

Volume 8

Issue 4

October 2004

ISSN 1361-1682

Transactions in GIS



Editors:

John P Wilson, A Stewart Fotheringham, Gary J Hunter

Research Article

Tangible User Interfaces (TUIs): A Novel Paradigm for GIS

Carlo Ratti

*SENSEable City Laboratory
DUSP and Media Lab
Massachusetts Institute of Technology*

Yao Wang

*SENSEable City Laboratory
DUSP and Media Lab
Massachusetts Institute of Technology*

Hiroshi Ishii

*Tangible Media Group, Media Lab
Massachusetts Institute of Technology*

Ben Piper

*Department of Architecture
University of Cambridge*

Dennis Frenchman

*City Design and Development Group, DUSP
Massachusetts Institute of Technology*

Abstract

In recent years, an increasing amount of effort has gone into the design of GIS user interfaces. On the one hand, Graphical User Interfaces (GUIs) with a high degree of sophistication have replaced line-driven commands of first-generation GIS. On the other hand, a number of alternative approaches have been suggested, most notably those based on Virtual Environments (VEs). In this paper we discuss a novel interface for GIS, which springs from recent work carried out in the field of Tangible User Interfaces (TUIs). The philosophy behind TUIs is to allow people to interact with computers via familiar tangible objects, therefore taking advantage of the richness of the tactile world combined with the power of numerical simulations. Two experimental systems, named *Illuminating Clay* and *SandScape*, are described here and their applications to GIS are examined. Conclusions suggest that these interfaces might streamline the landscape design process and result in a more effective use of GIS, especially when distributed decision-making and discussion with non-experts are involved.

Address for correspondence: Carlo Ratti, SENSEable City Laboratory, Room 10-485, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA. E-mail: ratti@mit.edu



Figure 1 *Illuminating Clay*: A landscape model made of clay provides the input/output for GIS simulations

1 Scenario

A geoscience professor and his student sit around a physical clay model of a landscape that is illuminated by computer projections. The projections display the direction of water flow in different regions of the model. As the professor flattens the crest of a hill, the student observes how the drain direction changes within the model. The student wishes to explore the likely velocity of the water in the same region and so requests the computer to project the slope value onto the model. Based on the projected color map, the student gains an intuitive sense of slope and likely water velocity (Figure 1).

2 Context

Before examining the system that would make the operations described in the above scenario possible, this research needs to be put into context.

In recent years, an increasing effort has gone into the design of user interfaces for GIS. First-generation line-driven GIS have rapidly become obsolete for certain operations, due to their inability to cope with new algorithms for spatial analysis and complex 3D modeling. According to Cartwright et al. (2001): “*Beyond aesthetics there is a need for more natural interfaces to geospatial information environments, to make these often*

complex environments accessible to more people". The importance of adequate input/output representations in GIS has been stated, amongst others, by Elvins and Jain (1998): "Comparison of objective and subjective measures showed a strong relationship between the amount of time wasted on errors and problems, and compatibility of the users' and system's conceptual models". The development of new user interfaces has been put forth as a short term research priority by the University Consortium for Geographic Information Science (UCGIS) in the area of Geographic Visualization: "Rather than doing creative work with traditional tools and then transferring the results into a computer graphics system for further work, we need to develop tools that allow the same subtle freedom as traditional tools in terms of greater expressiveness, more rapid development of prototypes, and sensory feedback. The challenge is to build interfaces and devices that allow the creative process of compiling a display to be developed with the computer as well" (Buckley et al. 2000). Similarly, Oviatt and Cohen (2000) have argued for the introduction of multimodal interface in GIS (and beyond), leading to a broader-band interaction between humans and computers. Several new approaches to GIS interfaces have been suggested in recent years: some developments are reviewed below, while a more thorough review of the state of the art can be found in Cartwright et al. (2001):

- **Graphical User Interfaces (GUIs).** Most first-generation line-driven command GIS have now been integrated with or replaced by GUIs. Estalrich and Trilla (1998) report on this having happened with GRASS (Geographical Resources Analysis Support System; Neteler and Mitasova 2002), the best known public-domain GIS, to facilitate the use of its most popular commands. GUIs for GIS are also constantly evolving in order to take into account design principles developed in the human-computer interaction community (Elvins and Jain 1998). GUIs provide more accessible interactive manipulations of GIS spatial data than first-generation line-driven command interfaces, although their standard components, such as mouse, keyboard, and monitor, have limitations when dealing with complex 3D forms.
- **Virtual Environments (VEs).** A VE is defined as "a computer generated, interactive, three dimensional environment in which a person is immersed" (Kaslawski 1993). With GIS acquiring powerful 3D output capabilities, the use of VEs is receiving an increasing amount of attention from the scientific community (Faust 1995). For instance, Kumaradevan and Kumar (2001) describe how a VR interface could be used for distributed GIS. Koller et al. (1995) report on the development of *Virtual GIS*, a system with immersive capability for navigating and understanding complex and dynamic terrain-based databases. Germs et al. (1999) discuss how VEs could be integrated in more traditional output, such as plan maps and bird's-eye views, to provide a multi-representation system. VE systems significantly reduce the cognitive effort necessary for users to explore and interact with data. However, they still have limitations in terms of the hardware needed to navigate immersive environments and the risk of users to get lost in virtual spaces that adopt unfamiliar distances, speeds and levels of detail (Cartwright et al. 2001). In addition, the power of VEs as output devices must be balanced against their unease as input systems. Cognitive and usability issues in using VEs for GIS are discussed, amongst others, by Slocum et al. (2001).
- **Augmented reality (AR).** AR systems are composite systems that use a combination of a real scene viewed by users and a virtual scene generated by a computer. The latter augments the real scene with additional information. An application of AR to

