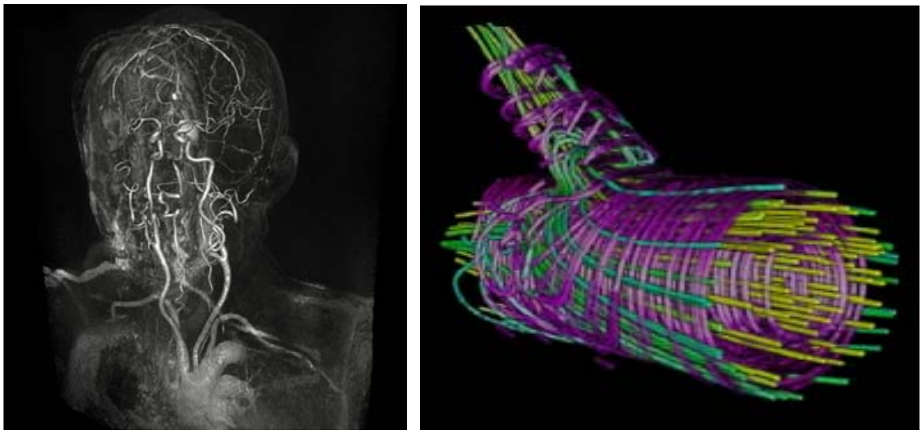


Figure 1. 3D renderings of volume datasets.

A great deal of the existing research on volume visualization focuses on algorithms for offline and real-time rendering. Research on these algorithms is fast-evolving due to the advent of graphics processing units (GPUs). Figure 1 shows two very different examples of volume datasets rendered in three dimensions. The left image is a rendering of a scanned human head and chest. On the right simulated blood flow in a branching coronary artery is visualized. For effective analysis of a 3D volume and the phenomenon it is capturing, users need to look at the rendering from various viewpoints, mentally integrate the various views to construct a 3D mental model of the volume, and, importantly, peer inside the volume. Unlike most computer graphics, which are represented as surfaces, volume data has important information throughout the 3D volume, and thus is inherently difficult to understand from a single image, or even from an animation or interactive session viewing the data from outside. Transparency can be used to make some of the internal structures visible, as in the human head in Figure 1, but can also result in ambiguous depth cues and visual clutter. Despite all the advances in volume rendering (Marmitt 2006), therefore, analyzing volume datasets is still extremely challenging.

Because viewing the raw volume data does not always reveal the structures of interest, the first step in volume data analysis is often *segmentation*, in which the transfer function is adjusted manually or automatically based on some thresholds, to mark out regions of interest (ROIs) in the volume (Schulze-Döbold *et al.* 2001). With a fully segmented volume, users can select which semantic layers (e.g., blood vessels, bones) they wish to view, making analysis easier, though still challenging in many scenarios, such as the fluid flow volume rendering on the right side of Figure 1, where the “transfer function” involves calculating and volume rendering a subset of the infinite number of possible curves so that internal structure is visible. Although segmentation can produce very good results, it can be extremely time-consuming (on the order of days or weeks) and often requires very precise selection of ROIs in every 2D slice of the volume. This is unacceptable when the number of samples that needs to be analyzed is large. For example, co-PI Socha would like to examine as many insect species as possible, but with over 400,000 species of beetles alone, only a small number of samples can be probed in any one study because segmenting a single sample can take weeks to months.

Traditionally, users look at 2D slices or 3D volume renderings on desktop computer monitors, which lack more realistic (higher-fidelity) visual stimuli such as stereoscopic 3D graphics and motion parallax from head tracking. Thus, it may be difficult for the user to judge the size, shape, or depth of the structures in the volume data. Judgments of this sort are required not only for general understanding, but also for performing interactive tasks such as segmentation of a dataset (Ragan 2012).

Due to the difficulty of manual segmentation, researchers have also tried interactive viewing alternatives to supplement segmentation. These interaction techniques include slicing, importance-driven rendering, and focus+context views, but all of these have significant limitations, such as removing or distorting some of the spatial context, or requiring users to specify the ROI precisely before analysis (see section 2.3 for an overview of prior work). Moreover, these techniques are normally controlled with 2D input devices such as the mouse, where the mappings between the input and the data being controlled are less natural.

In summary, the analysis of volume data is often time-consuming and tedious. Because of the low fidelity of display devices and interaction techniques, users have great difficulty understanding 3D volume datasets. These problems hinder scientific progress and limit the insight that can be gained through visualization of otherwise information-rich datasets.

1.2 Research questions and approach

Prior research on volume rendering techniques has not fully addressed the problems above. We take a different approach. Instead of developing new rendering or visualization methods, we propose to study the use of **displays with higher levels of fidelity**, as well as **natural and innovative 3D interaction techniques**, to allow scientists to view and analyze volume datasets easily without prior segmentation. Our work will address the following questions:

1. *How do various display characteristics or components of display fidelity impact the effectiveness of volume visualization?*

There has been a great deal of debate about the merits of "immersive" displays such as CAVEs and head-mounted displays for visualization tasks. We plan to run controlled experiments to gather empirical data, demonstrating how high-fidelity display features (e.g., stereoscopic rendering, head tracking, and wide field of view), combined with standard volume rendering techniques, affect user performance and preference with volume data analysis tasks. Our results will shed light not only on the question of "immersive" vs. "non-immersive" displays, but on what combinations of display characteristics have the greatest benefits for volume data analysis tasks.

2. *How can we design 3D interaction techniques to improve the effectiveness of volume visualization as compared to traditional desktop interaction techniques?*

Starting with our recent technique called *Volume Cracker* (Laha 2013a), which allows inspection of the interior of volume datasets without distortion or loss of context, we will design a suite of 3D interaction techniques and tools based on natural metaphors to improve user performance in volume data analysis tasks. Again, these techniques will work with standard volume rendering approaches. We hypothesize that natural 3D interaction with volume visualizations will allow easier and more accurate analysis.

3. *How can we describe volume data analysis tasks in a generic and comprehensive way?*

Addressing questions 1 and 2 above requires that we understand the types of tasks performed by scientists when analyzing volume datasets. Based on surveys and interviews, we will generate a task taxonomy for volume data analysis so that our results will be generalizable across domains.

Having addressed these three research questions individually, we will be able to provide specific design guidance regarding the choice of displays and interaction techniques for volume data analysis. We propose to demonstrate the use of these guidelines by designing an interactive visual analysis workstation that maximizes the benefit-to-cost ratio and is feasible for use in everyday volume data analysis work.

1.3 Transformative contributions

The aim of the proposed work is to transform the process of volume data analysis, not through new rendering or visualization techniques, but through the use of displays with higher levels of fidelity and innovative 3D interaction techniques. Through our empirical studies we will determine what combinations of display characteristics and user interface will result in improved efficiency, accuracy, understanding, and insight. Through our design research we will demonstrate how natural 3D interaction can be used to enable both analysis and interactive segmentation of volume datasets. Through our system development work we will show how these findings can be translated into practical solutions for volume data analysis users. If successful, this work will demonstrate how to transform volume data analysis from its current tedious, error-prone, and difficult-to-understand state into a rapid, intuitive, natural, and accurate process. Ultimately, this should result in breakthroughs in science, medicine, education, and many other fields.

2. Background

In this section we briefly summarize prior work on volume data analysis, immersive visualization, and 3D interaction with volume data.

2.1 Volume data analysis with traditional displays and interaction

Traditionally, researchers look at 3D volume renderings on desktop computer monitors or larger displays (GE-Healthcare 2012; Philips-CT-Scan 2012), which lack the more realistic visual stimuli found in more advanced displays, such as stereoscopic 3D graphics and motion parallax due to head tracking. Thus, it may be more difficult for the user to judge the size, shape, or depth of the structures in the volume data.

Judgments of this sort are required not only for general understanding, but also for performing interactive tasks such as segmentation of a dataset. Conducting such tasks with traditional displays, therefore, may result in slower performance and/or erroneous interpretation (Ragan 2012).

The most standard method used to enable volume data analysis is called *segmentation* (3D-Slicer 2012; Amira 2012; GE-Measurement-and-Control-Solutions 2012; Xradia-Solutions 2012), in which a transfer function for mapping the material properties is adjusted manually or automatically based on some thresholds, to mark out the regions of interest (ROIs) in the volume. Automatic segmentation techniques can be effective in some scenarios, but it is not always possible to find a transfer function that produces the desired results (Boykov 2001). Although manual segmentation can produce very good results, it is quite time-consuming and often requires very precise selection of ROIs in every slice of the volume. It can also be very subjective, with substantial differences occurring even between experts. Thus, it would be useful to have alternative techniques that allow analysis of volume data and viewing of an ROI without requiring segmentation.

The most widely used alternative is to remove all the voxels that occlude the important ones. Traditionally, scientists have used the standard orthogonal or axis-aligned slicing (AAS) technique, which gives axial, coronal, and sagittal slice views. The AAS technique has been actively and widely used by scientists and researchers around the world for decades as part of various free, open-source, and commercial software packages for volume data analysis, like MITO (MITO-DICOM-viewer 2012), 3D Slicer (3D-Slicer 2012), Amira (Amira 2012), Avizo (Avizo 2012), and others. Commercial 3D imaging hardware manufacturers, like Xradia (Xradia-Solutions 2012), GE (GE-Measurement-and-Control-Solutions 2012), GE healthcare (GE-Healthcare 2012), Toshiba (Toshiba-Medical-Systems 2012), Siemens (Siemens-Healthcare 2012), Philips (Philips-CT-Scan 2012) provide the AAS interaction as a de facto technique in the factory software that comes packaged with their hardware. However, the AAS technique presents only 2D views of the 3D dataset, and users require extensive training and experience before they can use it effectively, because they must mentally integrate the restricted 2D views into a 3D mental model (Tietjen 2006). The sectional anatomy shown by these tools is quite different from 3D anatomy and requires separate training to become adept at interpretation.

2.2 Immersive VR for volume data analysis

There have been prior uses of immersive VR for visualizing volume datasets from geophysics (Ohno 2007), biomedical sciences (Brady 1995), and other fields. Midttun et al. from Norway's Norsk Hydro (Midttun 2000) built a CAVE system (Cruz-Neira 1993), for use in designing/drilling production wells, and for seismic exploration using volume visualization. They claimed that the VR system produced measurable improvements in many of their work processes by lowering cycle time costs, and increasing recovery. However, immersive VR systems are still not commonly used for volume data analysis, in our estimation, perhaps because of a lack of evidence for the benefits of immersion, or because of the issues of cost, convenience, and workflow integration when using immersive VR facilities.

Researchers have run empirical studies to find the effects of using immersive VR for volume data analysis. Based on studies of visualizations of diffusion tensor magnetic resonance imaging (DT-MRI) datasets for brain tumor surgery (Zhang 2001), Zhang et al. reported that users could interpret the data better in a CAVE than with a desktop display. In another experiment with DT-MRI datasets using streamtubes and streamsurfaces (Zhang 2003), Zhang et al. reported that the stereoscopy and interactivity of the VR system aided in understanding complex geometric models. Prabhat et al. (Prabhat 2008) compared three display systems (desktop, fishtank VR, and CAVE), for various tasks with confocal datasets. They reported significant quantitative and qualitative benefits of the more immersive environments for analyzing volume data.

