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HYBRID DESIGN ENVIRONMENTS: IMMERSIVE AND NON-IMMERSIVE ARCHITECTURAL DESIGN

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SUMMARY: *In pre-industrial times, decisions related to the design of buildings were often made and applied directly to the project under construction. Space and form were shaped in this way, inspired by the direct perception of the forms and spaces under construction and the problems that were defined within the building under construction. Recent virtual reality systems offer modern day designers a similar opportunity by allowing them to get immersed inside an imaginary, computer-generated "virtual world" large enough to walk through. In this paper some approaches for integrating immersive virtual environments in the architectural design process will be introduced and evaluated based on experience made using a CAVE facility designed, built and operated by the author in a school of architecture.*

The findings suggest using hybrid design environments as a new paradigm combining, on one hand, non-immersive design tools such as sketches, models and CAD, and on the other hand, immersive design tools such as virtual reality. This paradigm merges both types of tools and suggests a new design environment that utilizes the high functionality of non-immersive tools with the capacities of the immersive tools without replacing one or the other.

KEYWORDS: *Immersive Design, Non-immersive design, Virtual environments, CAD, Design process.*

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1. BACKGROUND

1.1 The Architectural Design Process

The design process comprises three main phases. In the first phase data and constraints imposed on the design are studied. The second phase deals with the search for a solution to the design problem. The designer produces mental models of anticipated design solutions which are then externalized through representation of the design thought in the form of graphic symbols. The designer interacts with the design by re-forming the representation. The designer's intentions remain ambiguous until the design is ready to move on to the next level where the designer's knowledge increases in quantity and precision. In the third phase a set of precise graphic representations is prepared to ensure the non-ambiguity of the information transmitted to other parties involved in the process. Within the design process, it is possible to identify two main types of activities: a) a formative (active) dealing with generating and evaluating ideas or conceptual design, and b) a descriptive (passive) dealing with graphic communication of information and presenting to others fully formed ideas. Because a design is thoroughly evaluated at a number of stages of the design process the design cycle should be quick and intuitive, capturing the flow of concepts as quickly and naturally as possible.

1.2 Analysis of Design Tools

1.2.1 Traditional Design Tools

Drawing free-hand sketches using pencil and paper is a common medium of communication in the conceptualization phase of the design process. Goldschmidt (1994) identifies two kinds of sketching activities: a) capturing thoughts that are already in the mind to paper in the form of symbolic representations; and b) sketching to help generate new ideas which do not yet exist in the mind. Do (2001) argues that sketching makes it easy for designers to draw, evaluate, and explore as well as to revise and correct. Because of the fast turn-around of the creation-feedback cycle, it supports the recursive nature of the design process. Sketching improves the creative process because all three processes (visual, mental and psychomotor) are involved. Sketches are often unfinished, rough in appearance and convey their intentions without expressing completeness (Fig. 1). This abstraction allows pushing back the specification of any details. Ambiguity allows maintaining several possibilities open for later selection or identification. It also helps the designer to discover new ideas because these can often be misinterpreted, thus offering incomplete information. The notion of the sketch also includes the use of physical study models which are very effective in relaying three dimensional spatial relationships. Models can be built in any scale and the decision making and the form validation can be made directly on them.

FIG. 1: Abstraction, ambiguity, and inaccuracy in a freehand sketch by Frank Gehry

1.2.2 Limitations of Traditional Design Tools

Traditional manual tools, despite their advantages, pose some problems. While many designers acquire the ability to interpret abstract information to understand and mentally visualize complex 3D objects, this capacity has its limits, particularly with less experienced designers. The spatial abstraction required to perceive complex 3D objects through 2D representations requires coding and decoding of information. This process imposes an additional mental load to that already required by the task of generating ideas and therefore reduces the exploration of new ideas.

Quick schematic perspectives can be very useful in the early stages of design but are often deceiving and easily manipulated to produce a desired effect. Constructed perspectives, on the other hand, can be very accurate and revealing but they require the application of lengthy and cumbersome construction techniques. They are static and show only selected angles of the design under consideration and cannot represent the effect of movement and change over time. This affects the proposal-verification-correction cycle of design. Another drawback with physical models occurs when representing large objects at reduced scale. Scaling affects the viewing parameters and thus distorts the perception of the object's real proportions.

Moore and Allen (1981) argued that traditional media fail in their attempts at representing space because they represent the plan views and sections within which space is hidden not the space itself. As a result, the attention is drawn to the media themselves not to the architectural space they represent.

1.2.3 Computer as a Design Medium

Computers have been used in architectural design for more than 30 years trying to replace the role of the traditional physical representations and providing a freedom to rapidly explore and alter ideas without the need to completely rework drawings and physical models. Computer Aided Design (CAD) gives designers the opportunity to generate detailed, dynamic and potentially complex architectural models, in contrast with the static images of traditional media that cannot represent the effects of movement and change over time.

1.2.4 Limitations of CAD in Conceptual Design

CAD graphical user interface approaches request precision and set ideas from the designer, both of which can challenge the designer's initial mental images and limit creative thinking. CAD representations give the designer the impression that design objects are precise, perfect and photo-realistic and this does not encourage further discovery, exploration and generation of new ideas at this early phase of the design process.

Given the way CAD interfaces are conceived (menus, commands, arrows, keyboard and mouse), they seem to block the designer in his process because he has to concentrate on the tool, rather than on the design task.

In ordinary computer systems the common medium is a 2D visual display, organized according to the desktop metaphor. As a result the limitations of traditional 2D media have been transferred to the 2D representation of the computer screen and to computer rendering software. These tools still impose a heavy mental load on the designer due to the task of abstraction and information encoding and decoding.

In the majority of CAD software, making 3D representations still requires many additional actions from the user part. This can inhibit a fluent transition from working in 2D to a 3D representation.

In practice, most designers continue to perform the most important part of the design process (conceptual design) using traditional methods. Then they enter this information in the computer to represent and communicate these ideas.

