Chapter 10:

Conclusions

I have argued that superimposing physical media and the digital medium to create new design tools and materials would have cognitive, motor, and emotional advantages for designers over the current desktop GUI. It would also remedy the frequent need to print and digitize that exists in the current side-by-side work environment. At the conclusion of this work, I am confident that superimposing physical media and computation would create more human-centered interfaces.

Combining tactile and spatial qualities with the CAD interface would include these advantages to the designer:

- **Cognitive:** The necessity to process understanding of three-dimensional forms from a reduced version of one sensory input, i.e., only vision in a two-dimensional plane, would be eliminated.
- **Motor:** Efficient and skilled motor control would be easier with increased sensory feedback, particularly touch.
- **Emotional:** Pleasurable feedback to the senses, which can motivate and inspire, may increase creativity, skill, and technique.
- **Practical:** The need to constantly digitize and print may be reduced.

As one example of superimposing, the Illuminating Clay prototype successfully combines advantages of physical and advantages of digital representations. The physical clay model enables the designer to quickly understand complex three-dimensional forms, because he or she can create and manipulate them by hand, while moving about and seeing (and feeling) the results of his or her actions in a physical three-dimensional space. The projected graphics from the analysis algorithms provide the designer with feedback as to how making formal changes in the landscape geometry such as slope or aspect, might influence complex dynamic effects, such as shadow-casting or drainage. By inserting Illuminating Clay into my taxonomy of physical and digital media qualities (Table 4, below) suggests that Illuminating Clay retains more useful qualities than either realm separately.

Qualities	Physical	Digital	Illuminating Clay
tactile	+	-	+
olfactory	+	-	+
spatial	+	-	+
ambiguous	+	-	+
persistent	+	-	+
real-time	+	0	+
physically transformable	+	-	+
logically transformable	-	+	-
ephemeral	-	+	0
explicit	0	+	0
representative of space	0	+	0
fast	0	+	0
intelligent	-	+	+
precise	0	+	0
visual	+	+	+
aural	+	+	+
reworkable	0	+	0
copyable	0	+	0
portable	0	+	-
(totals balance out)	6	6	8

Table 4: The ratings suggest that a quality is present (+), not present (-), or in between (0).

10.1 Experiments with Illuminating Clay

The evidence from the user experiments with Illuminating Clay substantiates that, compared to current practice with existing CAD systems, IC brings some of the advantages of computation to the beginning phases of design without losing the tactile, spatial advantages of a physical medium. It does this by enabling the designer to easily rough out a design concept, while making the process more informed by supplementing the designer's eyeball analysis with objective analysis. Illuminating Clay also facilitates communication among designers by allowing them to utilize a physical model—which is easy to gather around, comprehend, and point to—but have the added fluid ability to try out various what-if scenarios and get immediate rough analysis of those options. Below is a more detailed summation of the findings of the experiments.

10.1.1 Findings

Fundamental Advantages and Disadvantages

Five fundamental advantages to Illuminating Clay were evident from the research:

1. **Illuminating Clay allows a designer to easily rough out a concept.** Although initially, a small amount of confusion existed over how to interpret the graphics, subjects found the low-resolution feedback useful for understanding the given site and roughing out a solution.

2. **Illuminating Clay makes the process more informed.** The designers' intuitions about the forms they were creating with the clay were confirmed by the feedback, and they could come to decisions easier and with more confidence. Subjects felt more certain that they were falling within the constraints of the design problem.

3. **Illuminating Clay facilitates communication among designers.** It did this beyond what a physical model does by supplementing human-to-human interaction with immediate visualizations that were more accurate than could have been sketched by hand. Subjects felt empowered with a better capability to express ideas on the fly to other designers and nondesigners.

4. **Illuminating Clay creates a real-time digital model of a physical model.** Although the digital model may not be of high quality (it is a "cloud of points" typical of three-dimensional scanners), the time and cost of digitizing and/or printing in the early design phase could be reduced.

5. **Illuminating Clay can impact learning.** By providing more varied representations of static landscape forms and dynamic effects, student subjects became more familiar with the site of the class project.

One fundamental disadvantage was evident from the research:

1. **Illuminating Clay presents the risk of "over-engineering."** It tended to keep the designer more focused on the physical constraints, taking him or her away from focusing on aesthetic concerns. Designers tended to explore the various algorithms of Illuminating Clay, which resulted in considering more of the practical problems that might arise with their solution. Just the presence of Illuminating Clay implicitly shifts focus from aesthetic to practical concerns. One student suggested:

   I think a lot of time could be saved if the two [design and analysis] were combined. Quite possibly, better decisions could be made. At the same time, perhaps it would be introducing the over-engineering of site planning, which could be a problem. In much the same way that engineers have controlled road systems with the over-engineering requiring such wide roadways and such, being overly conservative could occur.

