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ABSTRACT

With this paper we would like to introduce a system which supports the early phases of the architectural design process. The system consists of two main components: the software solution “voxDesign” and the physical environment “platform”. Our aims are: to formulate, develop, and evaluate an architectural design system through the use of VR (virtual reality) space. The exploration and development of design intentions is supplemented by a new method of three dimensional sketching. In the second part of this paper we will show how these components were used to train students in architecture and design at our university. Parts of this paper were published to the academic public at “Designing Digital Space”. (Regenbrecht 1996)

Keywords: virtual reality, architectural design, human-computer interfaces, design techniques

INTRODUCTION

Currently available computer aided design systems are conceived with the purpose of generating a two-dimensional drawing and, eventually, to attach to it information and calculation sheets. The nature of the I/O of such systems, i.e. the interaction techniques and of the two-dimensional output, both in the form of drawings and presentation tools, is therefore two-dimensional, although the data to which it refers is often three-dimensional (3D). With the newly available Virtual Reality (VR) technology, it is nowadays possible to build a design system that allows to work in three dimensions in all stages of the design process. This paper describes the conception of a new modeling system, based on VR techniques, which can be used during the early phases of the architectural design process. Such early phases of the design process are characterized by the shaping, in German “die Gestaltung”, of the three-dimensional space into architectural forms. The system allows the user, in this case the architect, to experiment with new 3D-interaction and sketching techniques while being immersed in a virtual design space.

VR BASICS AND EXPLORATORY SYSTEMS

Virtual reality can be defined as the component of communication which takes place in a computer-generated synthetic space and that embeds humans (actors) as an integral part of the system. The tangible components of a VR system are the set of the hardware and software providing the actors with a three-dimensional, or even more-dimensional, input/output space, in which, at each instant, the actor can interact in real time with other autonomous objects. Under these premises, we define Virtual Reality Aided Design (VRAD) as computer aided design using the methods of virtual reality. VRAD is nothing particularly new and can be seen as a new application of human computer communication in VR spaces. In general, communication in virtual reality is characterized through individual differences between the actors, through the presence of a private sphere for each actor, through sensory-motor experiences, and through the relationship between information, navigation, orientation, and the different forms of user expression. Thus, a virtual reality aided design system has to be configurable for each actor, to be separable into a public and a private sphere and able to react in a sophisticated way, as well as to offer access to external information, and, ultimately, to be navigable, i.e. made of recognizable cues, which are perceived as being non-
chaotic and bear correspondences to the real world. One main design-goal of an VRAD-system should be the possibility for the actor to experience the space. This is, according to (von Foerster 1991), not possible without active doing. Thus an interaction space has to be provided in the real world which is large enough to move in an appropriate way, i.e. an architecturally sized space. Current virtual reality systems do not provide these capabilities (Butterworth 1992, Pentland 1990, Regenbrecht 1994, Encarnacao 1994, HIT Lab 1991, Riedel 1993, Schmitt 1993, Thompson 1995, WorldToolKit 1993, DIVISION 1995, Superscape 1993).

A great deal of development and research has been undertaken during the last few years to establish virtual reality techniques in architecture. Most of these systems are simply viewing programs, also known as walkthrough systems. With the exception of viewing controls there is no real interaction. Other (research) systems attempt to provide information displays, computer-aided design or planning support in VR. To these belong interesting projects such as the Architectural Space Laboratory ASL in Zurich or the Virtual Design / Given project at the Fraunhofer Society / Germany to mention only a few. Essentially, the geometrical methods that can be used to develop VRAD systems fall into three main categories. In a boundary representation model (BRep), an object is described by points, edges and faces, i.e. by its boundaries. In the second category, constructive solid geometry models (CSG) build the objects from readily available simple geometrical objects. Finally, voxel space models partition the 3D space into equal elements, each of which represent an atomic element of the space. An object is represented here as a connected set of voxels of the whole space. A BRep model requires a tedious process of construction before an object comes into existence, and therefore distracts from the real task of the first phases of architectural design, where creativity is most important. CSG models don't allow sketching with 3D-shapes other than those predefined and are thus too inflexible for the task of shaping space. Voxel models instead look much more promising, since they allow sufficient fuzziness in the conception phase but are also accurate enough to provide enough information for rendering on a VR output device.