1.2.5 Virtual Reality as a Design Environment

Virtual reality can be defined as the systems and techniques that provide the feeling of presence in a three dimensional computer generated world. This sensation of presence is the result of the user's ability to interact directly and in real time with the virtual environment.

Virtual Reality has the following interrelated characteristics:

- Real-time rendering-the graphics are photo-realistic and dynamic;
- Immersion-the information environment surrounds the user;
- Presence-One has a feeling of actually being in the environment;
- Interactivity-One has a sense of being involved in the environment;
- Autonomy-One is free to act and explore the environment; and
- Collaboration-Multiple users can interact in the same world.

From a design point of view these characteristics can impact the design process as follows:

- Virtual reality can reduce the amount of spatial abstraction required of the designer by reducing the encoding and decoding of 2D information used to represent a 3D environment. By relieving the designer of all unnecessary mental work, he is set free to concentrate on more advanced design problems.
- Virtual reality is an efficient tool for providing feedback of the 3D characteristics of the design object such as scale and proportion. This helps improve the management and reduce the quantity of errors produced in comparison with traditional media.
- Virtual reality allows designers immediate, direct, and intuitive control over the 3D design objects. Composition becomes an experiential process because the designer is immediately confronted with the consequences of his design decisions. This improvement in the frequency and the characteristics of the feedback provided in the design process would lead to a corresponding acceleration in the design hypothesis creation/feedback/modification cycle.
- A much higher level of engagement with the design object can be reached with virtual reality systems which are controlled by natural movements of the user's hand and allow direct manipulation of the design object. This allows generating digital models in much the same way that free hand sketches or physical models are constructed.

- VR as a visualization tool affects several of the designer's cognitive aspects. It can empower visual thinking if it succeeds in stimulating the designer in achieving various classes of abstraction and invoking a dynamic and interactive understanding of space and place.

1.2.6 Limitations of Virtual Reality as a Design Environment

The primary goal of introducing virtual reality in architectural design was not to use it as a presentation tool at the end of the design process, but to use it from the very start of the design process. Currently, typical design work seldom uses virtual reality in conceptual design. Research in few experimental setups has been undertaken during the last few years to integrate virtual reality techniques in architectural design, but most of these setups are simply virtual reality viewing programs which offer some viewing controls and display some information but no real interaction with the design object and cannot provide the entire creation/feedback/modification cycle offered by CAD or more traditional design media and therefore cannot replace other design media. As a result virtual reality still appears to be passive with regard to the creation process inside the virtual world. Visualizing, navigating, or even moving objects and opening doors make the designer interact with this virtual environment in a passive way from the design point of view.

The challenge remains to enable design inside the virtual world as easily and as intuitively as sketching, without all the problems of computer interfaces associated with CAD and 3D modelling.

1.3 Typology of Display Environments

With the use of sophisticated computer equipment such as head-mounted displays, projection environments as the CAVE and 6 degrees of freedom input devices, virtual reality is often seen as immersive. The goal is to place the user inside a 3D environment and isolate him from the real surrounding. However, using a conventional personal computer system (screen, keyboard and mouse), a user can still experience a limited sensation of presence in a virtual world without being totally isolated from the real surrounding environment. This can be referred to as non-immersive virtual reality. Non-immersive virtual reality is seen as an accessible and less complex alternative to the immersive virtual reality. Dave (2001) evaluated a range of typologies and variations that exist between both schemes.

2. METHODOLOGY

Using immersive environments as design environments is relatively new and paradigms for integrating them into the design process is extremely challenging. This paper tries to examine the different methods of integration and to identify the most productive integration paradigm. A surround display environment (Fig. 2) was designed and built by the author at the Department of Architecture, UAE University. This facility, named the UAEU-CAVE, is composed of three large vertical projection screens, three standard digital projectors and a cluster of three standard PCs. A software called "Cortolink server", developed in-house, synchronizes the display of and navigation through 3D VRML models projected on the 2.65m x 2.65m x 2.65m rear projection screens (Fig. 3).

FIG. 2: Layout of the UAEU-CAVE facility and a real-time full-scale exploration of an architectural project.

