Augmented Sketches and Models: The Hybrid Ideation Space as a Cognitive Artifact for Conceptual Design

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Abstract

Actual 3D modeling tools and virtual reality systems are affecting creativity during the early stages of the design process. They are often used as communication tools (passive) rather than ideation tools (active) because of their interface complexity. Among other reasons, this is due to abstract commands that demand precision in the execution and always suggest inconsistent default values. Being adapted to this task, ideation is still being done through analog tools such as sketches and physical models, which are direct ways of representation with the ambiguity, inaccuracy and abstraction of their intuitive depictions. Even with generative parametric solutions, common designers are not expressing their actual intentions but are inspired by digital propositions that always request computer savvy users to master them. Moreover, actual VR systems are either hard to set or too complex to be used as ideation tools since they force the user to be focused more on the system rather than on the design task itself. This situation is hindering the representational conversation (Schön, 1983) and cognitive artifacts (Visser, 2006) during the design process. This paper presents the implementation of a new innovative system: the Hybrid Ideation Space. This system allows users to sketch and make models all around them in real-time and in scale using a digital tablet and an immersive projection device. Stemming from hybrid techniques we developed earlier, the Hybrid Ideation Space allows the designer to use traditional techniques augmented by the advantages of a virtual environment, which provides a sense of immersion and presence.

Keywords: ideation; immersive sketching, immersive models; design cognition; human-computer interfaces.

1. Detours of Technology in Design

In order to express a thought, we need direct channels to let our mind exteriorize it. We use gestures, verbal, graphical and physical representations, and with language, we can give a specific meaning. The better we master the use of these channels and language, the better we express our ideas. During design, we also need to master straight channels to express design ideas. Graphical and physical representations have always been the channels that helped designers to express and exteriorize concepts, and the computer is one technology intended to refine or assist them.

The problem is that technology has made designers lose the directness of the mind, expressed through words and gestures when engaging in "design thinking", forcing the mind to focus on the tool as a channel rather than on the design itself. In addition, we must consider that humans are limited in their information-processing capacity to allow design (Simon, 1999). In order to respect its logic and accuracy (or computer language) (Kalay, 2004), the discourse of current human computer interfaces demands designers to feed the system with information that is not even figured out in the designers' mental images. Interfaces are asking for their own data without considering the designer's expectations and uncertainties regarding the project itself (Lebahar, 1983). Some computer interface commands have so many preconceptions about how the design process should be that they affect decision-making and ultimately limit the use of computers to a passive role. Therefore, computers have become, in practice, an instrument of rhetoric instead of design, developing and communicating in their own particular ways ideas conceived using more traditional, direct and intuitive channels: analog freehand sketches and manual physical models.

The time spent by users configuring and dealing with computer requirements also deters them away from design thinking to digital representational or programming model thinking. Again, this eventually leads designers to opt for other, more traditional tools for ideation. Even specialized users can find analog design tools more efficient and intuitive when taking on this important task of the design process. In addition, designers who are not computer specialists will never become so, since they don't believe they will be able to design with them but rather use them just to represent or communicate their ideas.

How many error messages can we try to understand, digits that we need to input, syntax to respect, trials and errors, "do" and "undo" to achieve a digital representation consistent with our mental image? The time it takes to forget it or to stop the creative flow, as when we stop writing a poem because our pen is empty. As analog design tools, we need digital instruments that can at lease respect the way we design and how abstract, ambiguous and inaccurate, vague design ideas are in the designer' mind before they can be exteriorized (Goel, 1995; Gross & Do, 1996), especially during ideation in several design disciplines like architecture, interior and industrial design (Stacey & Eckert, 2003). CAD research has proposed several ways in which to use the computer in design, but in practice, they are not being used, partly because research software has not been commercialized yet, partly because these solutions are so complicated or so abstracts that they fall short of the scope they were intended for. Computers are aiding in technical drafting, photorealistic renderings and presentations, detail development, accuracy, data management, construction information, selling ideas or convincing clients, but, are they used to make better designs?

