AN EXPERIMENTAL COMPARISON OF THREE METHODS FOR COLLISION HANDLING IN VIRTUAL ENVIRONMENTS

by

Jeffrey Jacobson

Bachelor of Arts in Computer Science, University of Texas, 1986

Submitted to the Faculty of the

Department of Information Sciences in partial fufillment

of the requirements for the degree of

Master of Sciences in Information Science and Telecommunication

University of Pittsburgh

1997

Dr. Michael Lewis

Dr. Stephen Hirtle

Dr. Paul Munro

AN EXPERIMENTAL COMPARISON OF THREE METHODS FOR COLLISION HANDLING IN VIRTUAL ENVIRONMENTS

Jeffrey Jacobson, BA

University of Pittsburgh, 1997

This study compares three common strategies for handling collisions between the user's virtual body and other objects in a cluttered virtual environment. Test subjects seek "treasures" in a maze of narrow corridors which are embedded in a jumble of irrelevant shapes. The application ran on a PC, with the mouse and screen as the interface. The user can either pass through an object, is forced to stop completely, or is deflected around it. Data show that the third strategy best facilitates goal-seeking behavior with this interface and for this type of problem.

This result is significant, because collision handling is critically important to the usefulness of Virtual Reality applications. Furthermore, the screen-and-mouse is both the most common and least studied interface for virtual environments.

FORWARD

I would like to thank my advisor, Dr. Michael Lewis for his guidance, encouragement and material assistance. Without his strong support, this project could not have been possible. Thanks to Dr. Lowry Burgess for introducing me to the concept of applying proxemics to motion upon which this study is based. Thanks to Dr. Marek Druzdel for offering his research-design course from which the research design and analysis benefited greatly. Thanks to Dr. Stephen Hirtle for the idea of graphing the "footprints" of test subjects as they traverse the maze. Utmost thanks to Emilie Morse for help with the statistical analysis and general editing.

Finally, I wish to thank the School of Information Sciences Lab Administration for supplying most of the hardware and all of the space available Also, my thanks to Craig Campbell for sharing the software setup he was using for his own work.

Table of Contents

List of Figures

Introduction

As we move through the world, we get around most objects using low-level psycho-motor behaviors, which require little conscious thought. For example:

> A person in a room wants to get to the door, but there is a chair between them. It is unlikely that he would move to some neutral point to one side of the chair, or even to follow some gently curved trajectory. Ordinarily, he will head straight for the doorway and step around the chair when he encounters it.

Navigating a cluttered VE should be comfortable in this way, but without an expensive display system, the user will not be able to simulate this type of motion. Unfortunately, most interfaces provide neither the range of perception nor the body control for the user to move about as they do in the real world. This is especially true with the basic screen-and-mouse interface, because his FOV is too limited and he has no direct connection with his virtual body. However, it is by far the most common interface and will be for some time. This study is concerned with making collision handling in virtual environments comfortable, where only a mouse-and-screen interface is provided.

Navigating through a Virtual Environment(VE) generally means that a user is moving her viewpoint or egocenter in the virtual space. A variety of cues indicate to the user "where" this point lies in the VE, [8]. To the user, this egocenter implies a virtual body or "self" that exists in the VE. What happens, or should happen, when it encounters a virtual object? For this study, I extend Hall's notion of a personal space, [55] or proxemic zone, to include the distance a person keeps from objects in general. For the experiments in this study, it is modeled as an invisible sixteen-sided cylinder, which extends from floor to ceiling, always surrounding the user's viewpoint. When the user's proxemic zone intersects an object, the collision handling strategy is engaged.

This study compares three basic strategies, one of which is engaged when the user's Proxemic Zone encounters and object. They are:

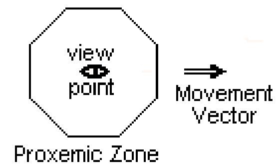

Figure One: Proxemic Zone. Actual implementation has sixteen sides. Eight shown here for clarity.

- **Ghost** No effect. User passes through object.
- **Clunk** Complete stop on contact with object.
- **Slip** User's movement is deflected, making him slide around the object.

Data shows that for a maze of narrow corridors embedded in extra geometry, slip mode allowed test subjects to be most efficient at finding objects in the maze. I generalize on this to claim that slip mode is generally more effective for such situations. Most high-performance video games use some variant of this strategy, but these are the first experiments of which I am aware that explicitly describe the **slip** collision strategy and test its effects. This thesis will:

- Characterize current research and development in perceptually three-dimensional cyberspaces.
- Review the existing theories and literature on how people perceive themselves within space-time and direct their actions.
- Summarize the perceptual cues needed to make a screen-and-mouse interface work for a user, to make them feel they are engaged in the action going on in the virtual space.
- In light of the cues described in the previous section, discuss the state of the art in commonly available video games, which almost all use screen-and-mouse, at least as an option.
- Discuss collision detection in general and compare the three modes mentioned.
- Describe experiments which compared the usefulness of the three modes.
- Present the results.
- Discuss possible future work

Literature on the Visual Perception of Motion

Our understanding of how a user perceives a virtual environment can be no better than our understanding of how he perceives the real world. In this section we will look at the literatures, most of them coming under the general heading of Cognitive Psychology, which address human visual perception of motion in the natural world. Discussion will be weighted toward perception of self location in a VE and related to the three collision strategies already introduced.

Artificial Intelligence

The main lesson to draw from this literature is one critically important idea: Processing for high-level navigation must be done separately from the handling of the low-level tasks used for dealing with collisions. [88] This has been postulated in theory and borne out in practice--the more successful robots built to navigate spaces such as office environments are programmed this way. [89-92] Those programmed with only reactive behaviors can do certain tasks well, but are very limited without real intelligence. [103] Those that use *only* intelligence are even more limited. [104] Their problem is that if every bump or corner in the environment has to be considered, it leads to a combinatorial explosion of possibilities and factors to consider. Using reactive behaviors for small obstacles or particular conditions allows for abstraction of these details to make the navigation problem tractable.

Evidence that reactive behaviors are necessary for robots, supports the notion that human must have them too. The idea of an intelligent agent navigating a dumb space can be inverted to say the VE should respond to the user's small or reactive behaviors with reactive behaviors of its own. A VR application wouldn't need to (and often could not) recompute its entire state every time the user took a step--it only needs to change things affected by the action. Slippery mode for collision handling is a perfect example of this.

An interesting branch of AI is the implementation of connectionist networks which can be very good at object or scene recognition and even control behaviors. [103] However, I am not sure how to fit this into a theory of motion perception in a useful way.

Intelligent agents in a virtual environment have the significant advantage that they can access information about the space directly from the application's database, rather than attempt to visually interpret the scene. This is also an interesting topic that is beyond the scope of this study.

Human Information Processing

Currently, the information processing (IP) approach is dominant in Cognitive Science, [105] and the general thrust visual perception research has to do with static models. The perception of motion is not studied much; for example, it is nowhere in Marr's analysis. [94] Even Ullman, in his experiments with the rotation cylinders composed of widely spaced dots, [94] did not deal with motion in his functional breakdown of human visual perception. in spite of this, the IP approach includes some useful studies, many of which come out of attempts by computer scientists to implement machine vision.

For example, Muller and Maxwell [93] present a model that the human mind has distinct visual filter that separate moving objects from stationary objects. At the next state of perception, the view of all objects, stationary or moving is passed to a form-recognition filter. The present experimental evidence which indicates that this model is at least congruent with actual visual perception.

A lot has been written about spatial cognition, wayfinding and navigation at a high level of abstraction, [70-79] which does not deal with low-level issues such as collision handling.

Situation Awareness

A sub-branch of the Information processing literature, studies under this heading are based on predicting human problem-solving behavior, in part, on some entity model of the mind. This is problematic. [61] Models of this type create a framework within which one can posit experiments, [62-67] but they provide nothing useful for the problem this study is concerned with.

The Ecological Approach

Gibson [98] provides a strong framework for locomotion, based on what the person sees around her. He defines the "optic array" as the overall pattern of information (encoded as light) in the viewer's entire field of vision. "Optic flow" refers to the changes in the optic array which indicate motion. For example, the viewer knows he is moving forward because objects or features appear in front of him, grow larger as he approaches and disappear off to one side or the other. (Ignoring collision for the moment.) She can see that she is moving backward or away from something when the reverse happens. Rotation is similar.

In terms of the optic array, the person can tell how close he is to an object by the level of detail seen in it and by what size it is. The same is true for virtual environments. as shown in empirical studies by Thomas [23] and DeLucia [17] .

Significantly, Gibson [98] proposes that people think about their location in terms of the affordances [100] it accords them in the environment. For example, an apple may be at viewing distance, touching distance or eating distance. The viewer decides if a collision is imminent with an object and will takes action accordingly, when the object's affordances include physical contact. The idea of affordances used in this way has important implications for the designer of any VE. For example, users will behave differently near the edge of a perceived precipice than on a normal sidewalk. [3]

Gibson posits that cognition is distributed between the organism and its environment. In my opinion, this view is strongly supported Kirsh's study [87] where experts were shown to change their environment to perform tasks. For example, a cook will physically arrange his ingredients in ways that remind him which order to use them. This makes the act of cognition something that happens not only in the brain, but the hands and the counter-top. The lesson of this is that user motion in a virtual environment will be strongly governed by what appears to be possible and safe.

