

New Directions in 3D User Interfaces

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Abstract

Three-dimensional user interfaces (3D UIs) support user tasks in many non-traditional interactive systems such as virtual environments, augmented reality, and ubiquitous computing. Although 3D UI researchers have been successful in identifying basic user tasks and interaction metaphors, evaluating the usability of 3D interaction techniques, and improving the usability of many applications, 3D UI research now stands at a crossroads. Very few fundamentally new techniques and metaphors for 3D interaction have been discovered in recent years, yet the usability of 3D UIs in real-world applications is still not at a desirable level. What directions should 3D UI researchers next explore to improve this situation? In this paper, we trace the history of 3D UI research and analyze the current state-of-the-art. Using evidence from the literature and our own experience, we argue that 3D UI researchers should approach this problem using new directions, which cluster around the concepts of *specificity*, *flavors*, *integration*, *implementation*, and *emerging technologies*. We illustrate and discuss some of these new directions using case studies of research projects undertaken in our group. These explorations indicate the promise of these directions for further increasing our understanding of 3D interaction and 3D UI design, and for ensuring the usability of 3D UIs in future applications.

Categories and Subject Descriptors

H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems - *Artificial, augmented, and virtual realities*.

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces.

I.3.6 [**Computer Graphics**]: Methodology and Techniques – *Interaction techniques*.

I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism - *Virtual reality*.

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1 Introduction

With the rise of virtual environments (VEs), augmented reality (AR), large-screen display systems, and three-dimensional (3D) applications of all sorts on the desktop, a new trend in HCI research began to emerge. Although principles gleaned from years of experience in designing user interfaces (UIs) for desktop computers still applied, they weren't sufficient to address the unique needs of these systems where interaction took place in a spatial context, with multiple degrees-of-freedom. Researchers and application developers gradually came to realize that user interfaces in these 3D arenas had some fundamental differences with traditional desktop GUIs, and that separate research was needed to examine interaction techniques and UI metaphors for 3D applications. This area of research gradually came to be known as *3D User Interfaces (3D UIs)*, or *3D Interaction*.

We define **3D interaction** as “Human–computer interaction in which the user’s tasks are performed directly in a 3D spatial context. Interactive systems that display 3D graphics do not necessarily involve 3D interaction; for example, if a user tours a model of a building on her desktop computer by choosing viewpoints from a traditional menu, no 3D interaction has taken place. On the other hand, 3D interaction does not necessarily mean that 3D input devices are used; for example, in the same application, if the user clicks on a target object to navigate to that object, then the 2D mouse input has been directly translated into a 3D location, and thus 3D interaction has occurred” (Bowman et al. 2004). With these concepts in mind, it is simple to define a **3D user interface** as “a UI that involves 3D interaction” (Bowman et al. 2004).

Although these definitions may not allow us to precisely classify *every* application or interaction technique, we can further clarify them by considering the various technological contexts in which one might find 3D interaction. These include:

- **Desktop computing:** For example, users of modeling software can directly specify the 3D orientation and position of an object using a mouse in conjunction with 3D manipulation techniques.
- **Virtual environments:** For example, a user can “fly” through a virtual world through 3D pointing in the desired direction of motion.
- **Augmented reality:** For example, a physical card can represent a virtual object, allowing the object to be selected, moved, and placed in the physical world.
- **Large-screen displays:** For example, a user can zoom into a particular area of a map simply by looking at that area.
- **Ubiquitous/pervasive computing:** For example, a user can copy information from a public display to her PDA by making a gesture indicating the display and the copy action.

Research in 3D UIs has addressed a wide variety of issues. These include the design of novel 3D input or display devices (e.g. Froehlich and Plate 2000), the empirical evaluation of user task performance with various input devices or interaction techniques (e.g. Hinckley et al. 1997), the development of design and/or evaluation approaches specific to 3D UIs (e.g. Hix and Gabbard 2002), and the study of various aids to user

performance such as physical props (e.g. Schmalsteig et al. 1999) or navigation aids (e.g. Darken and Cevik 1999), just to name a few.

By far, however, the most common research topic, and the one we principally address in this paper, has been the design of 3D interaction techniques for the so-called “universal 3D tasks” of travel, selection, manipulation, and system control (Bowman et al. 2001b). These techniques are the fundamental building blocks of 3D UIs. Their analogues in traditional GUIs include techniques such as the scrollbar (navigation), point-and-click (selection), drag-and-drop (manipulation), and the pull-down menu (system control).

As we will argue in more detail later, the mid-1990s saw a boom in the discovery of such fundamental 3D interaction metaphors. This period witnessed the development of the pointing technique for 3D travel (Mine 1995), the occlusion technique for 3D selection (Pierce et al. 1997), the Go-Go technique for 3D manipulation (Poupyrev et al. 1996), and the ring menu technique for 3D system control (Liang and Green 1994), among many others. But in recent years, the publication of fundamentally new 3D interaction techniques has slowed tremendously. Based on this evidence, we suggest that most of the design space for these techniques has been covered, at least at a coarse level.

The problem currently facing 3D UI researchers is that despite this broad coverage and extensive knowledge of 3D interaction techniques, the usability of 3D UIs in real-world applications is still surprisingly low in many cases. Thus, we argue that the community needs to consider some new directions in 3D UI design.

In this paper, we discuss some of these new directions and propose research topics whose results, we believe, will further improve the usability of 3D UIs, and further their application in the real world. These proposals come both from our own experience and from our analysis of the 3D UI literature. In particular, we argue for the potential of new research directions based on the concepts of *specificity*, *flavors*, *integration*, *implementation*, and *emerging technologies*. We also illustrate several of these new directions with case studies that summarize research projects in our group and class projects in an advanced graduate seminar on 3D interaction. The results indicate that, in general, much more research is needed to ensure 3D UI usability, and that our proposed research directions can produce tangible progress towards this goal.

2 Selective history of 3D UIs

As a research area, 3D interaction has roots in a number of older research areas, including computer graphics, human-computer interaction, psychology, and human factors. Because 3D UI researchers rarely have a background in more than one of these areas, there are several more-or-less distinct threads that one can identify when tracing the history of 3D UIs.

For example, some human factors researchers began to work on 3D interaction when considering how to engineer training systems for pilots, military personnel, machine operators, etc. This led to many research projects attempting to quantify human perception and performance when interacting with a virtual 3D space (e.g. Barfield et al.

1997; Zhai and Milgram 1993). A general feature of much of this work is that it assumes a “natural” 3D interface (i.e. 3D interaction that mimics real-world interaction as closely as possible), rather than focusing on the design of the 3D UI itself. This is certainly appropriate when considering training applications, but may not be the best approach for other types of applications, which may benefit from the use of “magic” techniques.

We would argue that much of the early work on 3D UIs was *technology-driven*. That is, new interactive technologies were invented and refined, and these technologies naturally lent themselves to 3D interaction. In other words, 3D UIs arose as a means of fulfilling the requirements of other technology research areas. This assertion is difficult to prove, but perhaps some examples will suffice.

Virtual environments (VEs) and augmented reality (AR) are two important technologies that invite 3D interaction because of their inherently spatial nature. VEs (sometimes referred to as virtual reality, or VR) are three-dimensional synthetic spaces that are rendered in real-time under the direct control of a user (Bowman et al. 2004). AR refers to a real-world environment that is enhanced (augmented) with synthetic objects or information (Bowman et al. 2004). Both VEs and AR use many of the same technological components (e.g. head-mounted displays, 3D position and orientation tracking), and both are points on the “mixed reality continuum” (Milgram and Kishino 1994). Historically, the technologies and technological integration for both VEs and AR were realized in the late 1960s by Ivan Sutherland (Sutherland 1968).

It is interesting to note that Sutherland’s work came from a background in computer graphics research, not HCI, although he clearly invented a new form of human-computer interface, and envisioned his work as transforming people’s visualization of and interaction with digital data (Sutherland 1965). Because of this, work on VEs/AR for the next 25-30 years was carried out largely by researchers with computer graphics and engineering backgrounds (although there are some notable exceptions). The focus, quite rightly, was on “making VEs work,” leading to research on real-time 3D rendering algorithms, display technology, and tracking technology. By 1994, according to Fred Brooks, VR “almost worked” in this technological sense (Brooks 1994).