2. What Happened with Ideation in CAD?

In the beginning of CAD, the "D" stood for "drafting", for it was designed specifically to help in the creation of technical drawings. Later, CAD, or Computer Aided Design, became CDD or CCD (Developing or Communicating Design), because only already existing designs made using analog intuitive tools could fit the requirements of the system. In design, there is a gap before resorting to CAD, and this step has been done using the same traditional techniques used since the Renaissance. Physical models and freehand sketches allow the designer to make ideation easily, but they have several drawbacks (Lansdown, 1994; Moon, 2005): they consume time, present deformations, scale and proportions problems, and are difficult to transform. Even further in the process, designers use these traditional tools to modify their ideas before starting the complex process of altering the 3D model, because it is governed by technology and it has its own language.

Ideation is not made in CAD because these systems are destined for computer specialists, draftsmen or modeling operators instead of design specialists. In fact, this situation is also due to the fact that some CAD systems came from other disciplines or were conceived for other tasks, like engineering, manufacturing, animation or film making, that are well adapted for later steps of the design process. This represents a challenge for designers since the complexity of the interface imposes a different logic (Raskin, 2000), closer to computer programming, on their way of working, even with actual GUIs.

Approaches of generative geometry have been proposed for ideation (Serrato-Combe, 2005; Johson, 2006). However, this paradigm calls for savvy users that, in the end, become passive, randomly inspired by computer solutions. In addition, they are making abstract programming to graphically represent ideas proposed by the system. This is like a one-way reflective conversation (Schön, 1983), a monologue by the computer. It is not because forms seem new, dynamic or interesting, that we can consider them as good design. Only if they are governed by the designers' principles, and the needs of space and function are considered in these solutions, could they be relevant. Are we now proposing a CID or Computer Inspired Design? And still, is this meant for regular designers or for computer specialists? Who does ideation?

3. Communicate or Design?

Early in CAD research, a distinction had been made concerning ideation as an active process and communication as a passive task, regarding design (Marshall, 1992). Of course, these elements are themselves related and, communicating between oneself and others is important during design. But how do ideas arise and what are the processes that rule creativity? We need reflective communication tools as direct channels of expression in order to be active in design. When these tools are affecting this directness, we only communicate or represent partial ideas in a limited way, and we become passive vis-à-vis design.

In practice, computers had inadequately taken this passive role during the process, being generally very active in the final steps, being reserved for the realization of construction documents and presentation of information. Active reflective tasks in design were mostly reserved for traditional analog manual actions.

4. Cognitive Artifacts

Reflective materials as direct channels to express ideas are essential in design. Tools that permit unintended changes (talk-backs), graphical or physical, can help and stimulate reflection and engage “conversation” with the idea to achieve better ideation

(Schön, 1983). The construction of internal or external representations with these kinds of materials and tools among other cognitive activities are considered as cognitive artifacts of design (Visser, 2006). They allow dialogue with mental images being directly exteriorized, and making design decisions.

Even if we do not need to exteriorize mental representations for simple geometry in order to understand or modify them (Bilda & Gero, 2005), adapted visualization tools are needed for complex shapes and configurations. External representations enable operations on themselves that are more difficult or impossible to perform on internal ones and this facilitates the discovery or exploration of alternatives (Do et al., 2000). Just by juxtaposing various drawings and mock-ups, designers compare different possibilities and see the consequences (Do et al., 2000). When the designer does not have the experience to mentally visualize and resolve design problems, these cognitive artifacts are essential to the ideation process. Furthermore, according to Zhang and Norman (1994), external representations activate perceptual processes, whereas internal representations usually activate cognitive processes. One type of internal representations is “percepts” that are mental representations resulting from perception (Visser, 2006). In addition, making ideation in a collaborative design team demands cognitive artifacts adapted to different visualization abilities, and pre-acquired representational skills so as to use these artifacts actively and intuitively.

The above can enable designers to take decisions “in situ” directly in front of their ideas, as knowing-in-action described by Schön (1987) and respond to the problem through improvisation by reflection-in-action (Schön, 1983).

5. Augment Instead of Imitate: Hybrid Techniques

Several digital tools imitating traditional design tools transform the computer into a “funnel” for design information treatment. And as mentioned before, despite the advantages offered by the machine, human computer interface approaches are not well adapted for ideation. The main goal of hybrid (analog and digital) design tools is to take advantage of each mode and not only transit in one direction: towards digital. In this way, designers and computers can treat design information when and where they are most competent.