A few voxel-based approaches are described in (Williams 1990) and (Galwey 1991). The most recent work in voxel-based architectural design has been undertaken by (Wang 1995). They use the metaphor of sculpting. A complex 3D-model is derived from a solid material by carving and sawing. This method is promising for the design of highly detailed objects. Through the use of interpolated voxels and textures, Wang and Kaufman attempt to generate realistic looking results.

As our purposes such fine gradation in design is not necessary. Our approach is from the opposite end - the coarse, simply 'bordered' model, the elementary form. The above approaches aim for 'near photorealistic' virtual images. This brings with it the resulting well-known problems associated with rendering time, resolution, textureing, etc. The second major criticism is the limited space of the users action / movement. Most of today's VR applications are desktop-based, some allowing the user to interact on a one square-meter floor. We want to emphasize the space required for Doing, that supporting a 1:1 experience for the user / actor.

A NEW APPROACH TO SHAPING

Our aim consists of three components: to formulate, develop, and evaluate an architectural design support system through the use of VR space. The exploration and development of design intentions is supplemented by a new method of three dimensional sketching. The developments of voxDesign choose not to exclude the model or the sketch. The possibility to directly and spatially (three dimensionally) design space EXPANDS the existing working methods of the architect with a third new design technique. The degree to which it will be used and the particular set-up in which it will be applied, is dependent upon the situation and the architect. The defined design environment of the experimental system aims to provide a 1:1 architectural interior space. Through the use of a 4m x 4m physically bounded movement space, any form element or spatial situation can be directly described, observed, modified or discarded.

Architectural Sketches

A universal and definite theory that describes the exact PROCESS of architectural design does not exist. The direction and individual steps of a design are dependent upon the task at hand and the designated site, not to mention the mentality of the architect him or herself. However, in direct contrast to the process of architectural design, much is known about the TECHNIQUES applied in the design process, in particular with relation to form finding and...
external expression. The model (working or development model) and the sketch play the most important role as traditional methods of design exploration. Sketching in particular has special importance as a design instrument. The sketch encompasses the entirety of a design, communicating the functionality of a floor plan in addition to its spatial definition. Sketches are the abstracted pictorial intentions of architects. In contrast to the finished architectural drawing, the sketch contains the thoughts and deliberations of the architect. This, as opposed to the drawing, is the early phase of the design process. Sketching is at once the direct formulation and the description of new ideas. It represents as much a method of feedback and testing as of documentation. The sketch is also the discovery of the unintentional. It occurs as memos, half-formed ideas, thoughts of the moment. The architect Norman Foster describes it as follows: "How can you design the plan, section and facade of a building, without sketching the three-dimensional aspects in the margins, without feeling it through the pen ..." (Blaser 1992). Sketching is, therefore, an essential part of the architectural design process.

The project "atelier virtual"

This project began by setting up a multidisciplinary project group in autumn 1994. Four different disciplines are involved in the project: computer science, architecture, product design and psychology. At first it was necessary to bring together the multiple views on virtual reality. The main topics of the discussion were: investigations about real and virtual space including the coherencies forms of communication and recognition in virtual worlds navigation in virtual space(s) interaction with virtual objects information displaying questions about ethics and social responsibility. Although the results of this discussion are not that spectacular this kind of approach was necessary for establishing a workable group. The different and individual views and attitudes were expressed via 3D-modeling and animation tools (non-VR). Some problems are still unresolved, such as realistic vs. symbolic information displaying and circumstances in which a private sphere is needed, to mention a few. The discussion and the results are documented in (Briefe an Vradmin 1995) (www.uni-weimar.de). To establish a more precise idea of the possibilities and limitations of VR, two additional sub-projects were set up: the "platform" project and the "vrDesign" project.

