

The Illuminated Design Environment: A 3-D Tangible Interface for Landscape Analysis

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M.A., Architecture, 1999, Cambridge University

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the Requirements for the degree of Master of Science in Media Arts and Sciences at the Massachusetts Institute of Technology.

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Abstract

This thesis outlines the reasons for the visual emphasis in current computer aided design interfaces. It describes the potential advantages of computer interfaces that allow a greater degree of physical interaction and it describes previous work that has attempted this goal. It describes the implementation of the *Illuminated Design Environment* as a platform that combines the advantages of physical and digital representation for the purposes of physical form design.

The representational needs for the domain of landscape design are discussed and the implementation of *Illuminating Clay*, a tangible interface for landscape analysis, is described. The system is evaluated in the context of a landscape design class held at the MIT Department of Urban Studies and Planning, 2002. The thesis concludes with a discussion of the wider impact if the approach taken on the field of landscape design and computer aided design in general.

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Chapter 1.



1. A Visual Vision

“If the creative process is to be assisted by the computer the machine has to act reciprocally and simultaneously to produce a smooth dialogue. For an urban designer this conversation must be graphical. His entire training, practice and design process are graphical: a progression from doodles to finished plans.”

[Negroponte, 66]

In his 1966 master’s thesis Nicolas Negroponte presents his vision for the future of computer aided design. He opens by describing the sophistication and sensitivity of the human visual system. He highlights the fact that, even in times of rapid technological advance, we are still dependent on the eye as one of our most powerful senses for understanding. He argues that only by making use of our inherent ability to perceive the world in visual terms can the computer aid in the process of design.

This thesis aims to show how this visual vision failed to recognize the role of tangible manipulation in the design process. While our eyes may be organs of understanding our hands are organs of creation. Only by combining the inherent ability of both our hands and our eyes can the computer meet its full potential as a design aid.

1.1 The Rise of the Visual Interface

The current emphasis on the visual design interface is the result of a complex history involving varying research trends, the rise of particular technologies and the influence of the broader cultural context. Early research efforts into graphical displays were extremely compelling and inspired others to explore ways of visualizing computational output. Sutherland’s *Sketchpad*, [Sutherland, 63], Newman’s *Markup*, [Newman, 75] and Baudelaire’s, *Draw* [Baudelaire, 79] were early attempts to mimic the visual directness of conventional pen and paper. Ivan Sutherland [Sutherland, 63], Romney [Romney, 70],

Gouraud [Gouraud, 71], Phong [Phong, 71] and Watkins [Watkins, 70] were among the first to pioneer developments 3-dimensional form rendering and animation techniques. Negroponte's background in architecture naturally led him and others in the *Architecture Machine Group*¹ to explore techniques for the graphical visualization of buildings and spaces.

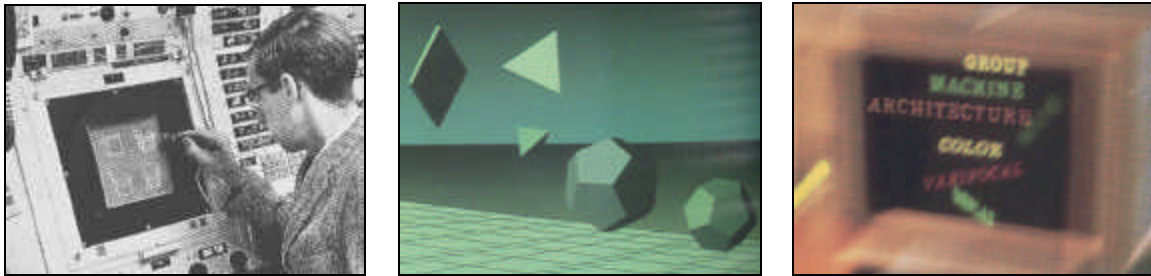


Figure 1.1 The 1963 SketchPad (left), an early Phong rendering (middle) and a visual display from the Architecture Machine Group (right).

The available technology had a critical impact on the development of the visual interface. The television had already been developed as a means for visual display by the time computers were powerful enough to make use of them as computer monitors. The monitor offered a means to display practically any image by varying pixel values. Supporting the rise of the visual display, the culture that had invented and propagated the television was well poised to accept another televisual window onto an emerging computational environment.

The rapid development of the visual output is in surprising contrast with the lack of development in input interfaces over the same period. Just as Negroponte recognized the primacy of the eye in understanding information so too did early computer engineers understand the role of the hand in manipulating it. Punch cards, and later the keyboard allowed users to express their intentions through physical manipulation. The keyboard proved extremely useful as a means of allowing text based input and defined the early

¹ The group that emerged from the MIT Department of Architecture and eventually became the MIT Media Lab.

days of human computer interaction as a primarily text based relationship². The invention of the mouse [Engelbart, 1970] allowed the movement of a physical object in space to be mapped to a digital cursor on the screen. Combined with the added physical interaction of the mouse ‘click’ a set of standard interaction techniques and metaphors were developed that forms the basis of today’s Graphical User Interface (GUI).

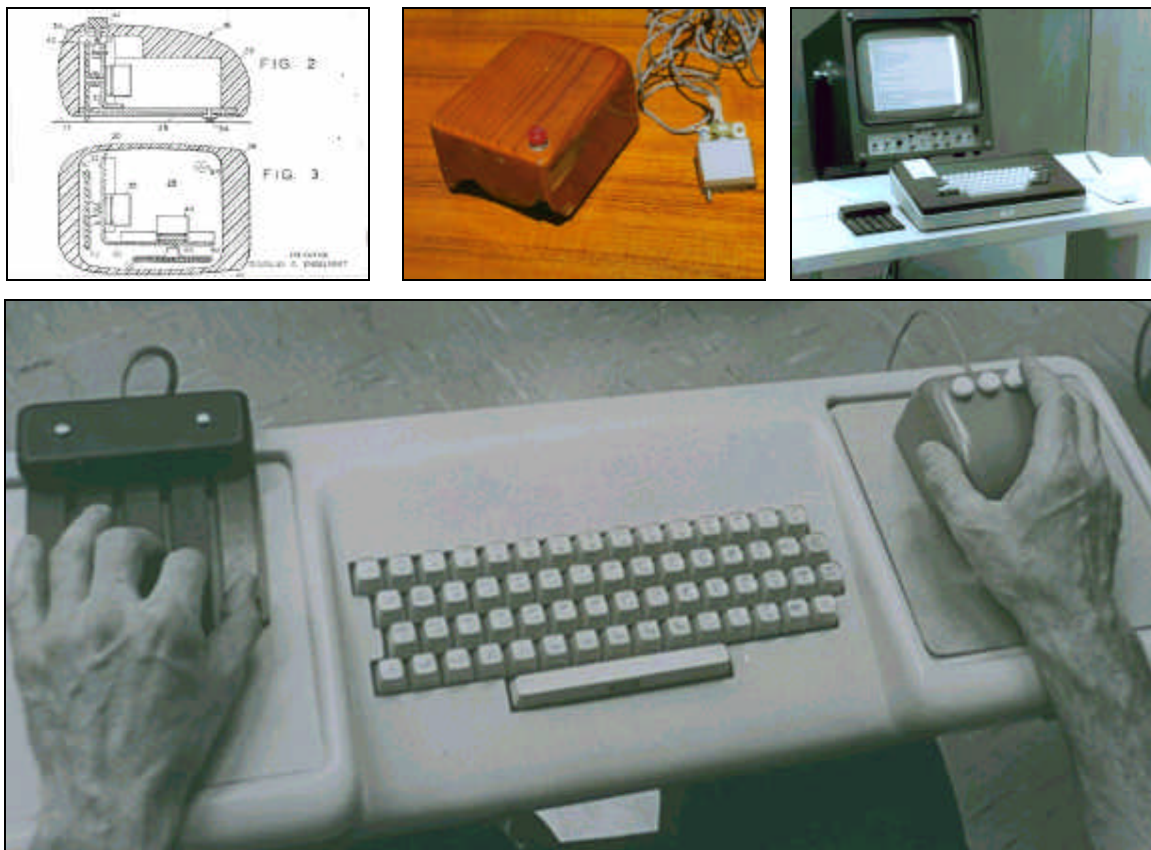


Figure 1.2 Construction diagram of Doug Engelbart’s mouse (left), the mouse as built (middle), an early workstation from the 1960s (right) and an early keyboard interface (bottom).

² It is interesting to note that the common QWERTY keyboard, still used today, was originally designed to have the least efficient layout, preventing key collisions on the first mechanical typewriters. While there is no longer a technical requirement for this arrangement, social and market inertia means that this historical vestige lingers on in the design of the contemporary computer interface.

Apart from the major breakthroughs of the keyboard and the mouse there have been few far reaching advances in the way in which users input their intentions. Perhaps this is owing to the fact that there is a fundamental cost in the development and sharing of physical input devices in contrast to the ease with which non-physical software can be developed to run on the standard platform of the graphical user interface.

This brief synopsis shows how the contemporary computer interface is the result of a complex history not of a clear or intentional design. As such, the vestiges of the past limit the potential of computers today. This is particularly evident in the fields of industrial, architectural, urban, landscape and other areas of physical form design.

1.2 Digital Representation of Physical Form Design

The adoption of computational aids for physical form design has been dramatic. The non-physicality of computational representation has led to vastly more efficient means of production, manipulation, reproduction and dissemination of representational models. 3-dimensional visualizations can be easily produced in unlimited variety of simulated materials. They can be reproduced with out cost and shared with distant collaborators. They can be understood in quantitative terms and constructed at accuracies that far surpass the tolerances of physical models. In addition the digital model can be used as an efficient means to produce working drawings. Perhaps, the most significant aspect of digital representation is that it can allow the designer to test a given model under simulated conditions and alter it accordingly.

Given all of these benefits, the current interface to digital representation is still fundamentally limited in a number of critical ways that make it particularly awkward as a to use during the early stages of design conception.

Lack of Intuitive Control

Computational representations offer a high degree of quantitative control through numerical data entry. The mouse offers some ability to adjust forms on the screen. However, neither of these forms of input provides a simple means of generating and manipulating initial forms.

Lack of Spatial Understanding

The visual output of the standard GUI means that any digital representation is understood through a visual medium alone. While perspective, fly through, elevation and cut-away views can help to describe the model in visual terms, this format makes it difficult to fully understand more complex spaces and relationships.

Lack of Scale

Owing to the lack of physical scale in digital representation there is no limit to the level of detail that can be added to a digital model³. While this scale-less quality may be useful for final representation, it can make it difficult for the designer to focus on the broader issues of a design since they are required to address all scales of representation simultaneously.

Lack of Materiality

Digital representations are not subject to the same physical forces or properties as physical models. This lessens the possibility for the discovery of design solutions through ‘happy accidents’. As Focillon expresses it:

“Man is a prestidigitator who takes advantage of his own errors and of his faulty strokes to perform tricks with them; he never has more grace than when he makes a virtue out of his own clumsiness.”

[Focillon, 34]

³ No limit to the level of detail apart from the physical limitation of computational memory.

Lack of a Collaborative Medium

The quality of collaboration between designers and between designers and their clients is critical to the outcome of a design process. While computer networks can serve to allow many members to collaborate on a design team the current GUI interface is not conducive to a face-to-face collaborative process since it has been designed around a single user model. Furthermore, the user is generally trained on expert software packages making it difficult for non-experts to play a creative role in a highly specialized design process.

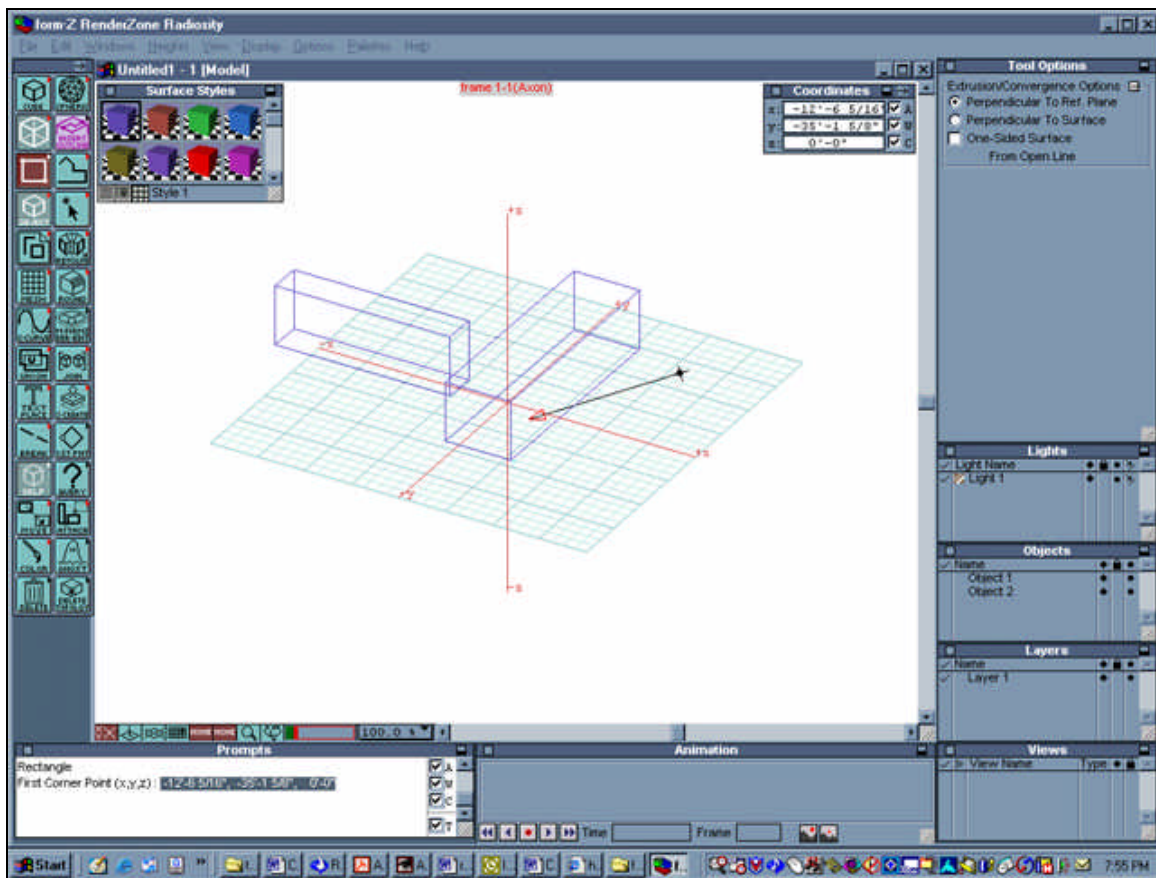


Figure 1.3 A screen shot from a conventional CAD package that makes use of the Graphical User Interface.

1.3 Physical Representation In Physical Form Design

Physical models are still widely used to aid in physical form design to make up for the fundamental limitations of digital representation.

Improved intuitive control

The physical nature of physical models means that they can quickly and easily be constructed and modified directly with the hands.

Improved spatial understanding

Physical models offer the user an intuitive understanding of complex geometries and physical relationships that are difficult or indeed impossible to describe through visual means alone.

Finite scale

The physical model can help the designer by constraining the modeling process to within certain bounds of scale.

Material Affordance⁴

Physical materials can be used to suggest possibilities through their inherent physical affordances – moldable clay, springy metal, foldable paper, translucent plastic can be useful physical design aids.

Physical Constraint

The physical model can help the designer to think about a problem through the act of physical manipulation. Kirsch [Kirsh, 94] refers to the value of *epistemic* action as the physical manipulation of a form to aid the discovery of an as yet unknown but desired result that is found through the physical modeling process. Since the physical models can

⁴ *Affordance* is a word coined by JJ Gibson [Gibson, 77]

be manipulated in a far more intuitive and direct manner than digital representations they provide a powerful medium for design exploration.

Improved collaborative medium

Finally, the physical model can be manipulated by collaborators or reworked by non-specialists. It can form the focal point to conversation, communication and experienced simultaneously by multiple viewers and so can aid in the process of collaborative design.

1.4 Model Model Makers

Three renowned architects serve to give concrete illustrations of how physical models have been used as powerful aids in the design of buildings.

Frank Lloyd Wright was said to discover many of his building forms through the manipulation of a set of wooden *Froebel Blocks* [Mitchell, 01]. The vocabulary of limited forms gave the architect a structure in which to *discover* formal relationships that were both rhythmically and functionally satisfying.

The German engineer, Frie Otto also used models to help in the design process. He used the natural behavior of physical materials subject to gravitational, air-pressure and tension forces to find building forms. By using the natural behavior of materials as a means of *calculating* form Otto was able to produce highly efficient structures that would have been impossible to generate without such physical aids.

The contemporary architect Frank Gehry was trained as a sculptor and works intuitively using physical models that incorporate materials such as cardboard, hot-glue and found objects. These rough maquettes result in extremely complex sculptural geometries that are later engineered. The level of control over form offered by working in this highly physical way has allowed Gehry to break with rectilinear forms of conventional architecture and maintain an intuitive and expressive quality at an architectural scale.



Figure 1.4 Lloyd-Wright's Froebel blocks (left), Hanging tension structures in Otto's studio (middle) and Gehry's sculptural approach to form making (right).

1.5 Merging Digital and Physical Representation

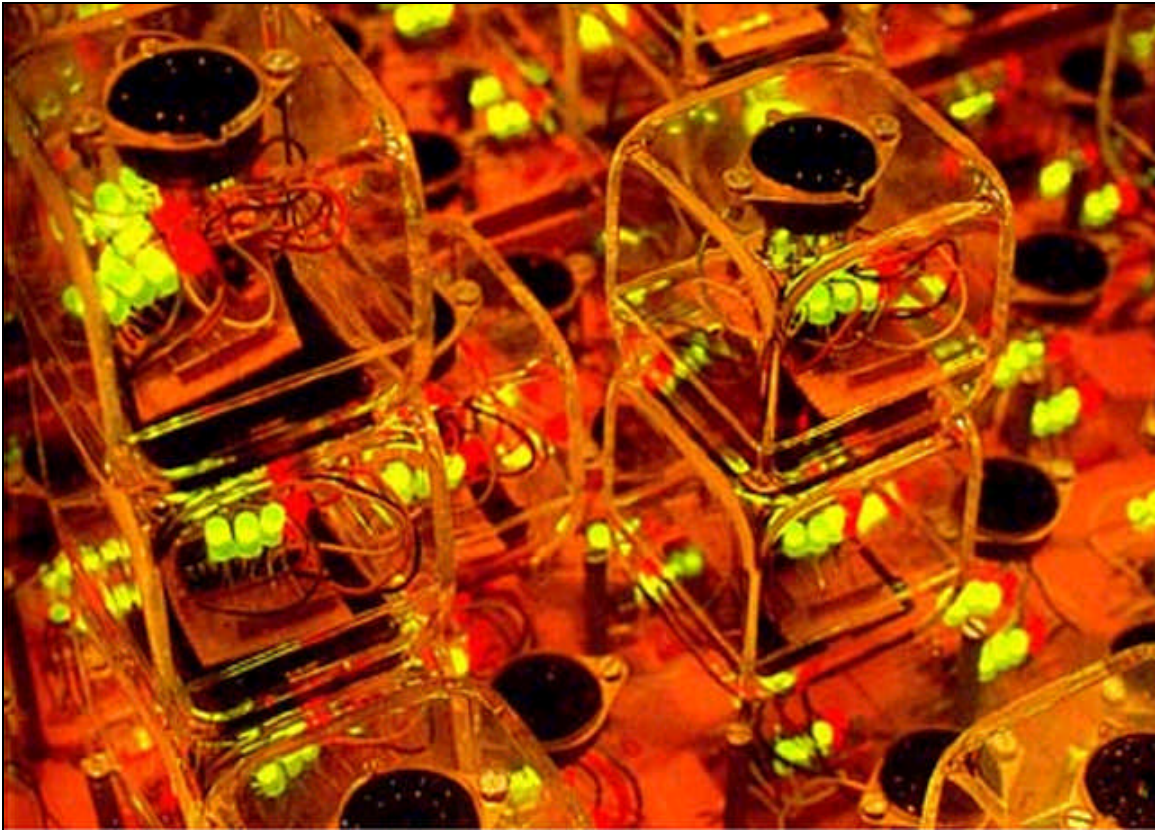
How then can we provide a computer interface that provides qualities of both physical and digital representation; an interface that allows design solutions to be discovered through constraints, calculated through natural material behavior and expressed through intuitive control while still bring the analytical power of computation to bear. As Marshal states:

"If a medium can provide an element of harmony between the creator and his/her ideas then it will aid the design process. If on the other hand it continually distracts the designer by calling attention to itself unnecessarily, it will certainly impede the design process."

[Marshal, 1992]

This thesis proposes a new form of computer interface that aims to combine digital and physical forms of representation into a single design environment. It is hoped that this approach will offer a means for physical form designers to work simultaneously with both physical and digital media and expand Negroponte's purely visual vision for computer-aided design.

Chapter 2.



2. TANGIBLE ALTERNATIVES

The idea of combining digital and physical representation in a single design interface is not a new concept. John Frazer was amongst the first to suggest the approach:

“Intelligent modeling systems could be used in design in any application where visualization of a three-dimensional form, coupled with some form of feedback, would increase the impact of a demonstration, particularly in examples which involve some form of growth or decay or where natural laws can be demonstrated...in architecture with growth and decay and the development of settlement patterns.”

[Frazer, 79]

2.1 Manipulable Hardware

Frazer and others at the *Architectural Association*⁵ developed re-configurable physical models with imbedded microelectronics as a means for exploring spatial relationships in architecture. In his description Frazer explains how this approach could influence the designer/client relationship:

“The interaction between designer and client could be improved by allowing the client to be more involved in the design process by using physical models which he could directly alter. There are applications in architecture and engineering where the three dimensional complexity of the problem would make the technique [of physical construction] valuable to the designer.”

[Frazer, 81]

Frazer built two early systems: the *Gridded System* and the *Universal Constructor* [Frazer, 81]. The *Gridded System* used a gridded baseboard into which flat components representing the walls of an architectural structure could be placed and then polled by the

⁵ A leading architecture school in London, UK.

computer. This system allowed models of partitioned spaces (such as those found in a standard office buildings) to be constructed relatively quickly by hand and then viewed using conventional CAD software. The system was limited in only allowing the exploration of two-dimensional relationships that conformed to the dimensions of the gridded baseboard.

A more sophisticated model was the *Universal Constructor*, a set of clear *Plexiglas*® cubes that could communicate through each of their six faces with any adjoining cubes. This system allowed forms to be constructed in three dimensions and again viewed as digital models using conventional software.

Frazer was also interested in exploring the potential gains of locating both the input and output interfaces within the same physical structure. He built a version of the *Universal Constructor* where a cellular automata program was influenced by differing physical configurations. The physical relationships between the blocks governed the execution of the cellular automata program and the state of a given cellular growth cycle was output through LEDs located inside the *Plexiglas*® cubes. This novel approach allowed software functionality to be directly influenced by the physical positioning of the blocks relative to each other and the output of the program was displayed locally within the blocks as a series of blinking LEDs. While the system was rather bulky and slow it was amongst the first to blur the boundary between digital and physical and had qualities of both forms of representation.

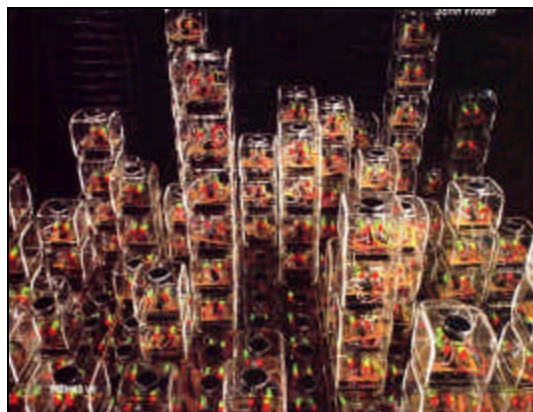


Figure 2.1 *Frazer's Universal Constructor System*

This interest in physical/digital construction was also pursued with the development of the *Physical Construction Kit* developed by the Mitsubishi Electronic Research Lab - MERL [Ryall et al., 00]. They developed a highly sophisticated building block method allowing *LEGO*® sized blocks to be assembled into arbitrary forms. The position of all the blocks in the assembly were sensed by the computer and redisplayed through a conventional CAD system. While the modeling application was more sophisticated than the *Universal Constructor* system, allowing up to 560 blocks to be simultaneously assembled, the approach was not fundamentally different from Frazer's original concept. Gorbet and Orth's *Triangles* [Gorbet and Orth, 98] did develop the concept by mapping non-physical data such as voice recordings or web addresses to individual objects allowing users to navigate digital content by reconfiguring the triangles.

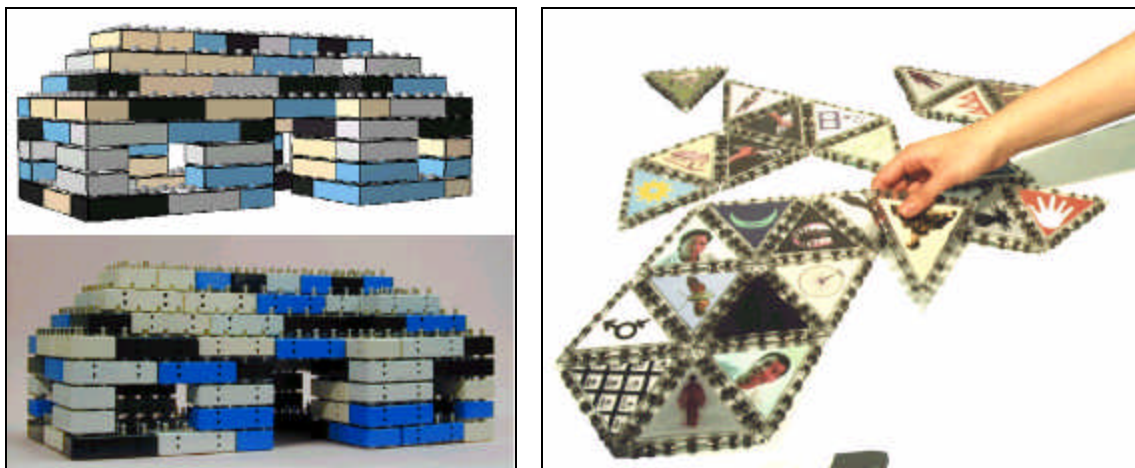


Figure 2.2 Ryall's Constructor Kit (left) and Gorbet and Orth's Triangles (right).