One of the problems with ghost mode is that it does not appear possible. More importantly, going through a wall causes a sudden and total change in the optic array; such shocks are not typical in the real world. The problem with clunk mode, at least in this study, it that the user quickly learns it is not safe. The time it takes to backup, reorient and get moving again is so onerous that the user tends to spend a lot of time carefully avoiding the walls.

Causality in Perceived Motion

In the early forties, Michotte [80] performed a series of experiments to explore how observed events can appear to be connected. Generally he would present the test subject with the illusion of two or more moving objects. Based on their relative motion and/or deformation the test subjects said the objects appeared to be interacting (or not) or appeared to be parts of a larger whole (or not). From this he was able to develop several theories of perceived causal relationships.

For example, the "launching effect" occurs (in one form) when one moving object moves to the vicinity of a stationary object and slows to a halt. Then, the stationary object begins to move in the same general direction that the first one had been.. An observer will usually believe that the first object caused the second one to move if:

- the second object must begin moving <u>soon</u> enough after the first one stopped,
- the first one must have stopped <u>near</u> enough to the second,
- and the motion of the second object must be similar enough to that of the first.

An extreme example of this would be of one billiard ball colliding with another. Michotte experimented with less definite cases, varying the parameters listed above.

It would be a short step to imagine that this sort analysis can and should be applied to problems in navigation. For example, if the user is moving her egocenter in a virtual environment toward a wall, how close must the wall appear for her to attribute a sudden involuntary stop to a collision with the wall? If he is forced to stop suddenly, will he look down at his virtual feet to see if she ran into something? Are there conditions, like overall environmental clutter, that will affect this? In some video games, the application shows the user that he successfully picked up an object by having the image of it follow the user's viewpoint. This could be seen as an example of Michotte's "entraining effect", where a moving object appears to capture a stationary one if the latter starts moving in the same direction at the right time.

Michotte wanted to show that gestault perceptions can extend over time for moving objects and not just static objects. Since that time, there has been no equally systematic study of apparent causality in motion.

Slippery mode provides behavior that more closely matches the generally expected rules of causality. Clunk mode is similar, but physically difficult to manage. Ghost mode is totally opposite to what we normally expect.

Biological Motion

Being animals, we are geared to perceive natural events, at great speed and with very little information. [98] Built-in constraints on the human perceptual system play a major role in this. Bassili [22] showed test subjects simple geometric shapes moving independently in a series of short animated movies. In some films, one appeared to be chasing the other, in a nother the seem to be in a neck-to-neck race, and so on. Viewers even ascribed emotional characteristics to the shapes--one is a sad square or a happy circle, for example. All of this was based on nothing more than their relative motion.

Johansson's experiments [86] show how our visual system will infer a great deal about an object or creature from certain patterns of motion alone. In the experiment, a person wore a black body stocking and a twelve lights, one on his head and the rest at major joints on his body. In a dark room, test subjects could only see the lights. At rest he looked like a random group of lights. When he began to walk, all of the test subjects determined in less than a second that not only it was a walking man, but that he had a slight limp. They were even able to correctly identify two similarly lit people doing a folk dance.

In a follow-on study, Verfaille [85] showed evidence of priming effects for recognizing point-light walkers. Interestingly, this effect was dependent on the observer's orientation to the observed walkers, but not the walker's dirctionof moiton or articulatory motion.

All of this indicates that visual perception occurs at a very low level in human cognition and it is reasonable to believe that reactive behaviors such as collision avoidance is similar. In perception of self-motion, the human perceptual system is probably optimized for certain types of changes in the optic flow, and the there are probably a host of instinctive responses. Putting your arms out when in danger of running into a wall, for example. The goal of slippery motion is to provide (visual) motion that rests within these preferred parameters, or at least does not conflict with them.

Psychophysics and Psychocybernetics

This literature looks at human motion and body control in space-time. [82-85] While most of it is concerned with specific motions or types of motions, the theoretical frameworks they develop are very useful. Turvey and Kugler [81] point out that under collision conditions organisms do not behave according to Newton's physical laws, but instead react to the information in the scene and according to their nature. In many VE applications, it is the attempt to treat the observer as simply a point-mass object that causes unnatural interactions. Clunk mode, for example, makes more sense for a bowling ball than a person.

Virtual Reality: Theory and Literature Review

In this section, we will examine the general nature of virtual reality, the state of the art and the literature. Again, discussion will be weighted toward issues concerning the experimental study outlined in the introduction.

What is Cyberspace and Virtual Reality?

All media technologies are converging. Television, telephone, radio, fax, computer networking, and even home stereos are increasingly integrated, using new digital formats. [11] As we find more uses for these technologies, they will play in increasing role in our daily lives. As human-computer interfaces become increasing complex and visually oriented, they take on higher dimensionality and present more sophisticated metaphors. To make them accessible to the common user, these metaphors will be crafted to take familiar forms. While some are to be found directly in the natural world, the best ones are already developed and available in the arts.

Since the beginning of humanity, we have told stories, made art and generally dreamed of different worlds. We also live in shared social and mental spaces as a matter of course. There is a huge literature on how social space is constructed between individuals and in a society as a whole. [56] Moreover, movies, fiction books, theater productions, photographs and even the mirror (the way we use it) all convey imaginary landscapes which we readily use for many purposes. A pure example is the notional world used by two people talking on the phone. If they are truly engaged, it could be said that there is a one-dimensional (time) space occupied only by their voices and their attention. It is created and maintained by them, with the help of the phone equipment, and goes out of existence when they hang up.

Socially, cyberspace can be seen as yet another paradigm for communication between people, and between people and computers. For the information scientist, it is a perceived information space that provides the user with the feeling of actually participating in an environment. [2][3][5][9][99] In fact, it is (or can be) a landscape with persistent qualities--a place, or universe, with its own “existence”.

The creation of virtual realities is one more step in a tradition long engaged in by computer and information scientists -- creating formal models of some process or entity to allow them to be translated into a format that can be programmed on a computer. In the case of virtual reality the goal is to formalize the laws by which a given reality operates -- its ontology -- as well as the laws by which people know about -- the epistemology. -- Michael B. Spring [2]

In common parlance, virtual reality refers to applications where the cyberspace is made visible through some immersive interface. The most common of these is the head mounted display (HMD), which provides a separate view for each eye allowing the computer to create stereopsis effects for the user. Significantly, the HMD also cuts the user off from seeing anything else, but this and other HMD-specific issues are beyond the scope of this study.

Early 1990’s Overview Literature

Cyberspaces have actually existed for as long as computers have, [2] although the term was not coined until 1984 by W. Gibson [99]. As computer interfaces become increasingly visual, the virtual environment (VE) metaphor increasingly makes sense as a metaphor with which to build application interfaces.

In the early 1990’s, the scientific community was engaged in a general debate on what the form and nature of cyberspace or virtual reality is or should be. Several authors proposed comprehensive models. [2][3][5][9] These are primarily concerned with the (possible) dimensional structure of cyberspace, the mapping of these dimensions to types of information and how the user would interact with the VE. Other comprehensive treatments do not disagree, but take a different level of abstraction [6] or a complementary approach. [101] Although the authors each have a different focus and contribution, they agree on most things, which reflects the trend of the larger debate at that time. Since then, independent theoretical overviews have rarely been written, which further indicates consensus. Those that are, tend to be strongly tied to some particular issue or product or aimed at a non-technical audience.

Unfortunately, the majority of technical papers on virtual reality/cyberspace and related discussions do not explicitly refer to anyone's general framework. Instead, some background is usually presented by the author as generally accepted fact. While this shows an encouraging air of consensus, it is left to a later generation of researchers or engineers to hammer out real standards.

Also in the early 1990's, another synthetic literature grew that addresses these issues, but is more focused on the human factors issues of how the user locates his "egocenter" in the virtual environment. [52][53][57] This is the location at which the user feels like he is located in the VE. At one extreme, he may actually feel like his body is there, but what really matters is that his "attention" must be focused on a point such that he feels that he interacts primarily with objects near to it This idea is comes from the research in environmental psychology [98][56] and supports related research in psychophysics and psychocybernetics. [82-84]. For VR applications, these areas support vigorous research, but most of it is focused on the creation of stereopsis effects using head mounted displays and other immersive devices. [30-33]

It is important to note that the egocenter is not necessarily the same as the viewpoint. This will be discussed in more detail in the next section.

General Framework for Visual Cyberspaces

What does this theoretical consensus on the nature of virtual reality say? The following is a partial synthesis of the overview papers cited, [2][3][5][9][52][53][57] and other discussions in the literature and the scientific community.

- A dynamic virtual environment (VE) is constructed of several dimensions, extrinsic to the objects in the space. At minimum there are four: the three Euclidean axes and time. It is generally assumed that these dimensions are scaled linearly--that space has a constant density. (This is not necessarily the case, [9] though I have never seen a functioning exception.)

- Objects or agents in the VE have intrinsic attributes such as color, shape, texture and so on.
- Information may be encoded in any of the dimensions or object attributes used in the VE.
- As with any interface, VE applications have their affordances [100] which determine how the user can interact with it.
- Interactivity, including navigation, is the most important factor. The importance of this cannot be overstated.
- Each user interacts with the VE with respect to an egocenter or self-location within it. The user defines this point primarily using some mixture of the visual cues and affordances presented by the interface. Sound cues can also be important if used properly. As described in the next section, the egocenter does not have to be co-incident with the viewpoint. [52][8]
- User navigation in the VE consists of moving the egocenter through it.