Moreover, considering the advantages of traditional tools as cognitive artifacts of design, one approach will enable computers to improve traditional tools, instead of simulating or imitating them. Neither sketchy-like renderings made from accurate primitives, nor perfect rapid prototypes share the same advantages of cognitive artifacts as real freehand sketches or rough handmade physical models. However, computers can immerse us into representations while avoiding scale and proportion problems. What's more, performance capabilities can be used for real-time execution, where digital information is applied to transformations, undo, copy and paste capabilities, difficult to achieve with manual instruments.

Several hybrid processes and techniques have been proposed to merge digital and analog conception tools for use in design (Bermudez & King, 1998; Fowler & Muller, 2002; Jabi, 2004). These solutions range from 3D scanning preliminary scale models and other depictions during the design process, to digitalizing handmade sketches to be used as input for the system (as digital sketches or triggering commands)

(Schweikardt & Gross 1998; Jung et al., 2001; Do, 2001; Jatupoj, 2005; Brito et al., 2005). In many cases, manual actions have been acknowledged in interface design for their relevance on “psychomotor perception” and their intuitiveness (Furness, 1987). We, however, have taken another approach to hybrid design techniques in design.

In order to avoid the funnel effect of digital systems during the design process, we foresee hybrid techniques which take the information out of the system so as to treat it with the skills and abilities already possessed by the user, and then put it back into the system so as to take advantage of its digital capabilities. It is a continuous back-and-forth between analog and digital realms, where actions are integrated into each representation. While users attend to the limits of one mode, they choose the more adapted one to represent and solve the design problem. As a consequence, traditional manual analog tools are augmented by the power of the system and not only re-presented or imitated, giving another kind of hybrid design tools.

5.1. Drafted Virtual Reality (DVR)

We started with the DVR technique (Dorta, 2004), where the designer can use non-immersive virtual reality techniques to be inside a virtual environment modeled and rendered using freehand sketches. The DVR technique begins by using basic modeled shapes (primitives) to represent proportions or referential elements to allow the computer to build a cylindrical 360° panoramic graphical template that serves to be sketched over. A custom or a generic template, as those used to draw axonometric or perspectives can be printed out to be worked with different freehand techniques, better mastered by the user. This printed template can also be sketched over directly using a digital tablet. Subsequently, the panoramic sketch is corrected in a normal perspective using QTVR, having as result that the computer screen becomes a window to a manually sketched virtual world (See Table 1).

5.2. Immersed Drafted Virtual Reality (iDVR)

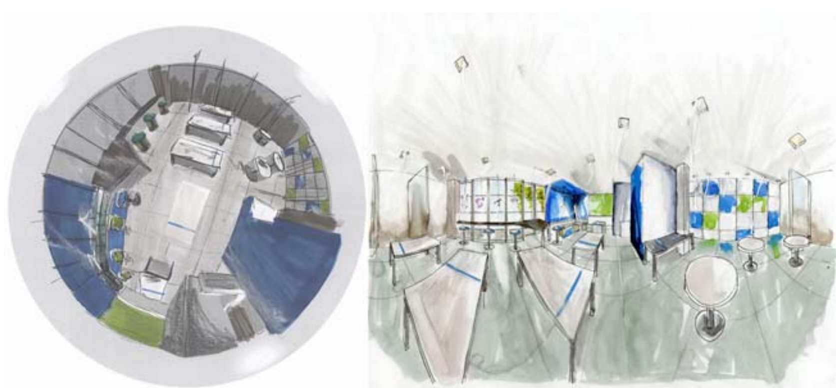

Figure 1: Spherical versus Cylindrical panoramic sketches.

Subsequently, we proposed an immersive version of the DVR technique (Dorta & Pérez, 2006a), where the user can sketch all around him/her in real time and at normal scale. This time, starting from some basic shapes or a grid, the system proposes a spherical 360° panoramic graphical template using a rendered reflective sphere inside a wire-frame or shaded 3D model. This template is then displayed in a spherical immersive projection system like the Panoscope (Courshesne, 2000). Using a digital tablet, the designer can sketch over the template while the sketches are projected in real-time over the spherical surface of the immersive system, which corrects the perspective and displays spaces and shapes in the user's normal scale (See Table 1) (Figure 1).