2.2 The Physical Display

These manipulable hardware systems tackle the issue of physical input. Other systems have been developed exploring the possibilities for physical output. *Sensible Technologies*⁶ have developed the *Phantom* arm and in collaboration with related research groups have produced a number of convincing haptic interfaces. These allow the

⁶ <http://www.sensible.com/>

tangible properties of materials such as rubber or the varying tissues densities of human anatomy to be simulated computationally and physically experienced through the *Phantom* arm. Plesniak has developed this approach to the physical display by combining the tangible input and output capabilities of the *Phantom* arm with the 3-dimensional visual qualities of real-time interactive holography [Plesniak, 97]. Her interface allows virtual forms to be lathed from a visually and physical perceptible material simulated by the computer.

The *Shader Lamps* [Raskar et al., 01] project takes a simpler approach to providing 3-dimensional physical display by projecting computer graphics directly onto the surfaces of physical objects. The work tackles the complex issues of projecting non-distorted and evenly colored graphics onto irregular forms using multiple projectors. It also provides some level of interactivity by changing the rendered highlights on the surfaces of the physical forms according the position of a viewer's head position.

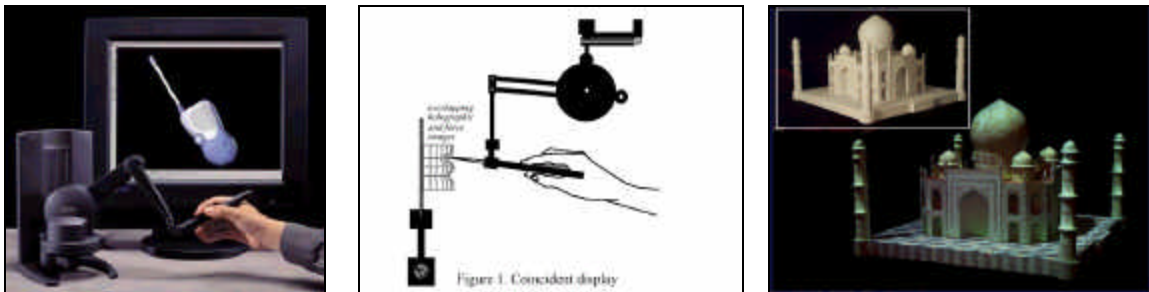


Figure 2.3 The *Phantom Arm* (left), Plesniak's *Tangible Holography* interface (middle) and The *Shader Lamps* project (right).

2.3 Spatial Navigation

The *Surface Drawing* project [Schkolne et al., 01] is a 3-dimensional design interface where the tracked physical movements of the users hands are used to define 3-dimensional forms. The graphical output is viewed in real-time through a binocular virtual-reality display. The significance of this approach lies in allowing the highly expressive and intuitive movements of the users hand and body in physical space to

provide a means for geometric input. The forms generated are entirely different from the Euclidean primitives normally associated with conventional CAD tools.

Ken Hinckley's *Neurosurgical Interface* [Hinckley et al., 94] makes the task of exploring the spatial complexities of the human brain, quite literally, child's play by using a position tracked doll's head and knife to allow users to dissect a graphical representation of the brain. By physically manipulating these two elements the neurosurgeon is able to intuitively explore the complex 3-dimensional structure of the brain. While the head was initially represented by a simple sphere, a dolls head proved much more useful in giving tactile cues about the orientation of the head (through the positioning of nose, eye and ears). Furthermore, the dolls head remains sufficiently abstract to prevent a false expectation that the digital and physical model are perfectly calibrated. The critical contribution made here is in showing the simple yet highly effective benefits of associating an abstracted physical object with a specific digital representation. The abstraction of the object allows it to stand for a variety of representations that fall with in a category – in this case a human head – while the visual medium is used to describe specific information relating to the task at hand – the spatial navigation of a particular brain.

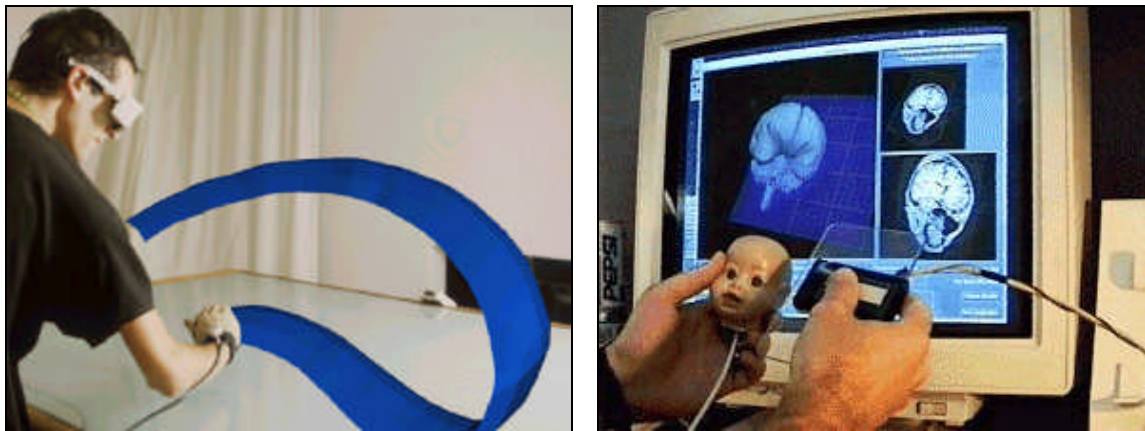


Figure 2.4 *Surface Drawing project (left) and the Neurosurgical Interface (right).*

2.4 Parallel Interactions

A similar kind of parallel digital/physical interaction to the *Neurosurgical Interface* is used in John Underkoffler's *Urban Planning Workbench* [Underkoffler, 99]. The *Urban Planning Workbench* consists of a table on which position tracked physical building models are placed. A range of dynamic simulations including wind, sunlight and traffic flow are projected onto and around the models and are directly affected by their physical position. The system is similar to the *Neurosurgical Interface* in allowing a combined physical/digital interaction. However it builds on this interaction technique in three significant ways. First, the physical building models are used as specific representations of the digital building where as Hinckley's doll head is just a physical metaphor or abstract handle through which to manipulate the digital model. Second, The *Urban Planning Workbench* utilizes the power of computation in order to simulate a physical system in real-time allowing users to view the implications of a given urban configuration – Hinckley's work only uses the computer to display a static digital model. Finally, the digital model in the *Urban Planning Workbench* is projected directly back onto the physical model workspace at the same scale and position seamlessly merging the two forms of representation to appear as two elements of the same model.

The *Urban Planning Workbench* has the general advantage over systems discussed here in that the user is not required to wear any specialized goggles, head-tracking gear or use any peripheral equipment in order to manipulate the digital and physical representations. This simplicity of approach means that it could be widely adopted as a practical design tool.

However, as we discovered from working with the system in a number of urban design teaching studios there are still a number of major drawbacks. The fundamental drawback is that the digital model is only calibrated to the physical model through visual tracking - the position and orientation of the physical representation is sensed and the digital model adjusted accordingly. Apart from this calibration of position there is no interrelation

between the digital and physical form. This means that the user can only alter the relationships *between* forms and does not have the ability to manipulate the forms themselves. If for example an urban designer wished to view the results of increasing a building height by a factor of two on the wind speed at ground level, they must first alter the physical model and then manually update the digital representation. It is perhaps for this reason that the work bench was designed around the specific domain of urban design where the relationships *between* building forms are more critical than the design of the forms themselves.

A second major drawback to the system is that while the physical model exists in three dimensions the digital representation exists only in two. Wind speeds are calculated for pedestrian level but this is not useful if the designer wishes to view the wind loading at the center of the façade of a forty-story building. Furthermore, because the system is limited to two dimensions it does not allow for a site of non-planar topography. Since almost all urban sites involve some change in elevation this is another significant limitation in the system.

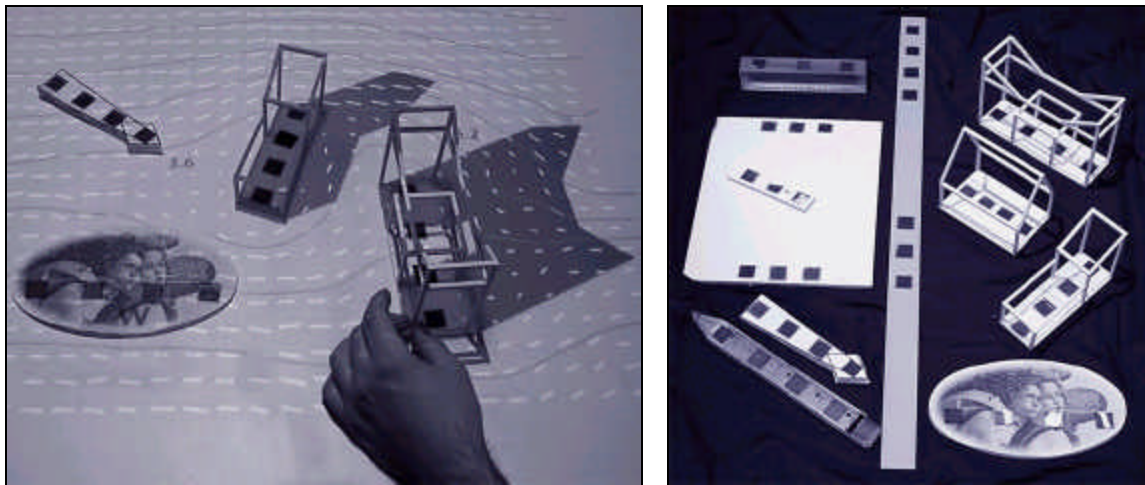


Figure 2.5 Urban Planning Workbench (left) and tracked building models (right).

2.5 Interface Prototypes

In order to explore ways of overcoming some of the limitations posed by the *Urban Panning Workbench* a number of experimental interfaces were built.

Prototype 1: *CoffeeShop*

CoffeeShop was devised as part of an installation for Davenport and Benton's MAS.878 MIT class - *Special Topics at the Center for Advanced Visual Studies*. The *PhotoShop*® graphics program was used to project graphics onto a physical real-world scene of a coffee shop. Interactors would sit at the coffee shop table and using the conventional *PhotoShop*® tools such as line, text and brush, alter the color of objects on the table and other surfaces in the physical scene. The *PhotoShop*® menu bars and floating windows were projected onto to planes held perpendicular to the angle of projection and users could paint over the 3-dimensional surfaces of the scene.



Figure 2.6 Images of the *CoffeeShop* installation.

Prototype 2: *Global View*

The *Global View* project explored ways in which global statistics could be represented in tangible form and compared in an intuitive manner. The image of a world atlas was projected from three angles onto a matt white sphere representing the earth. As the user turned the control ring the relative sizes of the countries would shift in proportion to sets of global statistics. These statistics included seemingly unrelated variables such as child mortality rates and computer network penetration. By translating this information into a visual and spatial form it was hoped that relationship between these kinds of statistics could be more easily observed.

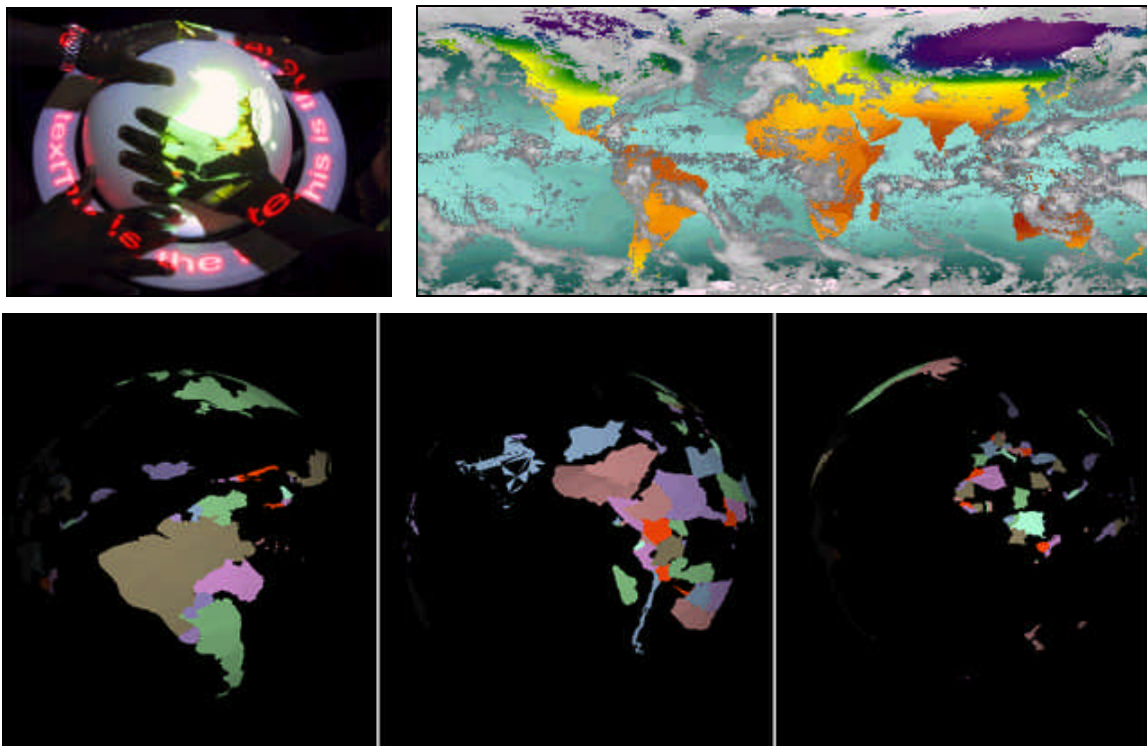


Figure 2.7 Different statistical sets from the *Global View Project*.

Prototype 3: *CADcast (v.1)*

CADcast (v.1) provided a 3-dimensional template for the physical construction of building models. A digital model of a desired building was created using conventional CAD tools. This digital model was used to generate a series of perspective images showing the model building at each stage of assembly. This sequence of perspective images, indicating the order and position of each components of the building model, was projected into the workspace and used to construct a physical model.

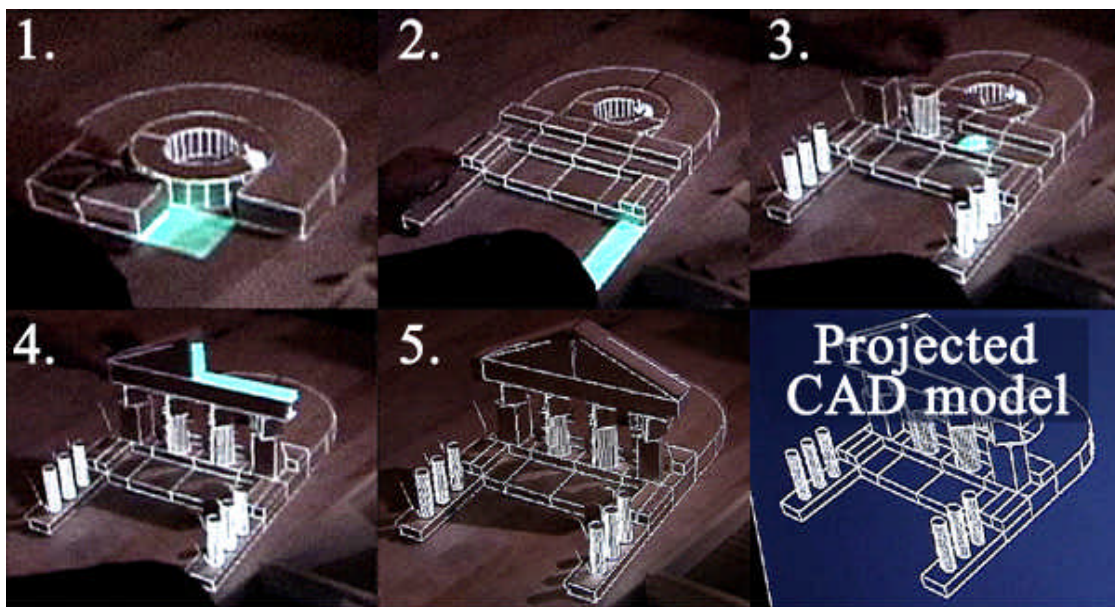


Figure 2.8 *CADcast (v.1)* - projected CAD guidelines for model assembly.

CADcast (v.1) went some way in demonstrating how physical and digital representation could be successfully merged in a spatial design environment. However, the interface was severely limited by only being useful under carefully controlled conditions. Furthermore, it resulted in a one-way human computer interaction where the user was essentially following projected instructions from the computer with out any ability to interact with this output.

2.6 Design Requirements

The advantages and disadvantages of the systems discussed above can be summarized as follows:

Interface	Advantages	Disadvantages
<i>Universal Constructor</i>	<ul style="list-style-type: none"> Physically manipulable Co-located input and output Universal system 	<ul style="list-style-type: none"> Large building blocks Crude system
<i>Physical Construction Kit</i>	<ul style="list-style-type: none"> Physically manipulable Universal system Small blocks Sophisticated system 	<ul style="list-style-type: none"> Conventional GUI output
<i>Triangles</i>	<ul style="list-style-type: none"> Physically manipulable Alternative out put (audio) 	<ul style="list-style-type: none"> Limited number of components Fragile system
<i>Phantom Arm</i>	<ul style="list-style-type: none"> Provides physical 'display' Simple concepts Universal applications 	<ul style="list-style-type: none"> No visual output Tethered arm – limited operations
<i>Tangible Holograms</i>	<ul style="list-style-type: none"> Physical display Co-located input and output 	<ul style="list-style-type: none"> Non-universal system Limited visual output
<i>Shader Lamps</i>	<ul style="list-style-type: none"> Physical display Simple 3-D display 	<ul style="list-style-type: none"> Complexity of multiple Shader lamps Little interaction
<i>Surface Drawing</i>	<ul style="list-style-type: none"> Intuitive control Tangible control objects 	<ul style="list-style-type: none"> Requires VR goggles Non physical input
<i>Neurosurgical Interface</i>	<ul style="list-style-type: none"> Intuitive control Tangible control objects 	<ul style="list-style-type: none"> Dislocated digital and physical representations
<i>Urban Planning Workbench</i>	<ul style="list-style-type: none"> Physically manipulable Simple enabling technology 	<ul style="list-style-type: none"> Inability to alter object forms Latent tracking system
<i>CoffeeShop</i>	<ul style="list-style-type: none"> Simple Design Simple 3-D display 	<ul style="list-style-type: none"> No physical interaction
<i>Global View</i>	<ul style="list-style-type: none"> Simple 3-D display Some physical interaction 	<ul style="list-style-type: none"> Minimal requirement for physical interaction
<i>CADCast</i>	<ul style="list-style-type: none"> Simple 3-D display More physical interaction Potential applications 	<ul style="list-style-type: none"> Unilateral interaction between computer and user Sensitive system requiring preprocessing and calibration

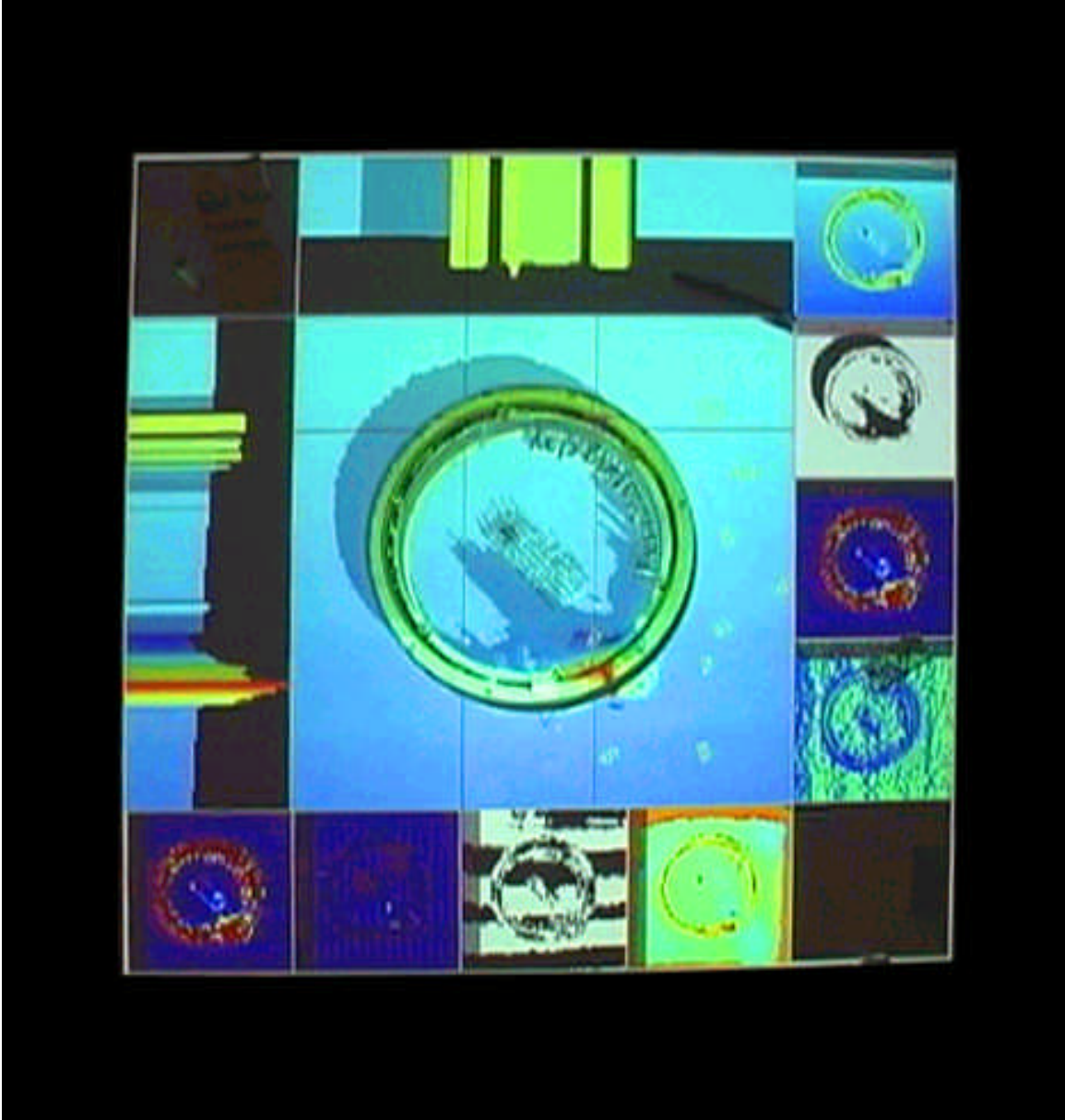
We hoped to bring together the advantages of the interfaces described above in building our own approach to the human computer interface. In particular we aimed to build a system, like Frazer's *Universal Constructor* that allowed the easy manipulation of form and provided a co-located tangible *physical* input and digital *visual* output. It was also important that we designed a system that had the potential for universal applications and was not restricted to one specialist domain as is the case for many of these examples. In order to accomplish this we needed to avoid the disadvantages of using tags or other technologies to augment physical objects, such as those used with the *Urban Planning Workbench*.

In summary we aimed to build an interface that allowed:

- The computational analysis of three-dimensional physical models
- A near real-time interaction and analysis
- A co-located source and display of analysis
- A broad spectrum of potential applications

The next chapter explains how the emergent technology of the 3-dimensional scanner was used to build such a system.

Chapter 3.



3. The Illuminated Design Environment

“Under normal circumstances the architect goes through the design process, ‘draws up the results’, builds a model and three weeks later makes a movie of some specified result. The result provides good analytical material but is useless in the design process because by this stage the project is in a period of refinement rather than germination.”

[Negroponte, 66]

The quote above illustrates the problem with the way that computers are generally used in design today. Underkoffler’s *Urban Planning Workbench* address this issue by displaying the implications of a designer’s decisions in real-time, within the design space allowing computational simulation to have a real affect the outcome of a design. However, as explained in the previous chapter, this project is somewhat limited by the sensing technologies used.

In order to combine the tangible immediacy of physical models with the power of computational simulation we needed to locate a sensing technology that could capture the form of physical objects without the need for tagging, tethering or demarcation. It was our aim to build a system that would allow any physical models to be analyzed in the manner of the *Urban Planning Workbench* and for this we needed to locate a suitable form of 3-dimensional capture technology.

3.1 Sensing Space

While there are a great number of methods for 3-dimensional capture employing sonar, radar and electromagnetic sensors we found that optical systems were the most suited to the scope, budget and scale of our project. These optical scanners fall under three main categories: structured light, time-of-flight and triangulation.

Structured Light

Structured Light scanning uses an LCD projector, slide scanner or similar optical device to project an illuminated pattern onto a physical scene. A camera, offset by a known distance from the projection source, is used to capture an image of the projected pattern. Software is used to analyze the distortion in the pattern caused by the irregular surfaces of the physical scene and a 3-dimensional point cloud is generated in computer memory. The approach has the advantage of using relatively simple technologies to project and capture the patterns of light. This means that the system can be built from scratch or purchased for under \$8,000. However, the algorithms required to translate this image data - separating the light patterns from other elements in the visual scene and compensating for areas of occlusion - make the method rather inaccurate.

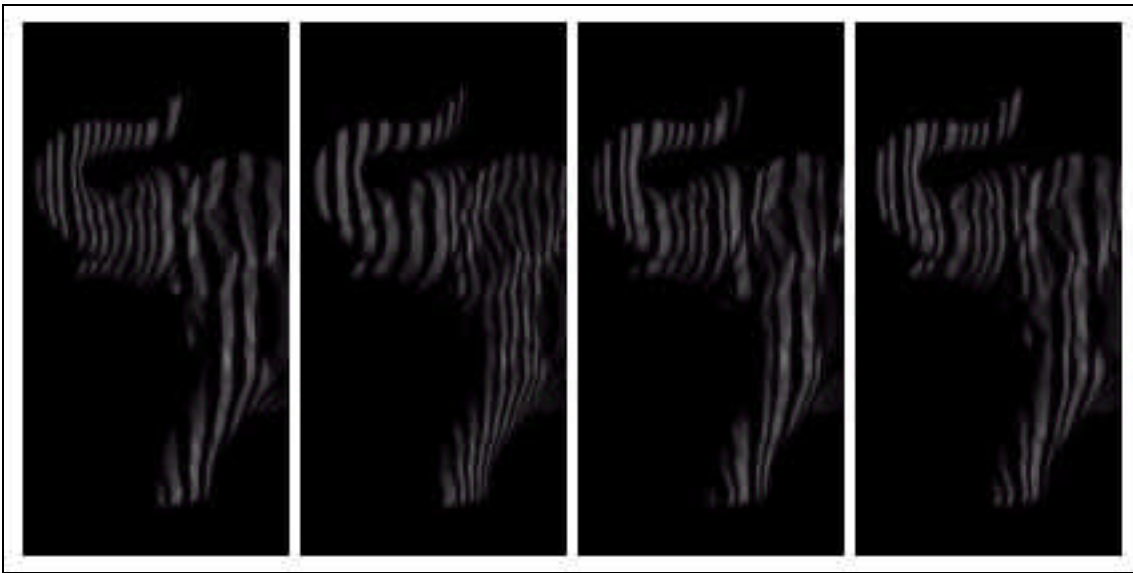


Figure 3.1 The Structured Light 3-dimensional scanning technique.