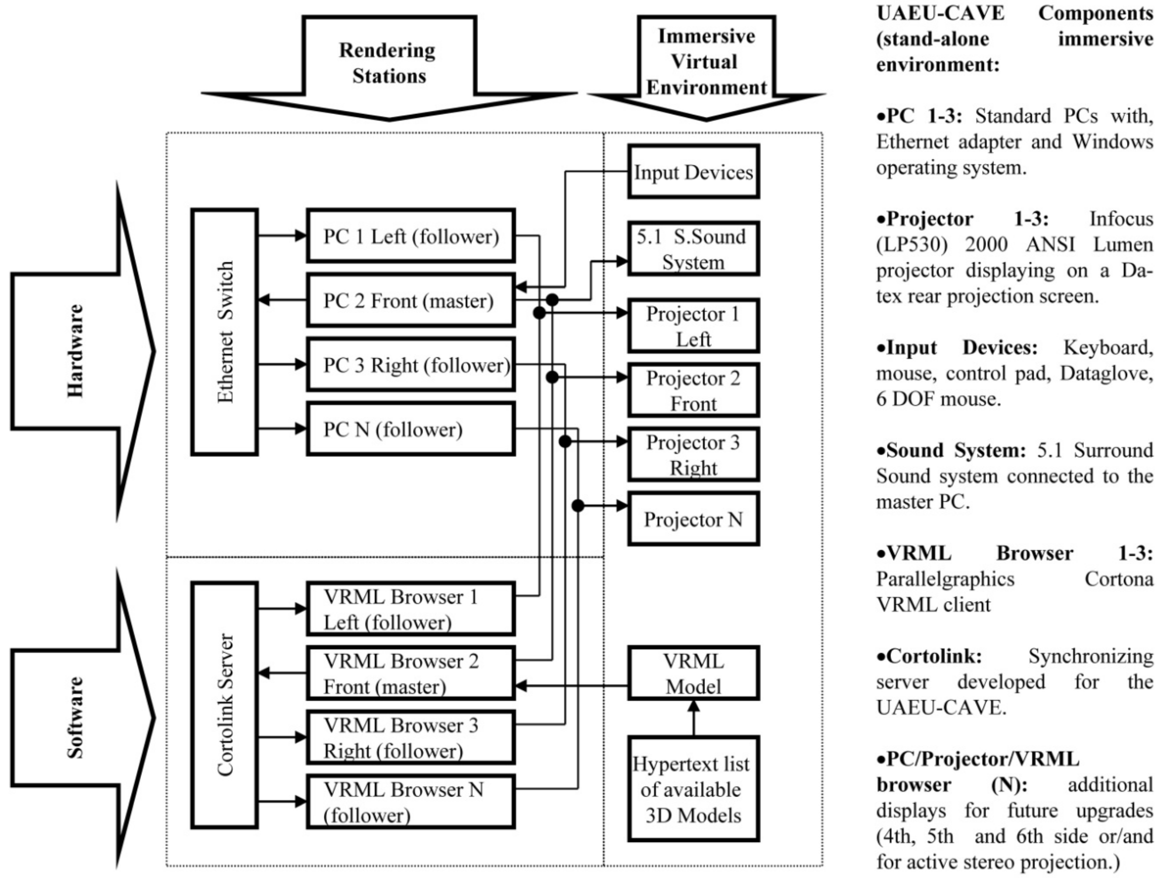
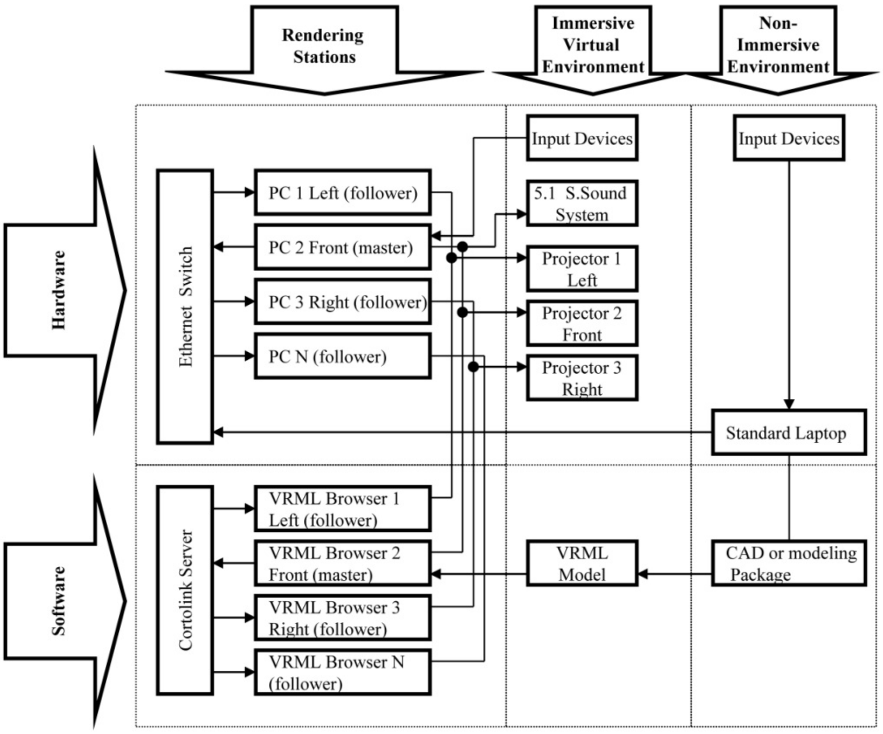


FIG. 3: Architecture of the UAEU-CAVE facility as a stand-alone immersive virtual environment.

This immersive virtual environment together with a more conventional workstation with a CAD/3D modelling package forming a non-immersive virtual environment were used to examine the following paradigms of integrating Immersive Virtual Environments in the Architectural Design Process:

1. Non-Immersive Virtual Design Environments;
2. Immersive Decision Support Environments;
3. Alternating Design Environments;
4. Immersive Design Environments; and
5. Hybrid Design Environments.

The first four paradigms of integration used the UAEU-CAVE as a standalone facility (Fig. 3). The fifth paradigm of integration required some modifications to the setup. Two alternatives have been tested (Fig. 4) and (Fig. 5). The first alternative involved having a laptop inside the UAEU-CAVE equipped with CAD/3D modelling software and connected through the Ethernet switch to the computers driving the CAVE. Modifications on the model on the laptop were exported to a VRML model upon request and appeared on the CAVE walls once the VRML viewers were refreshed. The second alternative involved replacing all three computers driving the CAVE with one computer equipped with a multi-display graphic adapter. Three graphic outputs were used to drive the CAVE projectors (immersive environment) and one graphic output was used to drive the monitor inside the CAVE (non-immersive environment). The CAD/3D modelling software was replaced by "Google Sketchup" and the Cortolink server was replaced by a free ruby script called "Multisketchup". Modifications on the model were conducted in Google Sketchup. Synchronization of navigation took place instantaneously but synchronization of created and manipulated objects required refreshing the SKP model loaded on the sketchup instances (Fig. 6). This alternative allowed a much faster synthesis/feedback cycle and eliminated the problems associated with VRML conversions.



UAEU-CAVE Components (Hybrid Environment 1):

•**PC 1-3:** Standard PCs with, Ethernet adapter and Windows operating system.

• Standard Laptop with CAD and 3D modeling software.

•**Projector 1-3:** Infocus (LP530) 2000 ANSI Lumen projector displaying on a Da-tex rear projection screen.

•**Input Devices:** Keyboard, mouse, control pad, Dataglove, 6 DOF mouse.