As the technologies improved, VEs were the object of a great deal of media attention, and many attempts were made to develop real-world applications of the technologies. Although Brooks was not able to find any examples of VR technology in production use in 1994 (he excluded simulator and entertainment systems), by 1999 he identified five other categories of VR applications that were being used routinely for the results they produced: architectural design and spatial layout, vehicle design, training, psychiatric treatment, and probe microscopy (Brooks 1999). Initially, of course, the interfaces to VE/AR applications were designed to be natural – to view a virtual room the user walked around it, to fly a virtual airplane the user used real airplane controls, and to examine a virtual molecule the user picked it up directly with her hand. Most popular conceptions of VEs, such as the Star Trek “holodeck,” also envisioned completely natural 3D interaction.

There are two major problems with a natural 3D UI, however. First, because of the limitations of the technological intermediaries, natural 3D interaction cannot be completely reproduced. One's view of the room may jitter and lag behind head and body motion because of the limitations of the tracking system; flying the virtual airplane doesn't feel quite right because of the mismatch between the visual and vestibular stimuli; picking up the virtual molecule is difficult because of the low-quality (or non-existent) haptic feedback.

Second, although a naturalistic interface may be appropriate or even required for some applications, it can be extremely inefficient, frustrating, or even impractical for others. For example, in an interior design application it's not important that the user physically picks up and moves virtual pieces of furniture with realistic force feedback. Instead, the user is only concerned with getting the virtual furniture into the desired positions. In the same application, there are some tasks that don't lend themselves at all to natural interaction. How should the user try out a new type of desk in a virtual office design? Does he have to travel to the virtual furniture store, pick out a virtual desk, and drive it back on a virtual truck? Clearly, some form of menu system makes more sense. Such situations call for the use of a "magic" 3D UI, where the user's natural abilities and aptitudes – perceptual, motor, or cognitive – are augmented by the system. For this type of interface, unlike the more natural 3D UIs, the design space seems nearly unlimited.

As researchers and developers attempted to create applications with complex, magic interaction, a crisis emerged. It was obvious that magic 3D interaction could greatly benefit many types of VE/AR applications, but how should such interaction work? How can a VE user travel thousands of virtual miles quickly and easily and still end up at the desired location? How should an AR user select a physical object that is out of arm's reach? What is the best way to select an item from a menu in a 3D context? Researchers quickly discovered that the answers did not come easily. Backgrounds in computer graphics and engineering did not provide good knowledge of UI design principles. Those with HCI backgrounds possessed general principles for the design of usable interfaces, and knew how to design good GUIs for desktop computers, but 2D interaction techniques did not transfer easily to the 3D realm. 3D UI design presented many new challenges and difficulties (Herndon et al. 1994), and most of the application prototypes using magic 3D interaction exhibited significant usability problems. This led Brooks to list 3D interaction as one of the most crucial research areas that would affect the speed of adoption and success of VR (Brooks 1999).

Starting in approximately the mid-1990s, then, research in 3D UIs (and 3D interaction techniques in particular) boomed. Since the only existing exemplars were the natural techniques and the ad hoc magic techniques developed for application prototypes, it was fairly easy for researchers to design magic techniques with much higher levels of usability – there was a lot of "low-hanging fruit." Research focused on tasks that were present in most VE/AR applications. These are the "universal tasks" mentioned earlier: travel, selection, manipulation, and system control (Bowman et al. 2001b).

The 3D interaction boom continued through the rest of the 1990s, with a large number of novel interaction techniques published in conferences and journals in the HCI, graphics, human factors, VE, and AR communities. In addition, many empirical studies of the usability of 3D interaction techniques were published during this period, and researchers developed classifications of 3D interaction tasks and techniques as well. By the year 2000, however, the boom began to slow significantly. Although there were still many researchers studying 3D UIs, the number of novel 3D interaction techniques introduced to the community decreased.

To quantify this argument, we analyzed the publication dates of the interaction techniques presented in the book *3D User Interfaces: Theory and Practice* (Bowman et al. 2004). The goal of part III of this book was to provide comprehensive coverage of the fundamental interaction techniques that have been developed for the universal interaction tasks. Although not all published techniques are discussed, the best-known, most widely-cited, and most widely-used techniques are all represented. In addition, the book lists techniques covering the entire range of published classifications of techniques. So although there is certainly some subjectivity involved, we feel that the book's coverage is currently the best representation of the state-of-the-art in 3D interaction techniques. We considered citations only from chapters 5 (selection and manipulation), 6 (travel), and 8 (system control). The cited publications cover desktop 3D techniques as well as techniques for immersive VEs or AR. Where a technique had more than one citation, we used the earliest one.

The results of our analysis are presented in figure 1. As the figure shows, the distribution of publication dates resembles a bell-shaped curve. The majority of the novel interaction techniques cited fall between 1994-1999 (37 out of 53, or 69.8%) with over 20% published in 1995 alone. In addition, five out of the six most cited years occurred in that span. In the five years immediately prior to the book's publication (2000-2004), only six techniques were deemed important or novel enough for inclusion.

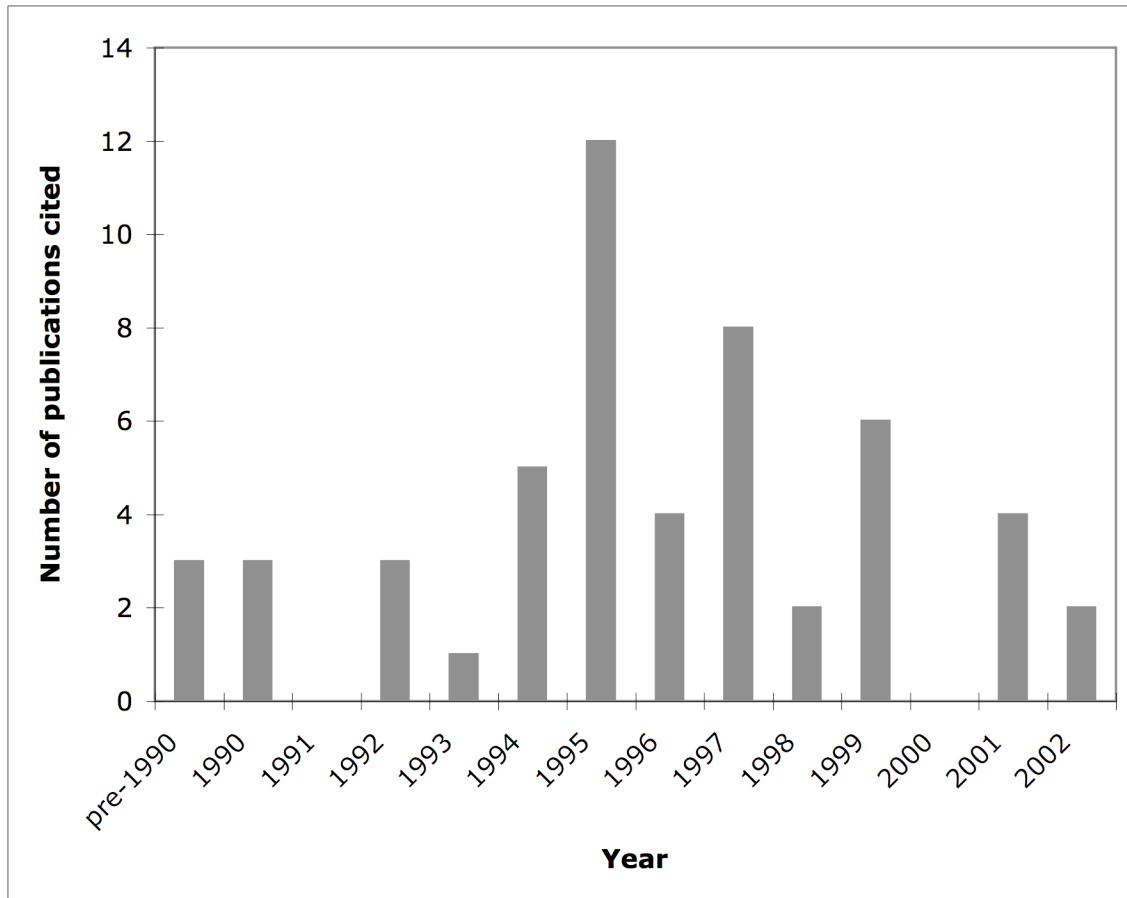


Figure 1. Number of novel 3D interaction technique publications cited by year in *3D User Interfaces* (Bowman et al. 2004)

A few fundamental techniques are missing from the analysis because we could not find any publication describing the technique as a novel research result (perhaps because the techniques are natural and/or obvious). These include the simple virtual hand technique for selection and manipulation, and the physical walking technique for travel. Clearly, however, these techniques were in use from the earliest days of VEs/AR.