VR equipment

Setting up a high-end virtual reality system is very expensive and often exceeds the budgets of architects. We are using a minimal hardware configuration for virtual reality according to the definition of VR given above. The hardware basis is a Silicon Graphics Crimson VOXT with 64 MB of memory. The output is realized with a Virtual Research VR4 head-mounted display (hmd), a video-multiplexer RGB4 and a Commodore monitor for presentation purposes. The tracking system consists of a Polhemus controller unit with a long range transceiver, one hmd-tracker and a Stylus (or 3Ball) as a pointing device. The head-mounted-display is operated in NTSC monoscopic color mode. The tracking system works with about 60 Hz for each tracker and can track a range of about 5 meters. All the wires are extended and modified for operating in such a large space. We assume that such a configuration will be available at a reasonable prices in the next few years. At present the price falls somewhere in the graphics high-end entry/midrange pricing.

"Platform"

With particular regard to usability tests and other methods of experimental psychology and human-computer interface design it is necessary to provide an appropriate physical environment. Today's VR-research testbeds are characterized typically by unstable laboratory conditions, but for hci (Human Computer Interface) testing and development a (real) environment is needed that will free the user/actor from all the technical restrictions (like wires around the legs). Unfortunately some things are not yet removable and still uncomfortable (especially the head-mounted-display), but we are working on it. To fulfill the desire of a large interacting room the main design goal of the platform-project was to provide an almost unconstrained physical space of about 4 x 4 x 2.5 meters 3. Within this space there are no obstacles to the movement of the actor. The second goal was to integrate all the technical equipment needed for the VR application (see VR equipment).
Thirdly, there must be an appropriate workspace for the operator and respective software developer. The platform should be used for both public and research presentations/lectures and for system development too. The result of the design process is shown in Figure 2. The actor interacts on a circular floor with about 4 meters in diameter. The hand and the tracker cables are lead through a rod-like construction. Integrated into the whole system is all the equipment needed for demonstrations and development. When used for presentations, the audience can follow the interaction process of the virtual world via two additional monitors and an optional large screen.

"voxDesign"

- The software solution “voxDesign” works together with the physical environment “platform”. “Platform” provides the free interaction space in the real world: voxelDesign is implemented in C/C++ based on the SGI Graphics Library GL. The main goals of voxelDesign are (see also Figure 3):
  - Realizing a simple (to use and to implement/modify) virtual reality aided design (VRAD) system for the early phases of the architectural design process.
  - Providing an experimental system for studying human-computer interfaces in virtual worlds.
  - Using the system in architectural and design education.
  - Formulation and evaluation of relevant functionality in architectural design.
  - Transferring a VR application from the laboratory to real usage.
  - Public presentation of the possibilities and limitations of virtual reality.

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- A testbed object/subject for multidisciplinary work in the future.
- Testing of software techniques for real-time critic-systems.

VoxDesign is based on the following premises:

For architects among others, sketching is an elementary form of the expression of design thoughts. VR extends the traditional sketch methods through the fundamental addition of the third dimension for the design process. Three-dimensional sketching is used as a medium for communication with other architects or non-professionals. The 3D-sketch in VR can, however, additionally be used for immediate reflection and feedback of the design process. The user can operate with the medium of the computer in an intuitive, game-like, experimental way. The early phases of the architectural design process are characterized by fuzziness, coarse structures and elements, and a trial-and-error process. Searching for form, shape ("gestalt") is the principal goal of the designer. Small cubes (voxel) are a sufficient minimum element for expression in these early phases. They are the virtual equivalent of the Lego brick in the real world. This is an intuitively comprehensible system for the user and avoids the need for extensive training before using the system.

The development of the software is separated into two phases: Phase 1, the so-called "VoxDesign" is already completed and allows the user to set and erase voxel-elements, choose one color of sixteen, load and save voxel spaces (see Figure 4). Even with this very simple functionality it was possible to achieve reasonable design results. "VoxDesign" was necessary to test and evaluate some basic interaction techniques and to formulate the requirements for "VoxDesign1", which forms phase 2 (see Figure 5).