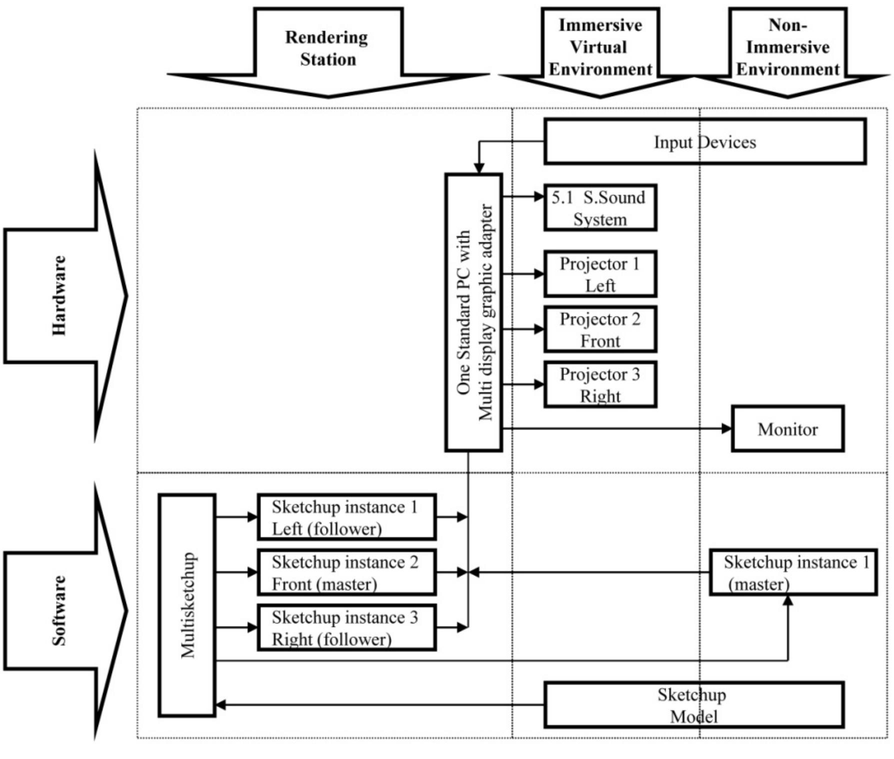
•**Sound System:** 5.1 Surround Sound system connected to the master PC.

•**VRML Browser 1-3:** Parallelgraphics Cortona VRML client

•**Cortolink:** Synchronizing server developed for the UAEU-CAVE.

•**PC/Projector/VRML browser (N):** additional displays for future upgrades (4th, 5th and 6th side or/and for active stereo projection.)

FIG. 4: Alternative 1 of the architecture of the UAEU-CAVE facility as a hybrid design environment.



UAEU-CAVE Components (Hybrid Environment 2):

•**PC 1:** Standard PC with, a multi display grephic adaptor and Windows operating system.

• Standard Laptop with CAD and 3D modeling software.

•**Projector 1-3:** Infocus (LP530) 2000 ANSI Lumen projector displaying on a Da-tex rear projection screen.

•**Input Devices:** Keyboard, mouse, control pad, Dataglove, 6 DOF mouse, head and hand trackers.

•**Sound System:** 5.1 Surround Sound system connected to the master PC.

•**MultiSketchup:** Synchronizing several instances of Google Sketchup.

FIG. 5: Alternative 2 of the architecture of the UAEU-CAVE facility as a hybrid design environment.

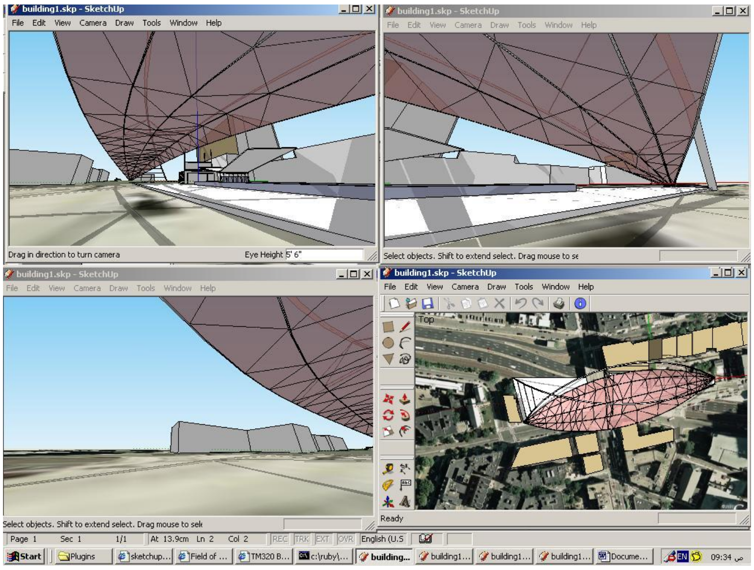


FIG. 6: Four synchronized instances of Sketchup: three full-sized to drive the CAVE (immersive) and one scaled view for object creation, manipulation (non-immersive).

3. ANALYSIS OF INTEGRATION PARADIGMS

3.1 Non-Immersive Virtual Design Environments

Non-Immersive virtual design environments are becoming very common in modern architectural practice. Representation of the design idea usually starts using traditional design media such as sketching and physical models followed by a more detailed phase using CAD on a workstation (Fig. 7). Finally, 3D models are built using 3D modelling software outside the virtual world, interacting with the mouse in a graphical user interface of menus and palettes. These 3D models are then experienced on the same computer screen using a VR viewer which supports a more or less photo-realistic display. The keyboard and mouse are used to interact with the virtual environment. The computer screen becomes a window on the virtual world. The designer benefits from the sophisticated interface of the CAD and 3D modelling software packages involved offering a few hundred functions and commands for creating, manipulating and representing design objects.

This setup helps improve visualization and exploration of design ideas. It offers a high level of scalability allowing the designer to work on scaled representations such as building layouts then to zoom-in to work on 1:1 details. The designer has the choice between 2D and 3D representations displayed on the screen. Some packages also include simulation capabilities which help predict environmental performance aspects for example.