Obviously, this analysis does not tell us what will happen in the future. There may be fundamental new 3D interaction techniques still invented, but the trend clearly seems to indicate that the most basic techniques for the universal 3D interaction tasks have been discovered and implemented.

3 The situation today

So where does that leave us? Given the evidence that suggests that the fundamental techniques for the universal 3D interaction tasks have been discovered already, what should happen next in the 3D UI research area? Certainly there is no lack of interest in this topic, despite the downward trend in the discovery of new interaction techniques. The 3DUI mailing list, a worldwide community of researchers in this area, currently has over 300 members from at least 28 countries. Attendance at workshops, tutorials, and

presentations on 3D UI-related topics is consistently high. The first international symposium on 3D UIs, sponsored by the IEEE in cooperation with the ACM, was held in 2006. But how should all of these researchers focus their efforts? What still needs to be done in 3D UI research? To answer these questions, we suggest that it is instructive to consider the current state of 3D applications.

If all of the important 3D interaction techniques have been discovered, one might expect to find a corresponding boom in usable, real-world applications involving 3D interaction. Unfortunately, this does not seem to be the case. Although there has not been another systematic study on production applications of VEs or AR since Brooks' report in 1999, anecdotal evidence suggests that there are only limited, incremental successes, many of which are similar to the categories of applications discovered by Brooks. Our experience with demonstrations of highly interactive 3D applications is that there are still significant usability problems in most cases.

We surveyed the 3DUI mailing list to check our intuition about the current state of production VE/AR applications. We asked for real-world application examples and information on the usability of those applications, if available. While this was not an exhaustive search or a fully-representative sample, we felt that the 3DUI membership would likely be aware of all new developments in VEs/AR.

We received 19 responses, two of which were duplicates of previous responses, leaving us with 17 distinct applications. Of these, six were clearly not yet production applications. These responses contained phrases like “serves...to conduct research,” “just begun to turn our prototype into a production application,” or “we are very close to using it.” The remaining 11 applications did appear to be in regular use for real-world work. However, only four represented new categories of production applications (beyond those identified by Brooks in 1999). These new categories were geoscience (petroleum exploration, drilling, and production), work planning (visualization to plan for decommissioning of nuclear facilities), radiation prediction (visualization of radiation flux and dose levels), and medical training (laproscopic surgery simulation). Interestingly, all of the production applications were VE applications – no AR applications were submitted.

In addition, most of the 11 production applications contained only simple and natural 3D interaction, or none at all. Only four applications made use of complex, magic 3D UIs. Three of these were in the category of “architectural design and spatial arrangement,” and used desktop PCs and standard input devices. These interfaces allow direct manipulation of the viewpoint and of 3D architectural elements at the desktop, and were rated as having either “moderate” or “somewhat high” usability. Desktop 3D UIs seem to be somewhat successful and usable, at least in the architectural/spatial design category.

Only one response described a production application in a new application category that also made use of complex, magic 3D interaction. Major oil and gas companies are making use of immersive VEs to visualize seismic and geological models, to plan the paths of new oil wells, to annotate specific features, and to collaborate with remote

colleagues. The usability of this application was rated as “somewhat high,” and it appears to make effective use of existing 3D interaction techniques for travel, selection, manipulation, and system control. But this appears to be an isolated example. Oil and gas is such a big business that perhaps companies are willing to invest in this technology despite shortcomings in 3D UIs. Overall, the survey did not reveal significant new real-world applications involving complex 3D interaction.

This lack of an application boom could be interpreted in several ways. First, it could be that there are fundamental 3D interaction techniques that have still not been invented, and that the use of these techniques would produce usable 3D UIs. Although this is possible, we have argued in the previous section that it is not likely. Second, the results of 3D UI research may not have reached the application developers, or the developers may have ignored the research results. In other words, although the knowledge exists to develop usable 3D UIs, this knowledge is not being used to its full potential. We believe that this interpretation has some merit, and that 3D UI researchers need to continue to push their results out of the laboratory and into the real world.

But there is a third possible interpretation: it may be that most or all of the basic 3D interaction techniques have been discovered, but that this knowledge alone is not sufficient to ensure the usability of 3D UIs. In other words, even if everyone developing applications with 3D interaction had access to all the most important research results, the applications would still have usability problems. What follows from this argument is that we need to discover what other types of knowledge are needed about 3D UIs – we need an agenda outlining the next steps in 3D UI research. The remainder of the paper is devoted to this topic.

4 Proposed new directions

In this section we propose a research agenda to move 3D UI research beyond the design and evaluation of 3D interaction techniques for the universal 3D tasks. To address the question of which directions 3D UI research should take next, we relied on our own experience in developing and evaluating 3D interaction techniques and complete 3D UIs (e.g. Bowman and Hodges 1997; Bowman and Wingrave 2001; Bowman et al. 2002), and on our experience with the usability of prototype 3D applications with high levels of interactivity (e.g. Bowman et al. 2003b; e.g. Bowman et al. 1998; Bowman et al. 1999). We also examined the most recent work by researchers in the area, as exemplified by the proceedings of two recent workshops on 3D UIs (Bowman et al. 2005; Froehlich et al. 2004), for clues about potential new directions. Our proposed agenda centers on five research directions:

- Increasing *specificity* in 3D UI design
- Adding, modifying, or tweaking 3D interaction techniques to produce *flavors*
- Understanding the *integration* of 3D interaction techniques
- Addressing the *implementation* issues in 3D UIs
- Applying 3D UIs to *emerging technologies*

4.1 Specificity

Although we have argued that most or all of the fundamental 3D interaction techniques for the universal tasks have been discovered, we do not claim that researchers should stop working on interaction techniques altogether. Rather, we believe that existing 3D interaction techniques do not provide sufficient usability in many real world applications because of the *generality* of these techniques.

Typically, generality is considered to be a desirable characteristic. If something is more general, it can be applied in more ways. For example, because the ray-casting technique addresses the general task of 3D selection, it can be used in any situation requiring 3D selection. The downside of this generality, however, is that the application of the technique is always to a *specific* situation, and a general technique has not been designed for the specific requirements of that situation.

The large majority of the 3D interaction techniques we surveyed in section 2 exhibit generality in at least four different ways:

- **Application- and domain-generality:** The technique was not designed with any particular application or application domain in mind, but rather was designed to work with any application.
- **Task-generality:** The technique was designed to work in any task situation, rather than being designed to target a specific type of task. For example, the design of the ray-casting technique does not take into account the size of the objects to be selected and becomes very difficult to use with very small objects (Poupyrev et al. 1997).
- **Device-generality:** The technique was designed without consideration for the particular input and display devices that would be used with the technique. Often techniques are implemented and evaluated using particular devices, but the characteristics of those devices are not considered as part of the design process. For example, the HOMER technique (Bowman and Hodges 1997) is assumed to work with any six-degree-of-freedom input device and any display device, but all of the evaluations of this technique have used a wand-like input device and a head-mounted display (HMD).
- **User-generality:** The technique was not designed with any particular group of users or user characteristics in mind, but rather was designed to work for a “typical” user.

To improve the usability of 3D interaction techniques in real-world applications, we propose that researchers should consider *specificity* in their designs. The types of specificity we have identified are parallel to the types of generality described above:

- **Application-specificity:** The most obvious way to improve usability in any particular application is to design the interaction techniques and user interface specifically for that application. This would mean basically starting from scratch with each application and using a complete usability engineering approach (Gabbard et al. 1999) to produce a usable 3D UI. The disadvantage of this, of course, is that it’s *too specific*. There is no guarantee that any interaction techniques or UIs produced by this method will apply to any other application.