	Advantages	**Problems**
DVR	Personal expression of sketches compared to the standardization of computer renderings; Inexpensive technique with respect to cost and computer processing; Maintains abstraction, ambiguity and inaccuracy of representations for ideation; Uses already mastered sketching skills; One panoramic view represents all the perspectives of a space; Strive for design expectations.	No switching from the drawing to the 2D scanner and then to the QTVR visualization in real-time; Well adapted to rendering spaces, but not objects or individual shapes; There is an adaptation time for beginners to sketch with panoramic cylindrical deformations (several minutes).
iDVR	Same as DVR, as well as: Real-time visualization of corrected and not deformed images during sketching; Real scale display; The sense of presence inside the virtual sketched space; Permits collaborative work up to 4 users; Non-intrusive immersive system which requires no special glasses or tracking devices; Better perception of space and errors.	Even if objects and shapes can be sketched, there is no 3D stereo vision or parallax; No possibility of walkthrough or rotating forms; The space can only be modeled from fixed viewpoints, not allowing real-time navigation inside the sketch; Scale limitations given while the designed space is smaller than the immersive projection system (16' diameter); Expensive spherical projection system (Panoscope); An adaptation time of 5 to 10 minutes for beginners to sketch over spherical panoramic deformations.
HM	Richer geometries agree with design expectation, compared to premature design decisions taken by 3D computer modeling in ideation; Easy mastering and visualization of complex shapes; intuitive modeling using the scanned model as a 3D template; Intuitive manual modeling without the complexity of computer 3D modeling interfaces; Use of previously acquired and mastered physical modeling techniques; Assists in ideation using RP models as matrices for shape explorations.	Proportion errors for scale models; RP malleable materials; Cost of RP models; Time spent on RP production and 3D scanning; 3D scanning techniques and the resolution of small physical details.

Table 1. Advantages and problems of previous hybrid techniques

5.3. Hybrid Modeling (HM)

In addition, we proposed a HM technique to work with physical models and master complex shapes (Dorta, 2005; Dorta & Pérez, 2006b). This technique lets the user go back and forth between manual and digital models using Rapid Prototyping (PR) and a 3D scanner to transit between analog and digital modes. Starting from rough hand-made physical models, the designer can create shapes quickly using malleable materials such as Styrofoam. Then, the model is scanned in 3D and applied as a template to form the virtual shape without using the conventional required orthogonal views as background. Once in the digital mode, all the digital capabilities can be exploited to make copies, play with symmetry and make transformations, such as scale, and explore Boolean operations. Later, this digital model is printed using RP techniques, and the prototype becomes a matrix used to continue design explorations manually. This cycle can be repeated frequently at the beginning of the process, integrating the control of manual actions in the process and mastering proportions in the creation of complex shapes (See Table 1).

6. The Hybrid Ideation Space

In order to combine all the advantages of these hybrid techniques for sketching and modeling in ideation, while avoiding some of their drawbacks, we implemented the Hybrid Ideation Space (HIS). This system is based on a new spherical mirror model to input and output information: an inexpensive immersive projection procedure as output inspired by the Panoscope and planetarium projection systems (Bourke, 2005) adapted to these kinds of applications, and a spherical image capturing method from scale models as input. The HIS combines real-time immersive sketching capabilities with physical model making in one system, allowing the user to carry out ideation by manual action on immersive graphical and physical representations (Figure 2 and 3).