How one locates oneself in the real world, much less an artificial one, is far from simple. Howard [53] demonstrates that we make perceptual judgments within what he calls:

- The occulocentric frame, essentially a coordinate system based on the viewer's eye.
- The head-centric frame, based on the viewer's head
- The body-centeric frame, based on the user's body. (He did not do experiments with this one, just defined it.)
- Exocentric frames, which are based on some origin point or object the viewer can perceive.

This seems to imply that one's egocenter is mobile; that we mentally locate ourselves differently, depending on the stimulus and what we are trying to do. According to Psoka, [52] every painting has an implied egocenter to which the viewer's attention is drawn. When you watch a play or a movie you are drawn into the action and tend to ignore the setting outside of the stage area, because of the stage effect and other factors. Perhaps this is why video game players, even children, seem to have no trouble adapting almost instantly when they change viewpoint in certain video game. Some have the user looking down upon his virtual body from above, (fig 4) some have him looking out of its eyes, (figs 2, 5 & 6) and so forth. (More on this later.) The key is to give the user some kind of investment or reason to be "in" the VE, then give their imagination enough to go on. This calls into question the great efforts being made to create photo-realistic environments. As Benedikt said, why recreate reality when we've already got one?

If the application is poorly made or suffering from forced tradeoffs, location cues may actually disagree. For example, the lighting may imply a different egocenter location than the perspective distortion, which is the case in the video game DOOM. [143] (fig 2) How the user decides which cues to pay attention to and which ones to ignore make be an interesting study.

Basic Visual Cues for Self Location

This study is primarily concerned with navigation in a visual cyberspace, which in turn is based on perceptual self-location in the VE. A great deal has already been written about how perceptual cues work in the real world. [13][56] Accordingly, this section will present a summary of basic visual cues and how they can be implemented in virtual reality applications. [4]

- Perspective The apparent convergence of objects in a scene to a certain vanishing point. Since perspective distortion is always based on the viewer's location, the perspective generated in the display provides her a strong egocenter location cue. [52][33][57][35] As stated before, she does not have to be located at the ideal viewing point to perceive it. [54][8]
- Shape and Occlusion The user can determine the (virtual) shapes and location of objects by looking at their geometric features and how they overlap in the visual field. [13][33][34] From this, the viewer can determine where he is in relation to the objects and thus in the VE, overall.

- Objects as Perceived With Relative Motion Objects reveal their form and to some extent their nature by the way they move relative to the observer. [16-19][83][102] Astonishingly little of an object must be seen of a familiar object if its motion is natural. [15] This is especially important when the viewer himself is in motion. All objects move relative to him in a consistent manner which is a very strong locator cue, one that can be simulated in the VE interface. [30]

- Point of Rotation When the user commands the interface to rotate "himself", he will tend to identify his egocenter at the actual point about which the virtual scene rotates. [30]

- Proxemic Zone In VE applications with collision handling, objects are not allowed to come closer than a certain distance to the viewpoint. (more on this later) As he encounters objects, the user quickly determines the shape of this exclusion zone [24] and usually assumes he is at the center of it.

- Lighting Effects Proper lighting allows the viewer to better distinguish objects and thereby understand the visual scene. [13] This effect is especially strong when the lighting is dynamic and stronger still when it is responsive to the user. Many video games use the trick of having an important light source centered on the user. With sufficient radiosity effects on surrounding objects, this becomes a strong locator cue because of the fall-off of illumination in the more distant objects. (fig 2) [98][142][143]

Figure Two: Screen shot from the game DOOM. Note the perspective and how the light diminishes with distance.

- The Virtual Body If the application creates a virtual body for the user and the interfaces makes it visible, that is also a strong self-location cue, but only if the user identifies with the body. Congruence with the other egocenter cues makes this highly likely, but the narrative also matters. If she is playing a game where she is told that the main figure displayed is her, she will tend to locate her egocenter in the same place it occupies. (fig 4)

- Stage Effect In a real theater, the back of the stage and the wings form an arc of up to 120-180 degrees which parallels the human field of view. This draws the viewer's attention (egocenter) to a point in front of the center of the stage. If a computer monitor is used as the "window" onto the VE, the flange around it can act in similar way. [102] The effect is enhanced if the display has a static band around the edge of the viewscreen.
- Stereopsis Disparity of view in each eye allows the brain to compute the distances of near objects. [30-33] It is usually provided by head-mounted display devices, which have been the subject of intense study by researchers interested in virtual reality.
- Other Cues There are several other very important location and perception cues not directly relevant to the study. They include spatialized sound, propioceptive stimulus, vestibular stimulus and even smell. So far no-one has built a lick-screen monitor, but it may yet happen.

One way to talk about the motion-based location cues is that they each represent changes in the user's "optic flow." That is the

The Screen-and-Mouse Interface

Most users will have only a screen, keyboard and mouse to be their physical interface with the expanding cyberspace of the internet and in new software applications. Still, there is little or no formal research which specifically addresses how it works as a VE interface. However, there has been some work in human factors focused on making better use of "monoscopic" displays, such as a computer screen, [35] and other work that is certainly useful. [34][36][8]. Most of the VR literature that examines monoscopic displays, at all, only does so in order to make unfavorable comparisons with stereoscopic displays, particularly the HMD. [30-33] It is useful to note that most of the egocenter location cues listed above can be conveyed quite well with a computer screen. Even peripheral vision can be simulated by warping the edges of the display. [25] Experiencing any virtual space actually occurs in the mind of the user not in the interface.

Consider the possibility of the user's egocenter being related to or connected to the VE, but occupy a point "in front" of the computer screen. It can happen with perspective, for example, where the distortion indicates an ideal viewing location in front of the screen in a similar way a painting does. [52] This is the case with most "first-person" video games, where the scene is supposedly seen through "your" eyes. (fig 2)

Current Research and Development With Virtual Reality

The bulk of research and development with VR and cyberspace fall into these broad categories. (General indexes are [107][108][109])

Some analog or model of information is presented, which in turn is the basis for some interface. The affordances of that interface limit or enable the user to manipulate the data.

1. Abstract Data Visualization. such as visual browsers for the web or other archives. Many are two dimensional, but some use three; all are visual cyberspaces. [39-44][48]
2. Scientific Visualization. Weather radar, 3d models of lava flows, structures in the body (medical imaging), [45] or visualization and manipulation of molecular structures.
3. Visual Languages. So far, most of these are two dimensional. [47][125-129] Those that are three dimensional [46][44] do not seem to be better for it.
4. Simulations. Of any working system, such as city or an anthill. [132]

Interface is still based on an information model, but the mapping between it and much of the subject matter is direct.

5. Architectural Walkthroughs. [116]
6. Historical simulations. Usually based on an architectural walkthrough of some reconstruction of an ancient building. Can include animations and interactive characteristics, [113] up to and including enough activity to make it an actual simulation of some social setting. Can also include hypermedia characteristics. [121]

Interface has a direct video feed or pass-through of some real-world scene, though it may also contain abstract constructs.

7. Telepresence: the user see's through the robot's camera eyes. [112] [120]
8. Augmented Reality. The user sees the real world through a special HMD which projects animated objects into his field of view. He then sees a mixture of a real and virtual world. [122] Can be networked for a shared experience.

Much of the imagery in the interface is there for aesthetic reasons and may not have an obvious mapping to information.

9. Video Games and Other Entertainment Applications. (See dedicated section.)
10. Artistic Applications. [114]

Most formal research takes place in military and academic think-tanks, industrial research departments and in academic departments. Most development occurs in certain branches of military contractors, small companies making VR related products, software developers who make information browsers and related products, and most notably, the robust video game industry.

In the area of software interfaces, there is a curious disconnect between the video game makers and the research scientists. The game companies are spending huge amounts of money to employ highly talented young people, often college dropouts, who hack out a variety of interface solutions for improved Interactivity. To anyone seriously studying 3d interfaces, these games are a rich source of ideas and tools. However, there is little explicit mention of games in scientific literature.[1] Also, the virtual environments used in (or the result of) many research projects, tend to be crude compared to those used in the

[1] A Silver Platter search on PsycLit, ERIC and Scientific Abstracts for "Video Games and (3D or graphics or virtual reality or immersive)" yielded only three hits. In the "softer" literature, ranging from ACM/IEEE proceedings to things like BYTE magazine, there appears to be slightly more. The same search on INSPEC yielded 93 hits. Most focused on education, training or rehabilitation. Some were sociological studies on the impact or social psychology of the games themselves. Some were based on military training exercises for applications like SIMNET. Many had to do with new technologies or products. Very few talked about taking ideas from video games and applying them elsewhere.

best games. On the other hand, video game makers often repeat each others mistakes or reinvent principles and practices, because they tend not to look at the relevant research.[2]

Video Games

In many ways, the current state of the art in 3D Virtual Environments (VE's) is in the video games, especially with the advent of powerful home systems. A sampling of video games [133][134][135] reveals a spectrum of perceptual immersion:

- Text Only   The experience is entirely text-based, so there is **no** perceptual immersion. The user travels the space in the same way one explores vistas described in a novel--completely within his own imagination. The difference is that this environment can be interactive.
- Narrative With Still Pictures and Movies   The user progresses from one still image to another. or small animated scenes that run through some script (called movies). Immersion is still primarily mental. Narratives tend to be complex and graphics quality high.
- 2D Animation, Side View   Characters are flat drawings that move upon a still background. It can be simple, as with the original Donkey-Kong, or cleverly done to create the illusion of a complex scene, like the side of a strange temple with various openings and monsters on it, in Crash Bandicoot. [137]

[2] This statement is made based on the author's personal experience with the game industry and people in it.