Not all studies reported benefits of higher levels of display fidelity for analyzing volume datasets. Demiralp et al. (Demiralp 2006) compared fishtank VR with a CAVE for task performance with an abstract visual search task, and reported that the users could perform the task significantly faster and with higher accuracy in the fishtank VR, as opposed to the CAVE environment. More recently, Chen et al. studied the effects of stereo and display size on five representative tasks performed with dense diffusion MRI (DMRI) data (Chen 2012). They found that task completion time was not improved by the larger display, and the use of stereo reduced accuracy of performance.

Many of these empirical studies reported significant effects of display fidelity for volume data analysis. But the problems with these results are twofold (Laha 2012b). First, most of these studies (with the exception of Chen 2012) have compared entire VR systems against each other. Thus, they failed to tie the observed significant effects to individual components of immersion, like field of regard, stereoscopy, and head-tracking (Slater 2003; Bowman 2007). As a result, they are not able to determine if a VR system with lower levels of immersion (thus with lower cost) might produce similar effects on task performance. Also, the results cannot be generalized to other domains of volume data or even to tasks in the same scientific domain, because the results were not tied to any generalizable task taxonomy for volume data analysis.

Our first two studies sought to address the first problem (Laha 2012c; Laha 2013b). We report the results of these studies in section 3.1. We discuss our plans to address the second problem in section 4.2.

2.3 3D interaction techniques for volume data analysis

Several researchers have designed 3D interaction techniques for analyzing volume datasets. Hinckley et al. designed a bimanual asymmetric interface allowing arbitrary 3D slicing (Hinckley 1994), based on Guiard's framework (Guiard 1987). Their technique used real-world props: a doll's head in the non-dominant hand to control the volume data, and a clear plastic plate in the dominant hand for the cutting plane. Going beyond simple cutting planes, researchers have used deformable cutting planes (Konrad-Verse 2004), clipping based on arbitrary geometry (Weiskopf 2003), and a filterbox tool (Mlyniec 2011). Others have proposed cutting tools like a rasp and knife for surgery training (Pflesser 1995), and scalpels, scissors, and forceps on volumetric meshes (Bruyns 2002). Sculpting metaphors have also been proposed (Wang 1995), and various sculpting tools like cutaway and ghost tools (Bruckner 2005), and tools for erasing, digging, and clipping have been explored (Huff 2006). Although these techniques allow the user to explore the volume in useful ways, they problematically cause the user to lose spatial context, because they remove voxels completely from the visualization.

This problem is addressed by the techniques of the second category, which are called *Focus+Context* techniques. They seek to preserve the entire volume, while letting the user focus on the ROI or the important details in various ways. One such approach is to use a 3D magnification lens metaphor, such as the Magic Volume Lens (Wang 2005), or the Conformal Magnifier (Zhao 2012). Some researchers have proposed focal-region-based feature enhancement (Zhou 2002), importance-driven volume rendering (Viola 2004), or energy optimization with distortion minimization (Wang 2008). All these magnifying or enhancing techniques, although highlighting the ROI over the surrounding areas in the volume, distort the volume or the ROI at least partially with respect to its neighboring structures. Also, many of these techniques are intended for use with segmented datasets. Thus they assume a partial and existing solution of the problem they are trying to address.

Other Focus+Context visualization techniques include layered browsing of volume data with an array of deformation tools (McGuffin 2003), and an exploded views approach (Bruckner 2006). These assume semantic layers in the volume data, which may not always exist, as discussed by McGuffin et al. (McGuffin 2003).

Our approach relies on using the two hands of the user for interaction with a volume. It lowers the cognitive load on the users through leveraging the muscle memory of the user by using postures from the real world (Leganchuk 1998; Balakrishnan 1999). We describe the design and evaluation of our first 3D interaction technique (Laha 2013a) based on this approach in section 3.2. Our plans to develop and evaluating a suite of 3D interaction techniques for volume data analysis and interactive segmentation are discussed in section 4.4.

3. Preliminary work

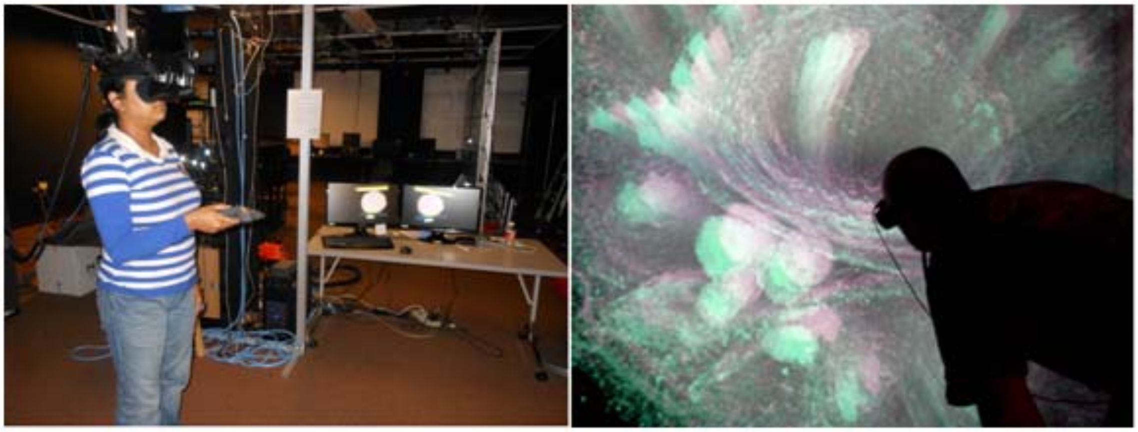
In this section we summarize our prior work, which partially addresses the research questions described in section 1.2. This research forms the foundation of the new work proposed in section 4.

3.1 Effects of higher display fidelity

We, like other researchers, have hypothesized that higher fidelity displays—those with advanced, more realistic features such as stereoscopic 3D graphics, wide field of view (FOV), large field of regard (FOR; the degree to which the display surrounds the user), "retina" resolution, and head-tracked rendering—should produce measurable positive effects for task performance with visualizations, including volume visualizations. We have aimed to demonstrate such effects through controlled experiments varying components of display fidelity independently. These are "simulation" experiments in the sense that we use a high-fidelity VR system to simulate lower-fidelity systems (e.g., by artificially reducing the FOV or by turning off stereo rendering). We call our approach *MR simulation* (Bowman 2012a) because we can in general simulate any lower-fidelity mixed reality (MR, which includes both AR and VR) display using a high-fidelity VR display, which we call the *MR simulator platform*.

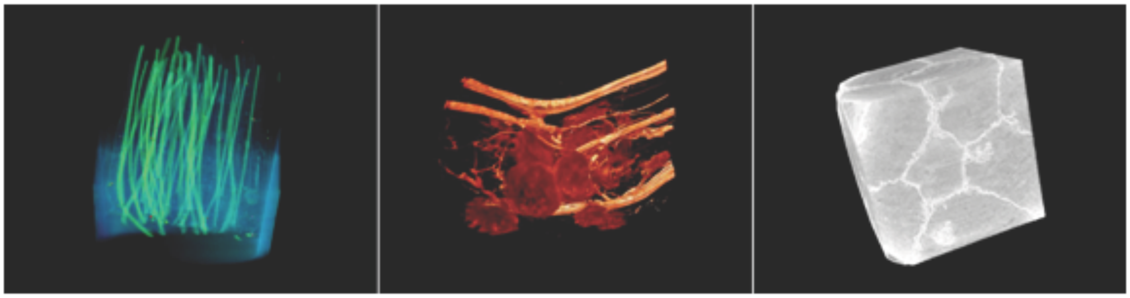
We have run two controlled experiments producing significant and generalizable results on the individual and combined effects of three components of display fidelity—FOR, stereoscopy, and head tracking (HT)—on task performance with volume datasets. Our first experiment used a CAVE (Figure 2b), while our second experiment used a head-mounted display or HMD (Figure 2a).

We used microscopic computed tomography (micro-CT) datasets from two different domains—a scaffold dataset (Figure 3a) and a mouse limb dataset (Figure 3b) from medical biology, and a fossil dataset from paleontology (Figure 3c). Two domain scientists—a PhD researcher from medical biology and a geophysics faculty member—worked closely with us in these two studies to define the various tasks of active interest in their research, and mapping those to different abstract and generalizable task categories. They also created grading metrics for formal evaluation of task performance in our studies. We measured task performance through grades and task completion time, and also gathered users' opinions on task difficulty and their confidence level in each response.



(a) A participant wearing the NVis SX111 HMD (b) A participant inside the Viscube (four-sided CAVE)

Figure 2: Participants using the Mixed Reality (MR) simulator platforms in our studies.



(a) 3D Scaffold dataset *(b) Mouse Limb dataset* *(c) Fossil dataset (Parapandorina)*

Figure 3: The volume-visualized microscopic computed tomography (micro-CT) datasets from our study.

The first study was run with 59 participants and produced several significant quantitative and qualitative effects of FOR, stereoscopy, and HT. In particular, we found that a 270-degree FOR (equivalent to three walls of the CAVE) was significantly better than a 90-degree FOR (one wall) for a variety of tasks. The combination of high FOR and HT, and the condition with low FOR without HT were both better than other combinations of those variables. Both stereo and HT improved performance for spatially complex search tasks. The results of this study improved our understanding of the effects of display fidelity on perceived and actual task performance, and provided guidance on the choice of display systems to designers seeking to maximize the effectiveness of volume visualization applications. Complete study description and results can be found in (Laha 2012c).

Our second study, in which 65 participants volunteered, extended the results from our first study by producing finer-grained results for the interactions between FOR and HT. For example, the graph on the left in Figure 4 shows such an interaction from the first study, in which the best performance is obtained with a 270-degree FOR and HT on, but we cannot tell what happens at levels of FOR between 90 and 270, or levels greater than 270. In our second study, we used four levels of FOR (90, 180, 270, and 360). The results for the same task are shown in the right-hand graph in Figure 4. We can see that an FOR of 270 or higher was required to gain the task performance benefits for this task when HT was on.

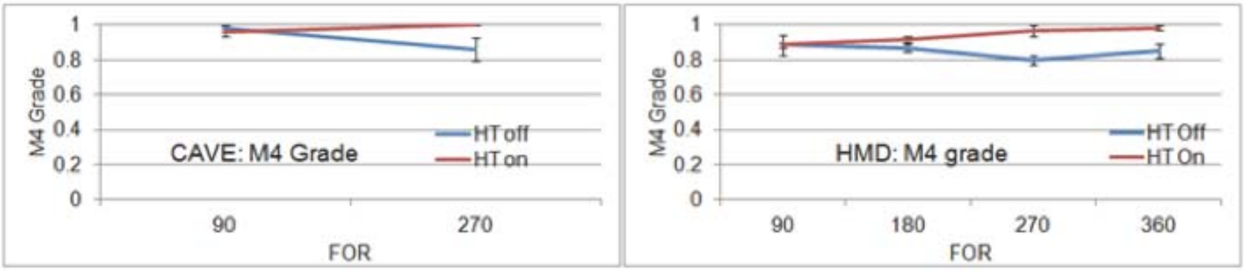


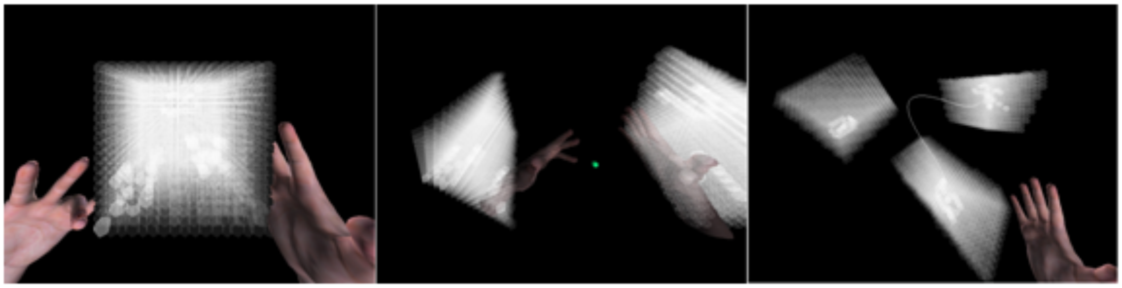
Figure 4: Interactions between field of regard (FOR) and head tracking (HT) for searching blood vessels

Comparison of the results from the two studies provided some evidence for the validity of the MR simulation approach for volume data analysis (Laha 2013b). The MR simulation approach suggests that any VR system could be recreated along the MR continuum (Milgram 1994) based on the levels of the different components of display fidelity. Validation of this approach for various tasks performed with volume data allows us to generalize our significant findings to any VR platform based on the levels of the components of display fidelity (Bowman 2012a).