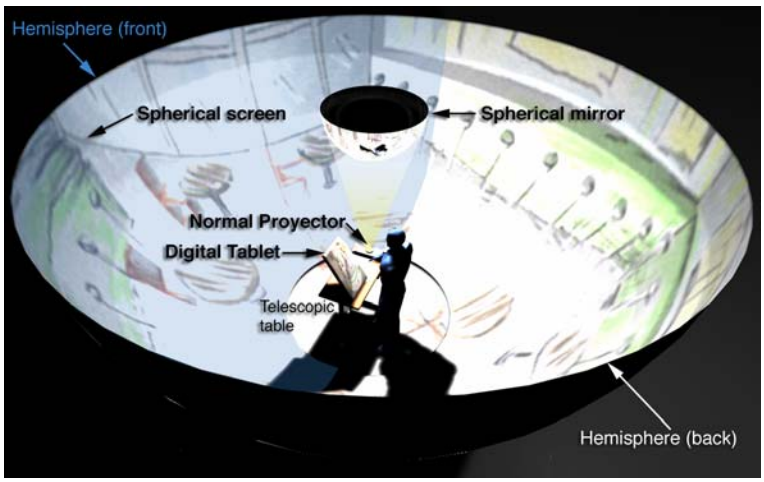

Figure 2: Hybrid Ideation Space.

6.1. Immersive Sketching

The spherical graphical template is constructed using a ray-trace render of a reflective sphere in a basic 3D model containing very elemental shapes or primitives. This gives proportions, which become graphical guides for sketching. This template can be used with any painter or image editing software (Corel Painter™ or Adobe Photoshop™) via a digital tablet (Wacom Interactive Pen Display™) as an input device connected to any powerful laptop. The computer has two displays, one for the digital table and another for a conventional projector. These two display devices are mounted on different supports in order to avoid shaking the projected image by manual actions. The digital tablet is supported by a telescopic table permitting work seated or standing, the latter being better for immersion. The projector, placed at table level so as not to disturb the user's gaze and supported by an individual tripod, points upwards (Figure 3).

Figure 3: Equipment used in the HIS.

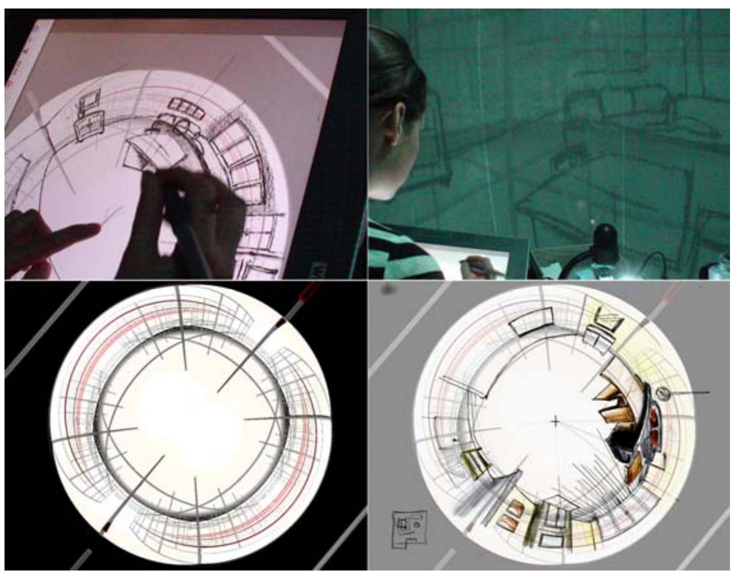

Figure 4: Immersive sketching in action – Spherical graphical template – Spherical sketch.

The full-screen image is inverted and projected over a semi spherical mirror mounted on the ceiling and centered on the projector. As a result, the spherical image is reflected over a semi spherical screen of synthetic fabric mounted in the ceiling or on a support and also centered on the spherical mirror. The minimum diameter of the HIS is 16' for 8' of height, allowing up to 4 users in the space. The projected spherical image is subsequently corrected, and the user can see all around her/him in a normal perspective, in real-time, while drawing with the digital pen. To sketch all the surrounding space, the user can move around the two sides of the rectangular table and sketch both hemispheres (Front & Back) (Figures 2 and 4).

6.2. Immersive Model Making

In order have improved model making and the hybrid modeling technique combined with sketches during ideation, we use a small high definition camera (1080i) for better image resolution and a small mirror-ball as a spherical panoramic lens. The camera is attached vertically to the table's edge and the mirror-ball is centered in front of its lens. As simple as the immersive projection system discussed earlier, this apparatus is now used not as output but as input. The camera captures a deformed spherical panoramic image reflected by the mirror-ball placed at eye level of the scaled physical model. The real-time monitored HD image is then displayed by the same laptop to the immersive projection system. In this way, as users move and modify the scaled model, they can see a normal scale immersive projection of the model all around them. In order to solve contrast problems, the model is sometimes placed in a small scene placed on the table, controlling color background and lighting (Figure 5).