Figure 5. VoxDesign 1 - a software for complex 3D architectural design functionality in VR

In the following section the functionality of "VoxDesign1" will be described. "VoxDesign1" allows the user/actor to place voxels (cubes with a volume of 2.5 x 2.5 x 2.5 cm³) into the virtual space. The virtual space is the same size as the real interaction space, i.e. about 40 m³. A voxel is represented as an untextured, colored (true-color) element. To provide an appropriate design environment it is possible to import three-dimensional CAD models via DXF or pixel pictures (bitmaps) into the system. In addition to this, the platform provides an analog audio environment with loudspeakers. The virtual design-space is lit by two ambient lights and two spot lights. The designer can load and save the virtual model. For presentation purposes a snapshot function has been implemented. With this function it is possible to print out some views of the model after finishing or during the design-session. With the platform environment it is also possible to record the session on video tape. Changing the different modes and actions in VoxDesign1 is very simple: you have only to twist the pointing device toward your face. After twisting a three-dimensional menu appears at the current position in virtual space. The actor chooses the desired option and continues the design process. All user-specific parameters are saved in a configuration file and can be overwritten with command-line options. An X-Windows based starting interface is currently under development. This simple functionality allows initial design thoughts to be expressed in an easy-to-use way. Resulting examples are shown in Figures 6-8.
USING voxDesign IN EDUCATIONAL TRAINING

It is still not usual practice at European universities to confront students with VR techniques in practice. We decided to provide such an opportunity to about a dozen of graduate students in architecture. They had to solve an architectural design task in virtual space. The two main topics for the students were to describe their design thought with voxDesign and to reflect the process of the design variants using this new technology. One side-effect of this course for us was the possibility of a first set of usability tests. The given task was not that spectacular and actually not that important: to design a personal (individual) virtual student room with all communicational and housing structures only in the very early phases of the design process. The complete design was to take place in virtual space (the voxel room). For presentation purposes the students were allowed to edit the model or views of the model with external programs, although the design idea itself had to be developed in the voxel space.

The course was offered to senior and graduate students only. Our intention was to give them a new tool to express their design ideas, not to teach them the basics of architectural design. Before entering the course most of our students had the following skills and knowledge:
- knowledge of the basics of computer-aided architectural design (caad)
- experience in architectural design using the traditional techniques and tools
- no knowledge of or experience with virtual reality
- experience in setting up architectural models
- readiness to explore a new terrain

One main goal was to give the students a feeling of what virtual reality can be. After finishing the course we wanted the students to be able to distinguish between the facts and fiction, to know the possibilities and limitations of this technique, and to estimate its influence on social life and especially on their own profession. For these reasons the course covered the following topics, in addition to practical work with the system:
- the fundamentals of virtual reality
- VR applications in general and especially in architecture
- the history of computer graphics and VR
- basics in using workstations and local and wide area networks
- basics in digital model and picture handling
- the social and psychological impact of virtual reality now and in the future
- ecological aspects of virtual reality and computers in general
- questions of perception and cognition using VR techniques
- some philosophical aspects of (virtual) reality (esp. Radical constructivism)
- some aspects of the theory of media
- For more details on this course see http://www.hab-weimar.de/vradmin/Courses/Course01/.

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The discussions about the general and theoretical subjects were very fruitful for both, the staff and the students. Thinking beyond one's own professional borders broadens one's field of view, not only in the context of virtual reality. The practical sessions took place in our [atelier, virtual] room. It is a 40 m² room with two workstations, two personal computers and the platform, not to mention the coffee maker, a lot of literature, records and CD's, and presentation equipment with 24 hours room and Internet access, a conference table and a lot of chairs. For special presentations a video-beamer was connected to the system so the inside of the virtual space could be displayed on a 4x3 m² screen; this was very impressive. For the auditory the actor acted inside the virtual space. The number of students and the "voxel-time" was limited because there is only one virtual reality system available. Each student used our VR system about 7 hours in practice to realize the design task, each session lasting an average of about one hour (between 30 minutes and 3 hours). Using the system longer than 1 hour led to simulator sickness in about one third of the students. The students liked the home-like ambiance in our atelier and the close contact to the staff (tutor, assistant, professor) too. In general, the discussions about interdisciplinary subjects helped us to understand the complexity of this new technology.