Time-of-Flight

Time-of-Flight scanners function by projecting a pulse-modulated beam of laser light onto the physical scene. A sensor records the time taken for the pulse to be reflected from the surface of a given physical object back to the source and the distance of that point of

reflection is calculated. A mirror is used to translate the laser beam through the x and y dimensions, allowing the single laser and sensor to measure an array of points from the physical scene. While the approach has the advantage of being very precise and working over large distance (up to several kilometers) it is still relatively slow since the mirror has to be physically cycled through all of the distance points to be measured. The scanners are also rather expensive with current models ranging from \$80,000 to \$150,000.



Figure 3.2 Source object and scan image from a Time-of-Flight scanner.

Triangulation

Triangulation scanners are a hybrid between the Structured Light and Time-of-Flight approaches and combine the advantages of both. As with Structured Light a camera is used to capture the distortions in a beam of projected light as it is cast on to the surface of a physical scene. The distortions of this single line are translated by means of a triangulation algorithm into geometric data. However, rather than using non-coherent light source, as with Structured Light, a near infra red laser beam is used providing greater accuracy and greater differentiation between the scanning stripe and other lit objects in the scene. As with the time of flight approach the laser beam is translated across the scene. However, instead of being translated in both x and y dimensions, the striped light source is only translated through one dimension allowing multiple point values to be calculated in parallel and increasing the over all speed of the scan. The

simpler technology (only one axis of translation) means that triangulation scanners can be purchased for less than \$50,000 while still providing an accurate (and potentially real-time) method for three-dimensional capture.

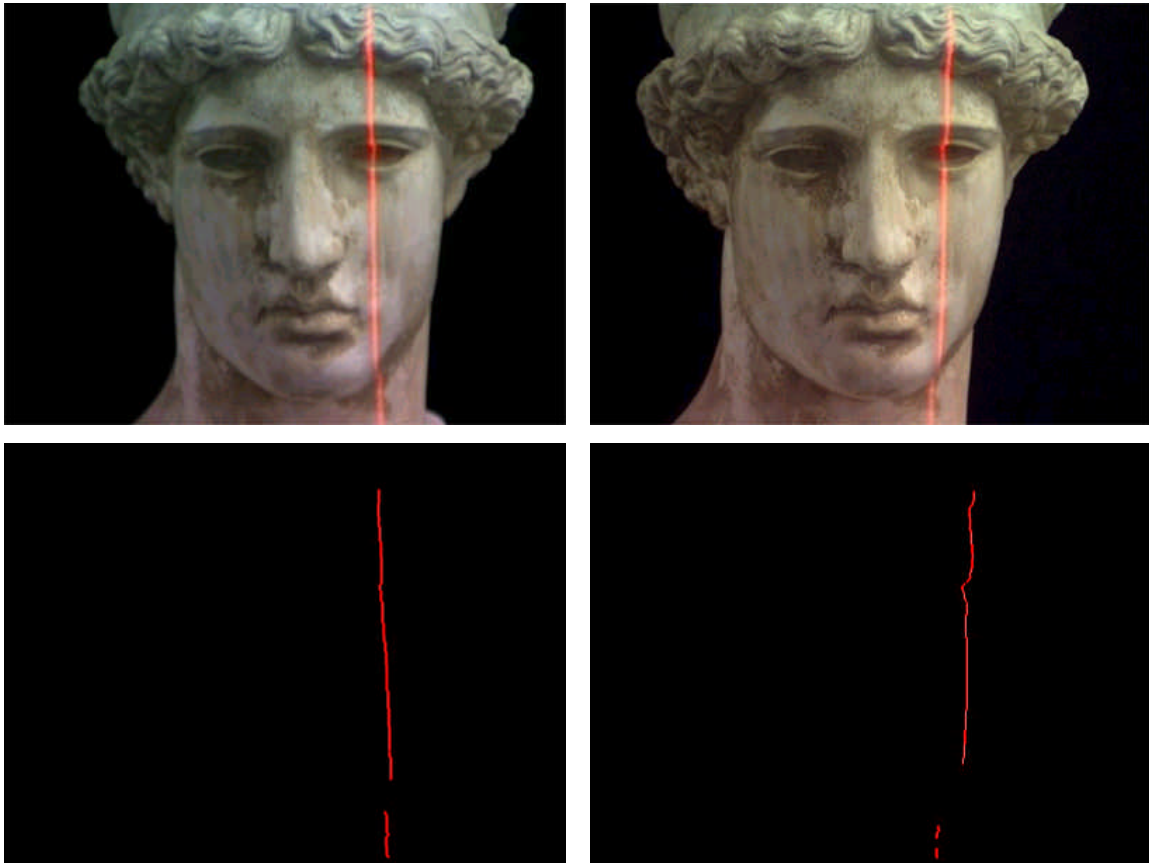


Figure 3.2 Source object and scan images from a triangulation scanner – notice the distorted line on the right used for triangulation measurement.

The initial purchase of the laser scanner was the largest single investment with of the research project and it was crucial that we bought a device that matched our requirements for speed and accuracy at a 3-meter range. The laser based triangulation approach was chosen because it offered a much faster scan rate than Time-of-Flight laser scanners and greater accuracy than structured light systems. From with in the range of available triangulation scanners we chose to use a Minolta *Vivid 900* [Minolta] scanner because of its appropriate scanning range and because it was provided with a software developer's kit.

The VIVID 900ä

The VIVID 900™ operates by projecting a near infrared laser stripe over objects in the scene. Distortions in the shape of this stripe are captured by a camera mounted in the scanner, which is offset by a known distance from the source of the laser stripe. The distortions in the stripe are analyzed by the Minolta firmware and converted, through triangulation, into distance information.

Figure 3.3

The stripe light is scanned on the CDD image plane at two horizontal lines per frame (FAST mode) or one horizontal line per frame (FINE mode), and the CDD is driven so that the block readout start position is shifted two lines per frame or one line per frame. Approximately 270 lines of the images are acquired in the FAST mode, while 600 lines are acquired in the FINE mode. The output signal from the CDD is then converted into a digital signal, which is then subjected to digital signal processing. The signal-processed data is finally saved in the frame memory.

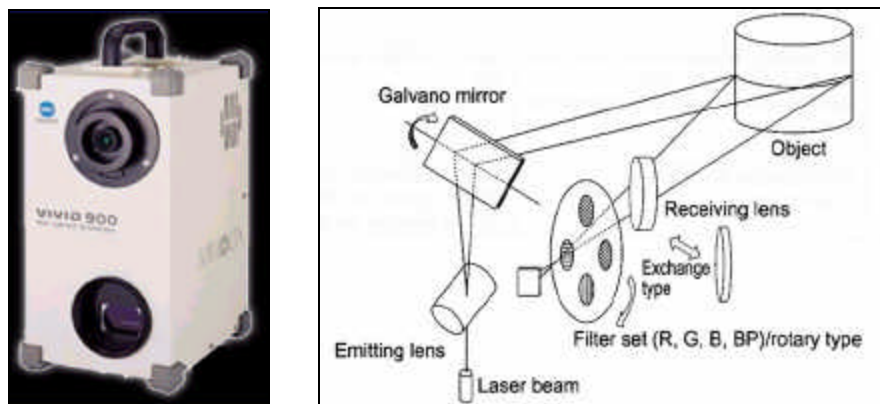


Figure 3.4 The Minolta VIVID 900ä triangulation laser scanner (left) and the internal measuring mechanism (right).

3.2 System Architecture

The *Illuminated Design Environment* was designed to allow any physical model placed within the design environment to be illuminated with a computational analysis. The system consisted of a ceiling mounted *Vivid 900™* laser scanner and computer projector which were aligned at roughly the same optical origin using an angled mirror. This allowed any surface visible to the scanner to be used as a surface for projection. Once calibrated the scanner/projector pair formed a self-contained I/O device that could be installed above any desired workspace.

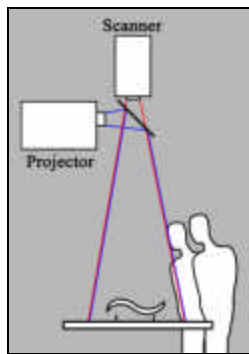


Figure 3.5 Proposed system architecture of the *Illuminated Design Environment*

We originally intended to align the scanner and projector at *exactly* the same optical origin by passing the laser beam through a half silvered mirror (see figure b). However, in building the set up we discovered that mounting an ordinary mirror to one side of the scanner had little affect on our ability to calibrate the system.

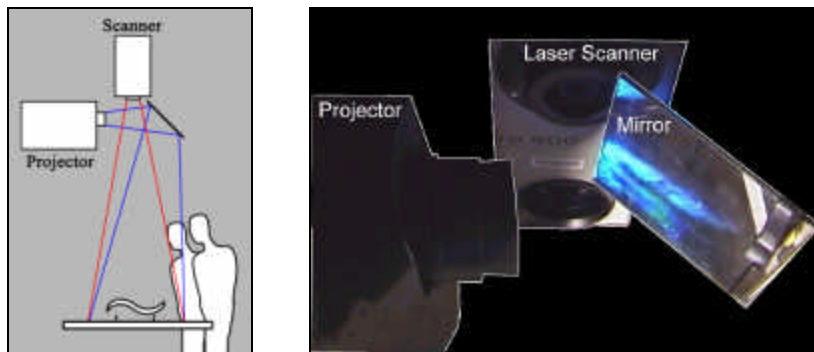


Figure 3.6 System Architecture of the *Illuminated Design Environment*

Projector

We used a standard *Mitsubishi LVP-G1A* 640 x 480 *Liquid Crystal Display* (LCD) projector to cast the results of the computational analysis back onto the surfaces of the model. LCD projection was found to cause less interference with the laser scanner than *Digital Light Processing* (DLP) projectors that use tilting micro-mirror arrays. We believe this is because the DLP projectors we tested cycle through the red, green and blue portions of the spectrum causing interference with the red laser stripe during the red portion of the color cycle.

Data Transfer

The *VI-900™* was originally designed to perform single scans of static objects and scenes. In order to capture the changing geometry of the workspace and physical model in real time, it was necessary to write a control script⁷ to perpetually scan the scene. Using the control script, we were able to repeatedly scan the workspace to capture 320 x 240 points every 0.3 seconds. The transfer of this data from scanner to processor (via SCSI) added an additional component to the scan cycle time. We streamlined the transfer time by discarding all color values and transferring only geometric information. This information was converted into x, y and z coordinates and then finally converted into an array of elevation values that represented the altitude of each scanned point as a single numeric value. This array of elevation values was used as the basic input data structure for any subsequent computational analysis.

3.3 An Application Domain

In response to the *Urban Planning Workbench* we originally planned to use the *Illuminated Design Environment* for the analysis of building forms in the process of urban design.

⁷ Written in collaboration with Joe Calkins of *New River Kinematics* - <http://www.kinematics.com>

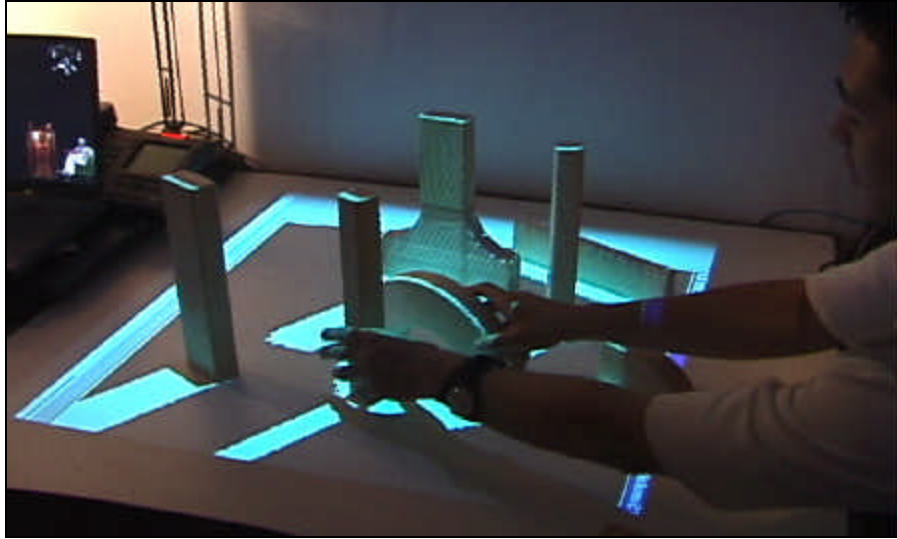


Figure 3.7 Early experiments with urban form analysis.

However, following the advice of Dean Bill Mitchell we decided to focus on the application domain of landscape design. Landscape form can generally be described as a continuous function and as such is ideally suited to the current technical limitations of laser scanning and projection. More significantly, there are a vast number of computational landscape analysis functions that have been developed within the geosciences. These are maintained by organizations such as *Geographical Information Systems* [GIS] and *Geographic Resources Analysis Support Systems* [GRASS]. While these functions are extremely powerful analytical tools there is currently no simple interface through which landscape designers can intuitively manipulate the form of landscape models while observing the resultant influences on these kind of landscape analysis functions. For this reason we aimed to build an interface that would combine the power of computational simulation with the tangible immediacy of physical landscape models.

Chapter 4.



4. Representing the Landscape

“The judgments expected upon viewing the displayed results of a model are the inferential purpose for which the model is made: and as with all representations, these inferential and sometimes rhetorical purposes turn out to be critical in devising and evaluating models.”

[Arnheim, 1969]

The landscape model forms the basis on which many of the decisions in landscape design are made. As Arnheim suggests above the quality of this model is entirely dependant on the purpose for which it is to be used. In landscape design an effective model must represent the landscape in a simplified and abstracted form that is suited to the range of complexity being considered. It must strike a balance between what is real and realistic and it must convey the most important quality of each factor in the landscape in a way that can be applicable to the task at hand [Ervin, 01].

The difficulty of representing the landscape is not just limited to the need to cover large scales and nested levels of resolution but also to represent the interrelationships between various elements of the landscape. These elements and the common techniques used to represent them are briefly described in the following sections.

4.1 Elements of the Landscape

Topography

The spatial relationships of the landscape are defined by the geometry of the underlying topography. The variations in landscape terrain are extremely broad covering a full spectrum from flat desert, to undulating hill, to craggy mountain. Agrarian, infrastructure or urban interventions can also radically alter the topography of the inhabited landscape.

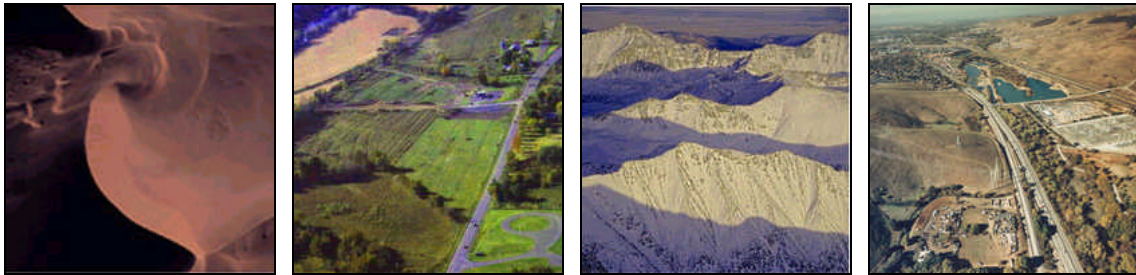


Figure 4.1 Variations in landscape topography – plane, hill, mountain and man made

As a physical (and mostly static) form the topography can be effectively represented using physical models. The physical landscape model is useful because it can be quickly constructed and directly manipulated by a landscape designer and unlike visual representation physical models can be experienced spatially.

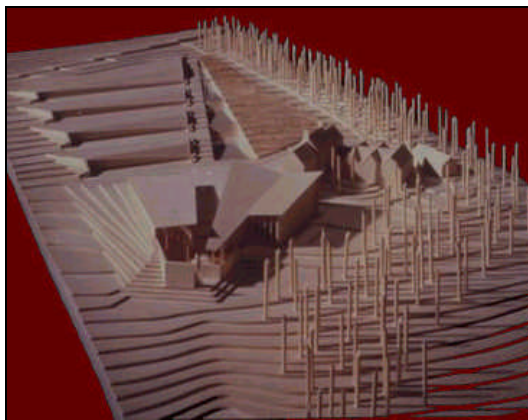


Figure 4.2 A physical landscape model.

However, the physical model is limited because it cannot be reproduced with the speed, accuracy or compact form offered by two dimensional paper based representations such as the topographic map. These maps, which represent height values as series of continuous lines of equal elevation, have been developed as a convention to quickly convey the 3-dimensional topography of a landscape in two-dimensional form and as such they provide a useful tool for the landscape designer.

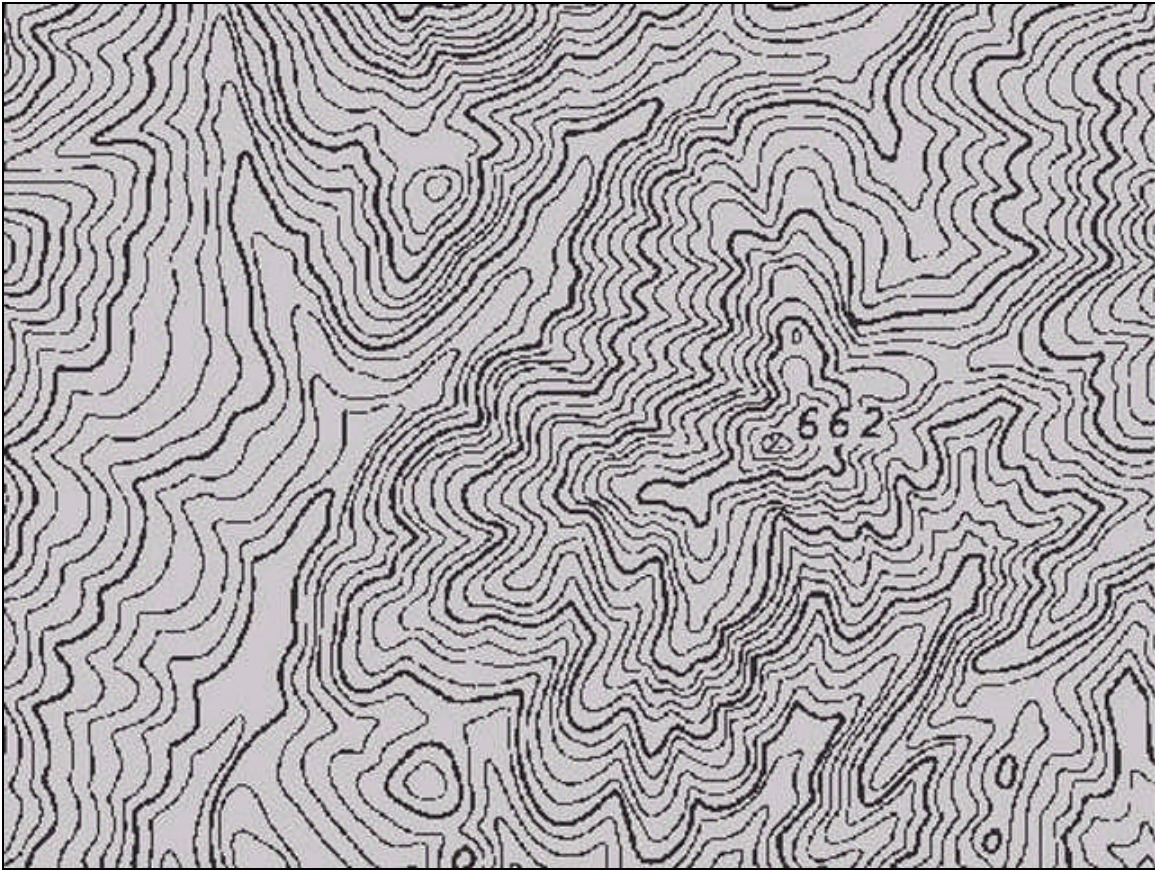


Figure 4.3 A topographic map.

Water, Atmosphere and Vegetation

The movements of water, the changes in the atmosphere and the lifecycle of vegetation are dynamic elements of the landscape and as such cannot be easily represented with static physical models. Some techniques have been devised to indicate lines of watershed, the ridge in a landscape topography dividing one drainage basin from another. Smoke and wind tunnel tests are used to model wind-flow and pollution patterns in the atmosphere. Sun tables or *heliodons* can be used to predict the shadow paths and other functions of sunlight with in the landscape. However, these techniques remain relatively crude owing to the necessity for highly specialized environments such as *heliodon* tables and wind tunnels. These kinds of tests are generally reserved for model analysis at the end of a design process - if they are used at all. As a result such physical simulations are rarely used to inform the early stages of the design process.

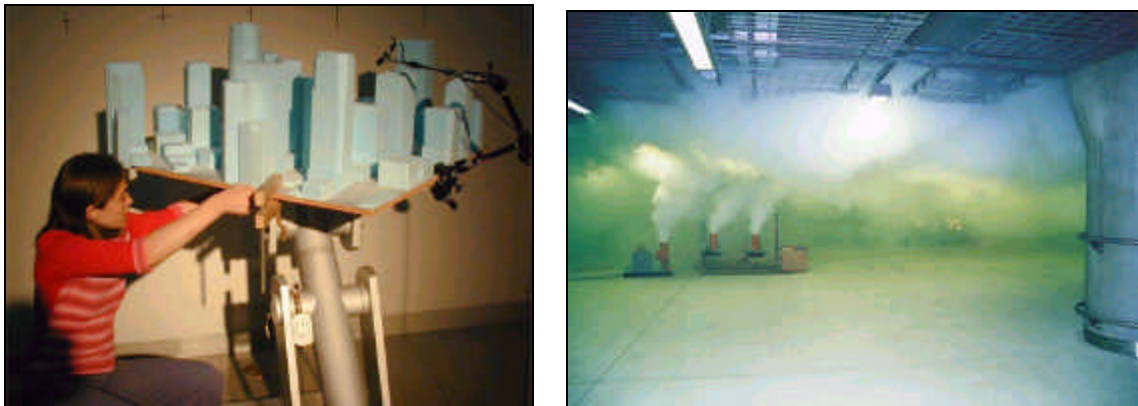


Figure 4.4 *Physical models being tested on a heliodon table and in a wind tunnel.*

Human intervention

Aerial photographs, plans, surveys and maps provide useful ways of understanding the human impact on the landscape. They help to easily identify interventions such as roads, transmission lines, and major buildings. Plans surveys and maps are critical in representing societal constructs such as land boundaries and zoning regulations.

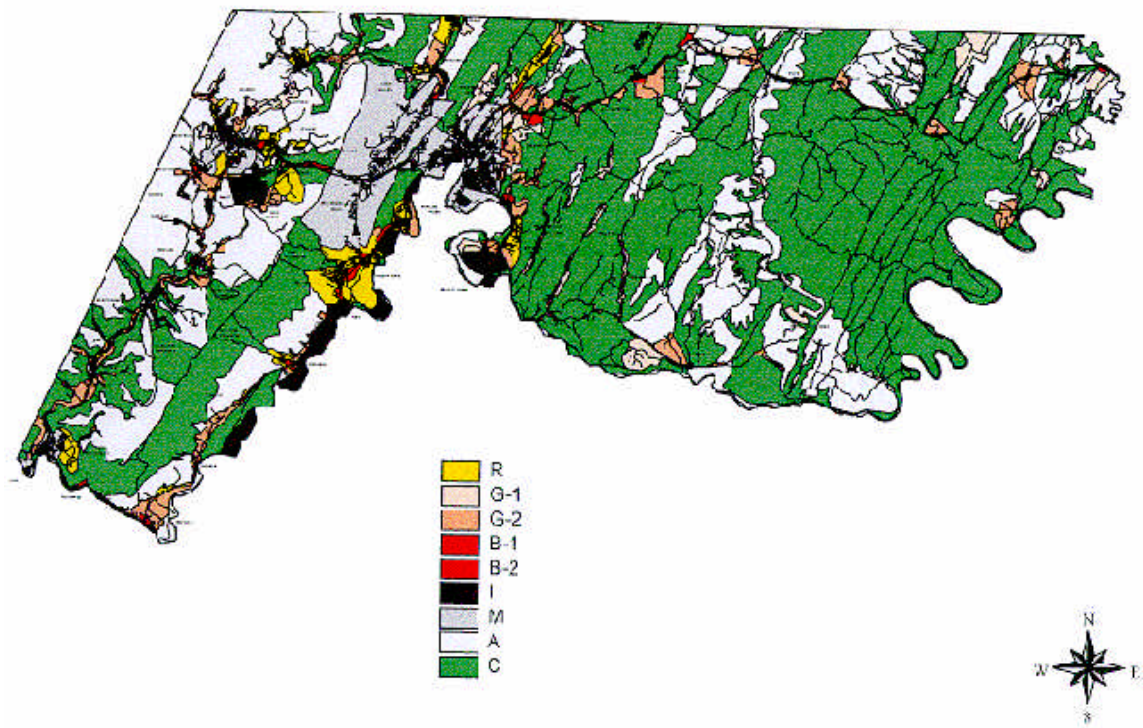


Figure 4.5 Typical landscape zoning map.



Figure 4.6 The human impact on the landscape.

4.2 Computational Analysis of the Landscape

New technologies for sensing and distribution

Developments in photogrammetry, high-resolution satellite photography, high-altitude airborne sensors, global positioning systems, digital image processing, database management and the globalization of information sources in general has led to an explosion in information resources for landscape designers. High-resolution topographic maps, information on soil types, population densities, variance in vegetation species are now routinely used in the landscape design process.



Figure 4.7 *The photogrammetry technique.*

The Digital Elevation Model

These technologies allow even more accurate and extensive representation of the landscape topography than ever before. It is now common to work with a *Digital Elevation Models* (DEM) as the primary topographic representation. The DEM is a two dimensional numerical array that describes the landscape topography as a grid of elevation values. It is now possible to acquire the DEM of almost any portion of the globe at less than three-meter intervals providing an extremely powerful and accurate means of representing landscape topography.