- <u>2D Animation, Overhead View</u> Some games provide the illusion of an angled overhead view onto a scene, which is always centered on the user's virtual body. [138] In this case, the three-dimensional illusion is dependent solely on shape and occlusion; the background scene is shown in a static orthographic perspective and lighting is similarly static. (fig 3) Objects move, but are pasted on, usually showing only one side. (Animations of this type are called "sprites". [14]) Some games make an object appear to turn by making it, in effect, a tiny self-contained movie. In this type of game, the player might locate his egocenter with his virtual body in the center of the screen. Seeing the body, it's reactivity to his commands, and the investment he has in its survival are his incentives. On the other hand, he may simply view it as a strategic challenge, like a board game and keep his egocenter out of it.

<u>Figure three</u>: Screen capture of 2D overhead view game, "Crusader; No Remorse". [138]

- <u>3D Animation, Long View</u> Here, the player sees his virtual body in a three dimensional scene which is rendered in real time. As with the 2D-overhead-view games, the body is responsive to his commands and the scene generally moves with it. In Tomb Raider (fig 4) the viewpoint changes constantly to (hopefully) provide the best viewing angle on the action. Some algorithm is at work, which allows

<u>Figure four</u>: A 3d long view game, Tomb Raider. [141]

the body to be somewhat off from the center of the screen and is probably situation sensitive. The game is unusually dynamic in the way it changes viewpoints. Mario-64 is also impressive in this way, but less sophisticated. As with most games of this type, there are different viewing options available. All of the depth/self-location cues listed above can be used, but perspective can be tricky. In figure four, perspective distortion is evident by the way the edges of the steps are converging. This enhances the three-dimensional illusion of the scene, but as a self-locator cue, it actually conflicts with the others, because it is geared for the real viewer, not the figure in the scene. Apparently, this conflict is not a problem for users, a question which deserves further study. Probably, the motion-based cues are dominant.

- <u>3D Animation, Near View</u> Like the long view, but the viewpoint is directly behind the virtual body, so that the back of the head and shoulders are visible in the foreground. Viewpoint moves in lock-step with the body. In this mode, all the egocenter cues can be used, including perspective. Perhaps because the body is in line with the user's actual line of sight, and disagreements along it are less disturbing.

- <u>First-Person View</u> Here, all depth cues are used to make the viewer feel like the PC screen really is a window onto the space and the action involves them, personally. In Quake, (fig 5) note how the lighting along the walls decreases with distance from the viewer. Also, the lighting is responsive to the monster's torches, which gives the viewer a solid fix on its location. The object in the foreground is the tip of the player's weapon, which implies a virtual body, centered somewhere in front of the screen. Unlike in DOOM, all cues in quake appear to be in agreement.

<u>Figure Five</u>: First-person view. Quake. [142]

- Flight and Driving Simulators Also first-person, but there is usually a terrain below, fewer objects in the environment and high-speed motion. Often, the cockpit or cab of the vehicle is visible. (fig 6) It is stationary, with respect to the user's viewpoint. Good ones will at least have it responsive to lighting changes.

Figure Six: Clip from Monster Truck Madness.

Another important aspect of gaming, and virtual environments in general, is the possibility of networking them to create a shared cyberspace. Early text-based "games", called MUDD's and MOO's did this. At the end of the 1980's, the first 2D artificial societies came out. [97] In the mid-1990's the first real-time multi-player combat games became popular. [142]

THE EXPERIMENT

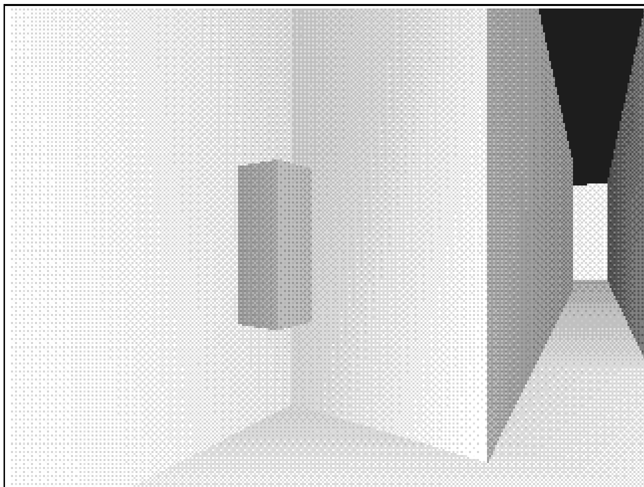

Figure Seven: The opening scene, when the application starts . The object ahead is a treasure.

Generally, the user needs to be able to move between and around objects in the VE smoothly and without getting lost. As an indirect measure of this, we tested subjects on the speed a which they were able to locate objects in a maze. The maze consisted of narrow corridors, low-lying obstacles and extra baffles between the walls. (Figs 1 & 2) The experimental hypothesis is that there would be a significant difference in the users' success in finding treasures, based on the navigation mode used. This was the result.

Models for Collision Handling

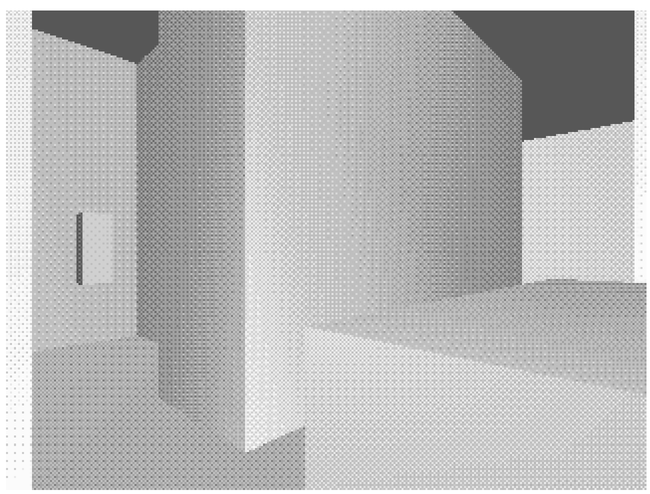

Figure Eight: Another part of the maze showing third treasure. Perspective and lighting strongly imply the viewer's position, even in this still image.

An effective model can be built on the notion of a personal space around the user's egocenter which responds to nearby objects. Extending Hall's notion of social-personal space, [55] I call it the Proxemic Zone. In this study, it is modeled as an invisible, sixteen-sided cylinder, (fig 1) which extends from floor to ceiling, always surrounding the user's viewpoint. When this proxemic zone intersects an object, the collision handling strategy is engaged. The strategies are:

- **Clunk** Complete stop on contact with object. The user tends to get stuck on almost everything he encounters. Upon collision she has to back up, reorient and get going again. It is still used in some tank simulation games, but in those objects are few and far between.
- **Ghost** User passes through object, with no effect. It can be the best choice for situations where there are many obstacles, but the visual field is still fairly open; the user can just point where he wants to go, and go there. However, cluttered spaces, like a maze, can be very confusing. The user tends to be disoriented every time she goes through a wall, because her entire visual field suddenly changes.
- **Slip** User's movement is deflected, effectively making him slide around it. This appears to be the best compromise for "realistic" situations, because it preserves the solidity of objects and at the same time allows comfortable movement. The best first-person video games use this. [138][140-142]

Implementation

The application runs on a PC using a standard monitor and mouse as the only interface. The virtual body is implemented as a single viewpoint, but it is surrounded with a shape that represents the user's proxemic zone, which is implemented as a sixteen-sided prism that extends from below the user's field of view (FOV) to just above it.

- In **ghost** mode, the viewpoint is moved according to mouse input without regard to collisions. The user can travel through walls and other objects.

- In **clunk** mode, the proxemic zone moves ahead of the viewpoint in the direction the mouse indicates. If no collision, the viewpoint is moved forward, back to the center of the zone. However, if the zone intersects any object, it is moved back, and the movement vector is discarded. The user has come to a full stop and must reorient (and usually back up) before he or she can get going again. (Fig 9)

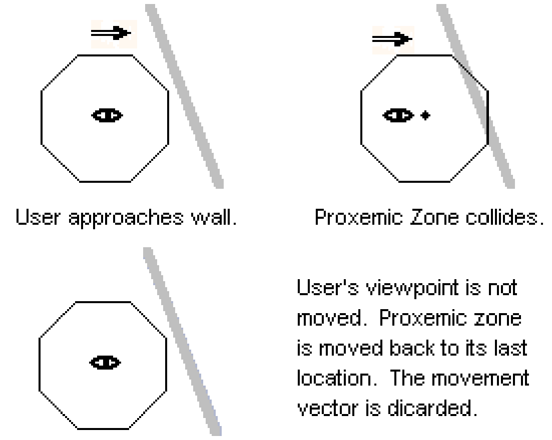

Figure Nine: Implementation of clunk mode. The proxemic zone had sixteen sides, but is shown here with only eight for clarity.