The results of the design task were very different from traditional techniques (see student work results). In a very different way the students tried to use and explore the new medium. Most of them left pure real-world metaphors (like chair, table, wardrobe) and "played out" the other opportunities and properties of virtual space like the absence of gravity or static laws. The first attempts of the students to go into design details or to express very accurate structures were not successful because of the coarse voxel structure (2.5 cm grid) and the limited functional features. In the actual use of the system our approach to sketching was very limited. So with this kind of usability experience it would be more accurate to talk about "brickling". At a certain number of act voxel it is necessary to sketch with voxel like a three-dimensional pen, it is necessary to set voxel after voxel. Offering faster workstations to the students would solve this problem, but nevertheless, the attempt to support the early phases of the architectural design process is possible with this sketching/brickling method.

Further results in brief:

- the Stylus exhibited very good usability including the twist mode
- sometimes there were problems with the stability of the tracking system
- colors are enough for the design task
- the system was slowed rapidly with applied textures as an environment, the textures were useful only for presentation purposes
- using sound as a design environment was very welcome
- during long sessions the students tended to lay down on the floor during the design process
- the most spectacular effect was to "experience" a virtual structure by just going around them
- a stereoscopic head-mounted display is not that necessary, other depth cues are much more important
- the students confirmed our assumed voxel size as fine enough for this phase of the architectural design process
- the rendering method is absolutely unimportant for the usage of the system (flat, gouraud, phong)
- unfortunately there was not enough time to edit the voxel models inside an other cad- or animation program
- primitive CAD functions were missed, like line, wall, circle
- at about 2000 voxel set into the virtual space the system was slowed down extremely
- the selectable value for the field of view is very dependent on the individual (between 30 and 100 degrees)
- the estimated duration time by the student was shorter every time than the real time
- most of the students were immersed (or at least involved) in the virtual voxel space during their design sessions
- all the external controls of the program should be integrated into the virtual world, such as field of view control, loading and unloading textures, switching between different variants/models
- for longer periods of usage the head-mounted display is not very comfortable
- using a pen metaphor as a pointing device seemed to be the right decision; the students associated it with sketching
- as assumed, uncomfortable wires were no longer a problem for using the system (see platform)
- there should be more depth cues in virtual space, like fog (aerial pollution), reference objects, well placed light sources, perhaps spatial sound applied to the objects and the space

**Student design in virtual space** (Figures 9 - 14)

To give a better impression of the system discussed in this paper here are examples of selected student work. These pieces are only selected snapshots of the students work. Every student tried out many variants and

![Figure 9. Student design in virtual space (example)](image)

![Figure 10. Student design in virtual space (example)](image)

Michael Oechslerger

![Figure 11. Student design in virtual space (example)](image)

![Figure 12. Student design in virtual space (example)](image)

Birgit Felsch

![Figure 13. Student design in virtual space (example)](image)

![Figure 14. Student design in virtual space (example)](image)

Peter Bringt

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situations. But this will give an impression to the reader what is possible if students work with such a system under the circumstances mentioned above.