Attribute	Definition	Applications
Elevation	Height above mean sea level or local reference	Potential energy determination; climatic variables – pressure, temperature, vegetation and soil trends, material volumes, cut and fill calculations
Slope	Rate of change of elevation	Steepness of terrain, overland and sub surface flow, land capability classification, vegetation types, resistance to uphill transport, correction of remotely sensed images
Aspect	Compass direction of steepest downhill slope	Solar irradiance, evapotranspiration, vegetation attributes, correction of remotely sensed images
Profile curvature	Rate of change of slope	Flow acceleration, zones of enhanced erosion / deposition, vegetation, soil and land evaluation indices
Plan curvature	Rate of change of aspect	Converging / diverging flow, soil water properties
Local drain direction (Ldd)	Direction of steepest downhill flow	Computing attributes of a catchment as a function of stream topology. Assessing lateral transport of materials over locally defined networks.
Upstream elements/area/Specific catchment area	Number of cells / area upstream of a given cell / upslope area per unit width of contour	Catchment areas upstream of a given location (if the outlet, area of whole catchment), volume of material draining out of catchment
Stream length	Length of longest path along ldd upstream of a given cell	Flow acceleration, erosion rates, sediment yield
Stream channel	Cells with flowing water / cells with more than a given number of upstream elements	Flow intensity, location of flow, erosion / sedimentation
Ridge	Cells with no upstream contributing area	Drainage divides, vegetation studies, soil, erosion, geological analysis, connectivity
Wetness index	$\ln\left(\frac{\text{specific catchment area}}{\tan(\text{slope})}\right)$	Index of moisture retention
Stream power index	$\frac{\text{specific catchment area}}{\tan(\text{slope})}$	Measure of the erosive power of overland flow
Sediment transport index (LS Factor)	–	Characterises erosion and deposition processes
Catchment length	Distance from highest point to outlet	Overland flow attenuation
Viewshed	Zones of inter-visibility	Stationing of microwave transmission towers, fire watch towers, hotels, military applications, visual impact for a new building or development
Irradiance	Amount of solar energy received per unit area	Vegetation and soil studies, evapotranspiration, location of energy saving buildings, shaded relief
Least cost path	Path between two points which minimises a set of parameters	Fastest path selection, Pipeline routing; Least cost path information has been integrated with viewshed information to determine scenic or hidden paths

[McDonnell, 1998]

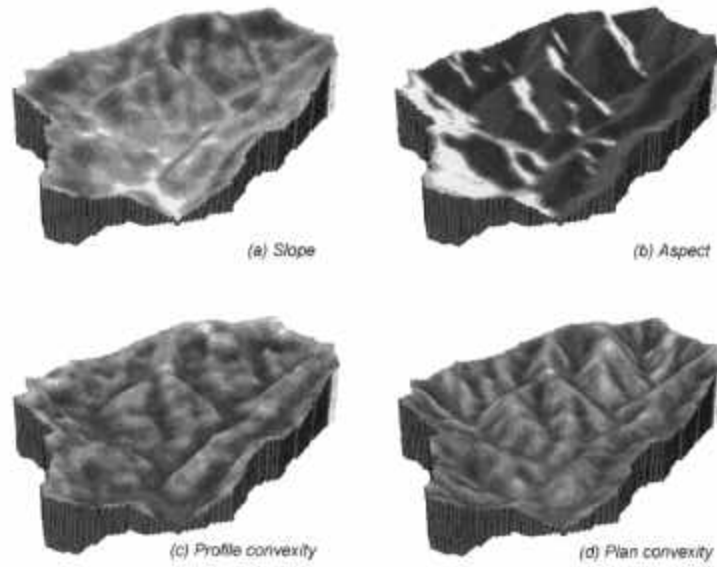


Figure 4.10 Examples of rendered DEM derivatives. [McDonnell, 1998]

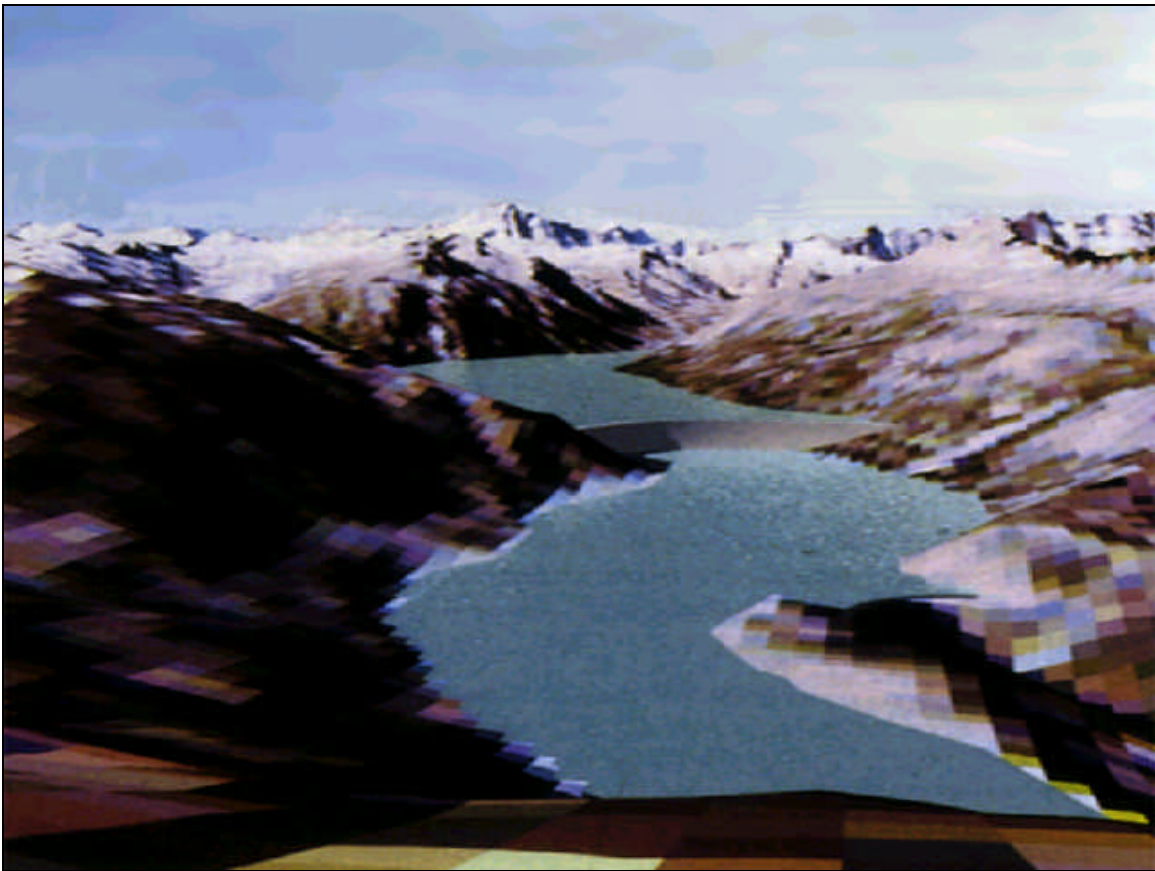


Figure 4.11 A texture mapped digital landscape. [Ervin,01]

The Lack of Interface

“Interaction with the landscape is barely addressed in any digital model. We are still far from having haptic interfaces and tactile feedback mechanisms available for most modelers, and we don’t have a good theoretical or empirical basis for determining the kinds of interactions we need to model.”

[Ervin, 01]

While the methods for computational analysis described above are extremely powerful, all of these simulation methods are understood visually through the computer screen. As a 2-dimensional form this does not support the intuitive 3-dimensional understanding offered by the physical landscape model. Furthermore, these simulations methods are limited by requiring the use highly specialized software environments and the expertise of a trained user meaning that computational analysis, which is potentially a far simpler process than physically based simulation, is still not fully integrated into the design process.

It is often difficult or impossible for the unaided designer to predict how small interventions in the landscape will affect complex, non-intuitive and dynamic systems such as the flow of rain-water over the terrain. These effects may be difficult to imagine but can be computed with some accuracy. By offering a means to represent these systems in real-time, as the user manipulates and adds to the landscape model, we hoped to provide an interface that would support more informed design decisions and give the landscape designer a more intuitive sense of complex and dynamic systems in the landscape.

The following chapter describes how the *Illuminated Design Environment* was adapted to provide such an interface in the form of a platform called *Illuminating Clay*.

Chapter 5.



5. Illuminating Clay

A group of road builders, environmental engineers and landscape designers stand at an ordinary table on which is placed a clay model of a particular site in the landscape. Their task is to design the course of a new roadway, housing complex and parking area that will satisfy engineering, environmental and aesthetic requirements.

Using her finger the engineer flattens out the side of a hill in the model to provide a flat plane for an area of car parking. As she does so an area of yellow illumination appears in another part of the model. The environmental engineer points out that this indicates a region of possible landslide caused by the change in the terrain and resulting flow of water. The landscape designer suggests that this landslide could be avoided by adding a raised earth mound around the car park. The group tests the hypothesis by adding material to the model and all three observe the resulting effect on the stability of the slope.



Figure 5.1 A group of designers using Illuminating Clay.

The scenario above describes how the *Illuminating Clay* platform can be used to aid in the process of landscape design. In order to build the new system, we first had to make a number of changes to the *Illuminated Design Environment*.

5.1 System Architecture Rebuild

We replaced the *Mitsubishi LVP-G1A* projector with a brighter *Epson Powerlite P810* allowing the system to be operated in a fully lit room. The smaller size of the new projector also allowed us to do away with the reflecting mirror by mounting the projector vertically next to the scanner. The scanner/projector pair was encased in a new housing that could easily be transported to other locations with out the need for recalibration. We added a rotating platform to the work areas onto which any physical landscape representation could be placed. This platform could be rotated to gain any desired viewing angle.

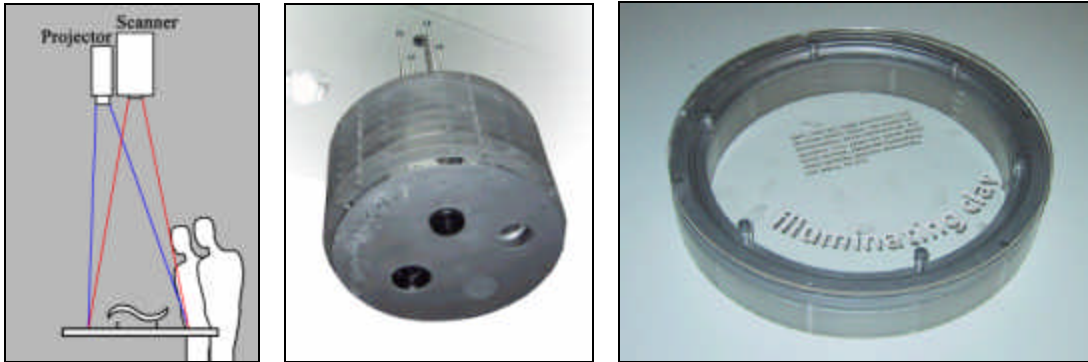


Figure 5.1 The new scanner/projector arrangement (left), the new housing (middle) and the rotating platform (right).

We experimented with a range of materials suitable for modeling the landscape including plastacine, sand, un-dried porcelain clay, *LEGO*[™] blocks and *Model Magic*[™], *Fimo*[™] and *Silly Putty*[™] modeling clays. We found that a thin layer of plasticine, supported by a metal mesh core provided a ductile material composite that could easily be sculpted into a landscape form. The matte white finish was highly suitable as a projection surface and did not leave a residue on the user's hands. While this was the standard material used during the development of the interface other materials were also used.

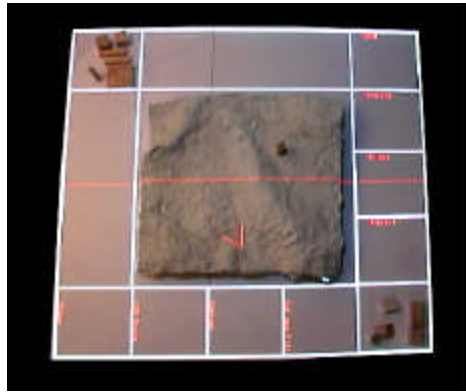


Figure 5.2 The clay modeling material (image center) and wooden blocks (corners).

5.2 Visual Interface Design

The visual elements of the *Illuminating Clay* interface were projected onto the physical surfaces of the worktable and the landscape model using a projected graphical display called the *Simulation Window*. Two additional projectors were added to display the *Control Window*, also projected onto the work surface, and the *View Window*, projected onto an adjacent wall of the design environment.

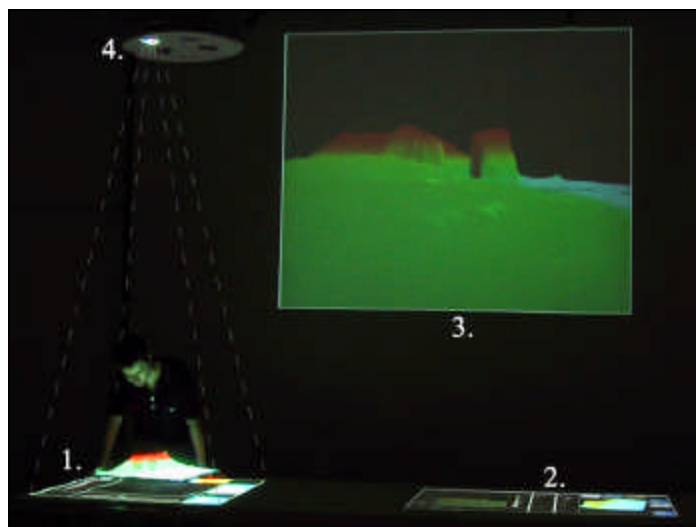


Figure 5.3 The three visual output windows used in *Illuminating Clay*: 1. *Simulation Window*, 2. *Control Window*, 3. *View Window* and 4. the scanner housing.

The Simulation Window

The *Simulation Window* is a projection of the landscape analysis functions displayed on the physical surface of the landscape model. While this form of display combines the benefits of the physical model with a visual computational display we found it necessary to maintain many aspects of a conventional graphical user interface. For example we continued to use a mouse cursor, controlled by a wireless trackball, in order to specify precise points on the model and to select different landscape analysis functions displayed as a series of thumbnails around the base of the model. These thumbnails remain active, updating with changes in the model, allowing the easy comparison of different landscape analysis results. The remaining two edges of the work surface are used to project computationally derived cross-sections of the physical model, enhancing the landscape designer's 3-dimensional understanding of the terrain.

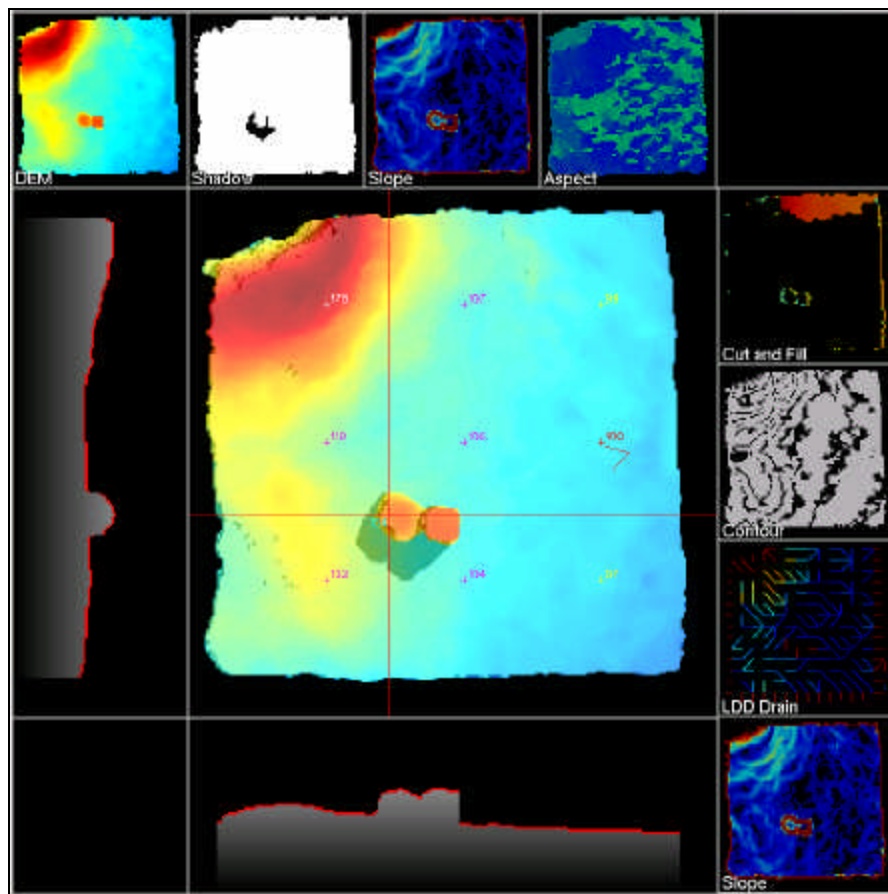


Figure 5.4 Top view of the Illuminating Clay Simulation Window.

As with the *Global View* and *CoffeShop* prototypes (see Chapter 2.) it was necessary to distinguished the 3-dimensional physical display on the surfaces of the model from the 2-dimensional graphical display on the work surface by setting the model several inches higher on the rotating platform. All of the graphical elements projected onto the table were oriented radially in order to prevent the formation of a user hierarchy – where one user has more control over the interface than another - based on different orientations to the table.

The Control Window

The *Control Window* is used to control the behavior and variables of the various analysis functions projected in the *Simulation Window*. The *Control Window* is broken into six control sections: *Preset Controls*, *Program Controls*, *View Controls*, *Analysis Controls*, *Image/Elevation Edit Controls* and *Color Bar Controls* summarized in the table on the following pages.

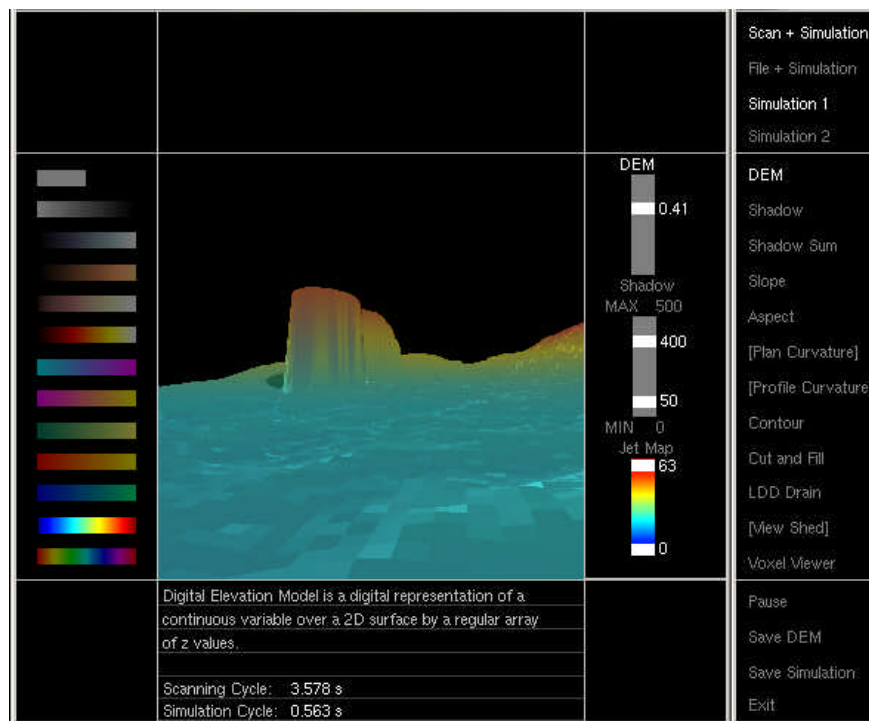
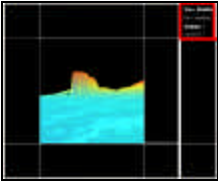
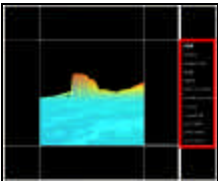
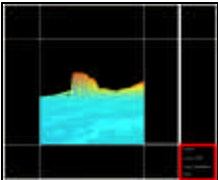
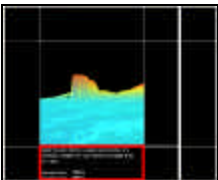
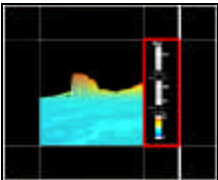


Figure 5.5 Screenshot of the Control Window.

CONTROL	FUNCTION
<i>Preset Controls</i>	
<i>Scan Analysis</i>	Scans the 3-dimensional topography of the landscape model to be analyzed with a given simulation.
<i>File Analysis</i>	Loads a 3-dimensional topography from memory to be analyzed with a given simulation.
<i>Set Analysis Alpha</i>	Sets the current Analysis Alpha analysis function
<i>Set Analysis Beta</i>	Sets the current Analysis Beta analysis function
<i>Analysis Functions</i>	
	See full descriptions below
<i>Program Controls</i>	
<i>Pause</i>	Pauses the scanning cycle.
<i>Save DEM</i>	Saves the geometric information as a DEM for future use
<i>Save Simulation</i>	Saves the results and settings of the landscape simulation for later use
<i>Exit</i>	Exits the <i>Illuminating Clay</i> program
<i>Analysis Descriptions</i>	
<i>(Text Based)</i>	Brief description of the analysis function and allows the user to alter variables relating to the function
<i>Analysis Controls</i>	

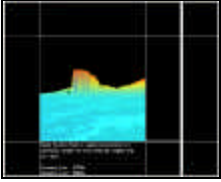
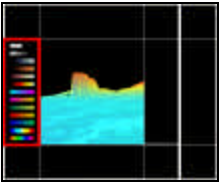
Alpha values	Sets the transparency Value of the Alpha Analysis function
Function ranges	Sets the maximum and minimum color values of given a function
Color range	Sets the maximum and minimum color values
Image/Elevation Controls	
Load Image	Loads a 2d image such as an aerial photograph
Load DEM	Loads a 2d image to be used as extra layer of detail on the scanned DEM model
Elevation	Sets the Elevation Values of the DEM paint option
Color	Sets the color value of the color paint option
Brush Size	Sets the DEM or color brush size
Eraser Size	Sets the DEM or color Eraser size
Color Bar Controls	
(Graphical)	Provides a palette of color ranges that can be chosen to suite the chosen analysis function

Figure 5.6 Table describing functions of the Control Window .

The Viewing Window

Due to its limited scale, the physical model cannot provide a perspective view of a given site. Since landscape designers are often concerned with the experiential quality of a particular design they will often use a handheld video camera or medical endoscope to view a physical model from a human-scale perspective. We aimed to provide this ability by rendering perspective views of the model directly on the computer.

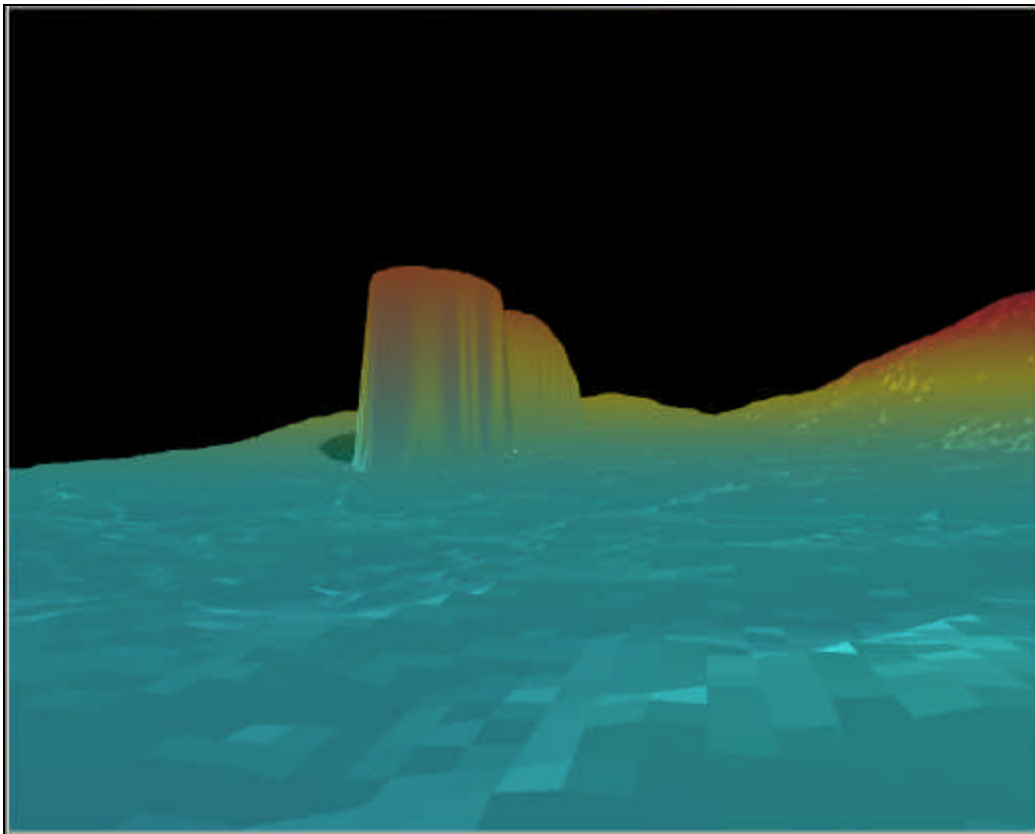


Figure 5.7 Screenshot of the Viewing Window.

The *Viewing Window* projects a 3-dimensional view of the landscape that is updated with each scan cycle. A cursor click on the physical model is used to define a view origin six feet above the surface of the model and the point of view dynamically follows the cursor as it is moved around the model. The fly-through function is currently being implemented that will allow the landscape designer to define a critical path through the physical model using a series of cursor-defined points.

5.3 Analysis Functions

Depending on the users' specific needs for landscape analysis *Illuminating Clay* can be operated in one of two modes – *SCANcast* or *CADcast* (v.2).

Mode 1 – *SCANcast*

SCANcast is the default-operating mode for *Illuminating Clay*. This mode allows the geometry of the landscape model to be 'scanned' and used as the input for one of a number of landscape analysis functions. The results of this function are then 'cast' back onto the surfaces of the model. These analysis functions range from augmenting the users geometric understanding of the model (for example highlighting areas of greater and lesser slope) to representing the relationship between dynamic systems (such as water flow) and the fixed topography of the landscape model.

Before analysis, the topography of the physical model is captured by the laser scanner and stored in memory as a 3-dimensional point cloud. This point cloud is converted into a regular matrix of elevation values identical in format to the Digital Elevation Model described in the previous chapter. This simple data format can be used as an input to a wide range of landscape analysis functions that have been developed within the geosciences.

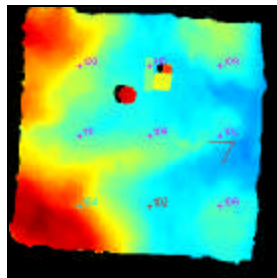


Figure 5.8 Digital Elevation Model represented as color values.

```
for each pixel [i, j]
do   If PixelDEMData > maxZ
      then DEM ← maxZ;
      else if PixelDEMData < minZ
           then DEM ← minZ;
```

Figure 5.9 Pseudo code for DEM generation.