3.2 3D interaction technique design

Based on interest shown by the domain scientists working with us (section 4.1), and feedback from the participants in our studies (section 3.1), we designed a new 3D interaction technique to address the drawbacks in the existing tools and techniques for volume data analysis (section 2.3), called the *volume cracker* (VC) (Figure 5).

In VC, the user uses her two hands to naturally crack open a volume, like we crack open a crab leg, to look at the structures inside. VC provides a cracking preview, which informs the user how the cracking will occur. The cracking preview is updated in real-time based on the relative position of the user's hands. After cracking, the two sub-volumes are joined by a curve preserving the context. A bimanual grab feature allows the user to open up the cracked faces like a book, to look at the internal features easily. Bimanual movement and rotations of connected sub-volumes relative to each other is restricted on a plane to preserve the integrity of the structures. VC allows recursive cracking of the sub-volumes, until the user has separated out the ROIs in separate sub-volumes, enabling a better view of the internal structures. The user can put the connected volumes back together by bringing them close, and releasing the grab.



(a) A simulated volume dataset *(b) The cracking preview* *(c) The cracked sub-volumes*

Figure 5: The Volume Cracker interaction technique

We ran a study to compare VC with a standard desktop interaction technique (AAS), and a widely known 3D interaction technique of arbitrary slicing (AS) for analyzing volume data (Hinckley 1994; Billen 2008). We found that VC had significant advantages over both the AAS and AS techniques for search and pattern recognition tasks in volume datasets (Laha 2013a). A short video outlining the design and evaluation of the volume cracker is available online (Volume-Cracker 2012).

One challenge for volume data analysis in immersive displays is that there is no keyboard or mouse. We have developed a number of interaction techniques that leverage gestures, body motion, 3D tracking, and other interaction mechanisms to perform biology-related volume data analysis. CavePainting is, perhaps, the most actively used, even ten years later. Users author 3D virtual reality worlds using its navigation, rich and efficient techniques for creating 3D surfaces, and ability to script temporal scenarios (Keefe 2001; Keefe 2007). Within CavePainting, several interaction styles for "painting" were implemented, experimentally compared, and formally modeled (Keefe 2007). Other scientific applications developed included Particle Flurries and an earlier unnamed system (Forsberg 2000; Sobel 2004); and ARCAVE, a system for studying archaeological artifacts in the spatial context they were discovered (Acevedo 2001). Each system was formally evaluated to establish overall utility as well as a better understanding of the strengths and weaknesses of visual representations and 3D interface techniques employed. We also created and evaluated several custom input devices for use in our virtual environments (LaViola 2004). One was a two-level button for navigation and interaction (Zeleznik 2002). A second allowed for hands-free navigation in VR (LaViola 2001).

We expect to identify, throughout the period of the proposed research, opportunities to continue this kind of interaction technique development and to incorporate it into our volume data analysis tools.

4. Proposed research

In this section we detail the research we will undertake to address the research questions in section 1.1.

4.1 Involvement of domain scientists

Although we are seeking fundamental, domain-independent advances in displays and interaction for volume data analysis, we recognize that our work *must* be informed by the tasks, problems, and experience of experts from various domains who work with volume datasets. Therefore, we will work closely with scientists throughout the project. In particular, Jake Socha at Virginia Tech (a co-PI on this proposal) and Kristi Wharton at Brown (see attached letter of support) will provide us with datasets, discuss problems and tasks of interest, give feedback on the user interfaces we design, and help us to find expert participants for our user studies.

Research in the Socha Lab focuses on comparative biomechanics, broadly investigating issues related to the biomechanics of flows in and around organisms. Currently, this theme encompasses two lines of work: 1) behavior, biomechanics, and aerodynamics of gliding flight in vertebrates, particularly flying snakes; 2) physiology and biomechanics of internal convective flows involved in breathing, feeding, and circulation in insects. A critical technique of the lab is the use of synchrotron x-rays to visualize movements within the insects, and to understand the corresponding anatomy with high resolution using synchrotron micro-CT (SR-μCT). The work of the lab also encompasses bio-inspired engineering, which aims to create novel designs based on the studied physiological mechanisms and discovered phenomena.

Our main biology collaborator at Brown, Prof. Kristi Wharton, studies cellular communication and its role in the motion of cells, their growth, and their differentiation during the development of multi-cellular organisms. She has collaborated with our group in the past, using a room-size virtual-reality display built in 1998, and is enthusiastic about extending that collaboration with the new virtual-reality room we are currently building. She also has had large-screen monitor-based stereo display stations installed in her lab as a way to bring some aspects of immersive VR back to her more local research environment.

Other domain experts we currently have relationships with include Dr. James Schiffbauer (Department of Geological Sciences, University of Missouri), Dr. Scott King (VT Department of Geophysics), Kriti Sen Sharma (VT PhD candidate studying micro-CT scanning), and Sharmistha Mitra (VT PhD candidate in Molecular Biology and Biophysics),. We are also in touch with Dr. Mike Munley (Radiation Oncology, Wake Forest University), and Josh Tan (Center for Injury Biomechanics, Wake Forest University) who work daily with volume datasets in their research.

4.2 Requirements analysis and task taxonomy

In order to meet the needs of domain experts for volume data analysis tools, we will first perform a requirements analysis, including surveys, interviews, and observation of laboratory work. We will gather requirements from scientists to understand their current and anticipated use of volume data in research, and to describe the most important current problems hindering the effective use of volume visualization.

A critical piece of this research is to understand what questions domain experts are trying to answer when analyzing volume datasets, and what tasks they must complete to answer those questions. We hypothesize that there is a relatively small set of fundamental abstract tasks that are used by scientists in volume data analysis, regardless of domain. Thus, we propose to develop a *task taxonomy* (research question 3; see section 1.1) as part of our requirements analysis. Based on our preliminary work, we have a draft framework, including six task categories (search, pattern recognition, spatial understanding, path following, quantitative estimation, and shape description). We are planning to refine the taxonomy by interviewing and talking to more domain scientists and researchers, by running a survey targeting a wider population of domain scientists, researchers, and graduate students who work with volume data on a daily basis, and by matching the task categories with those suggested through guidelines created by a recent DICOM consortium.

We will use the task taxonomy to develop tasks for the user studies on display fidelity (research question 1) and interaction techniques (research question 2). After running these experiments, we will have evidence for predicting the effects of display fidelity components and 3D interaction tools on the various volume data analysis tasks.

4.3 Display fidelity experiments

Our previous studies (Laha 2012c; Laha 2013b) looked at the effects of display fidelity and the validation of MR simulation (section 3.1). We want to know if the significant findings from these experiments are generalizable to domains other than paleontology and medical biology.

Our prior research also touched upon very few of the groups from our task taxonomy (section 4.2). For a complete understanding of the effects of display fidelity on a variety of task types, we need to run MR simulation studies with tasks covering all the groups from our generic task taxonomy.

To address these issues and questions, we propose to run additional controlled experiments comparing conditions created by various levels of different components of display fidelity, and produced by multiple MR platforms, for task performance with volume datasets. Co-PI Socha will provide some of the volume datasets for our studies, including both segmented and unsegmented datasets (see Figure 6). He is also working closely with us to define the tasks from his active research to formally evaluate in our experiment, and mapping these tasks to our generic task taxonomy (section 4.2).

In the first study, using tracheal datasets such as the one shown in Figure 6, we plan to compare two levels of field of regard (FOR: 90° and 180°), and two levels of head tracking (HT: on and off). We also plan to compare the levels of fidelity produced by two different MR simulator platforms—a head-mounted display and a two-wall rear-projected stereoscopic display, which we call the Viswall. Thus our final design would be 2x2x2 = 8 conditions for our study. Of these, the MR platform variable needs to be within subjects to have results from participants with comparable spatial abilities. The other conditions need to be between subjects, to avoid learning effects, producing four distinct groupings in our study as shown in Table 1.

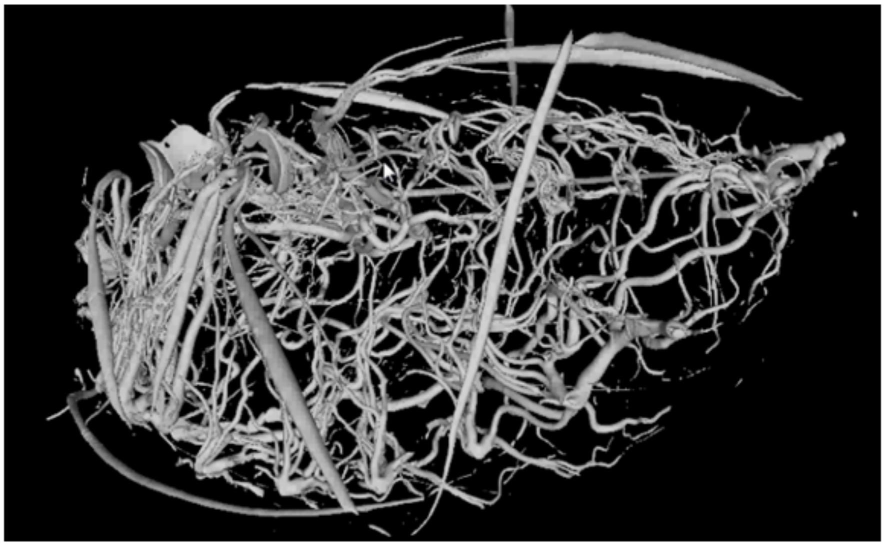


Figure 6: The rear portion of the tracheal system in an insect (a carabid beetle).

We have two research questions for this study, and two corresponding hypotheses, based on observations and results from previous research studies:

RQ1. What are the individual and combined effects of FOR and HT?

H1. Higher levels of FOR and HT will produce best task performance overall. Conditions with "FOR high HT on" and "FOR low HT off" will give better results than the other conditions. These are based on findings from prior studies (Laha 2012c; Laha 2013b).

RQ2. Are the fidelity conditions from two MR simulator platforms comparable?

H2. The results produced from two MR simulator platforms should be comparable if the simulated conditions are created through similar levels of various components of display fidelity. Results from prior studies support this hypothesis (Lee 2010; Bowman 2012a; Lee 2012; Laha 2013b).

Table 1: The Different Variables and conditions in the study

MR platforms (within subject variable)	FOR 90°		FOR 180°	
	HT on	HT off	HT on	HT off
HMD	Group 1	Group 2	Group 3	Group 4
Viswall				

We will continue to study different tasks, application domains, and components of display fidelity through similar controlled experiments at Virginia Tech throughout the duration of the project. We will aim to have covered a significant portion of this space by the end of the project, in order to develop guidelines and systems (section 4.5) that will provide real benefits based on empirical data for users of volume data analysis tools.