GIS is described by Takuma et al. (1997), whose system allows the retrieval of information from a database by clicking real objects in live video images (for instance, clicking on a building on a live urban video prompts information such as name, address, direction and distance from viewpoint to be displayed). Ghadirian and Bishop (2002) report on a similar system developed for monitoring environmental change, while Pasmán et al. (1999) address some technical issues in accurately overlaying virtual information on real-world views.

Our work aims at introducing a novel approach to GIS interfaces, based on recent developments in human-computer interaction with Tangible User Interfaces (TUIs). TUIs are increasingly accepted as an alternative paradigm to the more conventional GUIs (Ullmer and Ishii 2000). They offer the ability to manipulate objects in space and aim to combine the benefits of physical and digital models in the same representation. More generally, they give physical form to digital information, seamlessly coupling the dual worlds of bits and atoms.

The early developments of TUIs date back to the early Eighties, when Frazer explored different approaches to parallel physical/digital interactions with his Three-Dimensional Data Input Devices (later discussed in Frazer 1995). Since then, there has been a number of impressive developments: Wellner's (1993) Digital Desk illustrates the efficiencies of augmenting paper-based office production with digital tools and methods for storage. Systems such as the Phantom Arm (SensAble Technologies 2003), when combined with virtual environments or holography allow for highly convincing interactions. Agrawala et al. (1995) have developed methods for painting directly on the surfaces of complex 3D geometries while Raskar (1999) and Bandyopadhyay et al. (2001) have looked into the possibilities for animating computational projection and highlighted some of the difficulties that arise when projecting from multiple sources. Special note should be made of the work of Underkoffler and Ishii (1999), which directly inspired the approach we have taken here. Their Urban Design Workbench uses digitally augmented tagged physical objects to represent buildings that can be rearranged to facilitate the process of urban design. A similar system has also been coupled with a GIS by Coors et al. (1999), becoming the first TUI applied to GIS to our knowledge.

Each of the approaches reviewed above illustrates the enhanced interactions that are afforded by the use of tangible objects in human computer interaction. We hope to combine their strengths and provide an interface that is truly practical in the context of landscape analysis. Two systems are described below, namely *Illuminating Clay* and *SandScape*.

3 Goals

We aim at introducing TUI concepts to GIS interfaces. We propose to address the field of landscape architecture and use conventional modeling materials, such as clay and sand, as input/output. Their tactile richness makes them pleasurable and easy to manipulate. In addition, they allow freeform landscape modifications in an immediate way, as noted by Massie (1998): "*consider the ease with which artists and designers can express themselves with familiar physical media, and compare that with the frustration they often encounter when using existing CAD and modeling packages to create within a 3D digital domain.*"

In particular we aim at constructing a GIS interface that:

- would be self explanatory and easy to interact with; as Cartwright et al. (2001) put it, “*the challenge is to provide flexible access to increasingly powerful geospatial (and related) representation software*”;
- would not require tedious and time consuming use of tagging, tethering or demarcation, as it has often been the case with past TUIs; ideally, any object in the landscape architect’s workspace could become part of the interface;
- would streamline the practice of landscape architecture, which is nowadays torn between the use of conventional physical media (such as clay) and GIS analysis;
- would promote participation of professionals in landscape analysis and design;
- would facilitate participation of non-experts in landscape analysis and design; it should be designed with the ‘universal usability’ concept in mind, in order to empower both experts and lay people to use the technology; in this sense, it should promote participatory design, engaging the public in the landscape architecture discussion (Appleton et al. 2002), and be particularly suited to teaching; and
- would allow potentially remote collaboration – i.e. different teams of researchers working on the same project in different physical locations.

4 System Architecture

Both systems described in this paper are based on the same principles. Users interact with a landscape model. The geometry of the model is continuously sensed with one of the techniques described below. Sensing output is passed onto a computer and transformed into the Digital Elevation Model (DEM) format. GIS analysis algorithms are applied to the DEM and results are projected back on the landscape model. The whole interaction loop is recursive and happens in near-real-time (approximately one second per cycle). Due to the difficulties of conveying a full sense of the functioning of the two systems in writing, some videos have been placed on the World Wide Web and can be freely retrieved from the SENSEable City Laboratory website (<http://senseable.mit.edu>).