We have provided a small library of standard landscape analysis functions to demonstrate the potential for *Illuminating Clay*. We have purposefully left this library open ended and allowing room for expansion. A road builder may, after all, require a completely different set of computational lenses on the landscape than a botanist, geoscientist or city planner. Some of these functions are described below.

Analysis 1. *Slope*

A thorough understanding of the slope is important to almost all aspects of landscape design. For example slope gradients affect the positioning of roads, buildings, power-lines and so forth.

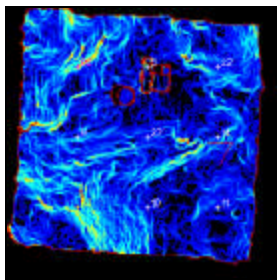


Figure 5.10 The Slope analysis function.

The calculation of slope, involves processing the DEM using two *Sobel* filters to determine the x and y derivatives of the topographic surface (f'_x and f'_y). The resulting gradient is: $\nabla f = f'_x \vec{i} + f'_y \vec{j}$. The absolute value of this function returns the slope at a given point in the topography. The slope value is displayed on the model using a color map ranging from red to purple, where the two extremes correspond to the maximum and minimum slope values.

The derivatives of the hypsometric curves of the landscape are computed locally for each cell on the within a 3 x 3 cell window and the cell is successively moved over DEM. The slope value is computed by using a second order finite difference algorithm fitted to the four closest neighbors in the window.

$$\tan S = [(\frac{dz}{dx})^2 + (\frac{dz}{dy})^2]^{0.5} \quad \frac{dz}{dx} = \frac{z_6 - z_4}{2d} \quad \frac{dz}{dy} = \frac{z_2 - z_8}{2d}$$

1	2	3
4	5	6
7	8	9

```

for each pixel [j, i]
do   for k ← 0 to 2 and for m ← 0 to 2
      do   if (i+k ≥ 0) and (i+k ≤ width) and (j+m ≥ 0) and (j+m ≤ height)
            then Cell[k*3+m] ← PixelDEMData[(j+m-1), (i+k-1)]
            else   Cell[k*3+m] ← 0

      diff1 ← (-Cell[1]-2*Cell[2]-Cell[7]+Cell[3] + 2*Cell[6] + Cell[9])*0.125
      diff2 ← (Cell[1]+2*Cell[2]+Cell[3]-Cell[7] - 2*Cell[8] - Cell[9])*0.125

      slope[j, i] ← sqrt(diff1*diff1 + diff2*diff2)*100 / PixelDistance

```

Figure 5.11 Pseudo code for the Slope analysis.

Analysis 2. Curvature

The slope analysis is sufficient for most purposes, being the first derivatives of the landscape surface. However for geomorphological analysis, the second differential of convexity is also useful. The curvature of the landscape is the rate of change of slope along a contour, measured in units of radians per millimeter and is useful for showing the tendency of water to converge in valleys or diverge on ridges.

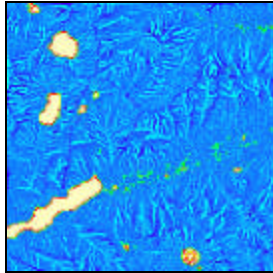


Figure 5.12 The Curvature analysis function.

The algorithm takes the input *PixelDEMData* and applies third-order finite difference estimator using all eight outer points of the 3 x 3 window.

$$planC = 2 * (DG^2 + EH^2 + FGH) / (G^2 + H^2)$$

$$D = [(z4 + z6) / 2 - z5] / d^2$$

$$E = [(z2 + z8) / 2 - z5] / d^2$$

$$F = (-z1 + z3 + z7 - z9) / 4d^2$$

$$G = (-z4 + z6) / 2d$$

$$H = (z2 - z8) / 2d$$

1	2	3
4	5	6
7	8	9

```

for each pixel [j, i]
do   for k ← 0 to 2 and m ← 0 to 2
      do   if (i + k - 1 ≥ 0) and (i + k - 1 ≤ width) and (j + m - 1 ≥ 0) and (j + m - 1 ≤ height)
            then   Cell[k * 3 + m] = PixelDEMData[(j+m-1), (i+k-1)]
            else   Cell[k * 3 + m] = 0

            dd ← ((Cell[3]+Cell[5])*0.5 - Cell[4]) / (pixelDistance*pixelDistance)
            ee ← ((Cell[1]+Cell[7])*0.5 - Cell[4]) / (pixelDistance*pixelDistance)
            ff ← (-Cell[0]+Cell[2]+Cell[6]-Cell[8]) / (pixelDistance*pixelDistance*4*4)
            gg ← (-Cell[3]+Cell[5]) * 0.5 / (pixelDistance*pixelDistance)
            hh ← (Cell[1]-Cell[7]) * 0.5 / (pixelDistance*pixelDistance)

            curvature[j, i] ← 2.0*(dd*gg*gg + ee*hh*hh + ff*gg*hh) / (gg*gg + hh*hh)

```

Figure 5.13 Pseudo code for Curvature analysis

Analysis 3. Profile Curvature

Profile Curvature is the rate of change of aspect along a flow line, again with units of radians per millimeter. It measures the rate of change of potential gradient, which is closely related to the flow acceleration and deceleration of water and influences soil erosion and deposition.

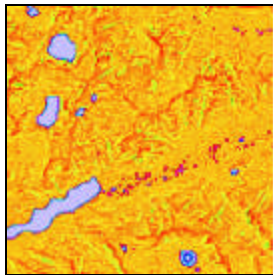


Figure 5.14 The Profile analysis function.

Again, the algorithm applies third-order finite difference estimator using all eight outer points of the 3 x 3 window.

$$profileC = -2 * (DH^2 + EG^2 - FGH) / (G^2 + H^2)$$

$$D = [(z4 + z6) / 2 - z5] / d^2$$

$$E = [(z2 + z8) / 2 - z5] / d^2$$

$$F = (-z1 + z3 + z7 - z9) / 4d^2$$

$$G = (-z4 + z6) / 2d$$

$$H = (z2 - z8) / 2d$$

1	2	3
4	5	6
7	8	9

```

for each pixel [j, i]
do   for k ← 0 to 2 and m ← 0 to 2
      do   if (i + k - 1 ≥ 0) and (i + k - 1 ≤ width) and (j + m - 1 ≥ 0) and (j + m - 1 ≤ height)
            then   Cell[k * 3 + m] = PixelDEMData[(j+m-1), (i+k-1)]
            else   Cell[k * 3 + m] = 0

            dd ← ((Cell[3]+Cell[5])*0.5 - Cell[4]) / (pixelDistance*pixelDistance)
            ee ← ((Cell[1]+Cell[7])*0.5 - Cell[4]) / (pixelDistance*pixelDistance)
            ff ← (-Cell[0]+Cell[2]+Cell[6]-Cell[8]) / (pixelDistance*pixelDistance*4*4)
            gg ← (-Cell[3]+Cell[5]) * 0.5 / (pixelDistance*pixelDistance)
            hh ← (Cell[1]-Cell[7]) * 0.5 / (pixelDistance*pixelDistance)

            curvature[j, i] ← -2.0*(dd*hh*hh + ee*gg*gg + ff*gg*hh) / (gg*gg + hh*hh)

```

Figure 5.15 Pseudo code for Curvature analysis

Analysis 4. Local Drain Direction

The representation of water flow and resultant erosion in the landscape helps the landscape designer to site housing complexes, dams, roads or other interventions while visualizing the (often non-intuitive) consequences on water flow systems. In particular, our land erosion algorithm can show the amplified effects of small modifications in the landscape. We have written an algorithm to calculate the Local Drain Direction (LDD).

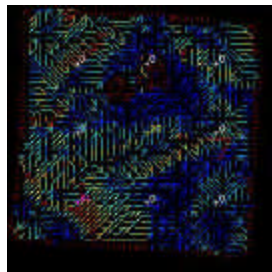


Figure 5.16 The Local Drain Direction analysis function.

The flow of water over a grid surface is determined by the steepest downhill direction in a 3 x 3 window of cells. The algorithm computes a new attribute of flow direction by taking eight different directional values expressed as degrees. This results the new grid overlay that is a so-called Local Drain Direction. Each cell contains a directional type integer of value flow direction:

$$\text{flow direction} = f \text{ for } \max_{(f=1,8)} \{ Z_f \mid Z_{ij} - Z_{i \pm 1, j, j \pm 1} \}$$

in which the distance w is 1 for North, South, East and West neighbors and $1/\sqrt{2}$ for diagonals.

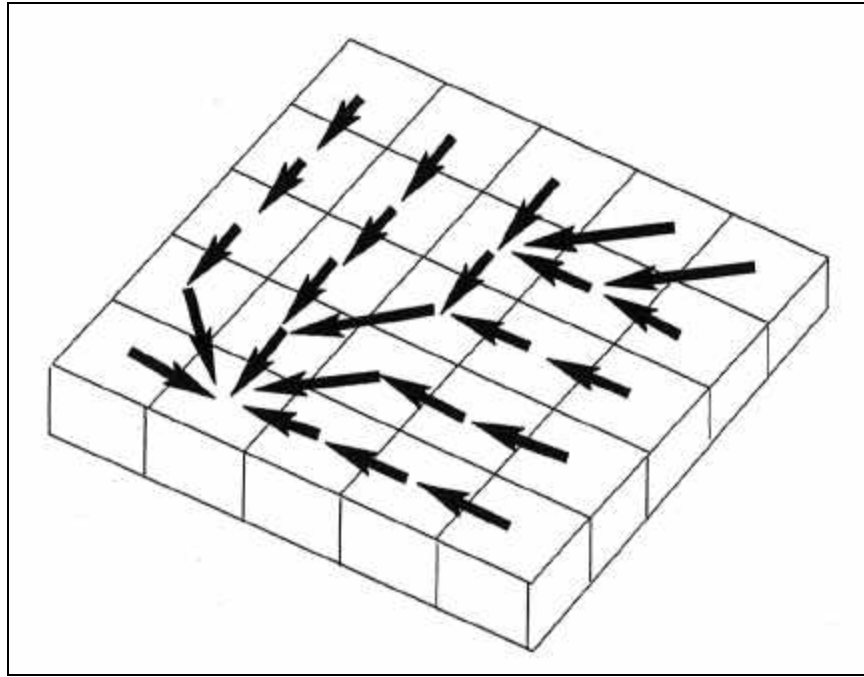


Figure 5.17 Local drain direction vectors. [Burrough and McDonnell, 1998]

Analysis 5. Aspect

The *Aspect* landscape analysis function returns a color dependent on the direction in which a particular area of the topography is facing, north, east, south or west. This analysis is useful when siting crops or building structures that would be particularly affected by their exposure to lighting conditions. The concept of aspect is inseparable from slope from a physical as well as an analytical perspective. The particular orientation of a slope is called the aspect. The aspect is also computed from the first order of the surface geometry.

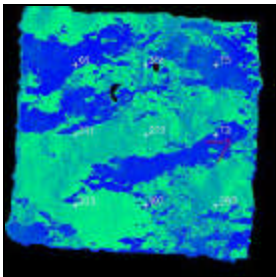


Figure 5.18 The Aspect analysis function.

The aspect value is computed by using a second order finite difference algorithm fitted to the four closest neighbors in the window. The result of the aspect algorithm comes in degrees of 0 – 360.

$$\tan A = -(\frac{dz}{dx})/(\frac{dz}{dy}) \quad \frac{dz}{dx} = \frac{z_6 - z_4}{2d} \quad \frac{dz}{dy} = \frac{z_2 - z_8}{2d}$$

1	2	3
4	5	6
7	8	9

```

for each pixel [j, i]
do   for k ← 0 to 2 and for m ← 0 to 2
      do   if (i+k ≥ 0) and (i+k ≤ width) and (j+m ≥ 0) and (j+m ≤ height)
            then Cell[k*3+m] = PixelDEMData[(j+m-1), (i+k-1)]
            else Cell[k*3+m] = 0

      diff1 ← (-Cell[1]-2*Cell[2]-Cell[7]+Cell[3] + 2*Cell[6] + Cell[9])
      diff2 ← (Cell[1]+2*Cell[2]+Cell[3]-Cell[7] - 2*Cell[8] - Cell[9])

      if diff2 = 0
      then if diff1 >=0
            then aspect[j, i] ← PI * 0.5
            else aspect[j, i] ← -PI * 0.5
      else if (abs(diff2) / diff2) >= 0
            then aspect[j, i] ← 270 - 180/PI*(atan(diff1/diff2))
            else aspect[j, i] ← 270 - 180/PI*(atan(diff1/diff2)+PI)

```

Figure 5.19 Pseudo code for Aspect analysis.

Analysis 6. Shadows & Solar Sum

It is also possible to simulate the positions of shadows in the landscape. The *Shadow* simulation displays shadow angles for a given sun position dependant on time, season and global position. These simulated shadows are projected onto the model as black and white images. By changing the sun position over time it is possible to view lighting conditions through the passage of a day or year. It also becomes possible to determine the total amount of solar radiation at a given point on a site of known latitude and longitude presented as an image of *Solar Sum* simulation. As with aspect this kind of information may help the landscape designer to position crops, housing complexes, solar energy collectors and other sunlight affected insertions in the landscape.

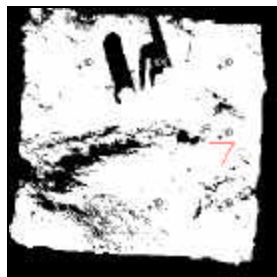


Figure 5.20 The Shadow analysis function.

The shadow-casting algorithm, developed by Carlo Ratti [Ratti, 2002], computes the upper surface of the volume of air that is in shadow. This can be done by repeatedly by shifting the DEM and reducing its height. The running time corresponds to the number of pixels of the DEM rather than the complexity of the model allowing shadows in the landscape to be generated in real time.

```

azimuth ← solar_azimuth(altitude, year, day, time)
altitude ← solar_altitude(altitude, year, day, time)
step ← 1

While (above zero level) and (inside the image)
  do    initialize shadow[i, j] all zeros
        assume below zero level

        if  $(\text{PI}/4 \leq \text{azimuth} \leq \text{PI} \cdot 3/4)$  or  $(\text{PI} \cdot 5/4 \leq \text{azimuth} \leq \text{PI} \cdot 7/4)$ 
          then  dy ← sign(sin(azimuth)) * step
                dx ← -sign(cos(azimuth)) * abs(round(step/tan(azimuth)))
                ds ← abs(1/sin(azimuth))
          else  dy ← sign(sin(azimuth)) * abs(round(step/tan(azimuth)))
                dx ← -sign(cos(azimuth)) * step
                ds ← abs(1/cos(azimuth))

        dz ← ds * step * tan(altitude) * pixelDistance

        xc1 ← ((dx+abs(dx)) * 0.5) + 1
        xc2 ← (imageWidth + (dx-abs(dx)) * 0.5)
        yc1 ← ((dy+abs(dy)) * 0.5) + 1
        yc2 ← (imageHeight + (dy-abs(dy)) * 0.5)

        xp1 ← xp1 - ((dx-abs(dx)) * 0.5) - 1
        xp2 ← (imageWidth - (dx+abs(dx)) * 0.5)
        yp1 ← yp1 - ((dy-abs(dy)) * 0.5) - 1
        yp2 ← (imageHeight - (dy+abs(dy)) * 0.5)

        differX ← xc1 - xp1
        differY ← yc1 - yp1

        for each pixel [i, j] of i ← yp1-1 to yp2-1 and j ← xp1-1 to xp2-1
          do    if DEM[(i+differY), (j+differY)]-dz < 0
                then  shadow[i, j] ← 0
                else  shadow[i, j] ← DEM[(i+differY), (j+differY)]-dz

        for each pixel [i, j] of the image
          do    if shadowVolume[i, j] < shadow[i, j]
                then  shadowVolume[i, j] ← shadow[i, j]
                    above zero level ← true

        step ← step + 1
end while

```

Figure 5.21 Pseudo code for the Shadow analysis.

Analysis 7. Shadow Sum

Shadow Sum simulates the accumulative sunlight on the surface of the landscape on any given day. Like the shadow simulation, shadow sum computes shadow volume, but is more computationally expensive. The shadow sum algorithm simply increases the time of day by a set interval and uses the solar position algorithm to compute the position of the sun. The combined values of these shadow simulations are merged to provide to total shadow sum.

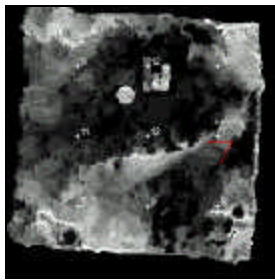


Figure 5.22 The Shadow Sum analysis function.

```
Initialize shadowVolume
for each hour h in a day
  do    azimuth ← solar_azimuth(altitude, year, day, h)
        altitude ← solar_altitude(altitude, year, day, h)
        if altitude > 10 rads
          then shadowVolume ← shadowVolume + shadow_simulation()
return shadowVolume
```

Figure 5.23 Pseudo code for Shadow Sum analysis.

Analysis 8. View Shed

It is often crucial to know the precise field of view from any given position in the landscape. The field of view can be calculated by passing the DEM through an image-processing algorithm that computes areas that are visible from a point in the model selected by the designer. Applications are varied, from helping to decide the positioning of line-of-sight telecommunication devices (such as a microwave transceivers) to the passage of routes that maximize or minimize views (scenic or smuggler's paths).



Figure 5.24 The View Shed analysis function.

The algorithm is based on the adaptation of the shadow casting routine. Recall the procedure to cast shadows on a DEM, based on the computation of the shadowing volume. The latter was obtained with iterative shifting of the DEM and its simultaneous reduction in height. It represented the height of the separation surface between shadow and light under a beam of parallel rays. The view-shed algorithm works in the same way, although light rays are now not parallel but divergent.

Analysis 9. Least Cost of Passage (under development)

This analysis function can help the user determine the most appropriate positioning of a roadway or path, since it indicates trajectories on the landscape that minimizes the cost of passage. This cost can be calculated to take into account different parameters such as the actual cost of construction or the cost in time taken to complete a particular route.

MODE 2 – CADcast v. 2

The *Illuminating Clay* interface relies on the initial production of a scale model of the landscape site. However, constructing this model in an accurate and efficient manner may appear to be a stumbling block in this physical modeling approach to landscape analysis. How does the user first construct an accurate model of the desired site? The third operating mode – *CADcast v.2* (based on the earlier *CADcast v.1* described in Chapter 2) – allows the user to make 3-dimensional models using standard materials such as clay or plastacine. The *CADcast* mode operates by comparing the geometry of the workspace

with a desired topography stored in computer memory as a 'CAD' file. This source of this computer model could range from DEM data purchased from GIS sources or it could be generated from the traced contour lines of conventional topographic maps.

As the user places clay material into the workspace it is illuminated with a color indicating when it is within or outside the volume of the CAD model. By varying this color (from purple to yellow inside the volume and from orange to blue outside the volume) the *CADcast* mode indicates the level of disparity between the physical and CAD models. For example if an area of the physical model is highlighted in orange this indicates that it is outside the volume of the digital model. As material is removed from the model the color of the surface becomes progressively bluer until the surface of the physical model and digital model are the same. At this point there is a discrete change to the color red to indicate that an exact match between the surface of the physical and digital models has been reached.

While this technique has the potential for allowing for the time and cost efficient construction of physical models of existing landscape forms the current set-up is not sufficiently accurate or speedy for practical use. Noise introduced by the CCD of the scanning device excludes sub-millimeter tolerances. The technique is also rather slow and laborious and would be vastly improved by faster and more accurate scanning technology. While these technologies are in existence they are currently too expensive for the scale of this research project it is possible to produce accurate physical models in a number of alternative, though less elegant ways. We have used *Lego* and cardboard laminates to build up a model substructures. It may also be possible to cast the landscape in a 3D mold (NC milled or 3D plotted) using fluidized clay.

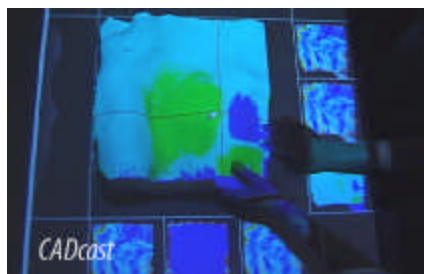


Figure 5.25 *CADcast allowing the comparison of physical and digital models.*

Analysis 10. *Cut and Fill*

While the level of tolerance offered by our current laser scanning technology currently limits the use of *CADcast* as an aid to model construction this ability to compare physical and digital models is extremely useful for calculating areas of cut and fill. From an environmental and economic standpoint it is in the interests of landscape designers to minimize the amount of earth taken from or added to the site. By extension it is also advantageous to equalize the amount of earth cut from one area or added to another since this will avoid the need to transfer soil, rocks to or from the given site. The *Cut and Fill* function offers landscape designers the ability to quantitatively and intuitively understand the amount of earth they are cutting or filling in a landscape model.

The analysis function captures the geometry of the model and then highlights any changes in the model in areas of color. As with *CADcast* the color of the highlighted areas both indicates the volume of earthy that has been removed and whether it is a positive or negative amount. While this color information gives an intuitive sense of the amount of material involved it is also possible to view a quantitative output put from the cut and fill function that describes the amount of earth move, taken away or added as a numeric volume.

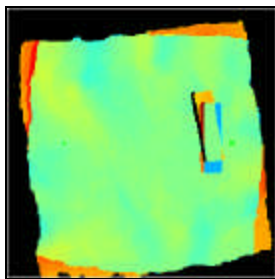
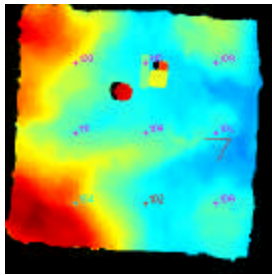


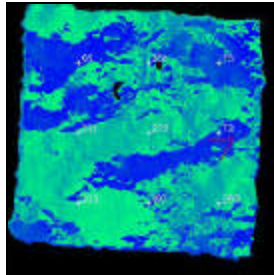
Figure 5.26 *The Cut & Fill analysis function.*

$$Cut = \sum_{E_c < E_i} (E_i - E_c) * Pixel^2 \quad Fill = \sum_{E_c > E_i} (E_c - E_i) * Pixel^2$$

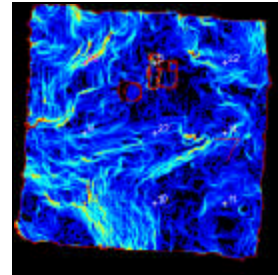
The computational algorithm simply subtracts the initial DEM elevation values any that are changed when the model is modified. The differencing volumes at each cell are integrated over the grid to produce the total cut and fill information on the site.



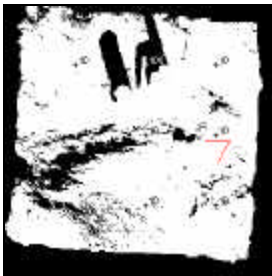
Elevation



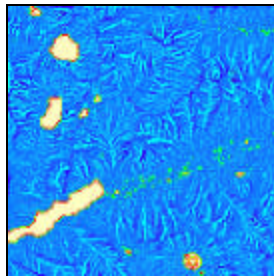
Aspect



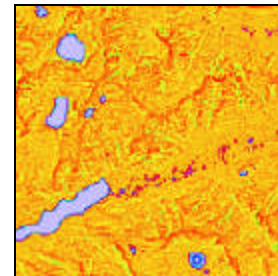
Slope



Shadowing



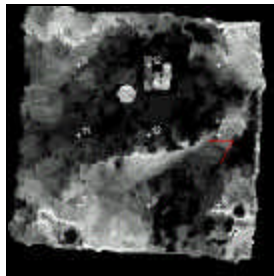
Profile



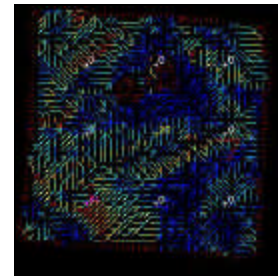
Curvature



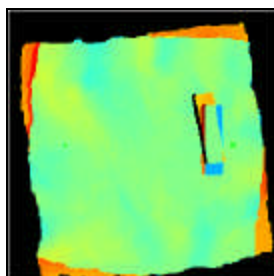
View Shed



Solar Sum



Local Drain Direction



Cut & Fill

Figure 5.27 Visual Summary of analysis functions.

5.4 Software Infrastructure

For simplicity the software infrastructure was organized into eight independent modules. Each module is a separate C++ class interconnected through a standardized data stream. These streams are *PixelDEMData* and *PixelImageData*. *PixelDEMData* represents the 3-dimensional landscape model as an array of elevation values, the Digital Elevation Model. It also contains a unit *Pixel Distance*, and two floating-point numbers indicating the maximum and minimum elevation values in the array. *PixelImageData* represents a 2D image in an array of 32-bit pixels, containing four 8-bit red, green, blue, and alpha values.

This modular structure allows each module to be separately rewritten or further improved without affecting the overall software infrastructure. An additional benefit of the modular structure is that each module can be processed in parallel and the different functions, such as scanning, simulation and user interaction, can be simultaneously processed. With out such an approach the system performance would be subject to frequent interruptions in the scanning process due to varying degrees of complexity in the simulation module or increased activity in the interaction module. Careful consideration also was put into how various sets of data, geometric or graphical, scanned or drawn were interrelated so as to minimize analysis overhead while still allowing separate inputs to be extracted from the system at a later point. Each component of the six modules in this structure is described below.

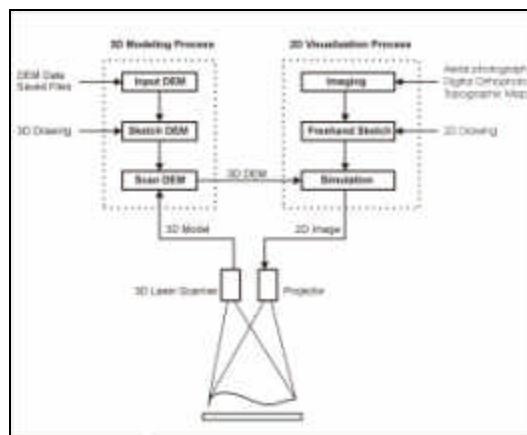


Figure 5.28 Modular infrastructure of *Illuminating Clay*.

Module 1. Scan DEM

The *Scan DEM* module is implemented on top of the *VIVID* Software Development Kit (SDK) to drive the automatic scanning process. The SDK provides basic functions to remotely control the *VIVID 900* scanner and to convert *VIVID* output data into 3-dimensional data. The *Scan DEM* module drives the scan operation through a SCSI interface, converts raw *VIVID 900* data into the standard *PixelDEMData*, processes a median filter to reduce the noise, and finally passes the result into the *Integrating DEM* module that integrates all *PixelDEMData* from multiple sources.