Short-Term Limitations

Numerous short-term limitations were highlighted by the research. These will likely be altered with anticipated advancements to the technology or by putting more resources into a subsequent prototype.

1. **Unclear feedback:** The design of the graphical feedback needs more refinement. It is too dense, complicated, and confusing at times. (See *Type and Amount of Feedback* in section 10.2 "Lessons Learned About Tangible Interfaces.")

2. **Choice of algorithms:** The selection of landscape analysis algorithms in Illuminating Clay needs to be modified, eliminating some and adding others that are more standard to landscape architecture and planning.

3. **Small scanning area:** The size of the scanning area, which is limited to an 18- x 18-inch square, is much too small for most landscape models, although it is appropriate for very small sites or quick sketches.

4. **Confusing mouse interaction:** It is awkward to interact with a mouse to activate specific algorithms and set parameters for those algorithms. For these experiments, a standard mouse was used (although a wireless mouse was intended but arrived late). Even so, the awkwardness arose not from being tethered by a mouse cord but from losing the curser that needed to travel between all three display windows. Ironically, although working with the clay model is so direct and hands-on, inputting commands to the software is more difficult than working in a standard GUI due to the various locations of the projected GUI windows.

5. **Little or no natural light:** Like most computer displays, Illuminating Clay works best in a dark or dim room. Indeed, the projection is invisible in a well-lit room. Balancing the light needed to see the physical model and the darkness needed to see the computer projections is tricky.

6. **Difficulty of making clay models:** Illuminating Clay requires physical models of some kind, preferably with a malleable material like clay. Not all landscape designers or site designers have the skill to build clay models, and having to do so by hand is substantial work.

7. **Immobility:** The prototype is completely immobile. This is inconvenient in that the designer must always be transporting potentially heavy or delicate models to the "Illuminating Clay room" from his or her own workspace.

10.1.2 Limitations of the Research

Evaluating Illuminating Clay proved challenging for several reasons, and as a result, I acknowledge some limitations to my methods.

1. **Size of the study:** This was a small study.

2. **Consistency of variables:** The students in the class were familiar with the goals and shortcomings of Illuminating Clay, and the two operators of IC each had a very different style of interacting with the subjects.

3. **Learning curve of the user:** The commands to operate the prototype were easy to learn, but Illuminating Clay was not necessarily easy to integrate into a personal design process.

4. **Choice of an appropriate task:** Real-life projects are long and have no control project. Short tasks lack reality but can be tightly controlled. Including both types of tasks appeared to be the best solution, but it involved compromises as well.

10.2 Lessons Learned About Tangible and Augmented-Reality User Interfaces

Regardless of the limitations of the research and in addition to the specific findings of the experiments, several fundamental issues were highlighted by this research that have implications for a broader scope of superimposed, tangible and augmented reality interfaces for CAD systems These issues include the ability to accommodate appropriate scale, the right type and amount of computational feedback, and the necessity or not of real-time feedback. Each is discussed in more detail below.

10.2.1 Appropriate Scale

Architects design using representations of buildings or tracts of land. To work, they need to scale these large projects to a reasonable size. What is reasonable? Not so small that the necessary elements are imperceptible and not so large that they cannot fit on a tabletop is what usually defines the limits, although there are exceptions. Large, complex projects sometimes require much larger models to be built. A variety of scale becomes important as the design process progresses from overall concepts to more-specific details. The original massing of forms for an idea might have been drawn on a dinner napkin, while toward the end of design development, a detail of a hinge could take up an entire piece of paper. Tolerances in scale vary between architects and landscape architects. Hasbrouck suggests that "…as landscape architects, our tolerances are much different. Whereas in architecture, you might be working up to 1/32 of an inch, depending on what material you are using, we might deal with six-inch tolerances in some instances. We also operate at a range of scales, from backyards to regions."