A significant drawback of this setup is that it includes most of the limitations discussed earlier which are associated with traditional tools and with CAD. However, more recent developments are improving the effectiveness of non-immersive environments. On the hardware side, wide-screen and stereoscopic displays are widening this window on the virtual model and enhancing the 3D experience. On the software side, free-form technologies such as DDDoolz (Achten et al., 2000) and Sketch-Up facilitate 3D computerized sketching during the early stages of design.

FIG. 7: Non-Immersive Virtual Environments on a Conventional Workstation.

3.2 Immersive Decision Support Environments

This setup is common whenever an immersive environment facility is available for shorter periods of time. In this approach the designer works in a conventional non-immersive design environment and takes the design to the immersive virtual environment when the design is almost finished or at distant intervals during the design process. The immersive sessions are helpful for group decisions (Fig. 8). Since most of the work is done on a conventional workstation, this approach requires from the designer the least level of adaptation to the new concept of immersive design and offers a very strong decision support tool. However, it does not exploit the full potentials of immersive design. The immersive environment is used as a presentation tool during the final evaluation stage rather than a design environment throughout the entire design development.

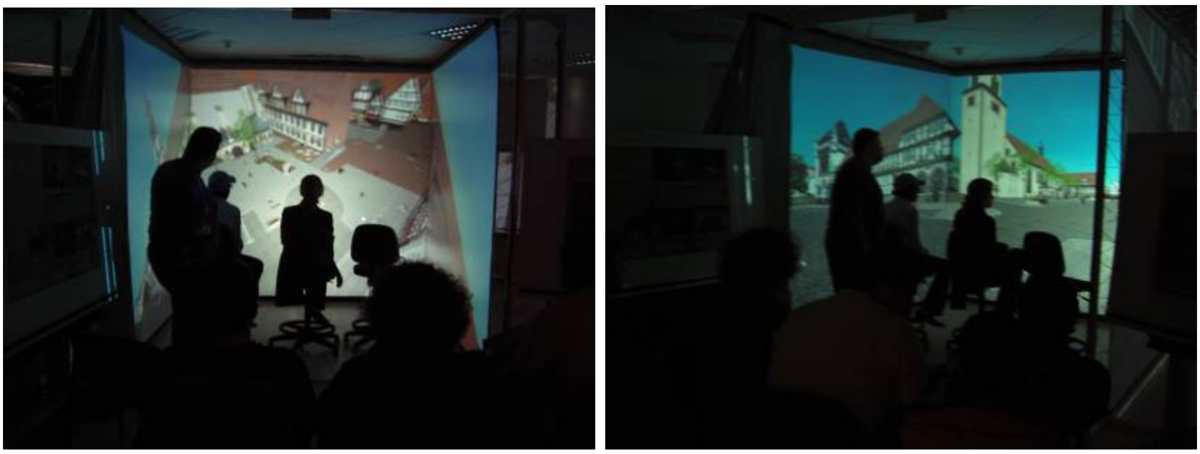


FIG. 8: The UAEU-CAVE as a Decision Support Environment for group discussions.

3.3 Alternating Design Environments

This approach is very similar to the previous setup except that the immersive sessions are more frequent. In this approach the architect works in a conventional non-immersive design environment and takes the design to the immersive environment at short intervals during the design process. Feedback from immersive sessions, though not directly linked to the designer's actions and decisions, can still influence the design development in the early stages of the design development (Fig. 9).

The approach has the following shortcomings:

- It requires a continuous movement from one environment to the other which interrupts the design workflow and leads to longer design periods to accommodate the immersive design sessions;
- In most cases it also requires converting the design from a CAD format to a format suitable for display in an immersive environment (Dobson, 1998), (Achten and Turksma, 1999), (Achten et al., 2001) which is sometimes associated with loss of information;
- The approach does not exploit the full potentials of the concept of immersive design since the formative phase takes part outside the immersive virtual environment and there is no immediate feedback from the walk-throughs; and
- The designer still has to deal with the limitations of traditional tools and CAD systems.

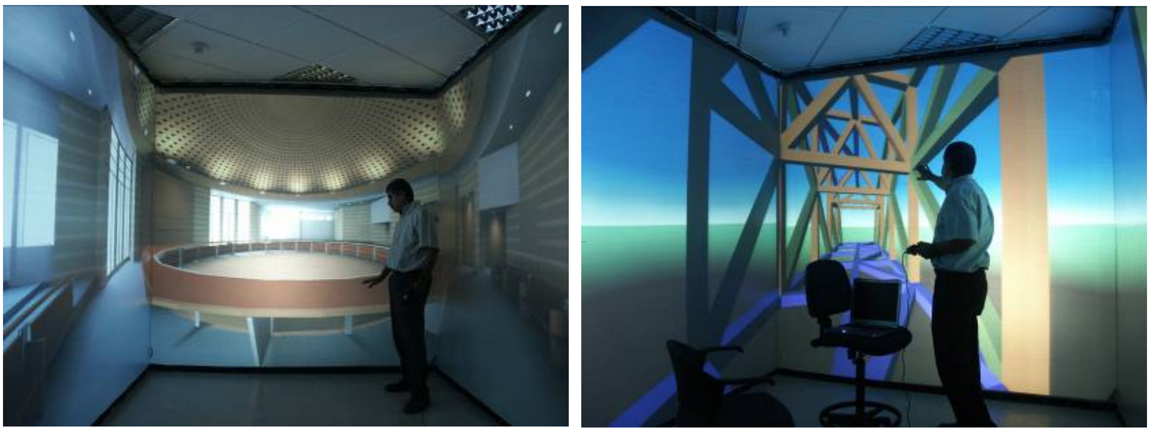


FIG. 9: The UAEU-CAVE as an Alternating Design Environment for exploration and obtaining feedback.