Early in year 2 of the proposed work, the volume data analysis software developed at Virginia Tech will be made operational at Brown on several display devices. These will include our new "retina-display" VR Cave, several large-screen monitor stereo displays, and monocular desktops. The software will also be modified, if necessary, to support the data formats and any other specific needs of the Brown biologists studying confocal microscopy data.

The retina-display Cave is unique to Brown and provides a display environment that is, in some ways, unsurpassable. The pixels of the display project onto a viewer's retina at the same spacing as the detector cells in the retina. The display is rear projected, with projector images overlapping and blended to provide a single seamless display surface. Because of this, the display can not only avoid the artifacts of many other large tiled LCD displays, it can also mimic them, with virtual boundaries between virtual displays, permitting more direct evaluation of the impact on users of these artifacts.

We will perform experiments with users in these environments, evaluating the effects of varying display fidelity and the preferences of the users. These experiments will follow the form we used in (Schulze 2005).

4.4 Design and evaluation of 3D interaction techniques

In section 3.2 we described the design and evaluation of Volume Cracker (VC) interaction technique. Based on participant feedback and our observations, we are planning to extend the design of VC by adding an asymmetric bimanual interface, in which the left hand will provide the frame of reference, and the right hand will be able to make finer manipulations on the data, based on Guiard's framework (Guiard 1987). This design will leverage a magnet metaphor, in which, as the right hand hovers around the volume, different voxels cling to it (like pieces of iron cling to a magnet), based on the position of the hand relative to the volume. The separation between the hands will determine how many voxels are attracted towards the right hand, and from what depth inside the volume the voxels come. The relative positions of the hands will determine from which face of the volume the voxels get attracted towards the right hand.

Based on the contours created by the right hand palm and fingers, we can modify the shape of the surface separating the two sub-volumes, along which the volume will crack. We are currently brainstorming different shapes of the cutting surface. We also want to consider how many of these shapes can be intuitively created by the user, without feeling the need to keep the shapes in their active memory. This will help reduce mental load on the user.

Aside from the extension to the VC, we are planning to design additional interaction techniques. Preliminary ideas include the following:

Volume Expander (VX): This design will involve making a hole in the volume, passing through to the center of the ROI, and then blowing air through it to blow up the volume internally, so that we can see the ROI and the associated structures from inside. This design is inspired by the sphere expander tool of McGuffin et al. (McGuffin 2003), and the exploded views by Bruckner et al. (Bruckner 2006).

Volume Scooper (VS): This is very similar to the VC extension discussed above, except that the 3D surface created by the right hand is used here to clear out the voxels surrounding the surface, exposing the inner layers (or scooping out the ROI). When the user closes the fist of the right hand, we can either confirm the removal of the voxels, which are clipped already, or we can define the outline of a portion of the remaining volume, which will be separated out and grabbed by the right hand.

Volume Peeler (VP): The design involves peeling off the voxels on top of any face or edge to expose the ones lying beneath. We can peel off geometric layers that are axis-aligned or oriented about any arbitrary axis.

Volume Grater (VG): This design will consist of grabbing the volume with the left hand and holding a grater or chisel with the right hand. The user will use the grater to remove the voxels from the volume, from any side of it, to expose inner structures. We can have different shapes of chisels offering various affordances for grating.

VS, VP, and VG suffer from the problem of losing context through removal of some voxels, but we believe these techniques would be useful in situations where users analyze ROIs in isolation, and removal of unwanted voxels will only speed up their analysis. The utility of such techniques may be realized in tasks such as pattern recognition (see section 4.2), where the researcher wants to separate or isolate structures or ROIs for closer analysis.

We may, however, choose to preserve the voxels by displacement, like the tools in McGuffin et al. (McGuffin 2003), but we will need to verify that for what task types (section 4.2) the preservation of voxels/context is really essential, and for which it could be detrimental, due to increased mental workload from any extra information not required for the task at hand.

4.4.1 Suite of 3D Interaction Tools for Interactive Segmentation of Volume Data

Manual segmentation of a typical raw volume dataset involves marking the ROI in orthogonal slices through the entire length of a volume, along any of the orthogonal axes. This may take from a few hours to a few days of focused and hard work by an experienced researcher to complete to her satisfaction. An automated segmentation might be quicker, but often the extrapolation algorithms that segment surfaces through the volume do not live up to the users' expectations.

We propose to design a suite of 3D interaction techniques, using the metaphors discussed above (VC, VX, VS, VP, and VG) and others, allowing users to quickly perform a *coarse* and *interactive segmentation* of a raw volume dataset to look more closely at the ROI. The goal will be to reduce hours/days worth of work to a few minutes, allowing more time to be spent on analysis and less on *preparing* for analysis.

Our process will involve using one or more of the techniques from our suite to clear out unwanted voxels, and to break the remaining useful volume in connected or disconnected sub-volumes with ROIs that the scientists want to analyze closely. Further use of the removal tools (VG and VP) would allow finer definition of the boundaries of the sub-volume, and isolation of the ROIs they want to analyze. Another method would be to interactively mark particular voxels, regions, or paths in 3D space. The interactive segmentation will be rough, but will be enough to make correct judgments in many cases, and will be able to inform easier and faster selection of ROIs for a follow-up manual segmentation in other cases.

We will also explore whether the interactive segmentation can be combined with automatic approaches in a semi-supervised learning method to take advantage of both the processing power of the computer and the intuition and domain knowledge of the user. For example, the user may interactively mark some portion of a structure as an ROI, and the system may learn from this example what sorts of voxels and structures are of interest in the remainder of the dataset, segmenting them automatically. This approach holds great potential to reduce the time spent in segmentation, while producing high-quality results.

4.4.2 Evaluation of the designed 3D Interaction Techniques

To determine the effectiveness of the designs of the 3D interaction techniques, we need to evaluate their performance for tasks in the different task categories of the task taxonomy. We will run several short user studies comparing these various techniques with AAS and AS (section 3.2), and among themselves. Each study will pick one or two of these techniques, and the task categories (section 4.2) in which they promise to show benefits of task performance, and evaluate them for tasks in those categories of the task taxonomy. Each study will inform the design of the subsequent studies.

Currently we have a set of preliminary hypotheses based on anecdotal and perceived evidence of the benefits of these various techniques to the different task categories in our task taxonomy (section 4.2), considering each technique is used in isolation. Table 2 below summarizes our hypotheses. A tick mark (√) in a box indicates a possible benefit of using the technique shown in the corresponding column, for the task type shown in the corresponding row.

Table 2: Hypotheses about the proposed 3D interaction techniques for the tasks in our task taxonomy

Task Types	VC	VX	VS	VP	VG
Search	√	√	√	√	√
Pattern Recognition	√		√	√	
Spatial Understanding	√		√		√
Path Following			√	√	√
Quantitative Estimation	√	√		√	√
Shape Description	√	√	√		√

4.5 Design of next-generation volume data analysis system

To put our findings on display fidelity (section 4.3) and 3D interaction (section 4.4) to a practical test, we plan to design and prototype a powerful but affordable interactive visual analysis workstation for scientists working with volume data. The design of this system will be based on the following criteria:

- *Insight generation*: the most important measure of success for volume data analysis is whether users gain insight about the data by using the system. Based on the results of our quantitative and qualitative analyses of various displays and interaction techniques, our system will be designed to enhance insight.
- *Accuracy and efficiency*: speed and accuracy are traded off against one another in any interactive system, but our experimental results should indicate to us which combinations of display characteristics and interaction techniques provide the most appropriate balance of speed and accuracy.
- *Cost*: the system needs to be affordable to make it a practical tool for working scientists, physicians, and other users.
- *Convenience*: users will be most likely to use the system if it can be located in the office or laboratory where they work (as opposed to a special facility somewhere else), if it is portable or modular, and if it fits into their existing workflow.

The design of the system depends on the findings from our proposed experiments, so we cannot describe it precisely here. But we envision a semi-immersive display based on large monitors or small projection screens, with stereoscopic graphics and precise head and hand tracking. Emerging consumer-level technologies such as 3D TVs, the Microsoft Kinect, the Leap Motion device, and the zSpace 3D desktop should help to make such a system affordable and easy to construct.

We will collaborate with Fluidity Software (see attached letter of support) in designing this system. Fluidity has experience designing practical systems for domain scientists working with visualization.

4.6 Longitudinal evaluation

Based on the initial survey results from domain scientists during year 1, we will follow up on at least a semi-annual basis with written surveys and oral interviews. Our interview approach will be to have the biologists work in pairs to promote speaking aloud. One of the pair will begin by articulating her scientific hypotheses and goals for a session using one of the volume data analysis environments. Once in the display environment, we will ask that she describe what she is doing and what goal she is addressing. We will remind the pair of the need to speak out throughout the session. The second scientist will serve as an audience, sounding board, and collaborator. The session will be recorded, and we will code it for insight generation (Saraiya 2005), which will be our primary quantitative measure. We will also identify effective or awkward interface aspects to address in subsequent versions. Finally, we will log use of the volume data analysis system in various environments throughout the period of the research. We hypothesize that use, engagement, and effectiveness with the system will increase as we make requested changes to the software, as the biologists better understand the benefits that 3D volume analysis may offer them, and as they incorporate that knowledge into their workflows. We will capture and report our ethnographic findings on those processes.

4.7 Tasks and timeline

Table 3 lists the tasks involved in completing this research. For each task, we identify the expected timeframe and leadership.

Table 3. Tasks and Timeline

Task	Expected timeframe	Task Leader
Requirements analysis (section 4.2)	Summer—Fall 2013	Bowman
Task taxonomy (4.2)	Summer 2013—Spring 2014	Socha
Display fidelity controlled experiments (4.3)	Fall 2013—Spring 2015	Bowman
Display fidelity qualitative experiments (4.3)	Spring 2014—Spring 2015	Laidlaw
Interaction technique design (4.4)	Spring 2014—Fall 2015	Bowman
Interaction technique evaluation (4.4)	Spring 2014—Fall 2015	Bowman
Design of next-generation system (4.5)	Fall 2015—Spring 2016	Bowman
Longitudinal evaluation (4.6)	Fall 2015—Spring 2016	Laidlaw

5. Broader impacts

The proposed work will provide a deep understanding of ways to innovate in the realm of volume data analysis. Easier, more accurate, and faster analysis can lead to improvements in healthcare, breakthroughs in science, and advances in education.

For example, in co-PI Socha's lab, our work may lead to insights into fundamental physiological mechanisms of feeding, breathing, and circulation in insects—one of the most important animal groups on earth. There are millions of insect species living in almost every habitat, and their lifestyles have profound impacts on human societies. Their effects in areas such as agriculture and health can be both positive (e.g., pollination) and negative (e.g., crop damage, disease), and understanding their fundamental physiologies is critical to controlling their impact.

We will leverage this project to improve education at both the K-12 and university levels. For example, we will develop educational efforts with local school systems to integrate the biomechanics of insects across the disciplines of biology, physical science, physics, and chemistry. In the university, we will educate undergraduate and graduate students in the classroom and the laboratory. The material developed here will be used in an interdisciplinary engineering physiology course taught by Socha. We will also contribute to an active IGERT program (MultiSTEPS) that trains graduate students at the interface between the engineering and biological sciences. The work proposed here will be interwoven with the research activities for new IGERT trainees, and can help provide a source of trainee support once their initial IGERT support is complete. Bowman will incorporate the findings into courses on human-computer interaction, virtual environments, and 3D interaction.