In the Illuminating Clay experiments, the tract of land used for the long-term project presented some scale challenges. Because the site was 200 acres, it needed to be scaled to 1:60 (1 inch = 60 feet) to create a model of it that was approximately $2^1/_2$ x 4 feet. This was a reasonable size for the class to build, store, and move around the studio as needed. However, at that scale, the proposed buildings were less than $^1/_2$ inch each—not a size to effectively work with the design of the housing development. Although the class needed that 1:60 model of the entire site to design the golf course, they would have benefited from another model at a larger scale for just the housing development footprint (which took up only about one-sixth of the land). But given the time constraints of the class, the second model was not made. As it was, the 1:60 footprint of the housing development did not fit under the scanner of Illuminating Clay all at once, anyway.

The scanning area of Illuminating Clay is restricted to 18 x 18 inches, a decision based on hardware and software constraints and tradeoffs. Students attempted to work with the model by moving it to various positions under the scanner. This worked only part of the time, because the scanner depends on detecting at least one corner of the table to calibrate itself. Obscuring the corner seemed to set off a series of confusing responses from the system, which then took several minutes to return to a normal state.

10.2.2 Type and Amount of Feedback

What is the right type and amount of computational feedback in a tangible interface? Feedback occupies our attention. How much feedback helps in the creative process and how much hinders, or brings the focus of the designer away from formal issues to the specifics of, say, slope or drainage? Should solutions to this question focus on type of graphics in the feedback, the intensity of the graphics, resolution of graphics, or all three? Should numbers, even approximate numbers, be provided in the feedback, or should it consist of only abstract, graphical representations?

In the experiments with Illuminating Clay, two qualities of the feedback were evident. First, it was somewhat confusing to understand. This may have been due to the density of the projected graphics or to the nonstandard style and color of some of the representations. Second, it was bright, busy, and attractive. This made for an attractive demo, or first impression, but may not be the best solution for productive work.

The question really becomes: What should occupy the designer's attention? In the experiments, the subjects' attention and time spent on a task were altered by the presence of Illuminating Clay. This could be a positive result, bringing attention to a neglected aspect of a task (such as drainage of a site) that is difficult to predict in detail without the aid of the computer. Or it could be a negative result, causing the designer to get distracted by the desire to make the physical constraints work, and not focus on his or her aesthetic concept.

10.2.3 Real-Time or Not

Real-time interaction is when the response or feedback from the computer is not noticeably delayed, i.e., it feels instantaneous. Gestures and movement, in particular, require real-time computer response in order to feel natural. For example, in a VR (virtual reality) system, when you step forward, you expect the graphics to respond instantly to your movement to reflect your forward movement. If, instead, they take several seconds to "catch up" with you, the system is disorienting and, in the end, ineffectual.

During the development of Illuminating Clay, it was a priority to get real-time response from manipulations of the clay model. We on the development team believed that otherwise, the system would be disorienting and ineffectual, like in the VR example above. Tradeoffs with the resolution of scans and graphical projections were made in order to keep the response time to just under two seconds, which we decided felt close enough to a real-time response.

As it turned out, the experiments showed that users didn't use the feedback in real time. Instead, they tended to manipulate the clay and then stop and look. The amount of time in between concentrated "lookings" changed with the particular task, but it begs the question: What is the frequency of looking, when considering specific tasks or specific kinds of feedback? One looks in real time while shaping clay in order to orient the hand and tools, and to see how the clay is changing. That looking likely varies (I'm guessing from my own experience) between being focused and defocused. So the looking is not just defined by frequency but also by type.

Information such as the analysis feedback that was coming from Illuminating Clay appeared to require a different type and frequency of looking from the kind that occurs when manipulating a clay form. It did not require the defocused, continuous looking that manual control or form-making does. Instead, the type of feedback that Illuminating Clay provides required periodic, focused check-ins. The designers used the computer feedback to confirm or adjust their own eyeball analysis, then would work without the benefit of the computer feedback until they wanted to confirm their intuitions again. I estimate that the frequency of looking ranged from a couple of seconds to at least ten minutes. And rather than being evenly consistent, the pattern of looking could be described as a declining curve, frequent at first then progressively less over time for a specific task such as determining and carving the driveways. Usually at the beginning of the task, there would be a few minutes of prolonged looking as the designer contemplated the analysis feedback for the first time.

The fact that having hands on the clay altered the feedback may have influenced the pattern described above. With the current configuration of Illuminating Clay, it is almost impossible to manipulate the clay and get accurate computational feedback simultaneously. A discrete update switch, that is either automatic when no hands are detected, or manual may be a good solution.