**THE ARCHITECTURAL FORM GENERATING FUNCTIONS (VRAD CONCEPT)**

There are many more methodical and technological problems to solve. Our focus is set on defining a wider set of architectural form generating functions. Some theoretical investigations have been undertaken on this subject. We have defined some general principles for object generation and manipulation, extending the voxel idea with

*Figure 15. Generating a line by pulling out a row of dots*  
*Figure 16. Generating a plane by extruding a line*  

*Figures 15-19. Intuitive gestures for generating forms in a Virtual-Reality environment*

*Figure 17. Generating a line by drawing*  
*Figure 18. Generating a plane by extruding a line*  
*Figure 19. Generating a solid by extruding a plane*

*Figure 20. Generating openings: pressing an opening out of an existing object (wall)*
Figures 21 - 24. Gestures for identifying objects

Figures 25 - 26. Orientation in design space by means of translucent visualization

Figure 27. Orientation in design-space: an overview (the picked object on the right hand: new point vision)
elements from brep and esg models. In this case an object is described by points, lines and faces. Moving a point will generate a line, moving a line will generate a face, and so on (see Figures 15-27). We want to evaluate this hybrid way of acting through extensive usability tests.

LIMITATIONS AND FUTURE WORK

We will continue teaching with voxDesign because of the positive feedback from our students. We are proud to present this work at cebit '96, the world largest fair in computer science, this year in Hannover / Germany. With this presentation we can give an example of and a starting point for discussion about using new technologies in university education. The use of the system without any knowledge of a UNIX system would be desirable because the time to teach the students in this kind of things will be much more useful for using the VRAD-system. A lot of time was wasted in using DTP (desktop publishing) programs and network wide file handling too. The environment of such a system should be useable in the same intuitive way as the VR system itself, but that is a very difficult task. It would be desirable too if every student in architecture could get the necessary education in using computer environments. The architectural office of the future will not be as traditional equipped as today, we believe making our attempt to teach students to work with virtual reality is both risky and necessary. On the one hand only a few architectural offices are fully equipped with CAD stations, but on the other hand using computer-aided design techniques, including virtual reality, will have a growing influence on more and more architects and living in general. One main task of a university is to prepare the students for the future and our contribution is only one piece of the puzzle. While introducing new technologies to the students a feeling for social responsibility should be encouraged or even required by the teachers. Our attempt is very humble but we think it is a step in the right direction.

The system in its current manifestation cannot satisfy all the needs of the early design phases. A step by step approach is, however, necessary to explore and evaluate the right techniques and to formulate the right questions. Developing and testing human computer interfaces is necessarily an experimental task. Our solution does not support multi-user-design (csw). More interesting are problems surrounded by the sensory-motor experience. How can we improve the immediate design feedback? We are looking for practicable, useable techniques. The state of the art in force, tactile, and auditory feedback is not yet satisfactory. More promising is perhaps the approach with graspable user interfaces as mentioned in (Fitzmaurice 1995). We will try to adapt these methods to our VR-system. The current size of the interaction space, and therefore the virtual space in a 1:1 experience system, is also too small; the area of design tasks is reduced to the scale of product and interior design. We are attempting to extend this space using long range tracking methods. Not yet resolved are the problems associated with rendering speed and resolution with large numbers of voxels. We are currently working on an algorithmic solution. In addition to this, we hope that the graphics and machine power of the computers of the future will increase.

In addition to this we are investigating the need for free-shape and unconstrained functionality in virtual space. Could this influence the real (buildable) design? Could this lead to a “VR style” in design? An additional development is to integrate dynamic gesture recognition into voxDesign. This could dramatically improve the intuitive handling of the system. We are trying to involve the potential user as much as possible in all stages of the development work. For this reason, most of the research are the result of multi-disciplinary university courses. This has two major benefits: firstly, there is an immediate and constant feedback of research results and secondly, the students are confronted with state-of-the-art technology.

Our next substantial steps are as follows:

- extending voxDesign with more VRAD functionality: for this reason we applied for a research grant from the DFG (german research society)
- academic research on immersion and abstraction in virtual worlds based on theoretical work and user tests
- the development of networked personal virtual worlds
- investigations and implementations hopefully answering some special questions about navigation and displaying of informational structures in virtual space

Finally, the ethical and social questions that arise from VR are just as much an integral part of our work. We cannot and do not want to ignore these questions.

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LITERATURE


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