- In **slip** mode, when the user's proxemic zone intersects one or more objects, the user's movement vector is minimally redirected. The new vector retains the original direction and velocity adjusted only so far as needed to prevent the collision from recurring the into subsequent frame. (Fig 10)

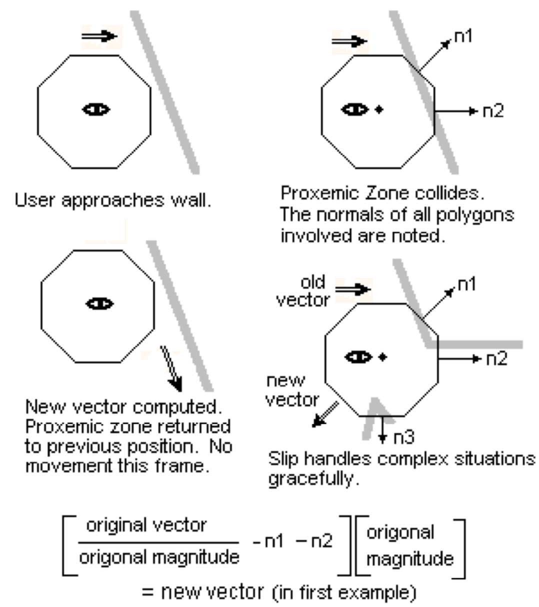

Figure Ten: Implementation of slip mode.

The Virtual Environment Used for Testing

The virtual reality application used for testing had the following characteristics:

- Most of the time, the users are able to accurately perceive the virtual space around them and their location in it. Failure of either perception is an error condition.

- Objects in the virtual world are stationary and rigid. The application is a simple architectural walkthrough.
- The virtual body is nothing more than the location of the egocenter, which is co-incident with the user's viewpoint.
- While the world is perceptually three dimensional, its layout is two dimensional. (fig 11) The "ground" is completely flat, resting on the x-z plane. While not all of the walls are tall, some are quite low, but all collisions can be thought of as occurring in the x-z plane.

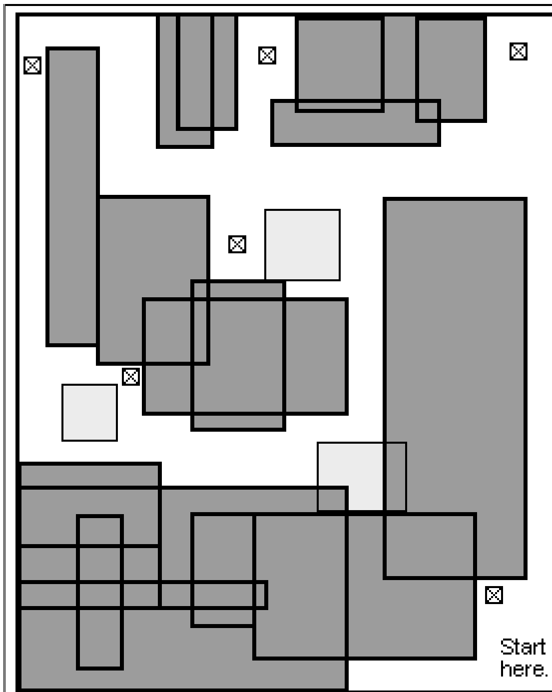

Figure Eleven: Schematic map of the maze. White areas are where the user is supposed to go. Light gray areas are low-lying obstacles, which s/he can see over but slip and clunk users must go

- User motion is constrained to the x-z plane; no flying, no changes in elevation.
- The application displays the user's view of the VE in a window on a monitor.
- Movement is controlled by the mouse in a mapping simple enough for most users to understand in the first minute. This seemed to be true for most of the test population.

The Pilot Study

The first study divided subjects into three groups of five, one for each navigation mode. They were told to "get" all of the treasures in the maze, by simply running into them. (fig 7 & 8) Subjects were told that there were four mazes and that the whole exercise would take no more than thirty or forty minutes. Most seemed to give themselves about fifteen minutes to complete the first.

Figure twelve illustrates the number of treasures each user was able to find in the first maze, compared with how far they had to travel to find them. Slip mode appears to be superior, both in efficiency and final success. Encouraged by these results, I undertook a formal study.

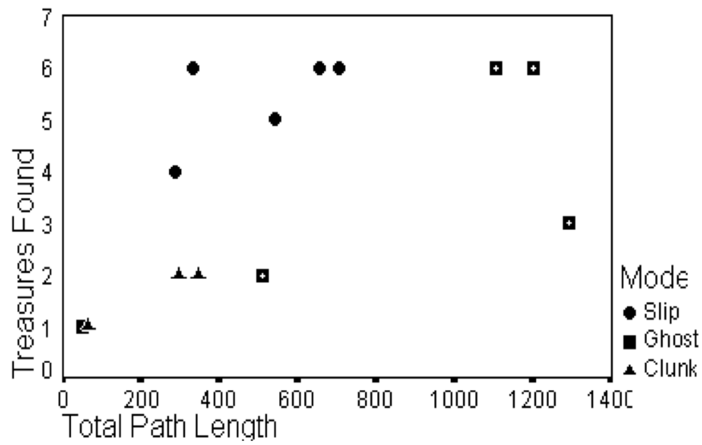

Figure Twelve: Number of treasures found vs the total distance covered in the pilot study.

Methodology for the Full Study

Twenty-six paid subjects were recruited from the University of Pittsburgh community. Upon the subject's arrival, he was read the instructions reproduced below accompanied by appropriate demonstrations.

In this test, you will travel through a three-dimensional maze. You navigate with the mouse, by holding down the left mouse button. Your movement will depend on where the cursor is.

- If the cursor is near the top of the screen, you will move forward. *demonstrate*
- If the cursor is near the bottom of the screen, you will move backward. *demonstrate*
- If the cursor is near the right side of the screen, you will ROTATE right. *demonstrate*
- If the cursor is near the left side of the screen, you will ROTATE left. *demonstrate*
- The closer the cursor is to the center of the screen, the slower you will go, the nearer to the edge, the faster you will go. *demonstrate and move forward*
- If you are ambitious, you can click on a corner of the screen, which will move and rotate you at the same time. *demonstrate*

The goal is to pick up as many treasures as you can. The floating purple box in front of us is a treasure. You "get" them by moving into or onto them, like so. *demonstrate The treasure disappears when the viewpoint nears it.*

The blue up there is the sky. *Point to it.*

> When you think you got all the treasures, press the space bar to quit. There is no right and wrong. You can hurry or go slowly as you choose. You are not obligated to go longer than thirty minutes, though you can if you wish.

During demonstration, the tester was careful to keep his viewpoint away from the walls and to make no mention of collisions or collision handling.

The test subject was then given the chair in front of the computer and the application was restarted. Once she appeared to be properly oriented and using the program correctly, the tester left the room. Then she subject was told to notify him when she thought she had found all the treasures..

Subjects were randomly assigned to three groups, one for each of the collision handling. [95] Performance was measured using the average time it took each subject to get from one treasure to another. This excludes time spent before getting the first treasure (orientation effects) and after getting the last one (diligence effects).

RESULTS AND ANALYSIS

Figure thirteen (next page) shows that average time between treasures for the twenty-six subjects. Difference in average between-treasure-search-times were found between each of the collision resolution strategy groups. Analysis of variance test between the three groups' times showed a significant difference of $p < 0.01$. Measures of the average speed