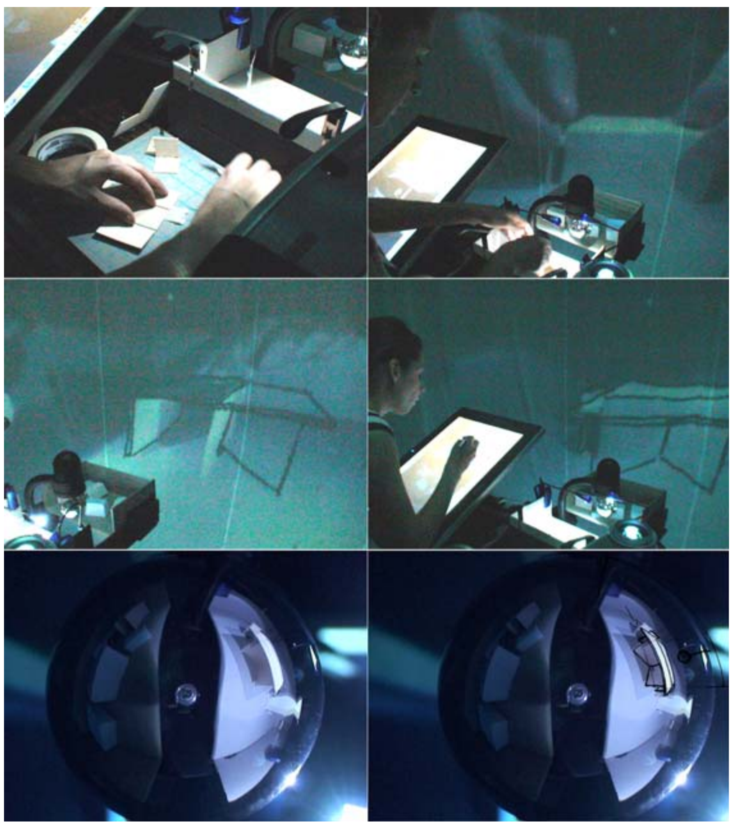

Figure 5: Immersive model making in action – Captured image – Spherical sketch over the image.

In order to combine immersive model making with sketches so as to explore graphically the physical modifications to be made, the monitored HD image is capture by the system and used as a background layer in the painter software. The user can therefore sketch over a graphical spherical panoramic template easily produced by the scale model and the mirror-ball (Table 2).

	Advantages	**Problems**
HIS	The same as for the iDVR and Hybrid Modeling techniques, as well as: Inexpensive spherical projection system; Elimination of the Gulliver effect inherent to scale models, which deform the user's point of view (the user becomes a giant); The sensation of presence, being inside or in front of real size models; Sketching over real scale model images and image editing for rapid decision making; Rapid life-sized visualization of modifications made on the scale model; Combination of freehand sketches with manual actions during physical model making; Intuitive and interface-less interaction (only manual actions) with graphical and physical representations.	The same as for the iDVR and the Hybrid modeling techniques, with the exclusion of: The Gulliver effect; The cost of the spherical projection system.

Table 2: Advantages and problems of the HIS.

7. HIS as a Cognitive Artifact for Conceptual Design

As demonstrated above, the HIS is presented here as a cognitive artifact for conceptual design because users can amplify graphical and physical reflective traditional channels of representation (as freehand sketches and physical models), allowing easy conversation within representations and between them. In order to achieve this, it maintains abstraction, ambiguity and inaccuracy of these augmented depictions, which are also adapted to the designer's initial mental image during ideation. It is an interface-less device, because designers can confront ideation with manual actions and already known and mastered representational skills. They can focus on the conceptual design task rather than dealing with system requirements or abstract commands. Designers working in teams and using this system seem more occupied by design considerations than by computer and software constraints, compared to current CAD and VR systems.