3.4 Immersive Design Environments

Immersive environments foster a sense of "being-in-the-world". They offer the designer a better perception of space. At the scale of a person within the building, the system can allow the designer to sketch in space while being inside that sketch. The designer's gestures can create walls, cut openings and adjust roofs. Floors and stairs can be added and subtracted according to the reaction and judgment provoked by the perception in an immediate and immersive fashion. The designer can examine details more intuitively with an easy-to-control viewpoint. Immersive Virtual Environments, which support this level of interaction between the designer and the object being designed, are still at an experimental stage of development. The following problems have been identified.

3.4.1 Availability of Tools

Most immersive virtual environments display 3D models using VR viewers or rendering engines which offer some tools to control navigation but no tools for creation and manipulation of objects. This is as if the designer enters the immersive virtual environment after leaving his powerful design tools behind. A few attempts to bridge this gap can be seen in the literature. VoxDesign, introduced by Donath (1999), and DDDoolz, introduced by Achten et al. (2000), both are voxel-based software environments which specifically focus at 3D sketch oriented creation of spaces with voxels and allow 3D sketching using a few commands without addressing any extra command structure through menu's or keys. Donath (1999) also introduced PlaneDesign which is a tool for the conceptual phase in the design process. It is space oriented making use of rectangular planes to describe room-like situations. Dobson (1998) and Coomans and Oxman (1996) proposed an approach based on a small library of architectural elements which is a conventional approach in current CAD systems. Using a pre-prepared library of 3D elements, architectural compositions are then produced. Other approaches are based on gesture recognition as a trigger to execute commands or control structured menus (Dorta and Perez, 2006).

All these solutions, however, do not offer the full modelling functionality of a conventional CAD system. As a result, the models created remain less sophisticated than those produced using conventional CAD and rendering software.

3.4.2 Scalability of Representation

Designing spaces and objects at the user scale inside the immersive environment is associated with some difficulties. Architects need to be able to view models in a self-selected scale, and be able to modify that scale to understand different types of design aspects. In a full scale immersive environment the designer's perception is restricted to the space where the designer is standing in the design. He loses the global view of the entire project. For example, pushing a wall to increase the width of a room could appear to be solving the problem of that narrow room but does not show if other problems are being generated on the other side of the wall.

3.4.3 Orientation and Way Finding

Immersion could also be a reason of disorientation. In real life situations people use 2D maps, signs and geographic positioning systems to navigate through real environments. In the immersive environment the designer needs similar tools.

3.4.4 Realism of Representation

While the perspective photo-realistic view of the design object helps in the design evaluation phase, this type of representation does not support conceptual design because it is too unambiguous and thus does not encourage idea generation.

3.4.5 Control of Proportions and Accuracy of Dimensions

Control of proportions and accuracy of distances and dimensions in the 3D space is more difficult in a perspective view in particular for distant objects.

3.4.6 Manoeuvrability

In a non-immersive design environment, scaled 2D representation such as plans and sections make many manipulation operations easy. For example, selecting several elements from one space at one end of the building, dragging them and dropping them in another space at the other end of the building is a common operation. In an immersive environment as in the real world some "physical" variables such as distance, time and visibility could become a burden for completing this simple operation. This would require selecting the objects, switching collision detection off, pushing the objects through doors, corridors, staircases, or other spaces over a long distance to the required destination. The problem becomes more felt the bigger and more complex the building is. This also creates a physical demand on the designer (pushing, turning, controlling, activating, etc.) To overcome such problems, concepts such as teleportation have to be developed to allow the designer to send objects or groups of objects from where he is standing to other locations in the virtual world. This requires developing a geographic information system so that the object arrives where the designer really wants.

3.4.7 Ergonomics

Immersive Virtual Environments are designed to immerse users in virtual worlds and most applications require being inside these facilities for shorter periods of time. Very little is known about the ergonomics of using such as design environments for prolonged periods of time. There are indications that prolonged use can develop strain and a reduction in productivity.

3.5 Hybrid Design Environments

In this approach Immersive Design and Non-immersive Design overlap. The designer takes his workstation with the conventional non-immersive design tools with him inside the immersive design environment (Fig. 10). During the design process he has the option to generate, manipulate and move objects in scaled 2D representations and thus save time and effort manipulating objects. He also has the option to generate, manipulate, and experience designs in full size 3D views for feedback and fine adjustments. The designer has the option to perceive plans, sections and layouts to get a global view and at the same time to explore space, volume and location in full size 3D views.

However, the smooth operation of this approach requires a software package built on top of a powerful CAD/modelling package with high functionality allowing the modelling package to display on multiple screens and to communicate with additional input devices such as wands. Such software is very much needed before virtual reality can significantly enhance the design process.

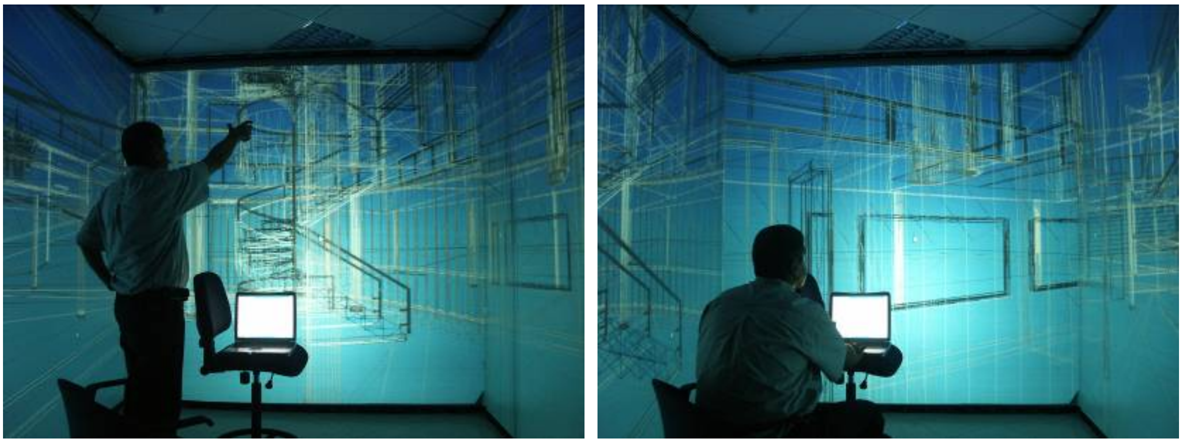


FIG. 10: The UAEU-CAVE as a Hybrid Design Environment for generation and manipulation and exploration of 3D objects with immediate feedback in full scale.