Scan operation

The *Scan DEM* module starts a scanning cycle by first initializing the SCSI device with a function call to SDK's *VividIISCSIInitialize*. After setting the SCSI interface, it specifies several scan parameters, such as auto focus range, the fast scan mode, and laser power. Based on these parameters, the *VIVID 900* scanner automatically refines the distance estimate, and adjusts the focus, the laser-scanning range and the laser power via a function call to *VividIISCSIActiveAF*. During the active auto focus the distance is more accurately estimated and the appropriate laser power is determined. Then another function call manually reduces laser power to 80% to minimize the noise caused by an excessive laser power. By using the pre-specified scan parameters, the *VividIISCSIRelease* function performs the scan operation. Finally, the *VividIISCSIReadPitch* function can read raw *VIVID 900* data, *range data*, from the scanner's image memory.

The scanning cycle is continuously performed at a rate of around 1Hz. The image memory data is renewed when a release operation is issued and retained until the next operation. In the continuous scan operation, the data in the image memory is correspondingly updated to record the current modeling process. The *VIVID 900* scanner can support two scan modes, the FINE mode and the FAST mode. Although it can gain 640 x 480 grid points in the FINE mode, the throughput drops down to 0.25Hz. To achieve a real-time user interaction, we used the FAST mode to gain a 320 x 240 grid

points with each scan cycle. The rectangle grid data then is cropped to a 240 x 240 array in order to fit the square format of the workspace. This scan resolution defines the standard size of the internal *PixelDEMData* dataset that is used for inter-module communication.

Data conversion

The *range data* transferred from the scanner's image memory contains 3D information, but it is not represented in terms of a 3-dimensional Cartesian coordinate system. The *VividIIConvertCdm2Raw3D* function converts raw *VIVID 900* data to raster 3-dimensional point data. Each point contains three floating-point numbers, x, y, and z values of the 3-dimensional coordinates. While the conversion is being performed the *VividIIConvertCdm2Raw3D* function performs a hole filling operation to average x, y, and z values of neighboring points to replace invalid or non-existent points in the data array.

The final stage of conversion is to translate the raster 3-dimensional point data into the *PixelDEMData* format before it can be passed to the *Integrating DEM* module. To ensure compatibility with the other *PixelDEMData* in the site model coordinate system, the z values are transformed to align with the coordinates of the physical workspace with the origin at the center of the turntable and the z-axis increasing towards the scanner. The x and y values of each of the 3D points are discarded and a single floating point *PixelDistance* is used to represent the average distance on the x-y plane between two points in the data grid. In this form the raster 3-dimensional point data are fully compatible with other forms of DEM data.

Median Noise Reduction

A serious problem with the *VIVID 900* scanning process is that it relies on the technology of a Charged Coupled Device camera and is therefore liable to generate non-stable data sets. Fluctuations in as much as 10mm were commonly encountered even if the physical model remained completely still while scanned. Adjusting the laser power led to some

improvement. However, it was also necessary to add a median value filter after the raster 3-dimensional point data was translated into the *PixelDEMData*. The median filter was found to be a far more robust method for reducing the level of noise than the mean filter since invalid z values did not affect adjacent values and so clear boundaries between forms and shapes were preserved.

Module 2. *Sketch DEM*

While the physical clay model is the primary means for inputting geometric information into the computational analysis, for practical purposes it is sometimes useful to be able to import or draw elevation values that can be used as the basis for simulation. This is especially important if there is an existing map of building layouts that the landscape designer would like to analyze. While it is possible to physically construct these kinds of structures physically it is much simpler to import a single image that describes the geometry of same structure in a purely visual representation. This form of input is also useful when the designer is beginning to investigate an issue and does not necessarily want to commit to a physical model design.

The *Sketch DEM* module is designed to allow users to sketch changes in topography directly on the physical model surface and view the resultant affects of these changes on the results of the analysis functions. The module provides a simple 3-dimensional painting program that allows designers to draw marks with can be given specific height values. While the mouse cursor can only be used to define the position of the 3-dimensional pen in the x-y plane, an elevation parameter can be set to a required z value. The output of the *Sketch DEM* module is kept separate from the *PixelDEMData* allowing the former state of the model before drawing to easily be recovered. The module finally outputs to the Integrating DEM module and merges it with other *PixelDEMData*.

Module 3. *Sketch Image*

The *Sketch Image* module provides a similar interface to the *Sketch DEM* module. Designers use the mouse to draw marks and lines directly upon the physical surface of the model. Instead of creating a *PixelDEMData*, the *Freehand Sketching* module produces raster image data *PixelImageData*. It allows designers to mark key points on 3D models, which can be easily cleaned up from the surfaces later. As with the *Sketch DEM* module the *Sketch Image* module allows users to import existing imagery-such as aerial photographs that maybe useful in aiding the landscape designer.

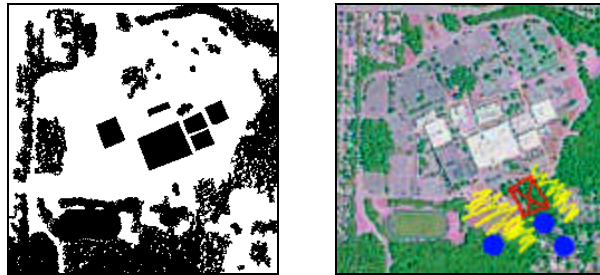


Figure5.29 The SketchDEM allowing bitmap DEM import (left) and the SketchIMAGE (right) allowing bitmap image import.

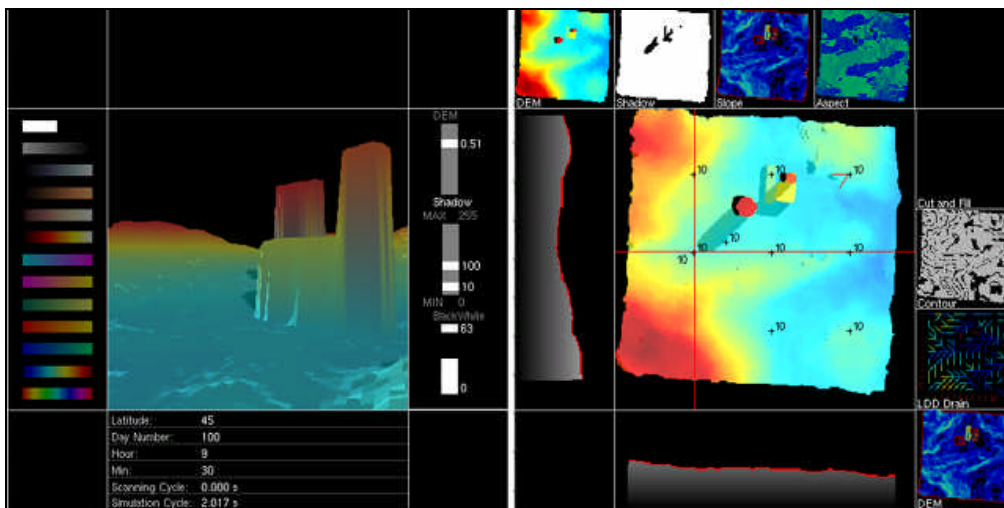


Figure5.30 The standard DEM based on a laser scan of the physical topography.



Figure 5.31 The Imported DEM Image.

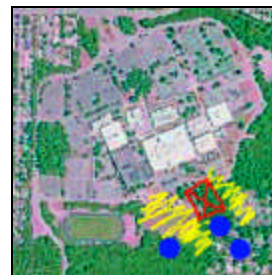
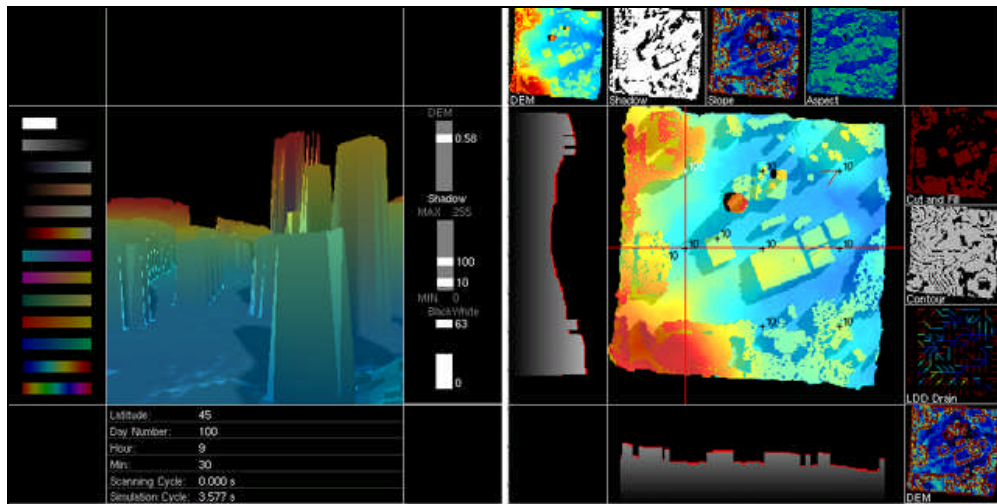
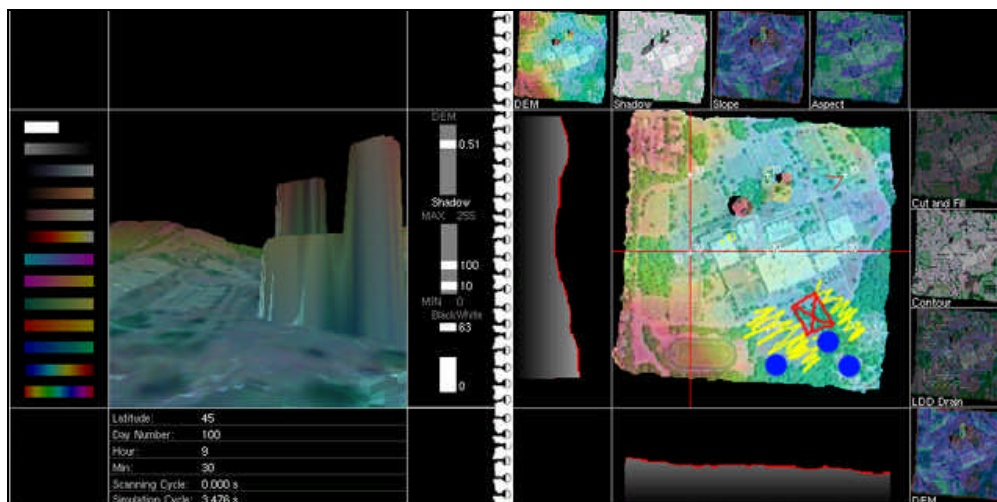


Figure 5.32 Imported aerial photograph.



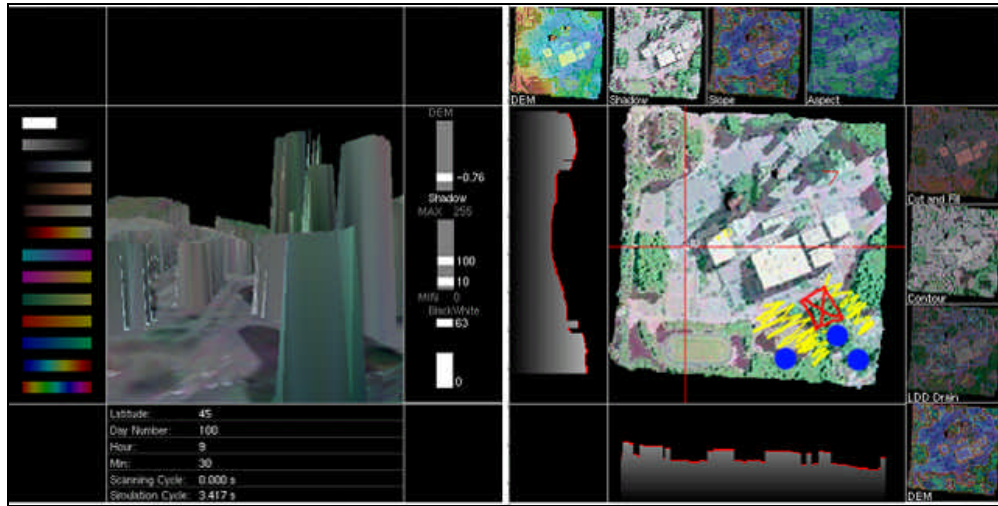


Figure 5.33 The combined DEM import and aerial photograph.

Module 4. Integrating DEM

The *Integrating DEM* module provides basic functions to import external DEM files (the standard in Landscape analysis), to overlay the external laser scanned *PixelDEMData* and internal drawn *PixelDEMData* and allows the user to export this as a single DEM file.

Module 5. Simulation Module

Simulation Module issues the *initSimulation* to initialize the data from the *Integrated DEM* array for the purposes of a particular analysis function. The *Simulation Module* calls *nextSimulation* to compute the simulation algorithm based on the current *PixelDEMData*, and then returns the result. The *Simulator* issues an *endSimulation* call to stop the analysis function and clean up the memory.

The completed analysis function returns an array in the same format as *PixelDEMData* but one that no longer represents elevation values, but simulation results corresponding to the grid points. Before the *Projection Module* can display the result, it needs to be visualized in a raster image represented by a *PixelImageData*.

The color conversion algorithm provides sixteen possible data color mappings. Each color map is described in 64 color entries. Each color entry contains three floating-point values in the range 0-1, representing R, G, B values, respectively. A *PixelDEMDData* of the simulation result is rescaled in the range of 0-255 floating-point values. The new floating-point values are further mapped into the range of 0-63, corresponding to the 64 color entries of a particular color map. Then, the integer is used to transfer a color entry from a color space, and the decimal portion is used to interpolate two color entries. The results are concatenated to describe a RGB value at the current point. For example, X is a floating-point value in 0-63. Int(X) represents the integer part of X and Dec(X) represents the decimal part. Then the color value of the point is:

$$Colorspace[Int(X)] + Dec(X)*(Colorspace[Int(X)+1]-Colorspace[Int(X)])$$

The *Simulation Module* finally outputs the *PixelImageData* translated through an analysis function and a colour mapping process to describe the results of the simulation in raster image format.

Module 6. Integrating Image Module

The *Integrating Image Module* provide integrates the two images of *PixelImageData* derived from the *Simulation Module*, *Analysis Alpha* and *Analysis Beta* with any free hand or imported image data. Compositing these multiple *PixelImageDatas* requires an alpha-blending algorithm. The *PixelImageData* implements non-premultiplied alphas, in which a pixel contains 8-bit R, G, B, alpha values, respectively. The definition of the compositing operation is:

$$C_{result} = Alpha_{foreground} * C_{foreground} + (1 - Alpha_{foreground}) * C_{background}.$$

This single merged *PixelImageData* is outputted into the *Projection Module*.

Chapter 6.



6. Illuminated Sites

The evaluation of *Illuminating Clay* took three different forms. First two experts in landscape design were interviewed about their reaction to *Illuminating Clay*. Second, a controlled user study test was carried out. Finally, *Illuminating Clay* was used as the basis for a landscape design course – *Illuminated Sites*.

6.1 Evaluation Methodology

Formal Interviews and Surveys

Formal interviews were arranged with landscape design faculty in order to gain expert opinions on *Illuminating Clay*. This was seen as a good starting point for evaluation in helping to quickly determine the perceptions and expectations of the system.

Transcribed Record

These interviews were transcribed to text. This proved to be extremely helpful in organizing the large number of recorded comments into discreet groups. It also provided a means for easy quotation.

Participatory Observation

The use of *Illuminating Clay* interface with in the controlled tests and with in the classroom setting was largely evaluated through participatory observation, a standard technique used in anthropology. The technique takes advantage of the fact that the evaluator is present during the activities being evaluated and can make real time judgments about what is relevant to record. The technique also allows for the observation of subtle, but often significant aspects of group interaction. While the students and faculty were aware of the presence of observers, every effort was made to minimize the effects on how the class would have otherwise proceeded.

Video Documentation

Participatory observation has the advantage of allowing the evaluator to be involved in the activity undergoing evaluation. However, this immersive approach means that there may be important aspects that go unnoticed or are forgotten by a human observer. For this reason we documented each working session that used *Illuminating Clay* with a stationary video camera. This technique provided a useful reference for regular offline discussions between the evaluators. It also allowed anecdotal comments to be precisely transcribed and images relating to a certain activities to be captured at a later time. In addition the video documentation allowed us to carefully analyze the gestures, facial expressions and body language of users of *Illuminating Clay*.

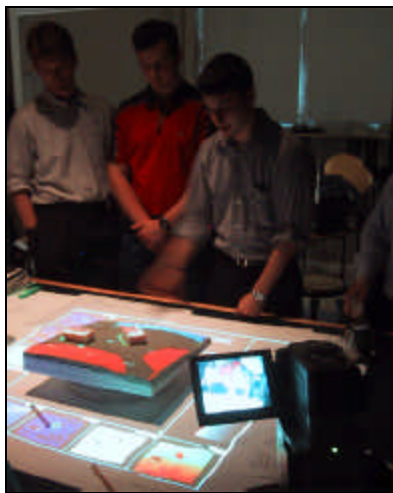


Figure 6.1 The use of the video camera to record controlled test and class sessions.

Photographic Documentation

We also took a large number of digital photographs. While these rarely captured specific aspects of student interaction they did provide a useful reference for offline discussion and were extremely valuable in illustrating more general aspects of the system in use.



Figure 6.2 Photographs from controlled test and class sessions.

Informal Comments and Discussion

Both during the implementation and during classroom use we received a great number of comments from visiting faculty, sponsors, landscape designers, students and other interested parties. These comments were extremely useful in gaining a general sense of the strengths and weaknesses of *Illuminating Clay*.

6.2 Formal Interviews

Interviews were arranged with Eran Ben-Joseph, a Hayes Career Development Assistant Professor at the *Department of Urban Studies and Planning, MIT* and Hope Hasbroucke, an assistant Professor of Landscape at the *Harvard Graduate School of Design*. These question and answer sessions proved to be extremely useful in formulating a clearer understanding of a number of relevant factors that are grouped under headings below. Since both interviewees are heavily involved in education this assessment is based around pedagogical goals.



Figure 6.3 Assistant Professors Eran Ben-Joseph (left) and Hope Hasbroucke (right).

General Comments

The overall response of both interviewees was generally positive. Prof. Ben-Joseph said of *Illuminating Clay* - *“In terms of understanding the site, in terms of understanding the limitation, in terms of understanding its impact, it's still great. Absolutely.”* Prof. Hasbrouke focused immediately on the power of dynamic displays on the surface of the physical models:

“What I liked about the Illuminating Clay is that after every action there was an immediately available visual display of analysis. Being able to model time and change, and the effect of weather and climate on a site, I think would be an important aspect in terms of what we encourage [landscape design students] to do.”

Prof. Hasbrouke went on to recognize our aims in bringing together the power of quantitative and qualitative manipulation - *“I think it would be a great design process tool, the ability to have all these measurements. And because it is physically present, the way that students are taught to draw, or to analyze at their desk is then also part of the digital experience as well.”*

Conventional Representation

Prof. Hasbroucke saw representation as key to the process of landscape design - *“...from making a representation they can actually learn; get some other types of information back.”* She describes her course as, *“A progression from numbers and words up through images, to 2D and 3D, then 4D representations”* and commented that *Illuminating Clay* could continue to support this cumulative approach to forms of representational media. She made the point that *“landscape suffers in its over-use of the plan as a way to communicate projects.... The plan describes the overall large- scale landscape systems work, where the perspective starts to deal with the experience. Which in many ways is what everyone is looking for....”* This final comment highlights the need for experiential understanding of the landscape in design and supports the motivation behind the 3-dimensional Viewing Window in the *Illuminating Clay* application.

When questioned about the particular issue of CAD based representation Prof. Hasbrouke raised the issue of cut and fill calculation - *“We use the Land-development Desktop module, which is part of the AutoDesk suite, to do the cut-and-fill and grading work.”* However, she focuses on some of the disadvantages of teaching this kind of tool:

“It's really hard to get through to their heads [students] that if I teach them ‘Change properties’ today in AutoCAD 14, then tomorrow in Auto CAD 2000 it's going to be some little icon in the upper right portion of the screen. Then next year it's going to be a different icon on a different portion of the screen. I refuse to do that. We try not to be application specific. Because of the international and nation-wide background of the students, it's difficult to dictate which software they should be using.”

Illuminating Clay addresses this issue by aiming to provide an interface that is not application specific and can allow designers (or in this case students) to focus on the task of design not the acquisition of specialized skills. For this reason Prof. Hasbrouke was supportive of the overall approach of *Illuminating Clay* as expressed in her own approach:

“I always encourage that there is a point where you change media. And you output, you draw on top of it, or you use the laser model and output a 3D model. You make an evaluation and then change it, and then you digitize that and go back into the computer, then work with that. So I use the 2D digitizers in studio, for a semester course studio now, and we have the 3D digitizer in the basement along with the laser cutter. As a design instructor I try to encourage the fact that they need to find ways to insert, then ways to move back and forth between the media.”

Prof. Ben-Joseph takes a more hard line view of introducing his students to new media:

“I force them in the intro class to start holding a pencil again, and at least do some drawings. Because I always tell them that drawing is a way of thinking and a way of synthesizing information.”

He comments on how drawing, as a form of tangible representation, helps in the design process describing it as *“a way of synthesis”* where as *“Computing sometimes eliminates it”* (the synthesis) and he expresses his appreciation for more tangible forms of media:

“For one, if it allows those people who are not as versed with drawing and their ability to read and understand drawings and its impacts in a traditional way, then what you have is something that is much more legible and much more tangible. Even to the planners, it can be used with tremendous impact.”

Representation - Dynamic Factors

Both professors emphasized the potential value of an interface that could represent the dynamic factors in the landscape: As Prof. Hasbrouke puts it - *“[Landscape design] is really based on ways on which you can represent or understand the dynamics of sites.”* Ben-Joseph expresses his ambition for a class using *Illuminating Clay* - *“some people take it through a couple of years [understanding dynamic forces in the landscape] and write a thesis on it in landscape architecture and I try to do it in one class.”* However, he points out that *Illuminating Clay* doesn’t necessarily help the experienced designer as much as a novice or non-expert - *“Some people can immediately see [dynamic systems in the landscape] in 3D; they know in their head what it looks like, what the shape of the earth is, and what impact it has. People who don't have that ability and experience won't be able to do that. So that's where it's extremely useful.”*

Scale

The most appropriate working scale remains relatively unresolved and the issue was raised in both interviews. Hasbrouke asked - *“I also was wondering at what scale it would be most effective. Is it at the backyard scale? Or 30-acre sites, or a regional scale? I think immediately if you know the slope is 30%, then you know that you're going to have to stabilize the soil. So it's going to impact construction and fabrication. I think it would then be really helpful. I think it would be helpful with the students too because sometimes with clay there's a scalelessness.”*

Collaboration and Communication

Hasbrouke recognized the power of *Illuminating Clay* in providing a platform for collaboration that was useful to specialists yet allowed non-experts to engage in the design process - *“I think that Illuminating Clay could do that also, in some ways, that it can be this collaborative workplace.”* However, Ben-Joseph raises the dilemma of having a representational aid that is too effective: *“It will create such an amount of information that somebody will find something wrong with the design.”*

General Problems

Hasbrouke and Ben-Joseph helped to identify a number of potential problems with *Illuminating Clay* and its use in a landscape design-teaching context.

Hasbrouke raises the specific technical issue of representing non-topographic volumes such as trees and buildings - *“How do you begin to address the volumetric types of representations that vegetation starts to address? Again, I think that's another problem for landscape architects when using digital representation techniques. Vegetation is pretty difficult.”*⁸

⁸ Since these comments were made, we have implemented the *Import DEM* and *Draw DEM* which allows these kinds of volumes to be easily rendered (see Chapter 5).

Ben-Joseph highlighted the fact that *Illuminating Clay* works best in terrain models with a dramatic elevation. - *“The laser works well when you have drastic changes in the landscape. And for that you have to go work in Nepal or Colorado.”* He also raises another potential problem - *“The big question is that [Illuminating Clay] is raster based, which is not any more necessarily the state of the art in terms of planning and computation. It's very rare to have raster based software.”*

An even more important consideration is the resultant effects of the use of such a novel technology on the teaching process in general. Ben-Joseph feels strongly about this issue and states:

“My frustration is mainly the integration of technology because a course starts to be about too many things. I think sometimes the students feel that it's actually making it more complex because we don't have time to concentrate on the more traditional way of doing it [engaging in landscape design exercises]. I think it may be better to have a class which just deals with the technology, that doesn't necessarily have all of the other elements that I need to cover from the curriculum point of view. But when you're trying to do both at the same time, build and improve a technology and run a course that has its own agenda and own focus and address its own situation, then it's extremely frustrating, particularly for me. What is happening right now is that it's thrown out of the lab into the class, with the expectation from the lab that the class is the vehicle to improve it, but the class is not specifically made for that.

I think there's an understanding, that it's not ideal. As much as you explain this to the students, the students are excited about it. I tell them you know, "it's only research and such", because it is also frustrating for them.

However, Hasbroucke takes a more optimistic view of the situation - *“That's what gets me excited about [Illuminating Clay]. It's that there's a sort of design environment and there's a sort of design thinking environment.”*

6.3 Controlled User Study

While the formal interviews helped to gain a general sense of how *Illuminating Clay* might be received in the landscape design context we wanted to compliment the relatively subjective opinions of the interviewees by running a series of controlled user studies with the hope of providing a more objective analysis of the *Illuminating Clay* platform.

Three groups of students balanced in sex, age, and experience were asked to solve a standard landscape design problem that involved the positioning of two building structures in a landscape site and the path of two driveways leading to the buildings. Students were asked to minimize the amount of cut and fill. Each group was given a different set of tools and materials. *Group A* was given only a contour map of the given site and some pens for annotation. *Group B* was given a clay model of the site as well as the map and pens. *Group C* was given was asked to use *Illuminating Clay* in addition to the topographic map and pens.