Moreover, by using the HIS designers deal with physical constraints with the augmented models as lighting, gravity and textures of materials, exploring and discovering ideas that are easily achieved by manual actions. Rough models become symbols as found by sketches (Goel, 1995; Lebahar, 1983) or physical cognitive artifacts changing the meaning and allowing reflection-in-action. This fact makes the designers' perceptual process of being involved in the creative activity, one of the important goals of the Bauhaus' teachings in basic design. Hence, the HIS may sustain mental representation as the "percepts" during design.

The HIS is proposed to fill the gap in ideation before the use of CAD and VR systems during the design process. This system, however, still has some problems which will need to be addressed in future work. Furthermore, several cognitive and usability tests have been made using this system involving different design disciplines and levels of design expertise, that will be the subject of articles in the near future.

8. Future work

In order to improve better communication between groups of designers using the HIS, we have proposed the use of laser pointers as visual markers on the immersive projection. After this experience, we are looking forward to develop a laser pointer image capture application, as used with flat displays (Cavens et al., 2002). This will allow initial sketching using a laser pointer over the spherical display. This could help in drawing without the spherical deformation and in the construction of the template, since the dexterity and the psychomotor interaction of the pen on the digital tablet for freehand sketching are not possible with the laser pointer at this time. Also, we are expecting to implement OpenRT (Open Ray-Trace) techniques to render in real-time reflective spherical images and to use the sketches and physical models made on this system as guides for 3D modeling. This will allow designers to insert this kind of representation into any 3D modeling software in order to improve the initial ideation, and fulfill later steps of the design process.

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References

Bermúdez, J., & K. King. (1998). Media Interaction and Design Process: Establishing a Knowledge Base. *Proceedings of the ACADIA Conference, Digital Design Studios: Do Computers Make A Diference?*: 7-25. Quebec: Association for Computer-Aided Design in Architecture.

Bilda, Z., & Gero, J. S. (2005). Do We Need CAD during Conceptual Design? *Proceedings of the CAAD Futures Conference*: 155-164. Vienna: Computer Aided Architectural Design Futures.

Bourke, P. (2005). Spherical mirror: a new approach to hemispherical dome projection. *Proceedings of the 3rd international conference on Computer graphics and interactive techniques in Australasia and South East Asia*: 281-284. Dunedin, New Zealand.

Brito, T., Fonseca, M. J., & Jorge, J. (2005). DecoSketch: Towards Calligraphic Approaches to Interior Design. *Proceedings of the eCAADe Conference, Digital Design: The Quest for New*

Paradigms: 665-670. Lisbon: Education and research Computer Aided Architectural Design in Europe.

Cavens, D., Vogt, F., Fels, S. S., & Meitner, M. (2002). Interacting with the Big Screen: Pointers to Ponder. *Proceedings of the ACM CHI Conference*: 678-679. Computer Human Interaction.

Courchesne, L. (2000). Panoscope 360. *Proceedings of the Siggraph Conference*: New Orleans.

Do, E. Y.-L., Gross, M. D., Neiman, B., & Zimring, C. M. (2000). Intentions in and relations among design drawings. Design Studies, 21:5, pp. 483-503.

Do, E. Y.-L. (2001). VR Sketchpad. *Proceedings of the CAAD Futures Conference*: 161-172. Eindhoven: Computer Aided Architectural Design Futures.

Dorta, T. (2004). Drafted Virtual Reality: A new paradigm to design with computers. *Proceedings of the CAADRIA Conference*: 829-843. Seoul: Computer Aided Architectural Design Research in Asia.

Dorta, T. (2005). Hybrid Modeling: Manual and digital media in the first steps of the design process. *Proceedings of the eCAADe Conference, Digital Design: The Quest for New Paradigms*: 819-827. Lisbon: Education and research Computer Aided Architectural Design in Europe.

Dorta, T., & Pérez, E. (2006a). Immersive Drafted Virtual Reality: a new approach for ideation within virtual reality. *Proceedings of the ACADIA Conference, Synthetic Landscapes – Digital Exchange*: 392-402. Louisville: Association for Computer-Aided Design in Architecture.