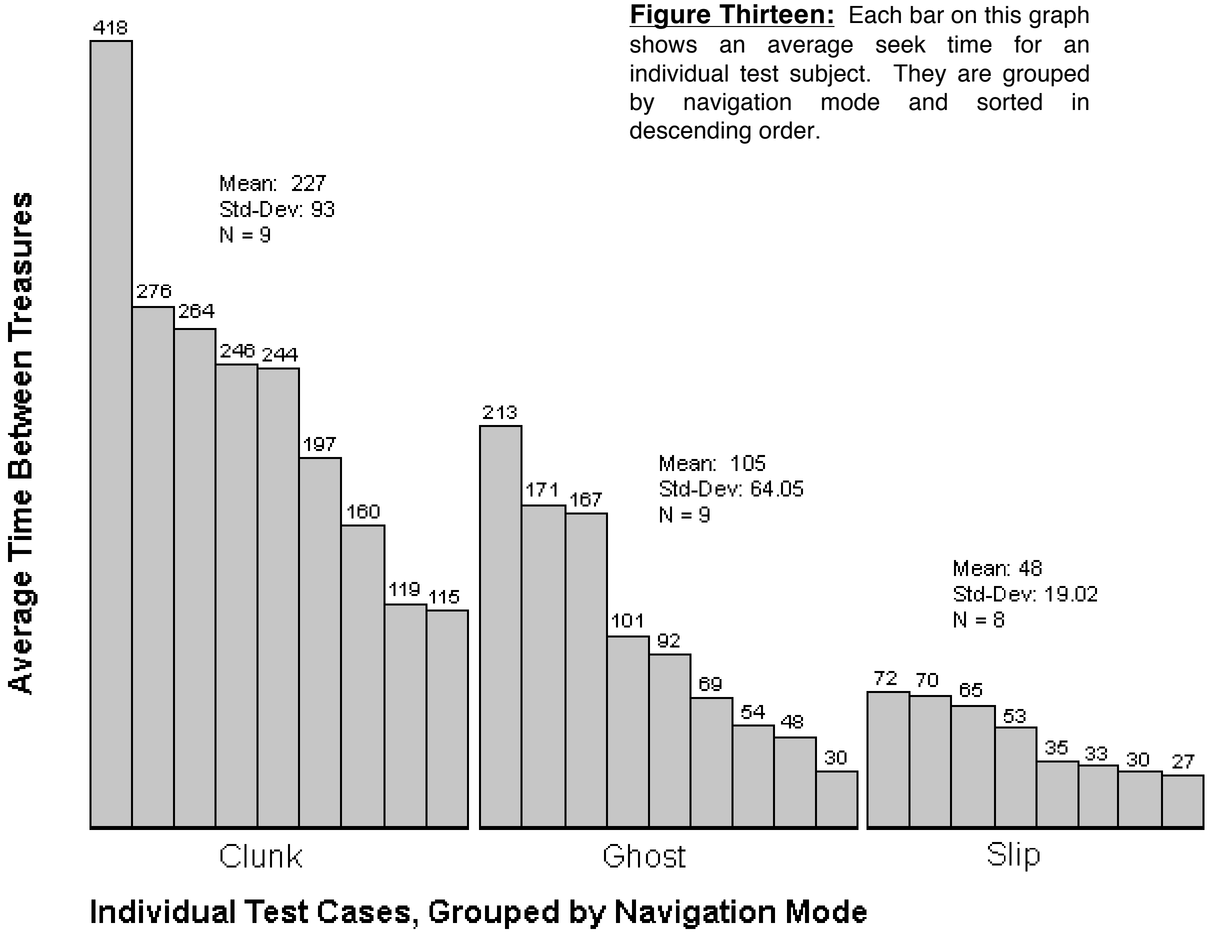

Figure Thirteen: Each bar on this graph shows an average seek time for an individual test subject. They are grouped by navigation mode and sorted in descending order.

of the user's viewpoint movement indicated that Clunk users moved more slowly than the others ($p < 0.05$). (Fig 14) Ghost users moved fastest ($p < 0.05$) but wasted a lot of time in the baffles between walls or outside of the maze altogether. (Fig 15)

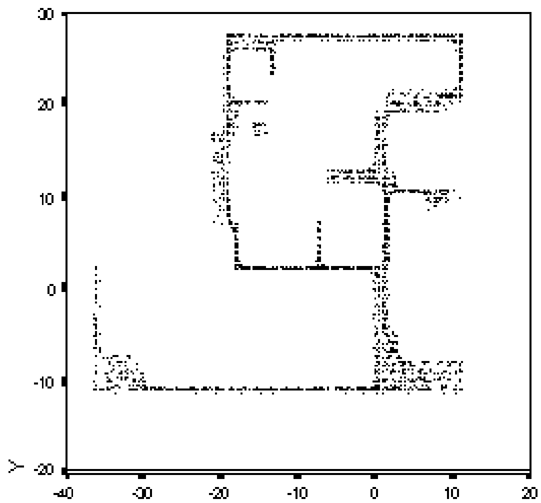

Figure Fourteen: Scatterplot of 10% of the x,y locations of the slip mode users. Plot for Clunk users looks much the same, though the density is lower

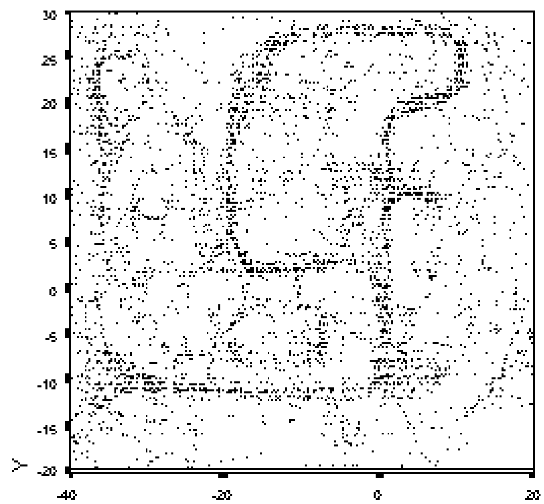

Figure Fifteen: Scatterplot of 10% of the x,y locations for the ghost mode users. Note the concentration in the upper left. That is an especially confusing set of baffles which are not part of the actual maze.

The results support the thesis that slippery mode is an efficient collision resolution strategy, and optimal for this type of situation. The maze was designed to be difficult to traverse, but all of its features are typical of what is found in many existing virtual environments. The independent development of similar strategies in video games and animation libraries support the generality of this finding.

It is important to keep in mind that slippery mode is not best for all situations. For example, if the user has to navigate a space which is visually open, but still has a lot of obstacles, ghost mode might be better. For ghost mode, the main problem is the potential for sudden and complete changes in the optic array, which would not occur in this case. Clunk mode is still used in various tank games, where the landscape is also quite open but with only a few obstacles. It makes sense in this case, because an actual tank really would come to a full stop upon collision with a large object. Finally, slip mode would not make sense for a flight simulator. The lesson here is that the collision mode used in the application needs to be consistent with the narrative theme of the VE. Slippery mode is best when the user is “a human” and moves about in natural settings.

In figure thirteen, compare the ghost users’ times with the slippery users’ times. Note that highly adept ghost mode users were able to get around the maze with very competitive times. This shows that a highly skilled person can use ghost mode effectively. Most of those that did do well tended to avoid going through walls, but they did cut corners, which you can see in the scatterplot in figure fifteen by the rounding of the paths near the corners of the maze.

Also in figure fifteen, there is a high concentration of footprints in the upper left. This illustrates the time ghost mode users wasted trying to figure out a set of baffles and dead-end corridors setup just to confuse them. This sort of footprint analysis would be useful in other studies to determine sticking points in the VE, or areas that are ignored, etc.

The utility of collision handling schemes for VR warrants more detailed study. In situations such as desktop VR where interaction techniques are some what arbitrary, it is especially important to identify the good ones. Slip mode does not attempt to replicate natural interactions, but instead minimizes the delay imposed by obstacles. There is great opportunity for the development of a wide array of such pseudo-realistic interaction techniques for navigation and manipulation which preserve the intuitions and affordances offered by VR while simplifying and facilitating users’ interactions .

FUTURE WORK

Beyond the rather simplistic implementation used in this study, slip mode has great potential for further research. By changing the shape and characteristics of the proxemic zone, very different aggregate behaviors can be achieved.

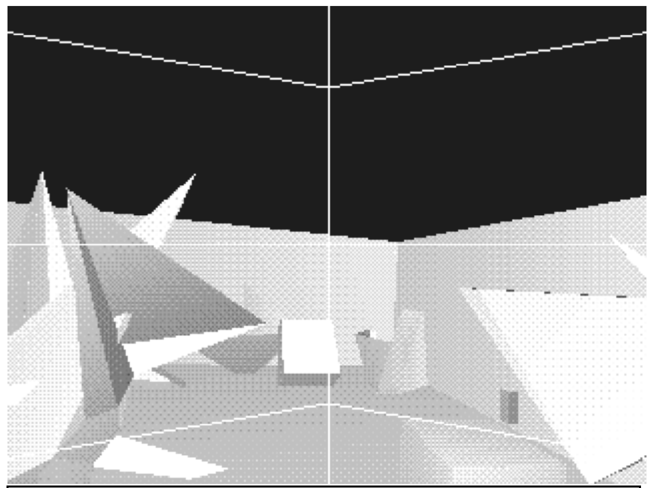

Figure Sixteen: View from atop a tetrahedral structure in the "junkyard" maze. The proxemic zone is a 64 polygon sphere, visible here as the white lines in the foreground.

- A proxemic zone with a convex bottom yields terrain-following behavior in a VE with gravity. For example, with a spherical proxemic zone, collisions on the lower hemisphere will cause normals that point down to be subtracted from the movement vector. That will cause the vector to point up, and the user will begin to ascend. With the addition of gravity in the VE, this allows for terrain following over obstacles below a height determined by the size of the sphere. An inverted cone with no top would always climb upwards.
- The proxemic zone could have more exotic shapes. For example, if it were surrounding a human figure, it could be shaped somewhat like an egg:. Actually, it could be put around a simple viewpoint and it would still yield sliding narrow near the figure's feet, widest at the shoulders, less wide near the head, flat in the back with a bulge out in front of the figure. This should yield behavior that is more approximately human than with a simple cylinder. [102]
- Experiments can be made with different algorithms to recompute both the direction and the magnitude of the movement vector.

- The proxemic zone could be elastic or spongy, so the user can squeeze through tight spaces or approach objects more closely. A variety of algorithms could be used to control this compressing "behavior".

  The reader is encouraged to think of this as an open challenge to persuse his own research in the use of proxemic zones.

Summary and Conclusions

This study compared three modes of collision handling in virtual environments:

- **Ghost** No effect. User passes through object.
- **Clunk** Complete stop on contact with object.
- **Slip** User's movement is deflected, making him slide around the object.

Experimental results showed conclusively ($p < 0.1$) that for visually and physically cluttered environments, slippery mode allowed users to navigate to goal points more effectively and efficiently.

The study looked at the scientific literature concerned with self-location and navigation. Important insights were gained from literature on:

- Artificial Intelligence – a viable agent must reactive behaviors and true intelligence handled by separate subsystems or processes.
- Cognitive Science: The Ecological Approach – An organism is inseparable from its environment; its cognitive processes are distributed between it and the world. The task of navigating (or doing anything) in an environment must begin with a look at the affordances it presents to the actor at the time of decision.
- Michotte's Work on Causality in Perceived Motion – Gestault perceptions extend over time, not just space. This means that certain patters of motion will produce particular impressions of causal relationships between moving actors. I contend this extends to the user's (virtual) self as an actor.
- Cognitive Science: Biological Motion – Our visuomotor systems are optimized for certain perceptions and behaviors. These abilities or biases should be exploited or at least treated with sensitivity.