- **Domain-specificity:** To balance the advantages and disadvantages of general and specific 3D UI design, we propose the concept of *domain-specific* 3D interaction techniques and UIs. In this approach, designers acquire knowledge about a particular application domain, and then use that knowledge in their UI designs. The resulting interaction techniques and UI components should be reusable in multiple applications in the same domain. For a case study on the design of domain-specific 3D UIs, see section 5.2.
- **Task-specificity:** Techniques can also be made more usable by designing for specific task requirements rather than for a general task category. For example, many general 3D travel techniques exist, but very few researchers have designed travel techniques for specific types of travel task, such as exploration, targeted search, or maneuvering. In addition, there are specific 3D interaction tasks that should be considered separately from the universal tasks. For example, 3D surface creation and modification, though similar to object manipulation, is a task that would benefit from task-specific techniques. We present a case study of task-specific technique design in section 5.3.
- **Device-specificity:** We can also increase the level of specificity relative to particular input and/or display devices. A technique or UI designed for a pen-shaped 6-DOF input device with a single button may exhibit serious usability problems when used with a multi-button 6-DOF SpaceBall™, for example. There are also numerous opportunities to exploit display device-specificity. In particular, many of the fundamental 3D interaction techniques were designed and evaluated for either desktop displays or HMDs, but we have little or no data on the usability of those techniques with surround-screen or large-screen displays. Two case studies on display-specific 3D UI design can be found in sections 5.4 and 5.5.
- **User-specificity:** Finally, techniques may be made more specific by considering specific groups of users or particular user characteristics in the design. For example, VE experts may use different strategies, and would therefore benefit from an expert-specific interaction technique (Wingrave et al. 2005). User-specific techniques could be created on the basis of age, expertise, gender, spatial ability, and the like.

There is a great deal of potential research in the area of specificity. In particular, it will be important for us to understand when the benefit of designing more specific 3D UIs outweighs the extra cost.

4.2 Flavors of 3D interaction techniques

Existing 3D interaction techniques are, for the most part, simple and straightforward. They are designed to do one thing, and to do it well. In some cases, however, usability can be improved by adding features or complexity to one of these basic techniques. The concept of *flavors* of 3D interaction techniques refers to such variations on fundamental techniques. Often such flavors can be designed by considering lists or classifications of usability problems discovered in fundamental techniques.

For example, consider the basic ray-casting technique (Mine 1995). Its design is extremely simple, and users find the metaphor clear and easy to understand. However, many researchers have noted shortcomings of this technique for the task of 3D object selection (e.g. Poupyrev et al. 1997). Adding features such as snapping the selection ray to the nearest object (Wingrave et al. 2005) or bending the ray around occluding objects (Olwal and Feiner 2003) could address some of these usability problems.

It is not clear which flavors will be useful, and what the tradeoff will be between the level of simplicity of a basic technique and the power of a “flavored” technique. In addition, the added complexity of flavors leads to difficult implementation issues (see section 4.4). All of these are topics for future research. For case studies on flavors, see sections 5.6 and 5.7.

4.3 Integration of complete 3D UIs

Another new direction for 3D UIs relates to the need for usable UIs, not just usable interaction techniques. Clearly, usable interaction techniques are the foundation of a usable UI, but they are not sufficient. Some of our previous work (Bowman et al. 2001a) was based on the assumption that if we could quantify the usability of 3D interaction techniques in various task situations, then application developers could simply choose the techniques that met their requirements. But when multiple usable interaction techniques are combined with one another and with specific input and display devices, the resulting UI will not necessarily be usable. Therefore, research on the *integration* of multiple techniques and devices into a complete and usable 3D UI is essential.

One potential approach here is the use of *cross-task* interaction techniques. These techniques are designed to address multiple tasks using the same basic interaction methods. For example, Pierce’s image-plane techniques (Pierce et al. 1997) can be used for the tasks of selection and manipulation or for the task of travel. In the manipulation mode, the selected object is moved relative to the scene; in the travel mode, the user’s viewpoint is moved relative to the selected object. In this way, users only have to learn one set of actions, and then simply choose the appropriate mode for their desired task.

There are a number of important research questions related to integration. Which interaction techniques integrate well with each other, at both the practical and conceptual levels? Can sets of similar interaction techniques be combined to create a consistent metaphor for a 3D UI? How can designers choose an input device that is appropriate for all the interaction techniques in a given application? This topic should be fertile ground for 3D UI researchers.

4.4 Implementation of 3D UIs

To a large degree, the 3D UI community has ignored the problem of implementation and development tools, although this problem has been recognized (Herndon et al. 1994; Jacob et al. 1999). Most techniques are implemented using existing VE, AR, or 3D graphics toolkits, and there is no standard library of 3D UI components available. For basic techniques, this may not be too great a burden. However, as we move toward more complex 3D UIs (including those resulting from the specificity or flavors approaches, or

from integrating several techniques into a complete 3D UI), turning a good design into a good implementation becomes more and more difficult.

There are many factors that make 3D UI implementation problematic, including the following:

- 3D UIs must handle a greater amount and variety of input data.
- There are no standard input or display devices for 3D UIs.
- Some input to 3D UIs must be processed or recognized before it is useful.
- 3D UIs often require multimodal input and produce multimodal output.
- Real-time responses are usually required in 3D UIs.
- 3D interactions may be continuous, parallel, or overlapping.

3D UI developers must manage all of this complexity while using tools and methods that were originally intended for simple 2D desktop UI programming, using 3rd-generation languages that lack the flexibility and power of more modern languages. The result is code that is very hard to design, read, maintain, and debug; code that contains a large number of callback functions with complicated interrelationships; and code that makes inordinate use of global variables as developers try to manage the state of the application.

Moreover, as HCI researchers, we know that the ability to perform rapid design iterations on low- or medium-fidelity prototypes is an invaluable part of the UI development process. But no tools for the rapid prototyping of 3D UIs currently exist.

To enable further research in 3D interaction, therefore, researchers must address these implementation issues. One important step, though not a complete solution, would be a standard library of interaction techniques or technique components. Such a library would contain generic, reusable implementations of fundamental interaction techniques for the universal tasks. To be truly useful, such a library would need to interoperate with other toolkits used for developing 3D applications. A second major research question is how to enable the rapid prototyping of 3D UIs – both those using existing techniques and those with novel interaction methods. Finally, we need to address the development tools themselves – current 3D graphics development tools based on procedural programming and callbacks may not be the most appropriate choice for 3D UIs. A case study describing some initial steps in this direction can be found in section 5.8.

4.5 3D UIs in emerging technologies

Finally, we propose that technological changes should stimulate additional 3D UI research. Up to this point, the majority of 3D UI research has targeted the desktop, VEs, or AR. But there are a number of emerging technologies or technological concepts, such as large-display technology, wide-area tracking technology, and pervasive computing technology, which will also provide an opportunity for further 3D UI research.

Perhaps the best current example is the trend towards visual displays that are larger in size and that display a much greater number of pixels than traditional displays. Specific systems range from multi-monitor desktop displays to large wall-sized displays to huge public displays. All of these systems could or should make use of some form of 3D

interaction, even if the display is showing 2D information. For example, in the multi-monitor desktop case, losing the mouse pointer is a common problem (Baudisch et al. 2003). Using a 3D input device allowing the user to point directly at the screen in some way might alleviate this problem. In the very large display case, users cannot physically reach the entire display, so interaction techniques based on physical walking, gaze direction, gestures, and the like may be appropriate (e.g. Guimbretiere et al. 2001).

Such emerging technologies provide an important test of the quality of existing 3D UI research. Fundamental principles and techniques developed by 3D UI researchers working with VEs (for example) should be applicable to some degree for large-screen displays (for example). In particular, researchers should address questions like: “What are the universal 3D interaction tasks for the emerging technology, and do they match the universal tasks already identified?” “Which existing 3D interaction techniques can be repurposed in applications of the emerging technology?” “What changes are required to migrate existing 3D UI techniques and principles to the emerging technological area?” This type of research should prove to be fruitful and challenging in the next few years.

5 Case studies of new directions

We now turn to examples of the new directions discussed in section 4. All of these projects were carried out in the 3DI Group at Virginia Tech, and many come from a graduate class on 3D interaction (see section 5.1). In the sections that follow, we summarize each of the projects. Many details are left out; we only provide enough information to give a sense of the problem, the proposed solution, the experimental results, and the overall approach taken by each project.

5.1 3D interaction class

At Virginia Tech, we offered an advanced graduate seminar class on the topic of 3D Interaction. Ten students participated in the class. Students learned about 3D UIs through a combination of readings (both a textbook and recent scholarly articles), group discussions and brainstorming, hands-on learning in our VE laboratory, and a few lectures by the instructor.

With this knowledge and understanding, teams of two students each were assigned a semester project on the topic of “enhancing basic 3D interaction techniques” (alternate title: “3D interaction beyond 15 minutes of thought”). Students were told to explore an existing 3D interaction technique and come up with ways to improve its usability. The project progressed through four phases. In the first phase, students implemented the existing technique, and completed an initial design and prototype for their enhanced technique. Phase two required students to run a formative evaluation of their new technique, iterate the design based on the results, and implement a revised prototype. In phase three, teams ran a summative evaluation comparing their new technique to the original technique. Finally, students wrote a formal report on their project in phase four.