Propositions exist to sketch inside the virtual space in a non-immersive approach. Do (2001) introduced the VR Sketchpad which is a freehand 2D drawing pen-based interface (Fig. 11). It enables designers to simply make diagrams for spatial partitions such as walls, columns and furniture on a 2D floor plan placed on a digitizing tablet using a pen stylus. It then translates the sketch into VRML objects which are quickly displayed using a VRML viewer.

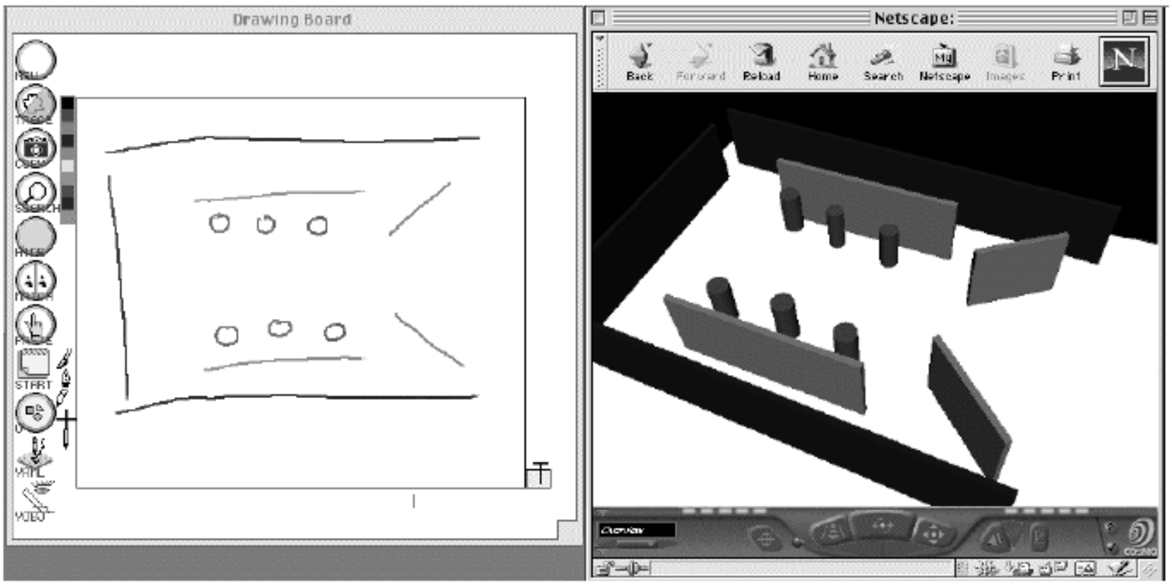


FIG. 11: The VR-Sketchpad system: Lines and circles of a freehand digital sketch are extruded to make a VRML model of walls and columns. Reference: Do (2001)

Dorta (2004) introduced the Drafted Virtual Reality (DVR) approach which was later enhanced to operate in an immersive environment (iDVR) (Dorta and Perez, 2006) (Fig. 12). Both approaches allow the VR representation to be enriched by a 3D sketching technique that closely resembles traditional 2D perspective developed by pen-on-paper using a cylindrical panoramic template in (RVD) and spherical panoramic template in (iDVR). This technique allows ambiguity while respecting scale and vision angles. However, the designer faces the challenge of drawing over a panoramic template where the reference lines are deformed. The result is also static so navigating in the 3D sketched space is not possible.

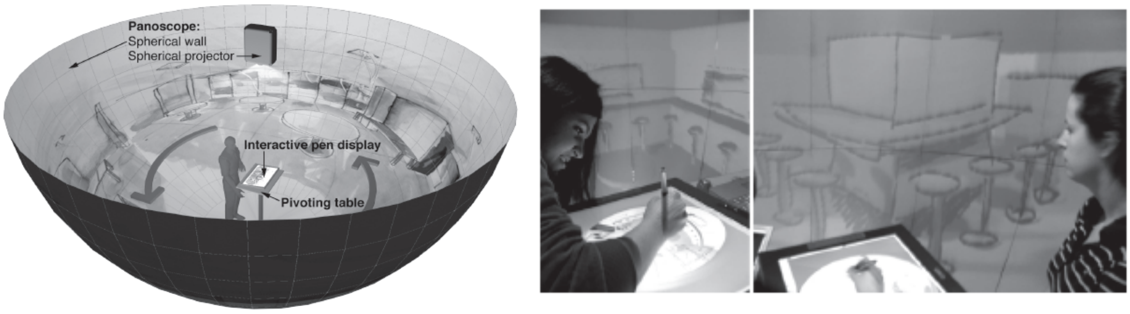


FIG. 12: The iVRD system allowing the immersive VR representation to be enriched by a 3D sketching technique. Reference: Dorta and Perez (2006)

3.6 Summary of Analysis

Table 1 summarizes the results of the comparison between different integration paradigms based on cognitive aspects. Table 2 summarizes the results of the comparison between different integration paradigms based on aspects of design workflow.

The comparison shows that Non-immersive Design Environments using CAD and 3D modelling software have some cognitive disadvantages but it also has many strengths such as a) a smooth design workflow, b) a powerful set of creation and manipulation tools, and c) some cognitive advantages. These strengths make non-immersive design environments more attractive than immersive design environments for practical reasons.