We will also use our research program to provide benefits to underrepresented groups. We will actively recruit women and minorities to work on this project (e.g., through undergraduate research or summer research programs). We will leverage our work to help recruit underrepresented groups to computer science through demonstrations and presentations for organizations such as the Association for Women in Computing (which runs an annual "Women in Computing Day" aimed at middle-school girls) and the Center for Enhancement of Engineering Diversity (which runs summer programs to recruit minorities to engineering and programs for first-year engineering students at Virginia Tech).

6. Results of prior NSF support

Bowman was the Principal Investigator on NSF Award #0237412, "CAREER: Domain-Specific 3D Interaction Techniques for Design and Construction Tasks in Immersive Virtual Environments," $500,000, 2003-2008. We investigated the potential for designing 3D interaction techniques with domain characteristics built in, rather than using generic techniques. Using the architectural domain as a testbed, we designed and evaluated a large number of domain-specific techniques for 3D modeling. We also developed tools to aid in the implementation of complex 3D user interfaces. The work resulted in a book on 3D UIs, two Ph.D. dissertations, and a variety of other publications (Chen 2004; Bowman 2005a; Lucas 2005b; Chen 2006; Wingrave 2008; Chen 2009; Wingrave 2009).

Laidlaw is the PI on an active NSF award OCI-0923393, "MRI: Development of a Next-Generation Interactive Virtual-Reality Display Environment for Science" $2M, 2009-2013. At this time, the display is under construction, and so there are not yet publications resulting from the award. Some of the broader impact will be in results from studies that the display enables, like the ones proposed in this submission. Additional impact will come from discoveries that will be made using the new display in fluid dynamics, biology, physics, and archaeology. Laidlaw is also a Co-PI on a collaborative award IIS-1016623, "GV: Small: Collaborative Research: Supporting Knowledge Discovery through a Scientific Visualization Language," $269K, 2010-2013. Publications include (Gomez 2010; Gomez 2011; Ziemkiewicz 2012) from Laidlaw's site at Brown along with several others from their collaborative sites. All are aimed at improving the scientific analysis of diffusion MRI data. The broader impact will be in a better understanding of brains and of how they can effectively be studied.

Socha is the PI of an NSF award, 0938047, "EFRI-BSBA: Complex Microsystem Networks Inspired by Internal Insect Physiology," which commenced in 2010. He leads a large multidisciplinary team, including engineers and biologists, to study how insects move fluids through their bodies and to derive new engineering principles for novel fluidic applications. To date we have produced 6 journal papers and 8 conference papers. Socha also runs an EFRI-REM (Research Experience and Mentorship) program, which mentors high school teachers, high school students, and undergraduates, which is related to this grant. Socha is a co-PI of a new NSF-IDBR program, 1152304, "Instrument development for three-dimensional fluid flow measurements of freely-flying animals," which just commenced in July 2012. This project is highly relevant to the current proposal, as the IDBR will develop computational methods for tracking 3D airflows around freely flying animals, which could provide valuable additional insight to the work proposed here.

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Education

Emory University, Atlanta, Georgia	Math/Computer Science	B.S.	1994
Georgia Institute of Technology, Atlanta, GA	Computer Science	M.S.	1997
Georgia Institute of Technology, Atlanta, GA	Computer Science	Ph.D.	1999

Appointments

Professor	Virginia Tech, Computer Science	08/01/12 – present
Director	Center for Human-Computer Interaction	08/01/11 – present
Associate Professor	Virginia Tech, Computer Science	08/01/05 – 07/31/12
Visiting Researcher	UCSB, Computer Science	08/01/08 – 07/31/09
Assistant Professor	Virginia Tech, Computer Science	08/10/99 – 07/31/05

Selected Funded Research

- T. Höllerer, **D. Bowman**, “Evaluating the Effects of Immersion on Naval Training Applications.” Office of Naval Research, September 2009-August 2013, $1,160,886.
- F. Quek, **D. Bowman**, W. Winchester, Y. Xiong, and D. Tatar, “CRI: Interfaces for the Embodied Mind.” NSF Computing Research Infrastructure Program, March 2006-March 2008, $400,000.
- **D. Bowman**, “CAREER: Domain-Specific 3D Interaction Techniques for Design and Construction Tasks in Immersive Virtual Environments.” NSF CAREER program, June 2003-May 2008, $500,000.
- M. Gutierrez, M. Mauldon, J. Dove, E. Westman, and **D. Bowman**, “ITR: Adaptive and Real-Time Geologic Mapping, Analysis and Design of Underground Space (AMADEUS).” NSF Information Technology Research program, Sept. 2003-August 2007, $1,067,117.
- **D. Bowman**, “3D Interaction and Information-Rich Virtual Environments for Building Security Visualization.” Robert Bosch Research and Technology Center, Jan. 2006-Dec. 2008. $140,869.

Selected List of Publications

- Ragan, E., Kopper, R., Schuchardt, P., and **Bowman, D.** Studying the Effects of Stereo, Head Tracking, and Field of Regard on a Small-Scale Spatial Judgment Task. To appear in *IEEE Transactions on Visualization and Computer Graphics*, 2012.
- **Bowman, D.**, McMahan, R., and Ragan, E. Questioning Naturalism in 3D User Interfaces. *Communications of the ACM*, vol. 55, no. 9, September 2012, pp. 78-88.
- McMahan, R., **Bowman, D.**, Zielinski, D., and Brady, R. Evaluating Display Fidelity and Interaction Fidelity in a Virtual Reality Game. *IEEE Transactions on Visualization and Computer Graphics* (Proceedings of IEEE Virtual Reality), vol. 18, no. 4, 2012, pp. 626-633.
- Laha, B., Sensharma, K., Schiffbauer, J., and **Bowman, D.** Effects of Immersion on Visual Analysis of Volume Data. *IEEE Transactions on Visualization and Computer Graphics* (Proceedings of IEEE Virtual Reality), vol. 18, no. 4, 2012, pp. 597-606.

- Ragan, E., Wood, A., McMahan, R., and **Bowman, D.** Trade-Offs Related to Travel Techniques and Level of Display Fidelity in Virtual Data-Analysis Environments. *Proceedings of the Joint Virtual Reality Conference*, 2012, pp. 81-84.
- **Bowman, D.** and McMahan, R. Virtual Reality: How Much Immersion is Enough? *IEEE Computer*, vol. 40, no. 7, 2007, pp. 36-43.
- **Bowman, D.** and Schuchardt, P. The Benefits of Immersion for Spatial Understanding of Complex Underground Cave Systems. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, 2007, pp. 121-124.
- **Bowman, D.**, Kruijff, E., LaViola, J., and Poupyrev, I. *3D User Interfaces: Theory and Practice*. Addison-Wesley, Boston, 2005.

Selected Courses

- *3D Interaction*: An advanced graduate seminar on 3D user interfaces and 3D interaction techniques. Students learn about and experience the state-of-the-art in 3D interaction technologies and software techniques. Students also complete a semester project involving the design and evaluation of novel 3D interaction techniques. Student projects are submitted for publication at leading academic conferences.
- *Virtual Environments*: Students learn the basics of VE technology and software, and complete a semester research project in which they design and run an experiment to evaluate the benefits of immersion.

Synergistic Activities

- General chair, IEEE Virtual Reality conference, 2007-2008.
- Director, 3DI research group, Virginia Tech
- Organizer and speaker, short course on 3D User Interfaces, ACM CHI 2008, 2009, IEEE Virtual Reality 1999, 2000; ACM VRST, 1999; ACM SIGGRAPH, 2000, 2001.

Recent Collaborators

Dr. J. Gabbard (Virginia Tech), Dr. T. Höllerer (UC Santa Barbara), Dr. D. Krum (Bosch RTC), Dr. J. LaViola (University of Central Florida), Dr. C. North (Virginia Tech), Dr. M. Pinho (PUCRS, Brazil), Dr. I. Poupyrev (Sony Computer Science Labs), Dr. F. Quek (Virginia Tech).

Advising

- Bowman’s advisor: Dr. Larry F. Hodges (currently at Clemson University)
- Marcio Pinho, Ph.D. Topic: Cooperative 3D manipulation. (Graduated 2002).
- Wendy Schafer, Ph.D. Topic: Spatial collaboration. (Graduated 2004).
- Jian Chen, Ph.D..Topic: Domain-specific 3D interaction techniques. (Graduated 2006).
- Nicholas Polys, Ph.D. Topic: Information-rich VEs. (Graduated 2006).
- Andrew Ray, Ph.D. Topic: Tools for 3D UI implementation. (Graduated 2008).
- Chadwick Wingrave, Ph.D. Topic: 3D UI development methodology. (Graduated 2008).
- Yi Wang, Ph.D. Topic: Contextualized Video interfaces. (Graduated 2010).
- Régis Kopper, Ph.D. Topic: Distal Pointing interfaces. (Graduated 2011).
- Tao Ni, Ph.D. Topic: Freehand gesture interaction. (Graduated 2011).
- Ryan McMahan, Ph.D. Topic: Display and interaction fidelity (Graduated 2012).
- Eight M.S. graduates

John J. Socha
Engineering Science and Mechanics
Virginia Polytechnic Institute and State University
jjsocha@vt.edu; http://www.esm.vt.edu/~jjsocha

Professional Preparation

Duke University, Physics and Biology, B.S., 1994
University of Chicago, Organismal Biology and Anatomy, Ph.D., 2002
Field Museum of Natural History, Postdoctoral Researcher, 2003 – 2004
Argonne National Laboratory, Ugo Fano Postdoctoral Fellow, 2004 – 2007
Argonne National Laboratory, Research Scientist, 2007 – 2008

Appointments

<u>Assistant Professor</u>, Department of Engineering Science and Mechanics, Virginia Tech, 2008-present
<u>Core Faculty</u>, School of Biomedical Engineering and Sciences, Virginia Tech and Wake Forest University, 2008-present
<u>Adjunct Faculty</u>, Department of Biological Sciences, Virginia Tech, 2008-present
<u>Lecturer</u>, Division of Biological Sciences, University of Chicago, 2004-2008

Publications *(http://www.esm.vt.edu/~jjsocha/Publications.html)*

Most closely related to the proposed activity:

Simon, M.A., W.A. Woods, Y.V. Serebrenik, S.M. Simon, L.I. van Griethuijsen, **J.J. Socha**, W.-K. Lee, and B.A. Trimmer. 2010. Visceral-locomotory pistoning in crawling caterpillars (*Manduca sexta*). *Current Biology* 20: 1-6.

Lee, W.-K. and **J.J. Socha**. 2009. Direct visualization of hemolymph flow in the heart of a grasshopper (Schistocerca americana). *BMC Physiology* 9:2. [‘Highly accessed’ status]

Socha J.J., F. De Carlo. 2008. Use of synchrotron tomography to image naturalistic anatomy in insects. In: *Developments in X-Ray Tomography VI: 2008*; San Diego, CA, USA: SPIE; 2008: 70780A-70787.

Socha, J.J., M.W. Westneat, J.F. Harrison, J.S. Waters, and W.-K. Lee. 2007. Real-time phase-contrast x-ray imaging: a new technique for the study of animal form and function. *BMC Biology* 5:6. [‘Highly accessed’ status]

Kaiser, A., C.J. Klok, **J.J. Socha**, W.-K. Lee, M.C. Quinlan, J.F. Harrison. 2007. Increase in tracheal investment with beetle size supports hypothesis of oxygen limitation on insect gigantism. *Proceedings of the National Academy of Sciences of the United States of America* 104 (32): 13198-13203.