Students were also given a list of ideas on the class website² to help them get started on the design of their enhanced interaction technique. These ideas summarized some of the potential new directions discussed in the previous section of this paper, including flavors, domain-specificity, device-specificity, user-specificity, and task-specificity.

To complete their projects, teams had access to a wide range of VE equipment, including a 4-sided CAVE, an HMD, a haptic device, six-degree-of-freedom tracking systems, and various input devices such as a wand, a stylus, pinch gloves, data gloves, and a chord keyboard. Students implemented their techniques and environments using one of three available software tools: DIVERSE (Kelso et al. 2002), SVE (Kessler et al. 2000), or Xj3D (<http://www.yumetech.com/products/xj3d.html>).

Five student projects were completed, and indeed the projects did demonstrate a range of potential new directions for 3D UIs. A paper on one of the projects was accepted and presented as a short paper at CHI (Lucas et al. 2005), another has been accepted as a full paper at the ACM Symposium on Virtual Reality and Software Technology (Polys et al. 2005), and a third currently has a conference submission pending. Although this indicates the high quality of some of the projects, we are not concerned here with arguing the significance of any of these specific results; rather, we intend to show the potential of the new directions in 3D UI research exemplified by these projects.

5.2 Domain-specific techniques: the AEC domain

As a testbed for the concept of *domain-specific 3D interaction* (see section 4.1), we considered the architecture/engineering/construction (AEC) domain. In the past, we have designed several 3D UIs for particular applications in this domain (Bowman 1996; Bowman et al. 2003b; Bowman et al. 1998), and we have attempted to use generic 3D interaction techniques within those UIs. Although we achieved moderate success in the usability of the applications, some significant usability problems could not be solved using generic techniques. We hypothesized that by learning more about the AEC domain and applying this knowledge to our 3D UI designs, we could both improve the usability of particular applications and, at the same time, design techniques that could be reused elsewhere in the domain.

This ongoing project has already produced some significant results, but not in the way we originally expected. We began by gathering as much information about the AEC domain as we could, and trying to extract from this information particular characteristics of the domain that might be relevant to 3D interaction. For example, it's clear that because the domain deals with concrete physical objects such as columns, walls, and furniture, that domain-specific object manipulation techniques need to take the physical properties of these objects into account (e.g. a chair must rest on a floor and should only rotate around its vertical axis). We quickly developed a short list of such characteristics, but most of them could be reduced to simple *constraints*, which are already widely used in 3D UIs (e.g. Bukowski and Sequin 1995; Kitamura et al. 1996). To have real impact on the field, we needed another method for designing domain-specific 3D interaction techniques.

² The website can be viewed at <http://people.cs.vt.edu/~bowman/cs6724/>

Our most significant results to-date came not from considering domain characteristics in the abstract, but rather from considering the requirements of a particular application in the domain. The Virtual-SAP application (Bowman et al. 2003b) is a tool for structural engineering students and practitioners. It allows them to design and build the structural elements of a building, and then simulate the effects of environmental conditions, such as earthquakes, on the structure. The 3D UI for this application uses generic interaction techniques such as pointing for travel, the Go-Go technique for selection and manipulation, a 3D snap-to grid to aid precise manipulation, and pen-and-tablet-based menus. These techniques were all relatively usable in our studies of engineering and architecture students. What we discovered, however, was that the *tasks* supported by the application were not sufficient for real-world work. In particular, users had trouble creating structures with sufficient complexity and size, because the UI required them to create each element of the structure via the menu, and then place it in the environment using the manipulation technique. For a structure with hundreds of elements, this became impractical. This problem was a significant one, because students and practitioners really only benefit from the application by analyzing complex cases where they could not predict the behavior of the structure.

We observed that most of the large structures users wanted to build contained a great deal of repetition (e.g. one floor of a building is identical to the one below it), and so we addressed this problem by developing interaction techniques for the task of *3D cloning*. These techniques allow the user to quickly create multiple copies of existing components of a structure. We went through many design iterations and now have several usable and efficient techniques (Chen et al. 2004a; see Figure 2), but the key was recognizing that the AEC domain required a 3D interaction task we had not originally considered.

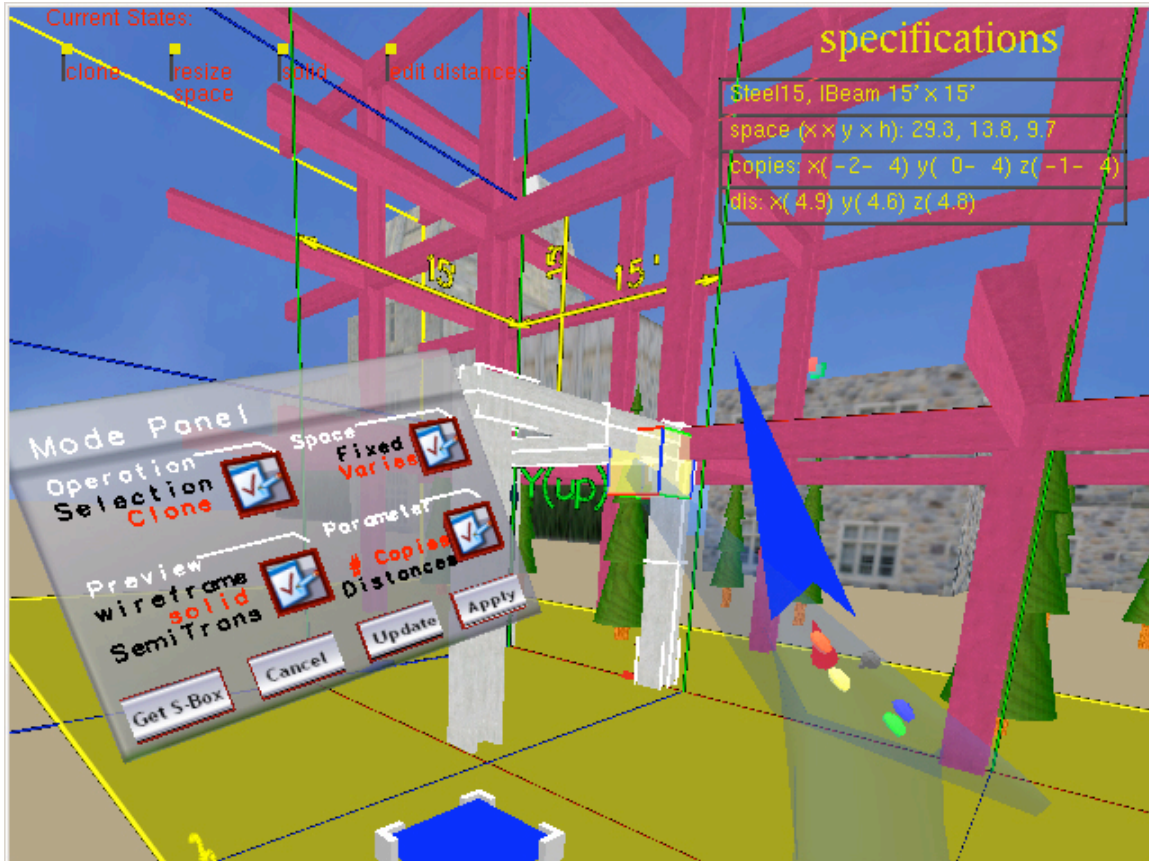


Figure 2. One of the 3D cloning techniques designed through domain-specific interaction research

In addition, our work on cloning techniques required us to consider another 3D interaction task – multiple object selection. In order to clone an existing component of a structure, the user must select all the elements (beams, walls, etc.) that make up that component. Of course, selecting the elements in a serial fashion with generic 3D selection techniques would address this requirement, but just as creating multiple copies is more efficient than creating one element at a time, selecting many objects in parallel may provide performance gains. We have developed and evaluated both serial and parallel multiple object selection techniques (Lucas 2005), and we are currently using one of the parallel techniques (3D selection box) in our cloning interface.

In summary, we have developed several successful domain-specific interaction techniques that provide clear usability gains over their generic counterparts. These techniques can be reused in multiple AEC applications, and may also be useful in other domains. But the process of developing these techniques has differed from our expectations in two important ways. First, real applications in the domain were a better source of UI requirements than general knowledge about the domain. Second, designing new techniques for domain-specific interaction tasks has been more successful than designing domain-specific interaction techniques for universal interaction tasks, at least so far.