Dorta, T., & Pérez, E. (2006b). Hybrid modeling: revaluing manual action for 3D modeling. *Proceedings of the ACADIA Conference, Synthetic Landscapes – Digital Exchange*: 304-316. Louisville: Association for Computer-Aided Design in Architecture.

Fowler, T., & B. Muller. (2002). Physical and Digital Media Strategies for Exploring “Imagined” Realities of Space, Skin and Light. *Proceedings of the ACADIA Conference, Thresholds – Design, Research, Education and Practice, in the Space Between the Physical and the Virtual*: 13-23. Pomona, California: Association for Computer-Aided Design in Architecture.

Furness, T. (1987). Designing in Virtual Space. In *System Design: Behavioral Perspectives on Designers, Tools, and Organization,* eds. William, R., & Kenneth, B.127-143. New York: North-Holland.

Goel, V. (1995). *Sketches of thought*. Cambridge, MA: MIT Press.

Gross, M., & Do, E. (1996). Ambiguous Intentions: a Paper-like Interface for Creative Design. *Proceedings of ACM UIST Conference*: 183-192. Cambridge: User Interface Software Technology.

Jabi, W. (2004). Digital Tectonics: The intersection of the physical and the virtual. *Proceedings of the ACADIA Conference, Fabrication: Examining the Digital Practice of Architecture*: 256-269. Cambridge, Ontario: Association for Computer-Aided Design in Architecture.

Jatupoj, P. (2005). Sketchboard: the simple 3D modeling from architectural sketch recognition. *Proceedings of the CAADRIA Conference*: 3-22. New Delhi: Computer Aided Architectural Design Research in Asia.

Jung, T., Gross, M. D., & Do., E. Y.-L. (2001). Space Pen: Annotation and sketching on 3D models on the Internet. *Proceedings of the CAAD Futures Conference*: 257-270. Einhoven: Computer Aided Architectural Design Futures.

Johnson, J. (2006). Complexity as a Creative Force in Design. *Proceedings of the ACADIA Conference, Synthetic Landscapes – Digital Exchange*: 510-517. Louisville: The Association for Computer-Aided Design in Architecture.

Lansdown, J. (1994). Visualizing Design Ideas. In *Interacting with Virtual Environments*, eds. L. MacDonald and J. Vince, 61-77. Toronto: Wiley.

Lebahar, J.-C. (1983). *Le dessin d'architecte. Simulation graphique et reduction d'incertitude*. Roquevaire: Éditions Parenthèses.

Kalay, Y. (2004). *Architecture's New Media*. Cambridge: The MIT Press.

Marshall, T. B. (1992). The Computer as Graphic Medium in Conceptual Design. *Proceedings of the ACADIA Conference, Computer supported design in architecture, Mission, Method, Madness*: 39-47: Association for Computer-Aided Design in Architecture.

Moon, K. (2005). *Modeling Messages: the architect and the model*. New York: The Monacelli Press.

Raskin, J. (2000). *The Humane Interface: new directions to design interactive systems*. Boston: Addison Wesley.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. New York: Basic Books.

Schön, D. A. (1987). *Educating the reflective practitioner*. San Francisco: Jossey-Bass.

Serrato-Combe, A. (2005). Lindebmayer Systems – Experimenting with Software String Rewriting as an Assist to the Study and Generation of Architectural Form. *Proceedings of the eCAADe Conference, Digital Design: The Quest for New Paradigms*: 615-621. Lisbon: Education and research Computer Aided Architectural Design in Europe.

Visser, W. (2006). *The Cognitive Artifacts of Designing*. Mahwah: Lawrence Erlbaum Associates.

Schweikardt, E., & Gross., M. (1998). Digital Clay: Deriving Digital Models from Freehand Sketches. *Proceedings of the ACADIA Conference, Digital Design Studios: Do Computers Make A Diference?*: 202-211. Quebec: Association for Computer-Aided Design in Architecture.

Stacey, M., & Eckert, C. (2003). Against ambiguity*. Computer Supported Cooperative Work*. 12:2, pp. 153-183.

Zhang, J., & Norman, D. A. (1994). Representations in distributed cognitive tasks. Cognitive Science, 18, pp. 87-122.