Other areas looked at were Psychophysics & psychocybernetics, mainstream cognitive science and the situation awareness literature.

The literature on Cyberspace and Virtual Reality was also looked at along with a sampling of video games. Discussion focused on how the user decides where she is located in the virtual environment. The video games were analyzed to point up the relevant visual cues presented to the user to locate themselves and navigate. They are:

- Perspective
- Shape and Occlusion
- Objects as Perceived With Relative Motion
- Point of Rotation
- Proxemic Zone
- Lighting Effects
- The Virtual Body
- Stage Effect

The reason for looking at video games is that they are optimized to make use the screen and mouse interface. An important goal of this study is to establish principles that make screen-and-mouse more useful for VR applications, because it is the most common and the least studied interface.

Given the theoretical background, it is safe to say that the experimental results indicate that slippery mode is generally more comfortable and natural for situations where the VE is cluttered.

Future directions for research could be

- Invention of differently shaped proxemic zones which yield different behaviors.
- Proxemic zones which have behaviors programmed into them.
- The exploration (or exploitation) of slippery mode travel to achieve universal terrain following.

BIBLIOGRAPHY

BIBLIOGRAPHY

1.
2. Spring, Michael B., "Being There" or Models for Virtual Reality. *ASIS Mid-Year Meeting, Santa Clara, CA*, 1991.
3. Slater, Mel, & Usoh Martin. Perceptual systems, Perceptual Position, and Presence in Immersive Virtual Environments, *Presence,* 1993 Vol. 2, No. 3, Summer 1993, 221-223
4. Loomis, Jack M. L., Understanding Synthetic Experience Must Begin with the Analysis of Ordinary perceptual Experience; Position Statement, *IEEE,* 1993, 0-8186-4910-0/93
5. Spring, Michael B. & Jennings, Michael C. Virtual Reality and Abstract Data; Virtualizing Information. *Virtual Reality World,* 1993 Vol 1, No. 1, Spring 1993
6. Zeltzer, David. Autonomy, Interaction and Presence, *Presence,* Vol 1, No. 1
7. Lampton, Donald R et. al., the virtual Environment Performance Assessment Battery (VEPAB); Development and Evaluation, *Presence,* 1994, Vol 3. No. 2, Spring.
8. Psotka, Joseph, & Davison, Sharon. Cognitive factors Associated With Immersion in Virtual Environments. Unpublished draft at the U.S. army Research Institute and Catholic University. Psotka@alexandria-emh2.army.mil or psotka@26.1.0.50
9. Benedikt, Michael. Cyberspace: Some Proposals. In *Cyberspace; First Steps.* 1991, ISBN 0-262-02327-X
10. Wexelblat, Alan. Giving Meaning to Place: Semantic Spaces. In *Cyberspace; First Steps.* 1991, ISBN 0-262-02327-X
11. Negroponte. The Media Lab. 1987 MIT Press
12.
13. Osherson, Daniel N., et al., *Visual cognition and Action.* 1990, ISBN 0-262-10536-1 (v. 2), ISBN 0262-65034-7 (v. 2: pbk.)
14. Marrin, Chris & Campbell, Bruce. Teach Yourself VRML2 in 21 days. 1997 ISBN 1-57521-193-9
15. Johannson, Gunnar. Visual Perception of Biological Motion and a Model for Its Analysis. *Perception and Psychophics,* 1993. Vol. 14, no. 2, 201-211.
16. Johannson, Gunnar, Visual Motion Perception. 1993 *"Perception & Psychophysics"* 1993 Vol. 14, No 2, 201-211.
17. DeLucia, Patricia R., Warren, Rik. Pictorial and Motion-Based Depth Information During Active Control of Self-Motion; Size-Arrival Effects on Collision Avoidance. 1994 Vol. 20, No. 4, 783-798.
18. Perceptual Integration of Motion and Form information: Is the Movement Filter Involved in Form Discrimination?, *Journal of Experimental Psychology; Perception and Performance.* Vol 20, No. 2, 397-420

19. Kaiser, M.K., perceiving Environmental Properties from Motion Information: Minimal Conditions. In Ellis, Stephen R., (1991) Pictorial Communication in Virtual and Real Environments. ISBN 0-74840-008-7.
20. Michotte, Albert Edward. The perception of Causality. 1963 New York: Basic Books, Inc., Publishers. (Annotate translation of the original 1946 French text.
21.
22. Bassili, John N. Temporal and Spatial Contingencies in the Perception of Social Events. *Journal of Personality and Social Psychology.* 1976, Vol. 33, No. 6, 680-685.
23. Thomas, Geb, et. al., video Texture cues Enhance Stereoscopic Depth Perception in a virtual Reality-Based, Telerobotic Interface.
24. Rosenberg, Louis B. & Adelstein, Bernard D. Perceptual Decomposition of Virtual Haptic Surfaces. 1993 IEEE 0-8186-4910-0/93
25. Slater, Mel, & Usoh, Martin. Simulating Peripheral Vision in Immersive Virtual Environments, 1993, *Computers & Graphics,* vol 17, No. 6. 643-653.
26. Kleiss, James A., Visual Scene Properties Relevant for Simulating Low-Altitude Flight: A Multidimensional Scaling Approach, *Human Factors,* 1995, 37(4), 711-734
27.
28.
29.
30. Sollenberger, Randy L., & Milgram, Paul. Effects of Stereoscopic and Rotational displays in a Three-Dimensional Path-Tracing Task., *Human Factors,* 1993, 35(3), 483-499.
31. Pauch, Randy, et al., A User Study Comparing head-Mounted and Stationary Displays. 1993 IEEE 0-8186-4910-0/93.
32. Barfield, Woodrow, & Rosenberg, Craig. Judgment of Azimuth and Elevation as a Function of Monoscopic and Binocular Depth Cues Using a Perspective Display. *Human Factors,* 1995, 37(1), 173-181.
33. Yeh, Yei-Yu, & Silverstein, Louis D., Spatial Judgments With Monoscopic and Stereoscopic Presentation of Perspective Displays, 1992 *Human Factors, 32(5), 583-600*
34. Lapping, J.S. & Wason, T. D. The Perception of Geometrical Structure from Congruence. In Ellis, Stephen R., (1991) *Pictorial Communication in Virtual and Real Environments*. ISBN 0-74840-008-7.
35. Nagata, S. how to Reinforce Perception of Depth in Singe Two-Dimensional Pictures. In Ellis, Stephen R., (1991) *Pictorial Communication in Virtual and Real Environments*. ISBN 0-74840-008-7.
36. Stevens, Kent A. the Perception of Three-Dimensionality Across Continuos Surfaces. In Ellis, Stephen R., (1991) *Pictorial Communication in Virtual and Real Environments*. ISBN 0-74840-008-7.
37.
38.
39.
40. Hirtle, Stephen C., & Kim, Hanhwe, Spatial Metaphors and Disorientation in Hypertext Browsing. *Behavior & Information Technology* 1995, vol 14, no 4, 239-250.
41. Rennison, Earl & Strausfeld, Lisa., The Millennium Project: Constructing a Dynamic 3+D virtual Environment for Exploring Geographically, Temporally and Categorically Organized Historical Information. *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
42. Dieberger, Andreas. Providing Spatial Navigation for the World Wide Web, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
43. Benford, Steve et al. VR-VIBE: A virtual Environment for Co-operative Information Retrieval, *Eugrogrphic*s, 1995. Vol 14, No 3.

44. Robertson, George G. et al., Information Visualization Using 3D Interactive Animation. *Communications of the ACM.* 1993, April, vol. 36, No. 4

45. Grunwald, Arthur J. & Ellis, Stephen R., Interactive Orbital Proximity Operations Planning System Instruction and Training Guide. 1994, July, *NASA Technical Memorandum 108835.*

46. Yazdani, Masoud, & Ford, Lindsey. Reducing the Cognitive Requirements of Visual Programming. 1996, IEEE 0-8186-7469-5/96.

47. Kahn, Ken. ToonTalk^{tm}--An Animated Programming Environment for Children. *Journal of Visual Languages and Computing.* 1996, Vol. 7, 1970217

48. Russell, Gregory. & Miles Richard., Volumetric Visualization of 3D Data. In Ellis, Stephen R., (1991) Pictorial Communication in Virtual and Real Environments. ISBN 0-74840-008-7.

49. Welch, Robert B., & Cohen, Malcom M. Adapting to Variable Prismatic Displacement. In Ellis, Stephen R., (1991) Pictorial Communication in Virtual and Real Environments. ISBN 0-74840-008-7.

50.

51.

52. Psotka, Josepth., Factors Affecting the Location of virtual Egocenters: From the Renaissance to Cyberspace. draft paper from U.S. Army Research Institute, ATTN: PERI-IIC, 5001 Eisenhower Ave. Alexandria, VA 22333-5600

53. Howard, Ian P. Spatial Vision Within Egocentric and Exocentric Frames of Reference. In Ellis, Stephen R., (1991) Pictorial Communication in Virtual and Real Environments. ISBN 0-74840-008-7.

54. Sedgewick, H. A. the Effects of Viewpoint on the Virtual space of Pictures. Sedgewick, H. A. the Effects of Viewpoint on the Virtual space of Pictures.