5.3 Task-specific techniques: resizing

A second project focused on the task of resizing, or scaling, virtual objects. In fact, this project was motivated by the 3D multiple object selection project described in the previous section. In the 3D selection box technique, the user encloses the objects she wants to select with a semi-transparent box. In order to use this technique for any set of contiguous objects, the user must be able to both position and resize the box. In a way, then, our consideration of this interaction task also arose from our examination of the AEC domain.

The scaling of virtual objects, of course, is not a new 3D interaction task. Prior research on this task has resulted in a number of widget-based techniques (e.g. Conner et al. 1992; Mine 1997). In the widget-based approach, small handles are attached to the selected object, and the user scales the object by manipulating one or more of the handles. The key word in the previous sentence is *manipulating* – most 3D UI designers have viewed the resizing task as simply a special case of manipulation, and have therefore simply reused existing manipulation techniques to position the widgets.

Our approach, on the other hand, was to consider the unique properties of the resizing task as an opportunity to do some focused design; in other words, we took a *task-specific* approach. We are not the first to take this approach for object resizing. For example, there are several published techniques using two-handed interaction to specify object scale (e.g. Mapes and Moshell 1995; Mine et al. 1997). Still, there are many other novel designs that have not yet been tried.

We designed object-resizing techniques for immersive VEs using an HMD. Our work resulted in two novel techniques, both of which require only one tracked hand for interaction. The Pointer Orientation-based Resize Technique (PORT) uses the orientation of the hand-held pointer relative to the object to determine the axis of scaling, and the amount of scaling is specified using a small joystick (Figure 3). With the Gaze-Hand Resize technique (Figure 4) the user specifies the axis of scaling using the orientation of the pointer as in the PORT technique. The user's gaze direction is then used to adjust the position to which the active face of the box will be moved. This technique takes advantage of the stability of the head to perform accurate resizing of objects.

We hypothesized that both of our novel techniques would be more efficient and more accurate than a widget-based technique for resizing an object along a single axis. However, our techniques also had a disadvantage: they only allowed scaling along one axis at a time, while our implementation of the widget-based technique allowed the user to scale along one, two, or all three axes simultaneously by choosing an appropriate widget.

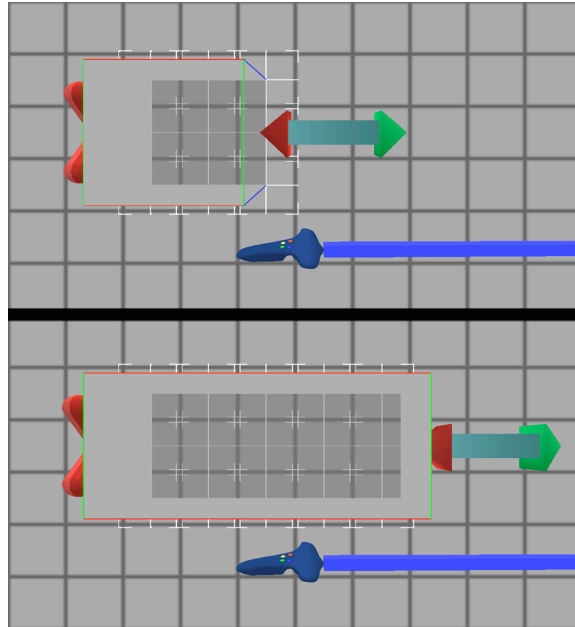


Figure 3. Resizing a box with the PORT technique

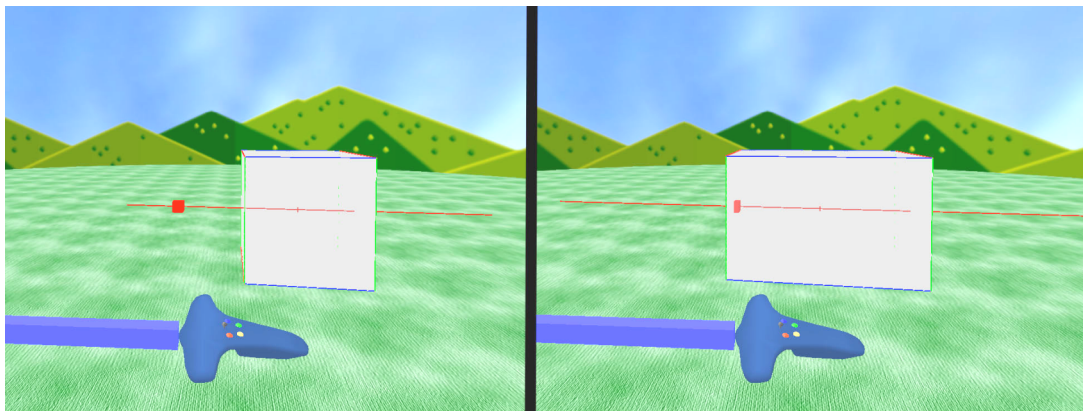


Figure 4. Resizing a box with the Gaze-Hand Resize technique

We evaluated our two techniques and the widget-based technique in a formal experiment. Both PORT and Gaze-Hand were significantly faster than 3D widgets. Initially, subjects preferred the 3D widgets because of their similarity to resizing techniques in desktop applications, but by the end of the experiment, the strongest preference was for the Gaze-Hand technique, while 3D widgets was the least preferred. Complete details and results can be found in (Lucas et al. 2005).

This project demonstrates the potential of the task-specific approach to 3D UI design. Designing for the specific task situation resulted in higher levels of objective and subjective usability as opposed to simply reusing more generic interaction techniques.

5.4 Display-specific techniques: CAVE travel

As we noted earlier, most of the fundamental 3D interaction techniques were designed, implemented, and evaluated with a particular display device in mind – most often either a

desktop monitor or an HMD. It is assumed that these techniques can be reused directly with other display types – a surround-screen CAVE, for example. But moving a technique to a new display can result in many unforeseen usability problems (Manek 2004), thus presenting an opportunity for a *display-specific* technique design. In this project, we designed a CAVE-specific version of a travel technique that was originally designed for HMDs.

The orbital viewing technique (Koller et al. 1996) allows users to easily attain any perspective on a single object or point in a 3D environment. The idea of orbital viewing is that the user's head rotations are mapped onto movements along an imaginary sphere surrounding the object or point of interest. By looking left, the user can move to a point directly to the right of the object/point; by looking up, the user gets a view from directly beneath the object/point. This technique makes sense for an HMD because an HMD provides a fully-surrounding virtual environment – no matter where the user looks, he sees part of the virtual world.

In a typical CAVE, however, the VE is only partially surrounding. The most common CAVE configuration (also the one we used) has three walls and a floor – the back and top of the cube are missing. Therefore a naïve implementation of the orbital viewing technique would not allow the user to obtain certain views. In addition, the head movement in the traditional orbital-viewing technique can be tiring, and it can be difficult for the user to maintain a particular view for long periods of time. Finally, the existing technique does not allow the user to reach a particular viewpoint relative to the object/point, then look in another direction at the rest of the virtual world.

To address these issues, we made a simple change to the orbital viewing technique, by mapping hand orientation to the viewpoint instead of head orientation. The effects of this design change are to allow the object to remain in front of the user in the CAVE, to allow the user to obtain any desired view of the object/point, to reduce fatigue, and to allow the user to look in any direction while orbiting. A simple user study confirmed these advantages: 71 percent of subjects preferred the wand-orbiting technique, and the new technique was just as efficient as the traditional technique.

Although this is a small example, it does show the potential of the device-specific interaction design approach for 3D UIs. There are many more basic 3D interaction techniques that could benefit from redesign for particular display devices.

5.5 Display-specific techniques: IRVE information layout

One of the current research thrusts in our group focuses on *information-rich virtual environments* (IRVEs), which combine realistic perceptual/spatial information with related abstract information (Bowman et al. 2003a). One of the important research questions related to IRVEs is how to best lay out the abstract information relative to the spatial environment. For example, information may be in *object space* (within the 3D environment) or *viewport space* (overlaid on the user's view of the environment), among other choices. Our previous research has compared these two layout options for desktop displays, but we were interested in how these layout techniques scaled to larger displays.