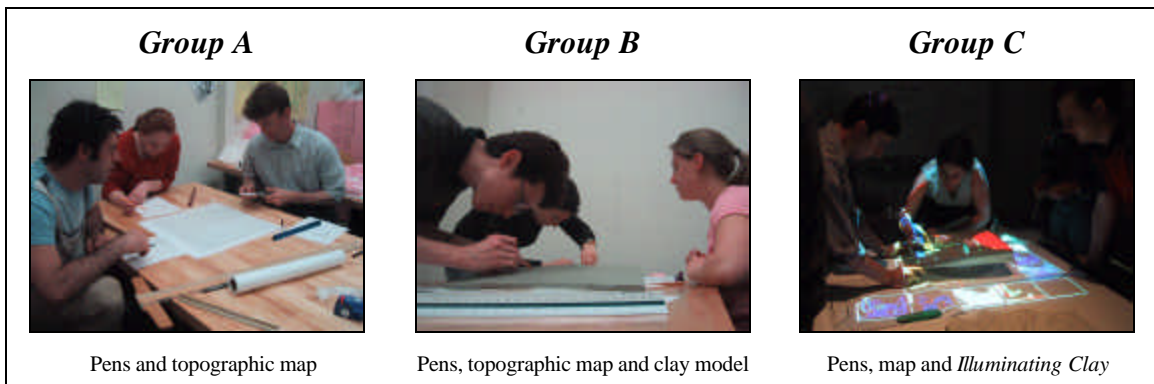


Figure 6.4 The three test groups

Each group was videotaped as they worked, and asked to voice their thinking process as much as possible over the twenty minutes allocated for the exercise. At the end of this period each group gave a ten-minute account of their solution using the same tools and materials as were used in the exercise. Finally, a group discussion allowed students to voice their experiences in retrospect and make any comments that had not been raised in either during the design process or during individual group presentations.

Explanation

Illuminating Clay can function as both a design tool and a presentation tool for landscape design. That is what we hoped to test in the design of this experiment. We also wanted to test *Illuminating Clay* during the early stages of the landscape design process and for this reason we kept the experiment length to twenty minutes and only supplied the control groups with tools and materials that are commonly used at the early stages of design – the topographic map, pens and a physical clay model. As a standard tool in landscape design *AutoCAD*[™] was also considered as a possible forth alternative, but the comments from expert interviewees suggested that *AutoCAD* is not commonly used as an early stage design tool but rather as a tool for later analysis and drafting.

The evaluation methodologies described above were used to ascertain how *Illuminating Clay* altered the design and presentation process. Finally, the projects themselves were critiqued by experienced faculty in order to verify if there was any appreciable difference in the quality of the schemes when design using conventional tools or when designed using *Illuminating Clay*.

General Usage Patterns

Group A worked with the available tools with a strong sense of familiarity. Pens and paper are very standard media and the group seemed comfortable with their use. They made a great deal of use of additional elements such as straight edges, rulers and erasers to adjust their landscape representation. *Group B* seemed less familiar with the medium of the clay model but seemed to enjoy the task and the act of manipulating physical form. They made a great deal of use of the pallet knife to carve out roads, pathways and other markings in the surface of the clay model.

Group C seemed the least confident in using their representational aids, perhaps because *Illuminating Clay* was so new to them. However, they did make a great deal of use of the ability of *Illuminating Clay* to project directly on the model providing an accurate template by which the group could alter the clay model.

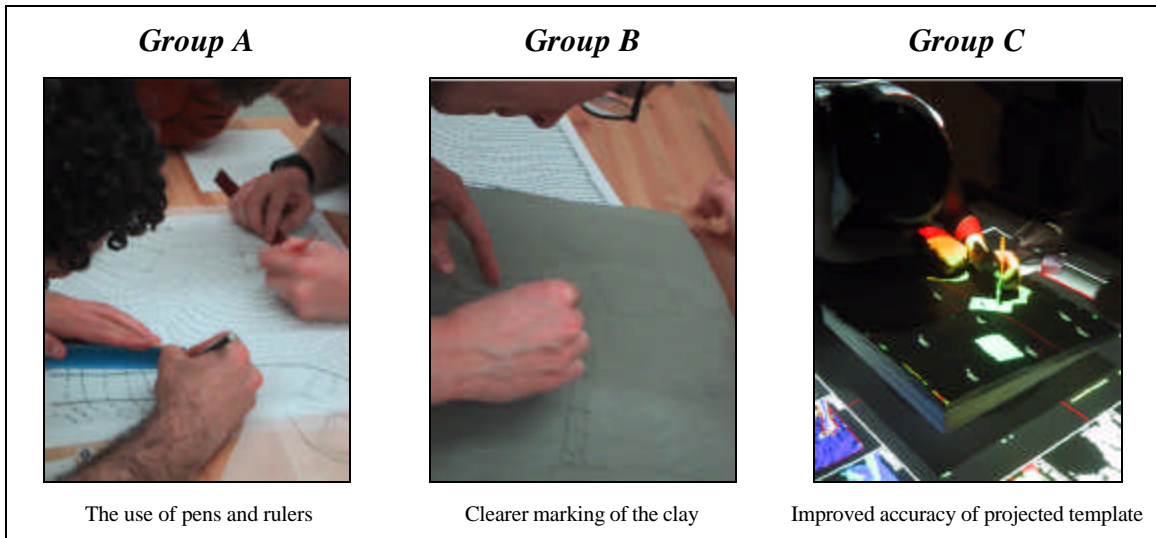


Figure 6.5 General usage patterns in groups A, B and C

As expected, *Illuminating Clay* was very helpful in clearly representing the implications of slope changes in the model on aspects such as drainage through the site. While this did not necessarily lead to better overall design, it did mean that *Group C* had a better understanding of the relationship between their forms and dynamic elements in the landscape.

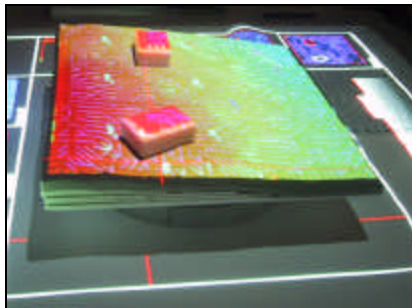


Figure 6.6 The Elevation and Drain Direction analyses superimposed on the model.

In addition, *Group C* used the quantitative output of *Illuminating Clay* – in the form of height values projected on the surface of their model – to help determine how best to shape the landscape. While these numbers were useful as a concept they were a little confusing to the group since there is currently no clear unit value to these numbers and they could only be understood as relative values. Furthermore, the frequent fluctuation of these numbers caused by limitations in the scanner (see previous chapter) meant that *Group C* still relied on physical measurements and ‘eye balling’ the model in order to get a better sense of spot-heights.

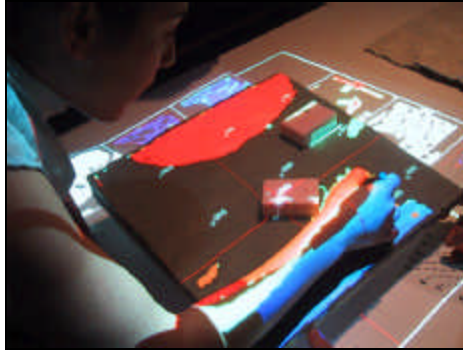


Figure 6.7 Group C member referring to quantitative values projected on the model.

The section lines also provided a useful tool for improved spatial understanding of the site. *Group A* (map and pens) spent a considerable amount of time producing a section to help in their analysis while *Group C* was able to generate sections instantaneously.

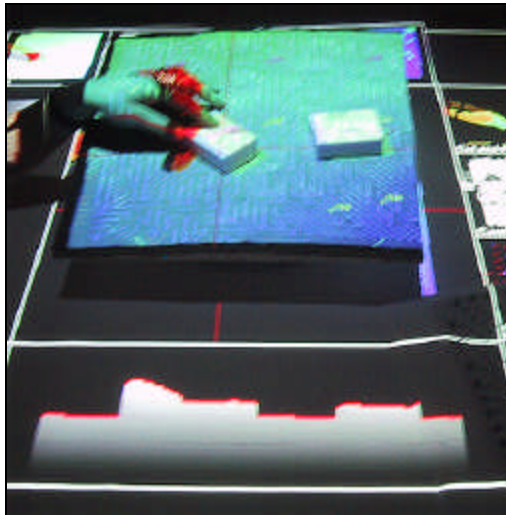


Figure 6.8 The use of the section cut functionality in Group C.

While *Illuminating Clay* does provide a full palette of digital measuring capabilities *Group C* members still made use of conventional tools such as the ruler to check measurements a more tangible means. This is possibly due to the fact that students were more familiar with the physical measuring tool and lacked of confidence in the accuracy of the scanning system.



Figure 6.9 The use of a physical measuring aid in *Illuminating Clay*.

The clay models used within *Illuminating Clay* and within *Group B* required the use of a palette knife to carve and mold form. *Illuminating Clay* proved to be very useful in providing a projected cut and fill template which users could follow with the palette knife.

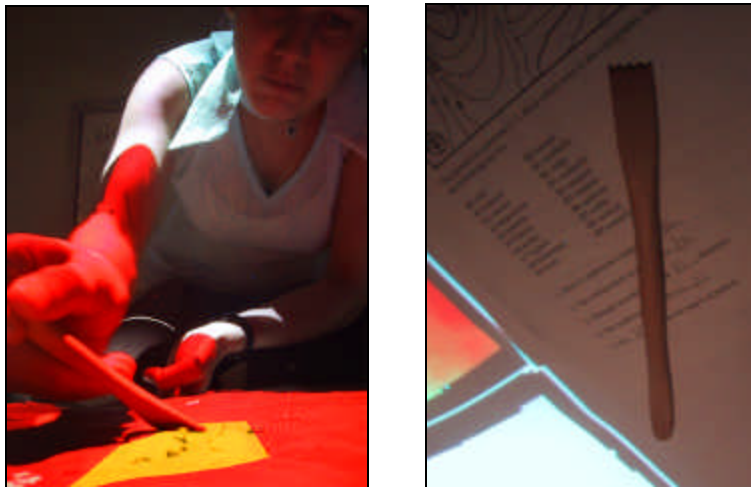


Figure 6.10 The palette knife used for cut and fill.

While the knife offered a simple, non-technological tool for physical manipulation the mouse, used to control the cursor, suffered from being tethered to the *Illuminating Clay* computer and having an orientation bias. We have since implemented a wireless, non-orientation biased trackball and are looking into the possibilities of a similar design for a wireless mouse.



Figure 6.11 The mouse (left) and the non-orientation bias trackball (right).

Illuminating Clay provided the ability for *Group C* to project the results of analysis functions directly on to the conventional topographic maps. This allowed the students to trace out regions of slope, drainage patterns and so forth onto the paper map using conventional, tangible media. One problem emerged with this approach, in that the secondary *Simulation Window* – projected in the control window for precisely this purpose – was of a different scale from the *Simulation Window* that was projected onto the model. This was due to a difference in projector resolution and could be easily corrected in a second implementation.

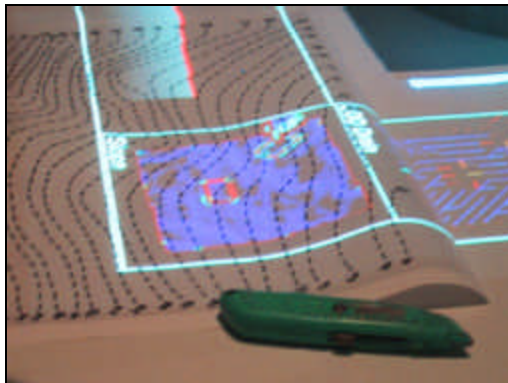


Figure 6.12 Image of computational analysis projected onto paper contour map.

There were some problems with the general layout of the *Illuminating Clay* setup. In our original lab setup we located the *Simulation*, *Control* and *Viewing* windows close together so that one user could potentially operate all three windows simultaneously.

However, the pre-existing projector configuration in the landscape design studio meant that these windows were positioned relatively far apart and it was often necessary for students to operate the system from opposite ends of the table. Again, this issue could be resolved in a second implementation.



Figure 6.13 The layout requiring users to be at opposite ends of the table.

In general terms the activities of each group can be summarized as follows:

Group A worked with the greatest confidence and made decisions about where to place the two building structure relatively quickly. They spent a considerable time of their allocated 20 minutes working on the section drawings.

Group B seemed to take a much more playful approach to the design exercise – laughing and joking while working with the model. While this may have been a particular characteristic of the group, representing the site with clay seemed to lend the exercise a sense of material engagement and fun.

Group C was rather serious about the task and in some instances was confused about how to use *Illuminating Clay*. Their lack of familiarity meant that there was a lot more hesitancy in their approach – yet at the same time they were dealing with a far greater range of issues that were not brought up in the other groups that did not use computational media.

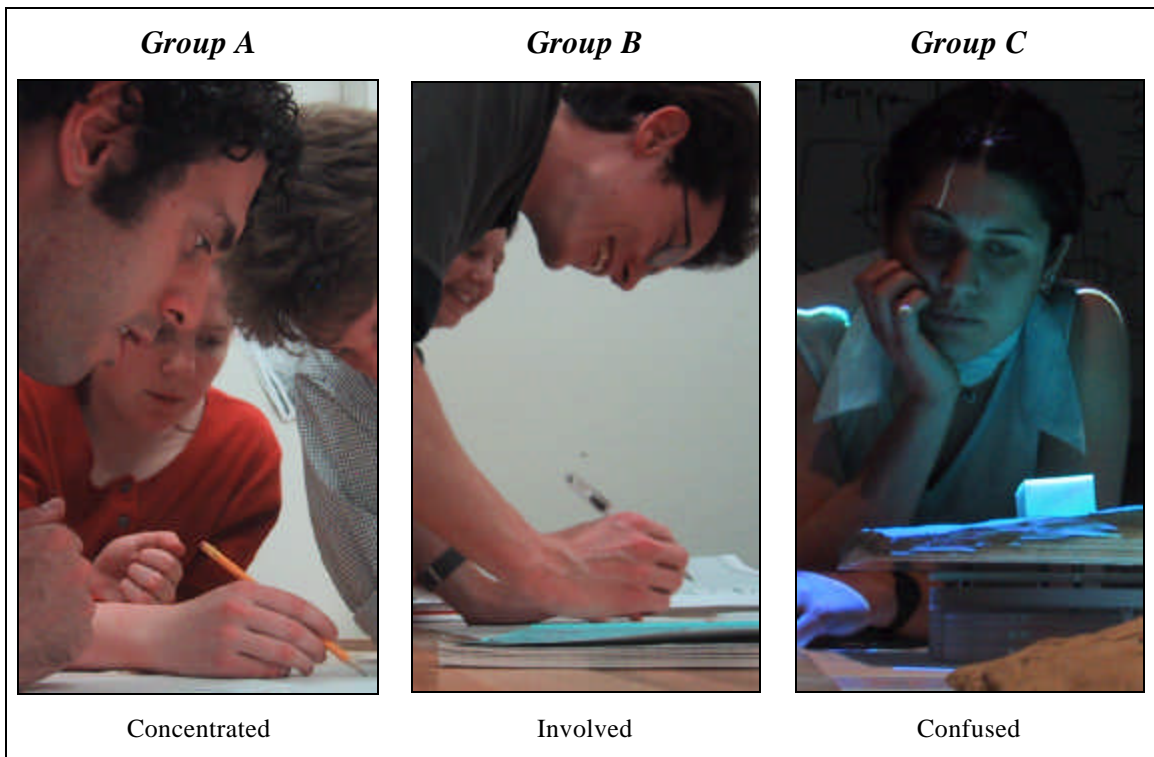


Figure 6.14 Typical expressions from students in groups A, B and C

During the final presentations it emerged that the design solutions from groups A and B were almost identical. *Group C* proposed the idea of combining two driveways to minimize cut and fill and there is some possibility that this creative solution was in part made possible by the ability of the group to cycle through a greater number of design iterations by using *Illuminating Clay*.

The quality of the final presentation was an important aspect in the evaluation. *Group A* showed a tracing paper image of altered contour lines. This image could hardly be seen by the student and faculty audience and gave little sense of the overall design. *Group B* was aided by the physical model, which allowed them to discuss their design rational in some detail and directly involve the audience in discussion. Finally, *Group C* used *Illuminating Clay* to some effect by combining the power of the physical model to convey spatial relationships with demonstrations of how their proposal would affect aspects of the landscape such as shadowing and drainage.



Figure 6.15 Overview of controlled exercise presentations
(1. Group A, 2. Group B and 3. Group C).

6.4 Illuminated Sites Class Presentations

The *Illuminating Clay* interface was evaluated in the broader context of a graduate landscape design course held over the entire semester of Spring, 2002. The course, entitled *Illuminated Sites* (11.304J) was run as a collaborative effort between Eran Ben-Joseph of the *MIT department of Urban Studies and Planning* and Hiroshi Ishii of the *Tangible Media Group, MIT Media Lab*.



Figure 6.17 *Illuminating Clay* in use in the *Illuminated Sites* Spring semester course.

The pedagogical aims of the class were as follows:

- To understand spatial as well as temporal relationships between individual site factors and local or regional context.
- To identify basic relationships between natural and cultural processes and how they influence site planning decisions.
- To apply a variety of methods for "reading" sites.
- To evaluate natural and cultural site systems as they shape design programs and goals.
- To evaluate and critique alternative site development proposals.
- To practice techniques commonly utilized by site planning professionals.

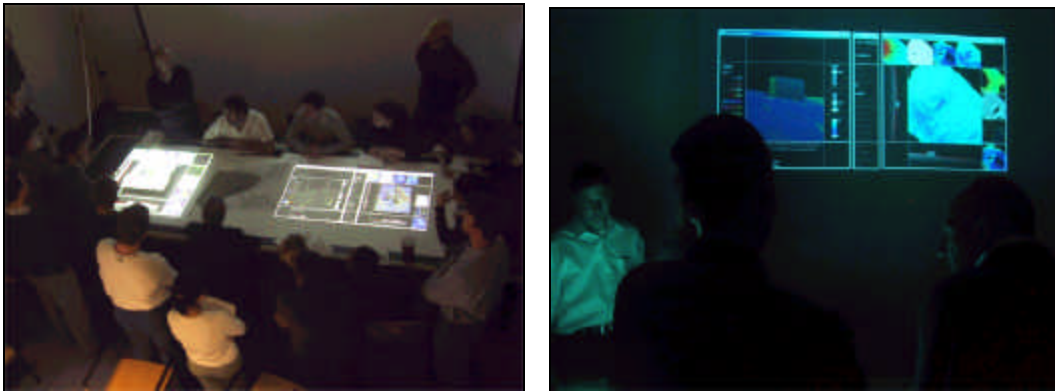


Figure 6.18 The Illuminated Sites Class.



Figure 6.19 Class members using Illuminating Clay.

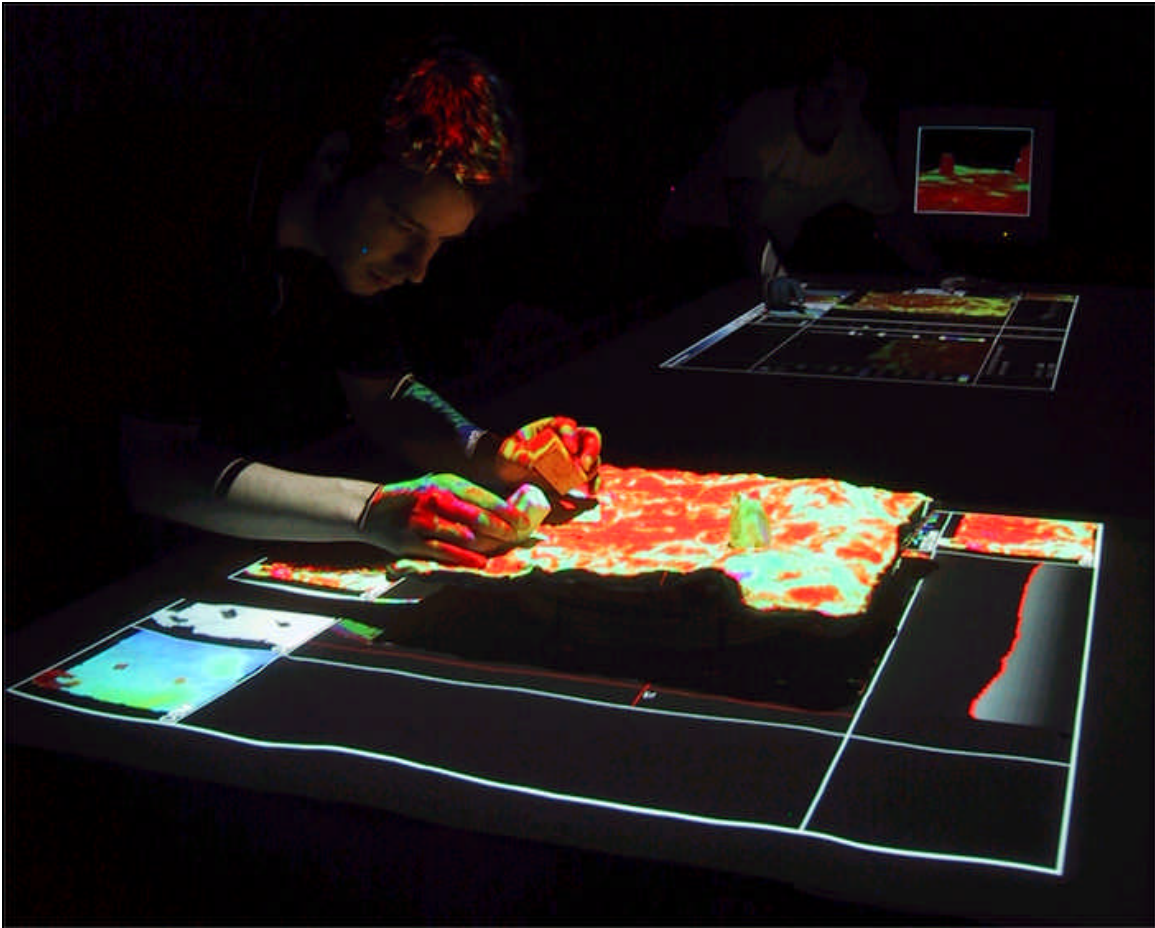


Figure 6.20 Explanation of Illuminating Clay platform.



Figure 6.21 Final critique of Illuminated Sites class.

Chapter 7.



7. Illuminations

This thesis initially set out with the aim of combining the advantages of digital and physical representation in physical form design. Through a greater familiarization with previous work and a better understanding of the specific application domain of landscape design this aim was refined: *to combine the power of computational simulation with the tangible immediacy of physical models*. This conclusions section discusses the extent to which these aims were achieved and the broader implications of our approach for design and the contemporary computer aided work environment.

7.1 Lessons Learned

Merging Physical and Digital Representation

Illuminating Clay manages to combine many of the advantages of physical and digital representation. The physical clay model conveys spatial relationships in the landscape and makes use of the designer's inherent abilities to create and manipulate forms by hand. This approach allows users to quickly create and understand highly complex topographies that would be time consuming and require an inappropriate degree of precision if produced using conventional CAD tools. The projected graphics give the landscape designer a real-time insight into how geometric changes in the landscape influence complex systems such as drainage, sun lighting and slope conditions. While other research projects have taken a similar approach in combining physical and digital representation, *Illuminating Clay* offers a new contribution by using the surface geometry of the model itself to act as the input and output juncture.

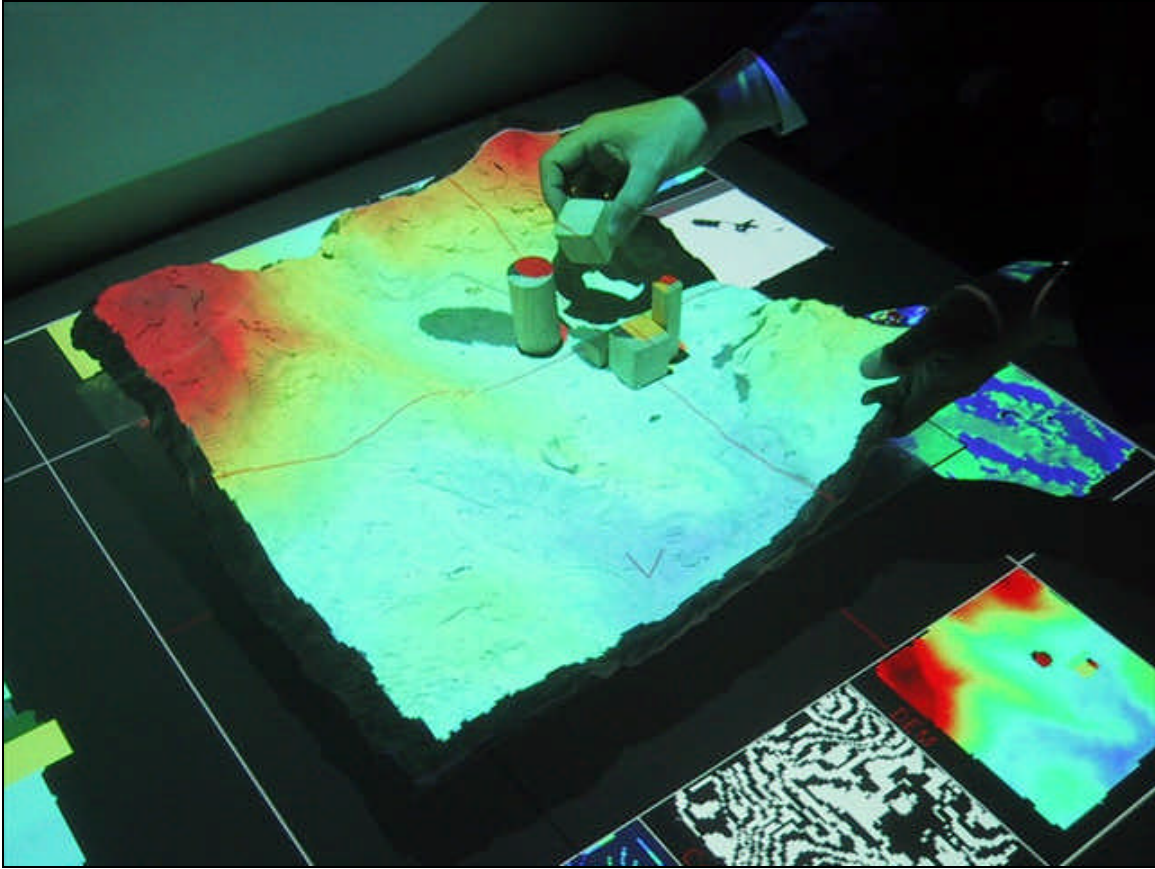


Figure 7.1 The merger of physical and digital representation in design.

Physical Input

A drawback with the systems reviewed in the related works section systems is that they rely the position of tracked objects, and not the geometry of the objects themselves, as the means of input. This tracked approach is limited by relying on fragile or unreliable tagging mechanisms, often with high periods of latency, that require the use of purpose-built objects of a suitable size, shape or material to accept the tracking mechanism. This prevents the user/designer from freely choosing objects or materials that suite their particular needs. Most significantly, this approach does not allow changes in the form of objects to affect the input since the computer has no means of detecting changes in geometry. For example, the *Urban Planning Workbench* [Underkoffler, 99], a direct inspiration for *Illuminating Clay*, requires colored optical tags to be attached to the bottom face of building objects, limiting the building structures to wire frame models.