55. Hall, Edward T, *The Hidden Dimension*, 1966, ISBN 0-385-08476-5

56. Stokols, Daniel and Altman, Irwin. *Handbook of Environmental Psychology* 1987, isbn 0-471-63016-0 (v. I).

57. Nemire, Kennith & Ellis, Stephen R., Calibration and Evaluation of Virtual Environment Displays, *VRAIS Proceedings,* 1993, IEEE 0-8186-4910-0/93.

58.

59.

60.

61. Flatch, John M., Situation Awareness: Proceed with Caution., *Human Factors,* 1995, 37(1), 149-157.

62. Stytz, Martin R., et al. Providing Situation Awareness Assistance to Users of Large-Scale, Dynamic, Complex Virtual Environments, *Presence,* 1993, Vol 2, No. 4, Fall, 297-313.

63. Stansfield, Sharon A., *Presence*, 1994, Vol 3, No. 4, Fall, 360-366

64. Endsley, Mica R., Toward a Theory of Situation Awareness in Dynamic Systems, *Human Factors,* 1995, 37(1), 32-64.

65. Endsley, Mica R., Measurement of Situation Awareness in dynamic Systems, *Human Factors,* 1995, 37(1), 65-84.

66. Adams, Marilyn Jager, et. al., Situation Awareness and the Cognitive Management of Complex Systems, *Human Factors,* 1995, 37(1), 85-104

67. Smith, Kip, & Hancock P. A., Situation Awareness is Adaptive, Externally Directed Consciousness, *Human Factors,* 1995, 37(1), 137-148

68.

69.

70. Galton, Antony., Towards a Qualitative Theory of Movement, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.

71. Zimmermann, Kai., Enhancing Qualitative Spatial Reasoning; combing Orientation and Distance, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
72. Chelyan, Jean-Paul & Lardon, Sylvie, Towards a conceptual Data Model for the analysis of Spatio-Temporal Processes; the Example of the Search for Optimal Grazing Strategies, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
73. Whigham, P.A. Hierarchies of Space and Time, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
74. Hirtle, Stephen C., et al., the Cognitive Structure of Space: An Analysis of Temporal Sequences, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
75. VIEU, Laure, A Logical Framework for Reasoning About Space, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
76. Tversky, B. Franklin, et. al. Spatial Mental Models from Descriptions. *Journal for the American Society for Information Science,* 45, 656-668
77. MaaB, Wolfgang, A cognitive Model of the Process of Multimodal Incremental route Descriptions, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
78. Kavouras, Marinos & Stefanakis, Emmanuel. On the Determination of the Optimum Path in Space, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
79. Golledge, Reginald G, Path Selection and Route Preference in Human navigation: A Progress Report, *International Conference GIS--From Space to Territory; Theories and Methods of Spatio-Temporal Reasoning*. 1992 Pisa, Ital, Proceedings.
80.
81. Turvey, Michael T. & Kugler, Peter N. *"Information, Natural Law, and the Self-assembly of Rhythmic Movement."* 1987 ISBN 0-89859-640-8
82. Schmidt, Richard A, "Methodology for Studying Motor Behavior"; in book *"Motor Control and Learning; A Behavioral Emphasis*.", 1988, ISBN 0-87322-115-X
83. Warren, Rik and Wertheim, Alexander, "Perception and Control of Self- motion", 1990, ISBN 0-8058-0517-6
84. Lee, David N., Visuo-Motor Coordination in Space-Time. In Stelmach & Requin, *Tutorials in Motor Behavior* 1980, ISBN 0-444-85466-5
85. Verfaille, Karl. Orientation-Dependent Priming Effects in the Perception of Biological Motion. *Journal of Experimental Psychology; Human perception and performance.* 1993 20, 4, 783-798
86. Johansson, Gunnar. Visual Perception of Biological Motion and a Model for its Analysis. *Journal of Personality and Social Psychology.* 33, 680-685.
87. Kirsh, David. The Intelligent Use of Space. "*Artificial Intelligence"* 1995 73, 31-68
88. Spector, Lee and Hendler, James. Knowledge Strata; Reactive Planning in a Multi-Level Architicture. *Technical Report,* Deparetment of computer Science, Univeristy of Maryland. 1990.
89. Adorni, Giovanni and Poggi, Agostino. Route Guidance as a Just- -In-Time Multiagent Task. *Applied Artificial Intelligence*, 1996 10:95-120
90. Overgaard, Lars and Petersen, Henrik G. Reactive Motion Planning; A MultiAgent Approach. *Applied Artificial Intelligence*", 1996 10:35-51
91. Nourbakhsh, Illah, et al. Dervish; an Office-Navigating Robot. *AI Magazine,* Summer 1995.
92. Gutierrez-Osuna, Ricardo and Luo, Ren C. Lola; Probabilistic Navigation for Topological Maps. *AI Magazine*, Spring 1996.

93. Muller, Herman J. & Maxwell Perceptual Integration of Motion and Form Information: Is the Movement Filter Involved in Form Discrimination? 1993 *Journal of Experimental Psychology; Human perception of an Performance* 20, 7-420

94. Biderman, Irving. Higher-Level Vision. In Oserherson et al. *Visual Cognition and Action.* Cambridge: MIT Press

95. Campbell, Donald T & Stanley, Julian C. *Experimental and Quasi-Experimental Designs for Research*, 1963. Library of Congress Catalogue Card Number: 66:25213

96. Heim, Michael. The Erotic Ontology of Cyberspace. In Benedikt, Michael *Cyberspace; First Steps.* 1991, ISBN 0-262-02327-X

97. Morningstar, Chip. The Lessons of Lucasfilm's Habitat. In *Cyberspace; First Steps.* 1991, ISBN 0-262-02327-X

98. Gibson, J. J., *The Ecological Approach to Visual Perception.* 1886, New Jersey: Hillsdale.

99. Gibson, William, *Neuromancer.*1984, New York: Ace Books.

100. Norman, Donald. *The Design of Everyday Things.,* 1988, ISBN 0-385-26774-6

101. McFadden, Tim, Notes on the Structure of Cyberspace and the Ballistic Actors Model. In Benedikt. *Cyberspace; First Steps.* 1991, ISBN 0-262-02327-X

102. Conversations with Prof. Lowry Burgess.

103. Jochem, Todd & Pomerleau Dean. Life in the Fast Lane. *AI Magazine.* 1996 Summer.

104. Lazanas, Anthony & Latombe, Jean-claude. Motion Planning with Uncertainty; A Landmark Approach.

105. Palmer, Stephen E. & Kimchi. The Emergence of Cognitive Psychology in the Latter Half of the Twentieth Century. In Knapp & Roberson *Approaches to Cognition: Contrasts and Controversies.* Lawrence Erlbaum Associate, Publishers.

106.

107. http://galaxy.einet.net/galaxy/Engineering-and-Technology/Computer-Technology/Virtual-Reality.html

108. http://www.hitl.washington.edu/

109. http://mambo.ucsc.edu/psl/cg.html

110.

111.

112. Virtual Motion Controller, HIT LAB http://www.hitl.washington.edu/projects/vmc/

113. Pompeii, SIMLAB, CMU http://topaz.rec.ri.cmu.edu/files/pompeii/

114. IE VR http://www.ukans.edu/~mreaney/

115. Virtual Worlds Project, MIT http://www.ai.mit.edu/projects/vworlds/

116. Walkthrough Project, UNC http://www.cs.unc.edu/~walk/

117. Live Motion Control, MEDIALAB http://www.demon.co.uk/mlab/ent_perf.html

118. Virtual Prototyping, CERN http://sgvenus.cern.ch/VENUS/vr_project.html

119. Virtualized Reality, CMU http://www.cs.cmu.edu/afs/cs/project/VirtualizedR/www/VirtualizedR.html

120. Dante Project, CMU http://www.cs.cmu.edu/afs/cs/usr/dsw/www/dante.html

121. Egypt, SIMLAB, CMU http://topaz.rec.ri.cmu.edu/files/egypt/

122. Shared Space, HIT LAB http://www.hitl.washington.edu/projects/shared_space/

123.

124.

125. Jacob, R.J.K. 1986, A Visual Programming Environment for Designing User Interfaces. In VL/1, 87-107.

126. Smith, David N., The Interface Construction Set. *Workshop on Visual Languages,* 1988,

127. Duisberg, Robert, visual Programming of Program Visualizations; A Gestural Interface for Animating Algorithms. Technical Report #87-20, Computer Research Laboratory, Tektronix, Inc.

128.

129.

130.

131.

132. SIM-City http://www.maxis.com/games/simclassics_3/

133. UGO yellow-pages http://www.ugo.net/yellowpages/

134. Net-Doctor http://www.net-doctor.com/action/

135. Lord Soth's Game Page http://happypuppy.com/games/lordsoth/

136. Observation of Mario-64

137. Observation of Crash-Bandicoot

138. Crusader, Origin Games http://www.origin.ea.com/crusader/noremorse/index.html

139. The 7th Guest, Trilobyte Software http://www.tbyte.com/digs/t7gf.htm

140. Super-Mario 64 http://www.angelfire.com/pages0/corny44/N64.html

141. Tomb Raider, Eidos Software http://homepages.enterprise.net/mfluderx/

142. Quake, ID Software http://www.kinglink.com/quake.html

143. DOOM, ID Software http://users.visi.net/%7Edjack/

144. DOOM Pic http://www.sysnews.com/doomer