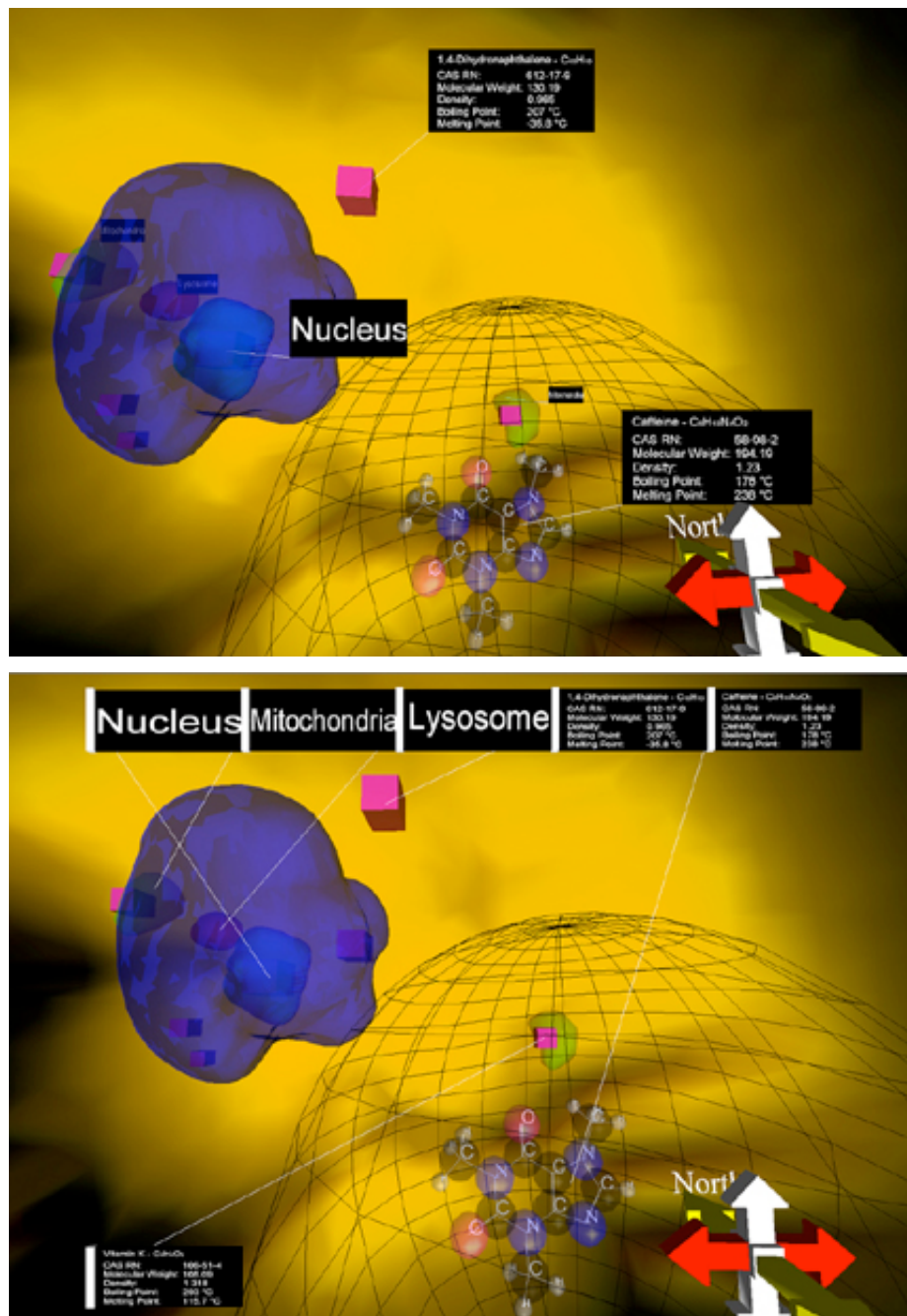


Figure 5. Layout techniques for IRVEs: object space (top) and viewport space (bottom) layouts

In this study, we compared a typical desktop monitor with a large, high pixel-count display made up of nine tiled LCD panels in a 3x3 configuration. We displayed an IRVE representing a biological cell, with abstract information labeling various parts of the cell and their properties. The object space layout technique (Figure 5, top) placed this abstract information on “signs” that were part of the 3D environment and that were attached to the appropriate 3D objects by lines. The viewport space technique was a heads-up display

(HUD) in which the abstract information was placed around the border of the display, in front of the environment (Figure 5, bottom). The HUD information was also connected to the 3D objects with lines. The labels in the HUD condition have a fixed size measured in pixels. Thus, in the large display condition many more labels can be viewed simultaneously without any loss of legibility; this was thought to be a significant advantage of the large display.

Overall, the HUD technique was more effective and preferred when subjects performed search and comparison tasks in the IRVE. However, a surprising effect was that some of the HUD's advantages were lost when the large display was used, while performance with the object space layout increased with the large display. Our interpretation of this result is that because we chose to place labels on the border of the display in the HUD technique, users of the large display were forced into greater head and eye movements, and labels ended up farther from their corresponding 3D objects. For a complete description of this study and its results, see (Polys et al. 2005).

This example shows that well-designed and usable techniques for one display may not migrate well to different display devices. In this case, the HUD concept clearly needed to be redesigned for the large display. For example, we might decide to place the labels on the image plane near to their corresponding 3D objects when using a large display, similar to the technique used in (Chen et al. 2004b). Further research along these lines is needed to determine the effects of display type on a variety of 3D interaction techniques and UI designs.

5.6 Flavors: The SSWIM technique

The *flavors* approach adds new features, additional complexity, or subtle tweaks to existing fundamental techniques for the purpose of improving usability. Our first example of this approach is the SSWIM technique – an enhancement of the well-known World-in-Miniature, or WIM (Pausch et al. 1995; Stoakley et al. 1995).

The WIM technique gives the user a hand-held miniature version of the virtual world. The user can select and manipulate objects in the world by directly touching and moving their miniature representations in the WIM. The WIM can also be used for travel – the user grabs and moves a miniature representation of herself in order to travel to a new location in the full-scale environment.

One of the major limitations of the WIM is its lack of scalability. In a very large environment, either the WIM will be too big to handle, or the miniature versions of the object will be too small to see and manipulate easily. Thus the simple concept of this project was to allow the user to “pan and zoom” the WIM's representation of the virtual world – we call this the “Scaled Scrolling World-in-Miniature” or SSWIM. The concept of enhancing the WIM is not original; LaViola's Step WIM (LaViola et al. 2001) also added the ability to zoom, but this design deviated significantly from the original WIM – the miniature was fixed to the floor and users interacted with their feet. Our goal was to remain true to the original WIM concept while adding more advanced features.