Users are free to change the relationship between the optically tracked objects but it is impossible to modify the model buildings themselves without first updating the associated digital model.

The ability of the designer to interact with the computer through the manipulation of physical material is made possible by the use of the laser scanner. This technology allows the designer to use any object, material or form as an interface. Just as the pixel display allows the *output* of any image that meets certain constraints of hue, luminosity, brightness and resolution, the 3-d scanner allows the *input* of practically any physical form providing a general platform for tangible object-based interaction.

This is especially significant in physical form design since existing ready-made or found objects are often used as a source of inspiration⁹. *Illuminating Clay* supports the critical relationship between the designer and their creative space by allowing objects from the physical design environment to be used as a means of interacting with the computer.

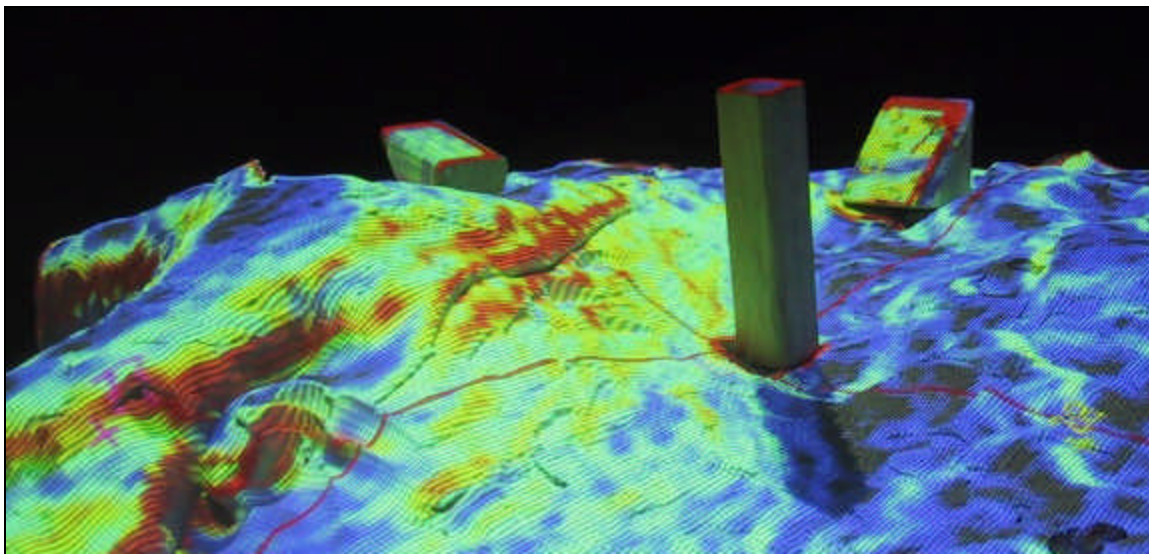


Figure 7.2 *The ability to use the geometry of physical objects as a direct form of computational input.*

⁹ These forms are sometimes referred to as *Object Trouve* (found objects) in fine art terminology.

Computational Materiality

A landscape designer has an intuitive understanding of earth, water, wind, sunlight and other natural systems that is built up over a lifetime of experience interacting with the physical world. However, assumptions that are made about the behavior of a particular element behave are based on interactions that occur on a human experiential scale. It remains extremely difficult to intuitively predict the behavior of the same elements at the scale of the landscape. It is far more affective for to represent these non-human scales systems mathematically and the power of mathematical modeling in these areas has led to the wealth of analysis functions that are now available. These functions are generally controlled through a set of given variables that are adjusted in numerical terms. While this approach has the benefits of accuracy and quantitative control it does limit the value of mathematical models in the process of design.

Kirsh speaks of the distinction between *pragmatic* and *epistemic* interaction in the design process [Kirsh, 94]. *Pragmatic* interaction involves the manipulation of a representational model to achieve a state that has been identified. *Epistemic* interaction involves the manipulation of a model in order to *find* a state that is as yet unidentified. The early stages of the design process can be considered as *epistemic* in as much as representational models are used to help the designer find a solution. Once represented it can be recognized but until that point the designer is trying to find a form that meets the multiple and often opposing requirements of a design.

Illuminating Clay supports an epistemic interaction with mathematically modeled elements of the landscape by allowing the designer to observe the results of a direct manipulation on landscape systems. Through a material experience of mathematical models that react in real-time to tangible manipulation, the user can build up an intuitive understanding of non-human scale systems that are impossible to experience in the physical world. This approach is particularly powerful in that it allows complex systems such as forests or human settlements to exhibit material properties when they have no material analogue at smaller human scales.

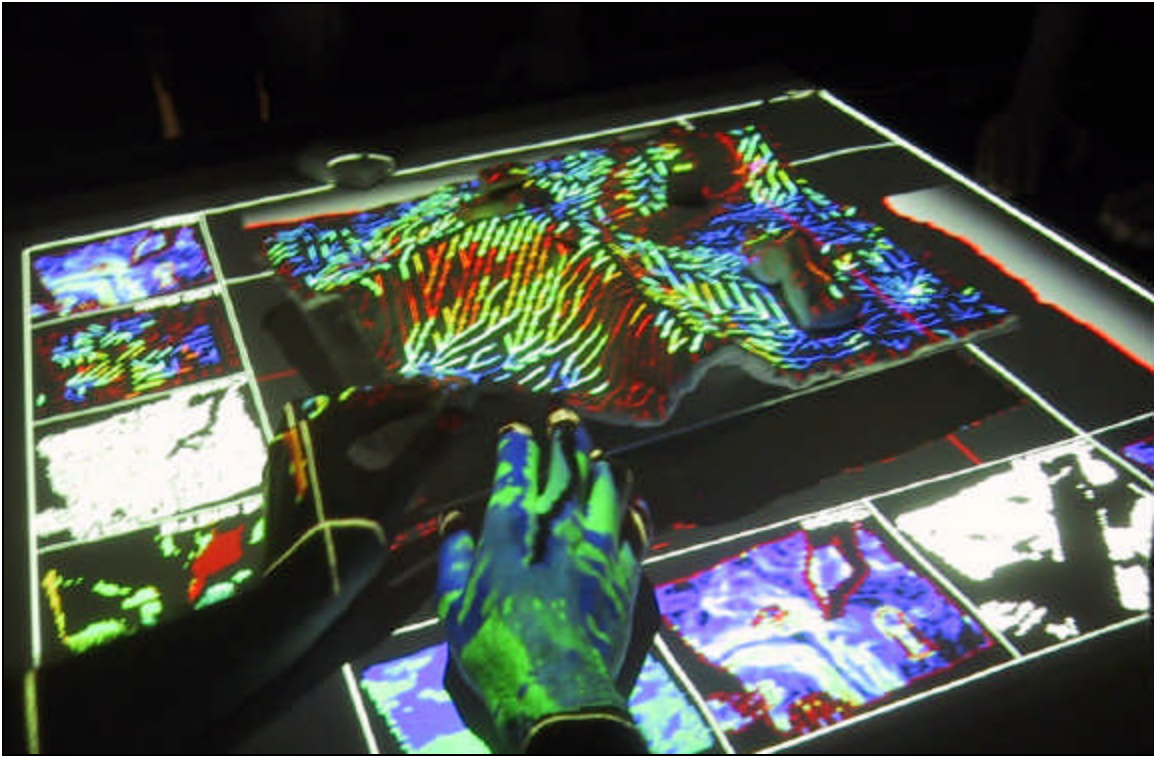


Figure 7.3 Human hands manipulating simulated water flow at landscape scales.

Constraint Aided Creativity

The current paradigm for computer human interaction is summarized in the Windows® marketing phrase – “Where do you want to go today?”. This approach to the computer interface and CAD in particular is typified by freedom of choice, limitless possibility and the infinite undo. However, we must ask what is the value of a tool that does not limit the imagination of its user. As Focillon states:

“What ever the receptive and inventive powers of the mind may be, they produce only internal chaos if deprived of the hand’s assistance. The dreamer may entertain vision of unimaginable landscapes... but he has no means for fixing fast these tenuous, insubstantial visions; and memory hardly retains them, except as the recollection of a recollection.”

[Focillon, 34]

If the computer-based design tools are to aid in the expression of the imagination then they must do so by providing constraints that aid the decision making process. It is only through the limited physical possibilities of clay, *LEGO*TM blocks or any other representational material that the imagination can be brought into physical form. *Illuminating Clay* helps the process of design by providing a physical and therefore limiting medium through which the designer can fix fast these ‘tenuous and insubstantial visions of the imagination’.

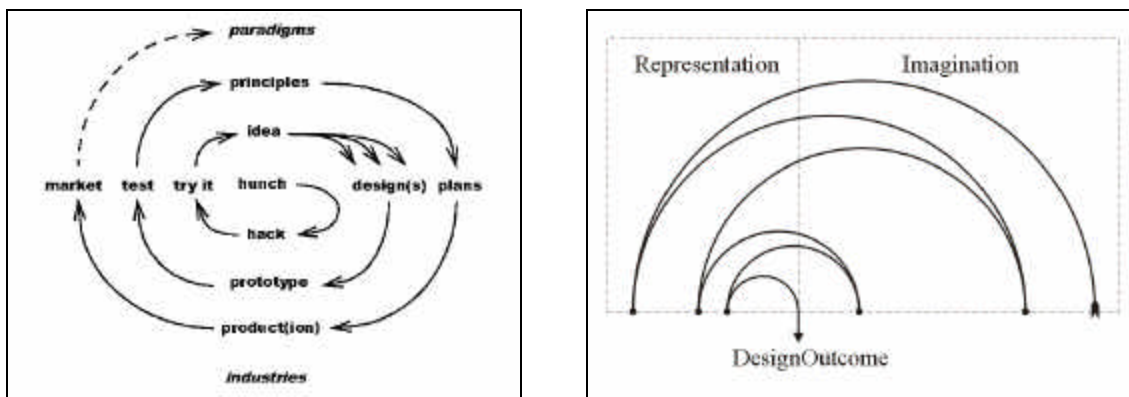


Figure 7.3 Diagram of the iterative design process.

Social Interaction

Owing to the scale of operation landscape design requires the collaboration of a great number of experts. These include specialists in earth engineering, water management, agrarian management, land economy, legal policy and transport infrastructure to name just a few. *Illuminating Clay* provides a platform for collaboration centered on the table workspace. Numerous form of representation can be combined in a single design environment offering the potential for greater cohesion between the large numbers of specialists working on a given landscape design problem.

In addition *Illuminating Clay* offers a goes towards tackling the problem of how to allow non-experts to have meaningful role in the design process.

“Many forms of representational aid end up serving presentation-only purpose that are difficult to modify in real time, preventing the easy incorporation of the public’s ideas and feedback.”

[Schweibinz, 01]

Landscape interventions inevitably affect large numbers of people living perhaps on or near a particular site. Owing to the simplicity and immediacy of the physical landscape models used in *Illuminating Clay*, non-experts can have a meaningful role in the design process by directly collaborating with landscape designers in community based participatory planning exercises.



Figure 7.4 The social and collaborative process of landscape design.

The Contemporary Workplace

The computer has been widely adopted as design aid in practically every area of physical design. The forces that have led to this widespread adoption are as related to the advantages of 'being digital' as they are to the disadvantages of not 'being digital'. If physical designers do not follow their competitors in adopting the latest technologies then they are likely to be replaced by those that do. This is regardless of the quality of design or the wishes of individual designers, since market-forces, efficiencies and economic saving are currently the main proponents of technological development.

It is now common for the contemporary designer to spend almost the entire productive day operating a computer via a screen, keyboard and mouse. While this has led to increased efficiency and production in the short term, over a longer period it is clear that computer-aided design has simply raised the level of expectation to the point where designers must now work, faster, harder and more efficiently than ever before¹⁰. The physical effects on the body, not to mention the less quantifiable effects on the mind are unnerving¹¹.

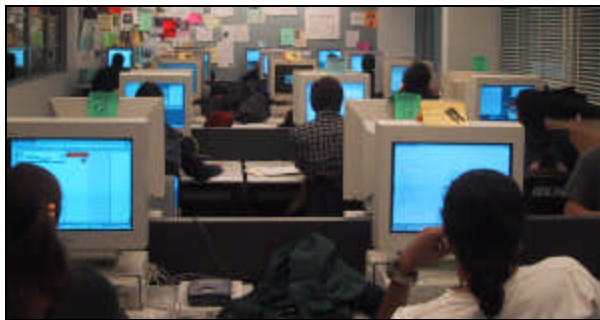


Figure 7.5 A typical scene from the contemporary workplace.

¹⁰ This pattern commonly appears when technological innovations are marketed and then widely adopted. It is said that the average traffic speed in London in 1899 (eleven miles per hour) was equal to that in 1999. Similarly the introduction of the vacuum cleaner – touted to save time – only had the affect of raising the standard of cleanliness in the home.

¹¹ Carpal tunnel syndrome caused by typing at the computer keyboard results in the highest number of days lost among all work related injuries. The U.S. Department of Labor has concluded that Carpal Tunnel Syndrome is the "chief occupational hazard of the 90's"-disabling workers in epidemic proportions and is said to account for 50% of all work-related injuries. Presently, 25% of all computer operators have Carpal Tunnel Syndrome, with estimates that by the year 2000, 50% of the entire workforce may be affected.

The rate of change in the work environment is related to the rate of change of technology, which has been shown to be exponential [Vinge, 91]. Today much of the western workforce operates in an environment that is in complete contrast to the environment in which humans biologically evolved. The role of the body in allowing people to move through and manipulate the physical world is being superseded by technologies that allow portions of society to exist merely through the manipulation of information.

While this has brought many quantifiable riches to society it has reduced the experiential quality of daily practice. *Illuminating Clay* is a step towards the goal of designing computer interfaces around more qualitative criteria by reinvesting the richness of the physical world into the computer interface. It aims to address the specific requirements of one user group - landscape designers - by increasing productivity and efficiency while still meeting the wider aim of providing a tool that is designed around the needs of its human users and provides a level of satisfaction in its use.

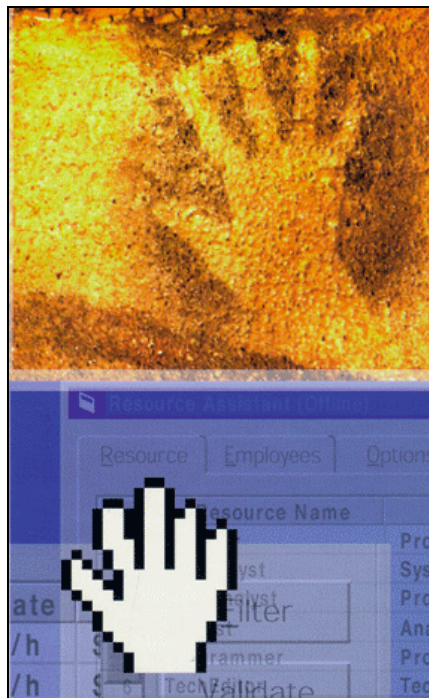


Figure 7.5 A Neolithic cave painting and a contemporary GUI icon showing the constancy of the human form with in an environment of rapid change.

7.2 Future Work

Additional Analysis Functions

Illuminating Clay demonstrates just a few landscape analysis functions that are publicly available. This particular set was chosen to demonstrate the potential of *Illuminating Clay* as a method for real-time interaction with computational analysis and as such we have used greatly simplified functions. Analyses such as *Local Drain Direction* are highly inaccurate and at present are only useful as a rough visualization of how water might flow through a landscape. A future system architecture, incorporating a faster analysis process, would allow a greater degree of precision and more complex functions for simulating more challenging systems such as tidal flow, erosion or deforestation patterns. Research into the visualization of human activity in the landscape could also be incorporated. For example the *Gigalopolis* project [UC Santa Barbara] is aiming to compute the likely growth of human settlements under different statistical conditions in California. While these kinds of simulations could be critical in the future landscape design process they are currently inaccessible to designers owing to the lack of a suitable interface.

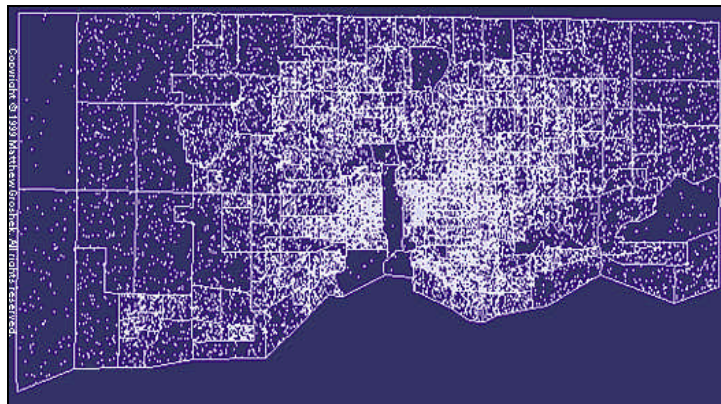


Figure 7.6 Predicting population growth in the *Gigalopolis* project.

***CUTcast* (under development)**

We have shown that the *SCANcast* mode offers the ability to display information on the surface of a 3 dimensional model. However, *SCANcast* does not allow 3-dimensional information, relating to conditions above the surface of the model, to be displayed. For example, *SCANcast* does not provide a means to represent airflow or temperature gradients in the atmosphere to be displayed on the model. If the designer of a wind farm wishes to know the precise wind speed at a point 3 meters above the surface of the landscape they need to insert surface for projection 3 meters above the surface of the model topography. However as soon as this new surface is added to the model the wind simulation is affected and so the wind speed at that point is not displayed accurately.

The *CUTcast* operating mode, which is presently under development, addresses this problem by offering the user the ability to freeze the geometry of a given scene or landscape for the purposes of 3-dimensional simulation. The user is then free to add surfaces for projection at will, and to ‘cut’ the space above the model without affecting the simulation results. Any surface can be used to make this cut, whether it is the surface of a stiff sheet of translucent plastic or cardboard or indeed a more complex form such as a sphere or even the user’s hand.

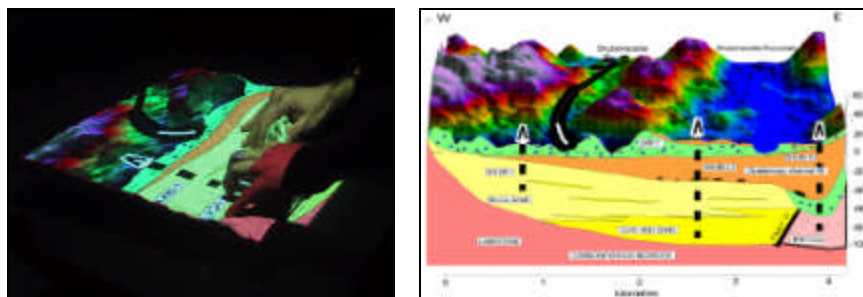


Figure 7.7 The CUTcast operating mode allowing a user to explore geological formation in a volume of the landscape.

Improved 3-Dimensional Capture and Sensing Techniques

The *Minolta Vivid 900* laser scanner was purchased in order to build a proof of concept system. However at \$45,000 this scanner is too expensive to allow the system to be easily cloned for external demonstration or evaluation. In the future we plan to achieve equivalent scanning speeds and accuracies by adopting the structured light approach implemented by Raskar [Raskar et al., 01] or perhaps using a conventional camera to capture the intensity of infrared light passing through a clay or sand model of the landscape in order to derive its geometry. There are also some new possibilities for improving the speed and accuracy of the system by using the *Z-Cam* [Z-Cam], a device that allows 3-dimensional capture at 30 frames per second.

We may also explore hybrid systems that combine the advantages of tracking tags – as used in systems such as Underkoffler's *Urban Planning Workbench* with the surface based input of the laser scanner. The tracked approach offers the advantage over a purely geometric input of allowing different objects in the system to possess unique properties. For example, the *Urban Planning Workbench* allows users to change the material (and resultant computed reflections) of different building models. Our approach makes no distinction between one object and another or even between the work surface and the model itself. It is therefore impossible (at present) to attribute particular properties to particular objects or regions in the landscape model.

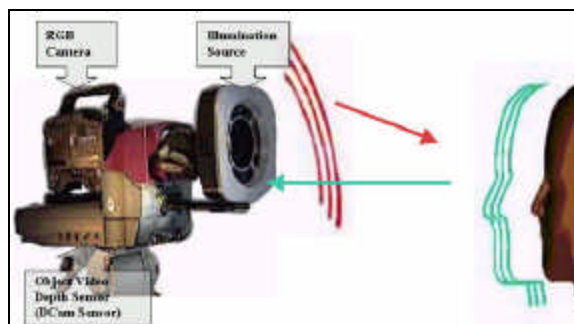


Figure 7.8 Z-Cam Technology

Further Evaluation

While the *Illuminated Sites* class went some way in evaluating the value of *Illuminating Clay* as platform for design a great deal more evaluation is needed to determine which patterns of use are most effective. We are currently planning a second landscape design workshop take place at the *Harvard Graduate School of Design* in 2002 and it is likely that a class similar to *Illuminated Sites* will be repeated next spring. We are currently preparing a bid to the *Cambridge/MIT Institute* (CMI) that may explore the use of *Illuminating Clay* as a platform for distance collaboration. It is also our hope that the interface will be transplanted to a working design practice and evaluated in a professional context.



Figure 7.8 Evaluations session (MIT)

Other Application Domains

Illuminating Clay was built in response to the needs of the landscape designer to project dynamic topography based simulations onto the surface of physical models. However, there are three significant ways in which the system could be refined to open up possibilities for other applications.

First, the current analysis functions only use the geometry of the physical landscape model as an input yet there is a vast array of information relating to the *material* of the landscape itself. It may be possible in the future to input values for these material

qualities such as the water absorbency of different rock types, the known depth of water tables or even the influence of man made artifacts that can have significant impact on landscape systems.

Second, it would be possible to produce a hybrid system that used some form of tagging (as with the *Urban Planning Workbench*) to ascribe *object* properties to different forms in the landscape. The current system makes no distinction between the landscape terrain and any object that is placed into it. There would be many advantages of combining the continuous, laser scanning based interface with the power of discreet object based recognition. For example a ‘school’ or ‘factory’ object could be associated with a particular level of energy consumption or a ‘forest’ object could exhibit properties that affected water tables, soil chemistry and other simulated factors.

Finally, an interface could be developed for the exploration of digitally represented *volumes*. In the manner of *CUTcast* users could operate within the *Illuminated Design Environment* in order to explore 3-dimensional representations of geological surveys, complex industrial design elements or the human anatomy. *Mitsubishi* has expressed an interest in developing *Illuminating Clay* for medical imaging purposes: the interface could be used to navigate Magnetic Resonance Imaging (MRI) or similar data and used as an aid in planning surgical trajectories. *Chevron Oil* has also expressed an interest in using the interface for navigating geological surveys and planning oil or mineral exploration.

By tackling the problems of how to represent *materials*, *objects* and *volumes* within the *Illuminated Design Environment* the system could be extended to provide a far greater range of potential uses.

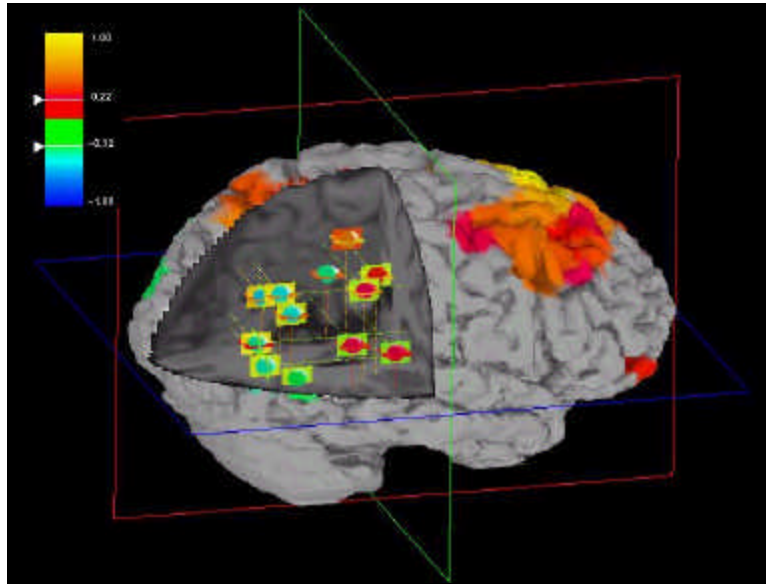


Figure 7.9 MRI data and geological survey for navigation with CUTcast.

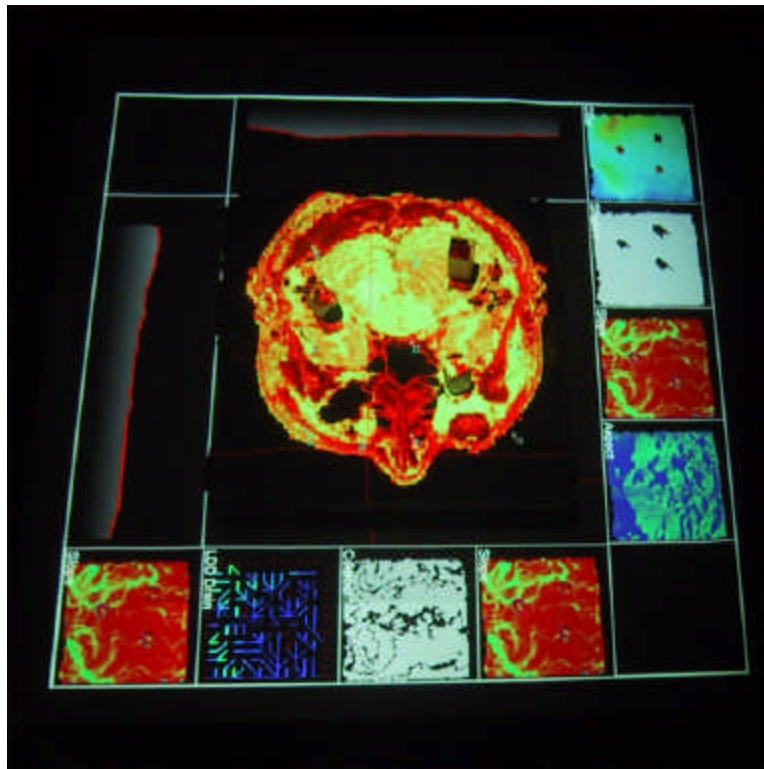


Figure 7.10 Current research into displaying MRI data within Illuminating Clay.



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