Other significant publications:

Webster, M., R. De Vita, J. Twigg, **J.J. Socha**. 2011. Mechanical properties of tracheal tubes in the American cockroach (*Periplaneta americana*). Accepted, Journal of Smart Materials and Structures.

Socha J.J., K. Miklasz, F. Jafari, P.P. Vlachos. 2010. Non-equilibrium trajectory dynamics and the kinematics of gliding in a flying snake. *Bioinspiration and Biomimetics*, 5 (2010) 045002. [featured on cover]

Socha, J.J., W.-K. Lee, J.F. Harrison, J.S. Waters*, Fezzaa, K., M.W. Westneat. 2008. Correlated patterns of tracheal compression and convective gas exchange in a carabid beetle. *Journal of Experimental Biology* 211: 3409-3420. [cover]

Socha, J.J. 2006. Becoming airborne without wings: the kinematics of takeoff in a flying snake, *Chrysopelea paradisi*. *Journal of Experimental Biology* 209 (17): 3358-3369. [cover article]

Socha, J.J. 2002. Gliding flight in the paradise tree snake. *Nature* 418: 603-604.

Synergistic Activities

- **Chair of the Public Affairs Committee**, Society for Integrative and Comparative Biology. I have initiated and led the development of new programs including a student science journalism mentorship. The results of the first six mentorships can be seen currently at http://sicb.org.
- **Developed multiple new biomechanics courses** at the University of Chicago: "Animal Locomotion" and at Virginia Tech: "Mechanics of Animal Locomotion." This latter course has recently been adopted as a permanent two-semester course series for undergraduate and graduate students. It is taught in a cross-disciplinary fashion for engineering and science students.
- **Organized and hosted the 2010 Joint DCB/DVM Southeast Regional SICB Meeting** at Virginia Tech (assisted by Dan Dudek). Along with biologists, engineers working on bio-related issues were invited to participate to encourage cross-disciplinary interaction. 51 attendees.
- Served as a the **subject and scientific advisor for two National Geographic Television documentaries** highlighting my research on flying snakes. The first was a half-hour episode of the series "Snake Wranglers" (2004), and the second was a full hour program entitled "Snakes That Fly" (2010).
- **Director of a new NSF mentoring program, EFRI-REM** (Emerging Frontiers for Research and Innovation, Research Experience and Mentoring) at Virginia Tech. EFRI-REM promotes innovation, and we designed our program to provide teachers, undergraduates, and high school students with research experience through multiple labs that span from science to engineering.

Collaborators & other affiliations

(i) Collaborators

Masoud Agah, Virginia Tech; **Xumei Chen**, Virginia Tech; **Francesco De Carlo**, Advanced Photon Source; **Raffaella De Vita**, Virginia Tech; **Rafael Davalos**, Virginia Tech; **Kamel Fezzaa**, Argonne National Laboratory; **Melina Hale**, University of Chicago; **Jon Harrison**, Arizona State University; **Deborah Hoshizaki**, NIH; **Sunny Jung**, Virginia Tech; **Jaco Klok**, Arizona State University; **Konstantin Kornev**, Clemson University; **Fritz-Olaf Lehmann**, University of Ulm; **Kevin Miklasz**, Stanford University; **Wah-Keat Lee**, Argonne National Laboratory; **Robin O'Keefe**, Marshall University; **Ishwar Puri**, Virginia Tech; **Steve Roberts**, UNLV; **Michael Simon**, Tufts University; **Brent Sinclair**, University of Western Ontario; **Anne Staples**, Virginia Tech; **Mark Stremler**, Virginia Tech; **Pavlos Vlachos**, Virginia Tech; **James Waters**, Arizona State University; **Matthew Webster**, Virginia Tech; **Mark Westneat**, Field Museum of Natural History.

(ii) Graduate and Postdoctoral advisors

Michael LaBarbera, graduate advisor; University of Chicago.
Wah-Keat Lee, primary postdoctoral collaborator; Argonne National Laboratory.
Mark Westneat, primary postdoctoral collaborator; Field Museum of Natural History.

(iii) Thesis advisor

Current students: Farid Jafari, Hodjat Pendar, Renee Pietsch, Matthew Giarra, Roderick La Foy: Ph.D. candidates, Virginia Tech. Catherine Twyman, Elan Dalton: Masters candidates, Virginia Tech.

David H. Laidlaw

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Professional Preparation

1983	Sc.B. in Computer Science, Brown U., Prov., RI, *Topology and Mechanics.* Also completed requirements for an A.B. in Mathematics.
1985	Sc.M. in Computer Science, Brown U., Prov., RI.
1992	M.S. in Computer Science, Caltech, Pasadena, CA.
1995	Ph.D. in Computer Science, Caltech, Pasadena, CA.

Professional Appointments

2008-present Professor, Computer Science Department, Brown University
2003-2008 Associate Professor, Computer Science Department, Brown University
2000-2003 Stephen Robert Assistant Professor, CS Department, Brown University
1998-2000 Assistant Professor, Computer Science Department, Brown University
1996-1998 Senior Research Fellow, Division of Biology, Caltech
1989-1996 Postdoctoral Research Fellow/Research Assistant, Computer Science, Caltech
1989-1993 Consultant Stardent/Advanced Visual Systems
1986-1989 Software Engineer, Stellar Computer
1983-1985 Research Assistant, Computer Science, Brown University

Publications Relevant to this Proposal

A. van Dam, A.S. Forsberg, D.H Laidlaw, J.J. LaViola Jr., R.M. Simpson. Immersive VR for scientific visualization: A progress report, IEEE Computer Graphics and Applications, 20(6): 26-52 2000.

C. Demiralp, C.D. Jackson, D.B. Karelitz, S. Zhang, D. H. Laidlaw. Cave and fishtank virtual-reality displays: A qualitative and quantitative comparison, IEEE Trans. On Visualization and Computer Graphics, 12(3):323-330, 2006.

T.M. O'Brien, A.M. Ritz, B.J. Raphael, D.H. Laidlaw. Interactive volume rendering of thin thread structures within multivalued scientific data sets, IEEE Transactions on Visualization and Computer Graphics,10 (6), 664-672, 2004.

S. Zhang, C. Demiralp. D.F. Keefe, M. DaSilva, D.H. Laidlaw, B.D. Greenberg, P.J. Basser, C. Pierpaoli, E.A. Chiocca, T.S. Diesboeck. An immersive virtual environment for DT-MRI volume visualization applications: a case study, Proceedings of the 2001 IEEE annual VIS conference, 437-584.

A.S. Forsberg, D.H. Laidlaw, A. van Dam, R.M. Kirby, G.E. Karniadakis, J.L. Elion. Immersive virtual reality for visualizing flow through an Artery. Proceedings of the 2000 IEEE annual Visualization conference Pages 457-460.

Other Significant Publications

S Zhang, C Demiralp, DH Laidlaw Visualizing diffusion tensor MR images using streamtubes and streamsurfaces. Visualization and Computer Graphics, IEEE Transactions on 9 (4), 454-462.

D. H. Laidlaw, R. M. Kirby, J. S. Davidson, T. S. Miller, M. da Silva, W. H. Warren, M. Tarr, 2005. Comparing 2D Vector Field Visualization Methods, IEEE Transactions on Visualization and Computer Graphics Jan 2005.

A. van Dam, D. H. Laidlaw, and R. M. Simpson (2002). Future interfaces: an IVR progress report, *Computers and Graphics*.

D. Keefe, D. Acevedo, T. Moscovich, D. H. Laidlaw, J. J. LaViola (2001). CavePainting: A Fully Immersive 3D Artistic Medium and Interactive Experience, Proc. 2001 Symposium on Interactive 3D Graphics.

C. Upson, T. Faulhaber, D. Kamins, D.H. Laidlaw, D. Schleigel, J. Vroom, R. Gurwitz, and A. van Dam, (1989), The Application Visualization System: A Computational Environment for Scientific Visualization, *Computer Graphics and Applications*, 9(4).

Synergistic Activities

A graduate/undergraduate class, *Interdisciplinary Scientific Visualization*, explores design issues in scientific visualization from two perspectives: visual design and computer science. The course is co-taught with Rhode

Island School of Design (RISD) Illustration Department Chairman Fritz Drury and biologist Sharon Swartz. Together we worked with students from both RISD and Brown to design and realize new virtual reality interfaces for exploring 3D time-varying flow. Students learn about communicating and working with researchers across multiple fields. See course web page for more info: http://www.cs.brown.edu/courses/cs237.

Co-taught one-day course at premiere computer graphics conference, SIGGRAPH, about using art-based methods for scientific visualization. I led a two-hour session where approximately 80 computer graphics professionals used traditional art media (paint, charcoal, markers, chalk, etc.) to represent multivalued scientific data.

Was a main designer and developer of AVS, a visualization software product created at Stellar Computer in the 80’s. It is widely used to process and visualize scientific data from many disciplines.

Advised and continue to recruit undergraduates for research projects both at Brown and, previously, at Caltech. Many of the projects have culminated in research publications. Several have been with women in computer science, a traditionally underrepresented group. Coordinating a crew of undergraduates to work on projects in a new virtual reality cave, to be brought online in the next year.

Collaborators and Other Affiliations

Collaborators and Co-Editors: Acevedo D, KAUST; Ahrens ET, CMU; Akelman E, Brown U; Barr AH, Caltech; Bennett J, UCHSC; Bennur, Sharath, U of Pennsylvania; Boller R, NASA Goddard Space Flight Center; Bowman D, Virginia Polytechnic Institute & State U; Bragdon A, Microsoft; Braun S, NASA Goddard Space Flight Center; Brennan-Krohn T, Providence VA Hospital and Butler Hospital; Breuer KS, Brown U; Brossay L, Brown U; Brown M, UCHSC; Cabeen R, Brown U; Cai H, Brown U; Callan-Jones AC, unknown; Cao L, Brown U; Chen J, Southern Mississippi U; Clark RC, Flinders U (Australia); Cohen R, Brown U; Conley J, Brigham and Women's Hospital; Connolly P, U of Pennsylvania; Coop K, Miriam Hospital; Corboy J, UCHSC; Correia S, Providence VA Hospital and Butler Hospital; Crisco JJ, Brown U; David SP, Brown U; Demiralp C, Stanford U; Drury F, Rhode Island School of Design; Ernst LA, CMU; Fabian A, Rowan U; Flanigan T, Brown U; Forsberg AS, self-employed; Fraser SE, Caltech; Friedland RP, U of Louisville; Gold, Joshua I., U of Pennsylvania; Gomez S., Brown U; Gordon E, Brain Resource Company; Grant JE, Brown U; Grieve SM, Brain Resource Company; Grimm CM, Washington U; Gunstad J, Brown U; Hageveld Weiss AP, Brown U; Halilaj E, Brown U; Hall M, U College London; Hege HC, Zuse Institute Berlin; Hester R, U of Mississippi; Hoth KF, Brown U; Huang J, Brown U; Hubel T, U of London; Hughes JF, Brown U; Hung N, Brown U; Iriarte-Diaz J, Brown U; Jackson CD, Aptima Inc.; Jakun-Kelly TJ, James Bagley College of Engineering; Janjic JM, CMU; Jianu R, Florida International U; Karelitz DB, Sandia; Keefe DF, U of Minnesota; Hedrick TL, UNC Chapel Hill; Kostandov M, Eureka Aerospace Corporation; Lawrence J, Butler Hospital and Brown U; Lee SY, Dartmouth Medical School; Lin JT, Brown U; Liu H, Brown U; Loriot GB, retired; Malloy PF, Butler Hospital and Brown U; Marai GE, U of Pittsburgh; Miles J, Brown U; Miller DE, UCHSC; Moore DC, Brown U; Morel PA, U of Pittsurgh; Navia B, Brown U; Nguyen V, Brown U; Niaura R, Brown U; O'Brien T, Google; Paul RH, U of Missouri St Louis; Pelcovits RA, Brown U; Pogun S, Ege U (Raphael); Raphael B, Brown U; Riskin DK, Brown U; Ritz A, Brown U; Rusu A, Rowan U; Salloway SP, Brown U; Salomon AR, Brown U; Schulz SC, U of Minnesota; Shakhnarovich G, Toyota Technological Institute at Chicago; Simon JH, Portland VA Hospital; Slavin VA, Lockheed Martin; Srinivas M, CMU; Stebbins G, Brown U; Swartz SM, Brown U; Sweet L, Brown U; Tashima K, Kochi Medical School; Tate DF, Brigham and Women's Hospital; Taylor G, U of Missouri St. Louis; Taylor LE Miriam Hospital and Brown U; Turkey BJ, Brown U; Turner MS, U of Pittsburgh; Ulin SP, Brown U; Voorn T, Hageveld; Weiss AP, Brown U; Willis DJ, U of Massachusetts Lowell; Wolfe SW, Hospital for Special Surgery; Yu K, Brown U; Zhang S, Mississippi State U; Zhou W, Oakland U;