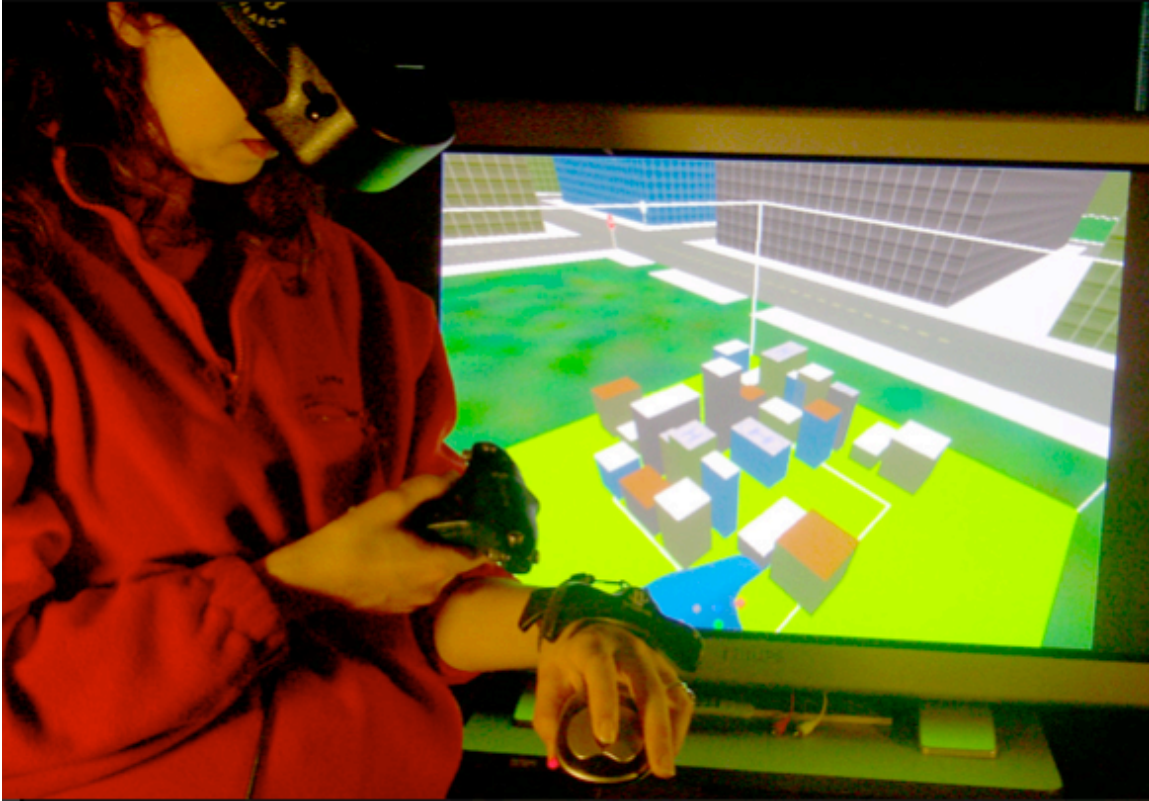


Figure 6. The SSWIM technique

The SSWIM (Figure 6) was designed for an HMD-based system where both of the user's hands are tracked. The SSWIM itself is held in the non-dominant hand and is automatically rotated to remain aligned with the full-scale environment. A wand is held in the dominant hand and is used to reposition the user representation within the SSWIM. Scrolling is accomplished by dragging the user representation towards the edge of the SSWIM, and a large arrow provides feedback as to the direction of scrolling. The most difficult design decision was how to allow users to zoom the miniature world. Initially we tried a glove-based approach where the user's hand posture (somewhere on the continuum between a clenched fist and a flat hand) determined the scale, but this was too difficult to use and control. We next tried scaling up or down with two additional buttons on the wand, but this prohibited the user from scaling the miniature and positioning the user representation at the same time. Eventually we hit upon the idea of using the scroll wheel of a wireless mouse held in the non-dominant hand for scaling.

Obviously, the additional features of the SSWIM make it possible to travel precisely even in environments with a wide range of scales. For example, in the city environment we used, it would be possible to travel from one side of the city to the other, and to enter a specific room within one of the high-rise buildings. Our question, however, was whether this additional complexity would cause a significant drop in usability for the travel tasks already supported by the WIM. We compared the two techniques in an experiment designed to test typical WIM travel tasks, and found no significant difference in efficiency or user preference. In fact, SSWIM users were significantly more accurate than

WIM users in positioning themselves in the world, because they consistently chose to use a zoomed-in miniature world representation.

This project demonstrates that it is possible to create usable new flavors of existing fundamental 3D interaction techniques that provide significant advantages. It also shows that the additional complexity does not necessarily lead to a drop in user performance, even on simple tasks. The other major lesson from this project, however, was that the implementation of such complex techniques is extremely difficult with existing tools. This has led us to consider alternative 3D UI implementation approaches (section 5.8).

5.7 Flavors: Game-like travel

The flavors approach is also exemplified by a student project on the topic of enhancing basic 3D travel techniques. Gaze-directed steering and pointing are probably the two most common travel techniques used in immersive 3D environments. Both allow the user to specify a direction of travel and then control her movement along that vector. In gaze-directed steering, the travel vector is determined by the gaze direction (usually assumed to be identical to the head orientation); while in the pointing technique, the travel vector is mapped to the hand orientation (Mine 1995). The major problem with the gaze-directed steering technique is that the viewing direction is coupled to the travel direction, so that it is impossible to look in one direction while traveling in another. The pointing technique alleviates this problem, but it can still be difficult to travel in some directions relative to the view (e.g. depending on the device, it may be difficult to point backwards).

The goal of this project was to investigate the use of typical travel techniques from 3D “first-person shooter” games in the context of immersive VEs. Desktop 3D first-person games usually make use of an enhanced “gaze-directed” technique allowing the user to change the gaze direction with one input device (e.g. the mouse) and to travel forward, backward, left, or right relative to that direction with a second device (e.g. the arrow keys on the keyboard). Traveling left or right is referred to as “strafing.”

Our techniques made use of a small 2-DOF joystick available on our wand input device in the CAVE. The wand itself is a 6-DOF tracker, and the user’s head is also tracked. Thus, we could enhance the basic gaze-directed steering or pointing techniques with the ability to travel in different directions using the joystick. Our initial evaluation showed that adding backward motion and strafing to the pointing technique was too confusing – the user had to cognitively process both the wand orientation and the joystick movement in order to determine how to move in a particular direction in the world. Adding backward motion and strafing to gaze-directed steering was much easier to understand.

We compared the enhanced gaze-directed technique with the traditional pointing technique by having subjects navigate an obstacle course in the CAVE. We found that the enhanced technique was significantly faster than the traditional pointing technique, but also that it required more training time to master. A majority of subjects preferred the enhanced technique and found it easier to use after training. However, the enhanced technique did result in more collisions with the obstacles in the environment.

This project again demonstrates the potential to add simple features to fundamental 3D interaction techniques in order to improve usability. In particular, this work shows that designers can draw inspiration from existing techniques used on the desktop.

5.8 Implementation framework for 3D UIs: CHASM

As the previous examples show, our research into domain-specific, task-specific, device-specific, and flavored 3D interaction techniques allowed us to generate a wide variety of new ideas for improving the usability of 3D UIs. Clearly there is no shortage of novel contributions that can be made to 3D UI design. But a consistent subplot to our research has been our frustration in implementing the envisioned techniques and interfaces. As we noted in section 4.4, it is extremely difficult with today's development tools to produce a robust, bug-free implementation of even a moderately complex 3D interaction technique. Our research group has a great deal of experience with 3D graphics, VE toolkits, and UI programming using an event-based or simulation-based model; still, we find it troublesome to translate our envisioned 3D UIs into working code.

We have been evaluating 3D UI designers' natural-language-based descriptions of their interfaces and interaction techniques. Our initial analysis shows that there is a large gap between these descriptions and the required implementations using today's tools. The descriptions do seem to match more closely, however, with a state machine representation of interaction. Therefore we have developed an initial prototype of an implementation framework based on state machines. This framework is called CHASM (Connected Hierarchical Architecture of State Machines) (Wingrave and Bowman 2005).

CHASM addresses the issues with event-based programming by using a state machine representation, but we quickly realized that simple state machines would not be sufficient. As UIs grow in complexity, there is a state space explosion that would be even more difficult to manage than the callbacks in traditional UI programming. Thus, CHASM uses a hierarchy of state machines, where each machine can be partitioned into manageable chunks, and where the designer can work at various levels of abstraction. CHASM also supports and encourages reuse, since each state machine is self-contained and modular.

We have just begun to use CHASM for actual 3D UI development, and should soon see whether our hypotheses about its benefits are correct. We are also continuing to study designers' representations and descriptions more systematically, and we will revise CHASM based on our findings. Finally, we plan both laboratory-based and long-term studies of developers using both CHASM and existing development tools.

CHASM is not the only possible approach for enabling more rapid and robust development of 3D UIs, but it is certainly promising. We hope that it will inspire others in the 3D UI community to investigate other methods for addressing the difficult implementation issues related to 3D interaction.

6 Conclusions

3D UIs are an exciting and important topic in the field of HCI, and a great deal of interesting work has been performed to date. However, the pace of growth in the area seems to have slowed significantly since the year 2000 or so. At the same time, an analysis of existing real-world applications of 3D UIs shows that there has not been a significant increase in the quantity or quality (usability) of those applications due to 3D UI research. Thus, the area is in need of some new research directions that can address this situation.

We have proposed that research topics related to *specificity* (explicit consideration of specific domains, tasks, and devices), *flavors* (adding complexity, features, or tweaks to existing techniques), *integration* (combining usable techniques into a usable complete 3D UI), *implementation* (enabling the rapid and robust development of 3D UIs), and *emerging technologies* (applying or redesigning existing 3D UIs for new technological contexts) will have a major positive impact on the field and on the usability of real-world applications of 3D UIs. Our case studies of several of these new approaches indicate the potential they have for improving 3D interaction design and development.

We have not covered all possible new directions in this paper. For example, the emerging theme of *embodiment* in HCI certainly applies to 3D UI design, where users are often bodily immersed in a real or virtual 3D space. And of course, these new directions are not entirely new – some of them have been used in other areas of HCI quite successfully. Based on the research presented at the two most recent international workshops on 3D UIs, even some 3D interaction researchers are already beginning to use these approaches. But they do represent a change from the traditional ways of doing 3D UI research. We hope that the directions outlined here can serve as a useful starting point for 3D UI researchers just entering the field or those looking for a new challenge.

Taking these approaches as a research agenda should help to increase our knowledge and understanding of 3D UI design. We look forward to exciting results based on these new directions, and eventually to usable 3D UIs in a wide range of real-world applications.

Acknowledgments

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