Using an immersive environment as a Decision Support Environment or as an Alternating Design Environment can provide a representation method that eliminates information encoding and decoding between 2D and 3D. This could be very useful in the cases of: a) decision makers who are not trained as architects or designers, b) less experienced designers such as students and c) experienced designers working on projects with complex forms and spaces. But these operation modes do not provide a smooth design workflow which makes these integration paradigms less attractive as a design environment for practical reasons.

The comparison shows that using an immersive environment as an Immersive Design Environment, although being considered by scholars for more than fifteen years, is still facing many obstacles that prevent it from providing a smooth design workflow. Although it has some cognitive advantages, it also creates other cognitive disadvantages. As a result it is less attractive as a design environment for practical reasons.

Looking at both cognitive aspects as well as on aspects of design workflow, it appears that using an immersive environment as a Hybrid Design Environment has many strengths that exceed the strengths of any of the other types of integration paradigms. But the comparison also shows that even hybrid design environments still have some inherited limitations. These limitations indicate the need of further development targeting: a) more tools to allow direct and intuitive control over the 3D design objects by natural movements of the hand, b) software that promotes creative thinking by not challenging the designer's initial mental images by requests of precision and set ideas in the early stages of design, c) software that encourages further discovery, exploration and generation of new ideas at the early phase of the design process by allowing ambiguity and avoiding the impression of precision, perfection and photo-realism, d) improved ergonomics to allow long working sessions.

TABLE. 1: Comparison of integration paradigms based on cognitive aspects.

	Non-Immersive Virtual Design Environments using CAD	Immersive Decision Support Environments CAD/ UAEU-CAVE	Alternating Design Environments CAD/UAEU-CAVE	Immersive Design Environments UAEU-CAVE	Hybrid Design Environments CAD/UAEU-CAVE
Reduces mental load by providing fluent transition from working in 2D to a 3D representation and eliminating information encoding and decoding allowing concentration on more advanced design problems.	Possible	Yes	Yes	Yes	Yes
Empowers visual thinking through stimulation and interactive understanding of space and place.	Possible	Yes	Yes	Yes	Yes
Formative phase takes place in an immersive virtual environment providing immediate feedback	No	No	No	Yes	Yes
Allows immediate, direct, and intuitive control over the 3D design objects by natural movements of the hand.	Depends on input devices	No	No	Depends on input devices	Depends on input devices
Composition is an experiential process immediately confronting the designer with the consequences of design decisions.	Possible	No	No	No	Yes
Supports the recursive nature of the design process through a fast turn-around of the creation-verification-correction cycle capturing the flow of concepts as quickly and naturally as possible.	Possible	No	No	No due to lack of tools	Yes
Promotes creative thinking by not challenging the designer's initial mental images by requests of precision and set ideas in the early stages.	Depends on Software	No	No	No	Depends on Software
Encourages further discovery, exploration and generation of new ideas at the early phase of the design process by allowing ambiguity and avoiding the impression of precision, perfection and photo-realism.	Depends on Software	Depends on Software	Depends on Software	Depends on Software	Depends on Software
Allows concentration on the design task rather than on the design tool and its interface (menus, commands, arrows, keyboard and mouse)	No	No	No	No	Requires further developm ent

TABLE. 2: Comparison of integration paradigms based on aspects of the design workflow.

	Non-Immersive Virtual Design Environments using CAD	Immersive Decision Support Environments CAD/ UAEU-CAVE	Alternating Design Environments CAD/UAEU-CAVE	Immersive Design Environments CAD/UAEU-CAVE	Hybrid Design Environments CAD/UAEU-CAVE
Allows shorter design periods and smooth design workflow by eliminating movements between both environments	Yes	No	No	No	Yes
Eliminates file format conversion and loss of information	Depends on software	No	No	No	Yes
Makes design tools available	Yes	Not in the immersive sessions	Not in the immersive sessions	No	Yes
Allows scalability of representation	Yes	Not in the immersive sessions	Not in the immersive sessions	No	Yes
Allows easy orientation and way finding	Yes	Not in the immersive sessions	Not in the immersive sessions	No	Yes
Allows control of proportions and accuracy of dimensions	Yes	Poor in the immersive sessions	Poor in the immersive sessions	No	Yes
Allows easy manoeuvrability	Yes	Poor in the immersive sessions	Poor in the immersive sessions	No	Yes
Ergonomics allowing long hours of work	Acceptable	Acceptable	Acceptable	Unknown	Unknown

4. CONCLUSION

None of the design tools discussed in this paper comes without shortcomings. Each medium has its strong and weak sides. By analyzing the problems of each medium it is possible to avoid the weaknesses and build on strengths to develop a more effective design environment than what is currently available in the practice. This design environment should have a positive impact on the development of design and its communication and understanding.

The paper identified the problems underlying perception of complex 3D objects when represented using traditional tools such as sketches and models. It also identified the problems underlying the inability to use CAD systems in the early, conceptual phase of the design process.

Virtual reality can support the early design process better than the conventional desktop based computer interfaces. It achieves this result by offering a higher interactivity and by its potential of presenting highly complex information in an easily understandable form. Despite its advantages, it still has problems that affect the design process especially in the first steps of the design process. The discussion shows that immersive virtual environment tools are still in a crude state which inhibits the effective use of VR systems in architectural design tasks. Experimental work has been limited to building models that are less sophisticated than those produced using traditional CAD and rendering software.

The findings suggest a hybrid design environments as a new paradigm combining, on one hand, non-immersive design tools such as sketches, models and CAD, and on the other hand, immersive design tools such as virtual reality. This paradigm merges both types of tools and suggests a new design environment that utilizes the high functionality of non-immersive tools with the capacities of the immersive tools without replacing one or the other.

Hybrid Design Environments are still at an experimental stage of development and much progress needs to be done. In addition to the efforts to overcome the limitations mentioned in this paper, other efforts are also underway to develop immersive virtual design environments that are much smaller than the UAEU-CAVE.

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