Advisees**:** Daniel Acevedo-Feliz, Stuart Andrews, Ryan Cabeen, Jian Chen, Cullen Jackson, Steven Gomez, Connor Gramazio, Hua Guo, Daniel Keefe, R. Michael Kirby, Georgeta Elizabeth Marai, Paul Reitsman, Eileen Vote, Song Zhang.

Advisors**:** Alan H. Barr, Caltech, Scott E. Fraser, Caltech.

Current and Pending Support
See GPG Section II.D.8 for guidance on information to include on this form.

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **Doug A. Bowman**

Other agencies (including NSF) to which this proposal has been/will be submitted:

Support: ☒ Current ☐ Pending ☐ Submission planned in near future ☐ Transfer of support
Project/Proposal Title: **Evaluating the Effects of Immersion on Naval Training Applications**
Source of Support: **University of California, Santa Barbara (flow-through from ONR)**
Total Award Amount: **$509,814** Total Award Period Covered: **08/01/09 – 07/31/13**
Location of Project: **Blacksburg, VA**
Person-months committed to project: Cal: **0.00** Acad: **0.00** Sumr: **1.00**

Support: ☒ Current ☐ Pending ☐ Submission planned in near future ☐ Transfer of support
Project/Proposal Title: **II-EN: Device and Display Ecologies**
Source of Support: **NSF**
Total Award Amount: **$600,000** Total Award Period Covered: **01/01/11 – 12/31/13**
Location of Project: **Blacksburg, VA**
Person-months committed to project: Cal: **0.00** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission planned in near future ☐ Transfer of support
Project/Proposal Title: **DARPA RC Team ViGIR**
Source of Support: **TORC Robotics (flow-through from DARPA)**
Total Award Amount: **$86,238** Total Award Period Covered: **10/01/12 – 06/30/13**
Location of Project: **Blacksburg, VA**
Person-months committed to project: Cal: **0.00** Acad: **1.02** Sumr: **0.50**

Support: ☐ Current ☒ Pending ☐ Submission planned in near future ☐ Transfer of support
Project/Proposal Title: **EXP: Exploring the potential of mobile augmented reality for scaffolding historical inquiry learning**
Source of Support: **NSF**
Total Award Amount: **$549,038** Total Award Period Covered: **06/01/13 – 05/31/15**
Location of Project: **Blacksburg, VA**
Person-months committed to project: Cal: **0.00** Acad: **0.00** Sumr: **0.75**

Support: ☐ Current ☒ Pending ☐ Submission planned in near future ☐ Transfer of support
Project/Proposal Title: **HCC: Small: Collaborative Research: Immersive Visualization and 3D Interaction for Volume Data Analysis (this proposal)**
Source of Support: **NSF**
Total Award Amount: **$249,946** Total Award Period Covered: **06/01/13 – 05/31/16**
Location of Project: **Blacksburg, VA**
Person-months committed to project: Cal: **0.00** Acad: **0.00** Sumr: **0.50**

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: John J. Socha

Other agencies (including NSF) to which this proposal has been/will be submitted.
NSF

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: RET: Biomechanics from molecular to organismal scales

Source of Support: NSF
Total Award Amount: $499,670 Total Award Period Covered: 05/01/2013 – 04/30/2016
Location of Project: Virginia Tech
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: EFRI-BSBA: Complex microsystem networks inspired by internal insect physiology

Source of Support: NSF
Total Award Amount: $1,992,607 Total Award Period Covered: 01/01/2010 – 12/31/2013
Location of Project: Virginia Tech
Person-Months Per Year Committed to the Project. Cal: Acad: 0.18 Sumr: 1

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: EFRI-REM: Complex microsystem networks inspired by internal insect physiology (Research Experience and Mentoring)

Source of Support: NSF
Total Award Amount: $100,000 Total Award Period Covered: 06/01/2012 – 05/31/2013
Location of Project: Virginia Tech
Person-Months Per Year Committed to the Project. 0 Cal: Acad: 0.23 Sumr: 0.18

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: How do animals harness interfacial water entry and exit dynamics?

Source of Support: NSF
Total Award Amount: $510,436 Total Award Period Covered: 5/1/12 – 4/30/15
Location of Project: Virginia Tech
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: IDBR: Instrument development for three-dimensional fluid flow measurements of freely-flying animals

Source of Support: NSF
Total Award Amount: $ 599,968 Total Award Period Covered: 07/01/2012 – 06/30/2015
Location of Project: Virginia Tech
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.67

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: John J. Socha

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
HCC: Small: Collaborative Research: Immersive Visualization and 3D Interaction for Volume Data Analysis
(this proposal)
Source of Support: NSF
Total Award Amount: $249,946 Total Award Period Covered: 6/1/2013-5/31/2016
Location of Project: Virginia Tech
Person-Months Per Year Committed to the Project. Cal: Acad: 0.27 Sumr: 0.36

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:
Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: David Laidlaw

Other agencies (including NSF) to which this proposal has

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: HCC: Small: Collaborative Research: Immersive Visualization and 3D Interaction for Volume Data Analysis

Source of Support: NSF
Total Award Amount: $ 249,955 Total Award Period Covered: 06/01/13 – 05/31/16
Location of Project: Brown University
Person-Months Per Year Committed to the Pro- Cal: 0.00 Acad: 0.00 Sumr: 0.45

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: III: Small: Collaborative Research: An Infrastructure for Designing Workflow-Appropriate Network Visualizations

Source of Support: NSF
Total Award Amount: $ 95,000 Total Award Period Covered: 9/1/13 – 8/31/16
Location of Project: Brown University
Person-Months Per Year Committed to the Pro- Cal: 0.00 Acad: 0.00 Sumr: 0.15

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title Collaborative: Scientific Visual Analytics: Advancing Theory and Practice through Cognitive Modeling

Source of Support: NSF
Total Award Amount: $ 6,749.916 Total Award Period Covered: 09/01/13 – 08/31/18
Location of Project: Brown University
Person-Months Per Year Committed to the Pro- Cal: 0.00 Acad: 0.00 Sumr: 2.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Visualizing the Immunological Genome: From Browsing to Discovery

Source of Support: NIH
Total Award Amount: $ 2,471,311 Total Award Period Covered: 04/01/13 – 03/31/18
Location of Project: Brown University
Person-Months Per Year Committed to the Pro- Cal: 0.00 Acad: 0.75 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Neuropathogenesis of clade C HIV in South Africa

Source of Support: NIH/Univ. of Missouri, St. Louis
Total Award Amount: $ 555,255.00 Total Award Period Covered: 04/01/09 – 03/31/14
Location of Project: Brown University
Person-Months Per Year Committed to the Pro- Cal: 0.08 Acad 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Functional Kinematics, Morphology and Osteoarthritis of the Thumb CMC Joint

Source of Support: NIH
Total Award Amount: $ 727,877 Total Award Period Covered: 04/01/10 – 03/31/14
Location of Project: Brown University
Person-Months Per Year Committed to the Pro- Cal: 0.08 Acad: 0.00 Sumr: 0.00

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: David Laidlaw

Other agencies (including NSF) to which this proposal has

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: MRI Development of a Next-Generation Interactive Virtual-Reality Display Environment for Science

Source of Support: NSF
Total Award Amount: $ 1,999,983.00 Total Award Period Covered: 09/01/09 – 08/31/13
Location of Project: Brown University
Person-Months Per Year Committed to the Cal: 1.25 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: GV: Small: Collaborative Research: supporting Knowledge Discovery through a Scientific Visualization Language

Source of Support: NSF
Total Award Amount: $ 261,596 Total Award Period Covered: 11/01/2010 – 10/31/13
Location of Project: Brown University
Person-Months Per Year Committed to the Cal: 0.75 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Neuromarkers of Age-Related Cognitive Decline

Source of Support: NIH/Univ. of Missouri, St. Louis
Total Award Amount: $ 355,811 Total Award Period Covered: 09/01/09 - 08/31/13
Location of Project: Brown University
Person-Months Per Year Committed to the Cal: 0.25 Acad 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support: NSF
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: David Laidlaw

Other agencies (including NSF) to which this proposal has

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Pro- Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
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Project/Proposal Title:

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Total Award Amount: $ Total Award Period Covered:
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Person-Months Per Year Committed to the Pro- Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Pro- Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

USE ADDITIONAL SHEETS AS NECESSARY

Facilities, Equipment and Other Resources

The work for this project to be done at Virginia Tech will be carried out using the facilities available to the Center for Human-Computer Interaction and the Computer Science Department. The statement below describes the facilities available for our research.

Virginia Tech

Major Equipment – VT Visionarium: The Visionarium incldues a four-screen immersive VR system (the VisCube) that provides three rear-projected walls and a front-projected floor in a 10x10x9-foot box. Each screen displays 3D stereoscopic graphics using the Infitec technology produced by four LCD projectors (16 projectors total). The user's head and hands are tracked with an Intersense IS-900 six-degree-of-freedom position tracking system. The system is driven by a cluster of five Linux-based PCs. We will use the VisCube to prototype our AR applications.

Center for Human-Computer Interaction

The growth of HCI research at Virginia Tech (stimulated by NSF RI and CRI awards) resulted in the expansion of the Center for Human-Computer Interaction (CHCI) into new facilities in the Corporate Research Center. This building houses the Center in a new complex of almost 16,000 square feet. Included in the CHCI complex, in addition to student and faculty space, are:

- Ten 145 square foot project rooms, some with two-way observation windows
- A 280 square foot general HCI laboratory
- A 2,330 square foot shared laboratory space including:
  - The 3D Interaction Laboratory (directed by PI Bowman) containing a wide variety of 3D and advanced input devices, as well as virtual environment display technology
  - The Gigapixel Display Laboratory containing several large, high-resolution displays
- Extensive conference and meeting facilities

3D Interaction Laboratory: The 3DI laboratory supports research in 3D user interfaces and interaction techniques, as well as immersive virtual environments. Position tracking is provided in this laboratory by an Intersense IS-900 system. In addition to the tracked input devices provided by this systems, the laboratory also provides advanced input devices such as Pinch Gloves, 5DT data gloves, a chord keyboard, Measurand ShapeTape, a 3D Connexion SpaceBall, and various handheld mice. Display systems include an NVIS SX100 wide field of view high-resoultion head-mounted display, a Virtual Research V8 HMD, and a two-wall rear-projected VisWall system capable of displaying stereoscopic imagery at 2800x1050 pixels. These walls are also reconfigurable and expandable. This lab space and some of the display and tracking hardware will be used in the development and formative evaluation of our AR prototypes.