10.3 Next Steps

Although this research was not an evaluation of the Illuminating Clay prototype, the use of it in my experiments revealed its advantages as well as some limitations. It is evident that Illuminating Clay is successful in its broad concepts but requires numerous small modifications should it be taken to another level of refinement. Some of the limitations have obvious solutions, such as adding desired analysis algorithms. Other solutions are not so obvious and may require several iterations of implemention and testing to get them right. Rather than comprehensively rebuilding the prototype and then doing a large evaluation, I believe it would be more informative to conduct discrete user tests on specific issues. In Section 10.3.1, "Discrete Tests Specific to Illuminating Clay," I make some suggestions for those tests.

It's tempting to want to leap into building other prototypes. However, in developing new prototypes, there is often not enough time or resources available to thoroughly investigate what makes sense for users. Prototype evaluations are often driven by the need to publish or to secure funding and approval to push that particular prototype to another level. In order to further the general development of tangible and augmented reality interfaces for CAD systems, I believe it would be valuable to conduct some small discrete tests that are designer-centric rather than prototype-centric. These could be tightly controlled and thorough. In Section 10.3.2, “Discrete Tests General to Tangible and Augmented-Reality User Interfaces,” I make some suggestions for those tests.

10.3.1 Discrete Tests Specific to Illuminating Clay

Clarifying feedback

Design different styles, colors, and intensities of computer graphics projections for several of the most-used analysis algorithms and see if they influence comprehension of the feedback.

Influencing focus

(1) Investigate if the feedback can become more peripheral and still have value, rather than demanding so much of the designer’s attention. (2) Try some algorithms that have aesthetic influence, rather than just analysis of practical features.

Investigating the need for real time

(1) Try different rates of refresh of the computational feedback. (2) See what designers would choose if could they set refresh rates themselves. (3) Try having refresh stop if hands are detected by the scanner.

10.3.2 Discrete Tests General to Tangible and Augmented-Reality User Interfaces

Comprehending three-dimensional forms

Present a three-dimensional form represented in various media: a CAD wire-frame model, a CAD rendered model, a physical drawing, and a physical model. Determine which medium is easiest to comprehend and recall the shape of.

Manipulating three-dimensional forms

Have subjects build a three-dimensional shape to specification with various media (as noted above). See how each medium influences the speed, accuracy, process, and results. Try the same test, but have subjects modify an existing shape.

Comparing vision and touch

Have subjects solve a design problem with one sense eliminated, either vision or touch. Look for subjects' efficiency and ways of compensating for the missing sense in the design process.

Influencing emotional state

Test to see if the emotional state of a designer is influenced by his or her use of different media. (Emotional states influence creativity, confidence, and memory.)

10.4 Summary

The sense of touch and space is fundamental to most three-dimensional designers such as architects. In our highly visual culture, we seem to have forgotten how important touch is in the design process. Design is often characterized as a highly conceptual activity. Early CAD researchers believed it could reside completely within the untouchable, ephemeral space of the computer, much like visualizing ideas in your thoughts. Who can design like that? Frank Gehry, one of the most notable architects working today, does the opposite: His design process is heavily dependent on touch and physical materials.

This is not to suggest that vision is not important. It is, in fact, the combination of vision and touch in a three-dimensional space that allows humans to excel at comprehending and manipulating tools and materials. It is these three elements—vision, touch, and three-dimensional space—that are crucial to design. To eliminate two of these elements—touch and three-dimensional space—and have only vision, as in the GUI, handicaps the designer. A GUI is appropriate under certain circumstances, such as text editing or, in some cases, creating measured drawings, but as the only interface to CAD, it severely limits how and when computation can be used in the design process.

To think that humans could or would want to design exclusively in a disembodied environment was a profound misunderstanding of human nature. Our educational system provides an informative parallel. Much of the last 200 years of education consisted of rote memorization from written or spoken words. During the past 30 years, influenced by the work of many, including Piaget and Papert, education has become multisensory. This includes doing field research, looking at artifacts, conducting experiments, building projects, singing songs, writing poems, writing stories, wearing costumes, and eating food, along with the traditional activities of reading books and writing reports. Substantial research suggests that this kind of educational environment is more effective because it *embodies* ideas rather than presenting them as abstract, disembodied events or facts.

I believe that it is time to engage the body with computer interfaces for CAD systems. This has particular relevance to the human-computer interface community, with the increasing interest in and popularity of ubiquitous computing, augmented reality, and tangible interfaces. All humans depend on their sensorimotor systems to interact with the physical world. Although it is possible that creative designers have a greater tactile and visual sensitivity that has drawn them to their profession, it is certain that some of what has been learned in this thesis can be generalized beyond the design community to all humans.