Gigapixel Display Laboratory: The Gigapixel Display Laboratory provides infrastructure for research using large-scale, high-resolution, and reconfigurable displays. Currently two display technologies are being utilized: tiled LCD panels and stackable rear-projection blocks. The largest tiled LCD display features fifty 20-inch touch-sensitive panels with thin bezels, each capable of displaying 1600x1200 pixels, for a total of about 100 million pixels. The panels are attached to columns, and each column can be moved or rotated, allowing the display to be reconfigured in various form factors (flat, curved, angled, etc.). A cluster of twenty-five PCs drive two displays each, with a head node coordinating rendering. The facility also includes various smaller tiled LCD prototypes, including several that are used routinely for individuals' daily work. The rear-projected display is based on VisBlocks, a stackable modular system from Visbox, Inc. Each block has a rigid frame and screen and an LCD projector, and blocks can be moved and stacked in a variety of configurations, including vertical walls and horizontal tabletops. The main advantage to this technology is seamlessness; there are no bezels between adjacent blocks. The facility contains 18 VisBlocks, each capable of displaying 1280x720 pixels; these are driven by nine PCs.

Computer and networking support: Project staff will have access to networked workstations and servers running Windows, Mac OSX, and Linux. Both wired and wireless connectivity is available in the Center's lab facilities. Infrastructure software includes database, file, proxy, and web server systems, as well as server software for custom collaboration tools developed by the Center. Custom and off-the-shelf tools for audio and video capture, processing and transcription support data collection activities. Analysis tools include custom session log processing software, as well as qualitative and quantitative data analysis packages. Development tools are also available for a variety of platforms and languages.

Department of Computer Science

In addition to the Laboratories already described, Virginia Tech's Department of Computer Science (the largest CS program, in terms of majors, in Virginia) is well equipped to support research in the areas described in the proposal. In addition to office space for faculty, students, and visitors (located on the same floor as the CHCI facilities), it hosts general computer labs.

Brown University - General Resources in the Department of Computer Science

The Department of Computer Science provides leading-edge computing technology to all its faculty and students. We have over 500 desktop systems running Linux or Windows 7. Most of these are custom-built machines configured and assembled by the department's technical staff. Components include quad-core processors with 4GB or 8GB of memory and dual 19" or single 24" flat-panel monitors. These systems are connected to the department's 1Gb/s switched Ethernet network with access to both Internet1 and Internet2 via the University's fiber-optic backbone. An 802.11g (54Mb/s) wireless network is accessible throughout the department.

The department has two electronic classrooms. One, a banked auditorium, holds seventy-three systems running Linux. This room serves as the primary computer facility for undergraduate computer science students. The other contains twenty-six systems running Microsoft Windows and an additional thirteen Linux systems. The layout of this space makes it an ideal room for sections, seminars, and interactive learning. Seven research labs further enrich the environment with specialized hardware and advanced workstations from a variety of vendors.

Desktop and research systems are supported by a data center with fully redundant servers that offer a wide range of services. Central file storage is built upon IBM's General Parallel File System (GPFS). This approach provides a scalable, high performance, cost effective solution based on IBM hardware and currently hosts approximately 215TB of RAID-6 storage. Computational servers in a Sun Grid Engine cluster, all running Linux, include 16 dual quad-core systems with 24GB each, 20 dual 16-core systems with 64G each, and a range of other powerful systems offering two to 24 cores each, and up to 96GB of memory, for a total of 177 machines with 1380 cores in all.

The Brown Biomedical Imaging Facility:

The Leduc Bioimaging Facility, open to all investigators, provides equipment and training dedicated to high-resolution imaging in the life sciences. The facility is staffed by a facility manager and director. The facility operates on a fee-for-service basis and offers its services in the Laboratories for Molecular Medicine and Sidney Frank Hall for Life Sciences. The facility in the Laboratories for Molecular Medicine includes a Zeiss LSM710 confocal laser scanning microscope, a Zeiss Axiovert 200M fluorescence microscope, and MetaMorph 7.0 image analysis software. The facility in Sidney Frank Hall includes a Philips 410 transmission electron microscope, a Hitachi 2700 scanning electron microscope, a Zeiss Axiovert 200M fluorescence microscope, a Zeiss Lumar fluorescence stereomicroscope, a Leica TCS SP2 AOBS confocal laser scanning microscope, a Zeiss LSM510 Meta confocal laser scanning microscope, and MetaMorph 7.0 image analysis software. The facility in Sidney Frank Hall also maintains equipment for sample preparation, including a critical point dryer, sputter coater, and microtomes for ultrathin sectioning.

Microinjection facilities for transformation of Drosophila are available in the adjacent Life Science Building.

Brown Magnetic Resonance Facility

MRI Facility: Functional magnetic resonance imaging (fMRI) will be performed at the Brown MRF located in Sidney Frank Hall at Brown University. The Brown MRF is a 3,000 sq. ft. research suite with a Siemens 3T Tim Trio scanner used exclusively for research. The scanner is equipped with 32 receiver channels for significant gains in signal-to-noise ratio and acquisition speed. Visual stimuli are presented through rear projection to a screen located at the back of the scanner. The Avotec SS-3100 Silent Scan™ Audio System includes noise reduction for presentation of auditory stimuli during scanning. Manual responses are recorded with a Mag Design and Engineering four-button response pad. Participants may be visually monitored using an infrared video system. The Brown MRF employs a full-time staff of imaging specialists that are available for both technical and design assistance. This staff includes Associate Director of Research, Michael Worden, PhD; Associate Director of MRI Physics, Edward Walsh, PhD; and Facility Manager, Lynn Fanella, RT R MR.

Brown's Center for Computation and Visualization (CCV)

In addition to the computing resources already mentioned, CCV maintains a high-end visualization lab with large scale immersive visualization capabilities. This includes a fully immersive Cave system and a multi-projector stereo display wall. Custom visualization solutions for software and hardware needs are available. A new "retina-display" cave will be available around the start of the proposed work.

Data Management Plan

Data to be produced and use of standards

This project will produce four types of data:

- 3D models and volume datasets
- Software used to implement the 3D interaction techniques and the experiments
- Data gathered during the experiments and surveys
- Synthesized data such as our publications, presentations, and website

Only the 3D models and software have applicable standards associated with them. We will use standard 3D model and volume data formats such as OBJ or 3DS to facilitate sharing. The software will be written using standard languages such as C++ and Python. As much as possible, we will use open-source software APIs such as 3D Visualizer. However, we do plan to use some proprietary APIs (e.g., Worldviz's Vizard or nGrain's volume rendering SDK) for certain experiments due to their feature sets.

Policies for access and sharing

The 3D models and volume datasets will be shared freely with any researchers who submit a request to us, as long as permission is granted by the scientists who are the original sources of the data.

The software we create based on free and open-source APIs will be shared freely with any researchers who submit a request to us. At the end of the project, we will make this software available on the project website.

The raw data from our evaluations will be shared freely with any researchers who submit a request to us. At the end of the project, we will make this data available on the project website. In order to protect privacy rights, the data will be anonymized.

Our publications will be available to anyone with the appropriate subscriptions for the conferences or journals in which we publish. Presentations and the website will be available online.

Policies for re-use

We will allow re-use, but not re-distribution, of the 3D models, software, experiment data, and presentations created through this project. Any re-use should carry an appropriate acknowledgement or attribution of the investigators, Virginia Tech, and NSF.

Plans for archiving data

We will maintain data on project or laboratory computer systems and backups. The project website will be the public repository for future access of the data.

Project Personnel

1. Doug Bowman; Virginia Tech; PI
2. Bireswar Laha; Virginia Tech; graduate student
3. David Laidlaw; Brown University; co-PI
4. John (Jake) Socha; Virginia Tech; co-PI
5. Kristi Wharton; Brown University; unpaid collaborator

BROWN

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30 January 2012

Dear David,

Thanks for getting in touch about starting up a collaborative research project involving volume rendering of biological data. As you know, my lab and a number of other researchers at Brown work with “stacks”, or volumes, of data collected on laser scanning confocal or multi-photon microscopes. These data let us study a number of biological questions at the cellular and molecular behavior.

I’m delighted to hear that the new immersive VR cave that you are building is coming together well. The collaborative work I was involved in with Computer Science and CCV folks a few years ago using your older cave was exciting and demonstrated that the cave will be very helpful in getting us to accomplish our research goals. I am also happy that you were able to realize some research goals in working with us, as a team of biologists.

Immersive VR visualization of our data was able to give us 3D insights that were much harder to discover than with 2D slices or even with 3D monocular visualizations. For example, we were able to follow the track of a convoluted tissue layer deep within an embryo and to resolve the co-localization of two proteins.

The new cave sounds very promising, since it will provide much higher resolution, brightness, and contrast. I expect that the increased brightness and contrast will be especially critical for our applications, but this is precisely a hypothesis that we should test.

I understand that, as part of your proposal NSF titled “Immersive Visualization and 3D Interaction for Volume Data Analysis” involves bringing interactive volume-rendering software back online in the new Cave. I would be very interested in analysing some of our new data in this new Cave and in aiding in your efforts to understand what aspects of the cave and of volume rendering in general are particularly useful for the kinds of applications we as cell and molecular biologists use in our studies of developing organisms. I will also be happy to help connect your work to other potential users. As the number of users expands, your work will be sure to have a broad impact as I’m sure other life scientists will find it as powerful a visualization tool has my group already found during our previous collaboration. I’m very excited about you proposed research and look forward to a fruitful collaboration.

Best regards,

Kristi Wharton

Associate Professor
Kristi_Wharton@brown.edu

Fluidity™
Software

289 Highland Ave., Suite 304
Somerville, MA 02144

December 13, 2012

Dear Professor Laidlaw,

I'm delighted to be able to collaborate with you at Brown and Professor Bowman at Virginia Tech on your upcoming proposal submission titled "Immersive Visualization and 3D Interaction for Volume Data Analysis." This work naturally builds on the collaborations you and I have had in the past as well as on the relationship between Fluidity and Brown. I see it as a continued step toward transitioning research results from the computer science research community onto platforms from which they can be sustainable made and kept available.

In this work, we will provide input on the factors that we have found empirically to be important to our users of volume rendering, and we think that will help with your experimental design process. We will also consult on experimental design at Brown; because I was closely involved with the earlier virtual reality volume rendering studies there, I should be able to help make the design and execution of the proposed experiments efficient and effective.

Finally, and perhaps most importantly, we will incorporate the findings from this work into our products so that they can have a broader impact with our users. Our users work with complex 3D images (static and time-varying) with structures and spatial relationships that are not easily understood with traditional 2D displays and interaction devices. We expect in some cases to be able to discuss ideas and early evaluation of prototyped techniques resulting from the proposed work with our users at the Leduc Bioimaging Facility at Brown University, the Marine Biology Laboratory in Woods Hole, Schier Lab at Harvard University, and The Stowers Institute for Medical Research.

Sincerely,

Andrew Forsberg
Vice President, Engineering
Fluidity Software, Inc.