4.1 Sensing Technology

We have assembled two configurations of the system, named *Illuminating Clay* and *SandScape*, which are shown in Figures 2 and 3. The primary difference between them is in the 3-dimensional sensing method used. *Illuminating Clay* was developed first, and proved very reliable and accurate, albeit rather expensive. Its preliminary setup was described in Piper et al. (2002), although it has been extensively modified since. *SandScape* has been developed at a later stage as a more affordable alternative. Both systems are still under development and they are described below, with their differences and limitations.

Illuminating Clay uses a commercially available triangulation based laser scanner (Minolta™ Vivid-900™; see <http://www.minolta-3d.com> for additional details) to capture the surface geometry of the physical clay model. This laser scanner is calibrated with a video projector, in order to ensure that the spatial coordinates of the surface of the model correspond precisely to the projected image coordinates. The scanner/projector pair is housed inside an aluminum casing at a height of approximately 2 m above the surface of the modeling material.

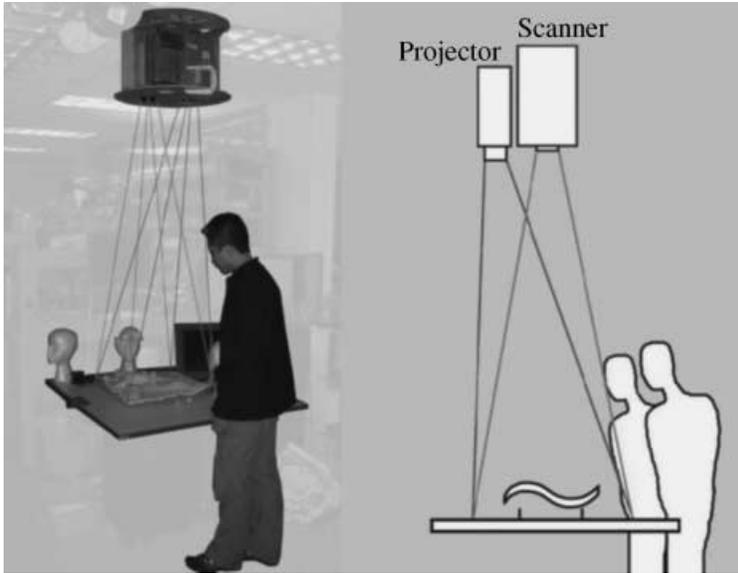


Figure 2 The *Illuminating Clay* system uses a commercial Minolta™ Vivid-900™ laser scanner to capture the geometry of the clay model

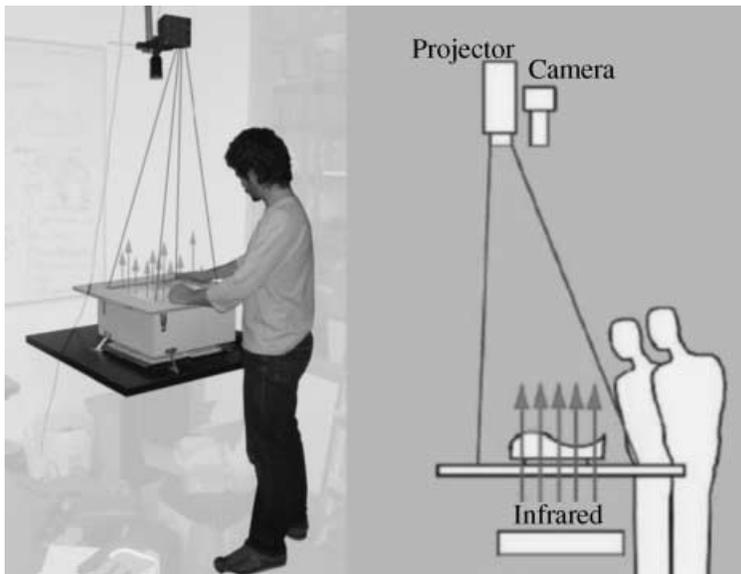


Figure 3 The *SandScape* system was developed as a more affordable alternative to *Illuminating Clay*. The geometry of the landscape model is captured with a sensing technology based on the measurement of infrared light transmitted through a bed of glass beads

The Minolta™ Vivid-900™ was designed to perform single scans of static objects and scenes. In order to capture changes in the surface geometry of the modeling material in real-time, it was necessary to modify the scanner controls using the Minolta Software Development Kit (SDK): 320 x 240 point values are scanned every 1.2 seconds, resulting in a near-real-time surface capture. Scanned data is re-sampled into x, y and z coordinates and then converted into a well established GIS format – the Digital Elevation Model (DEM), a gridded array of elevation values.

In an ideal configuration the video projector and the scanner would be located at the same optical origin to avoid problems of shadowing, occlusion and image distortion. This could be achieved using a coated mirror transparent to the laser scanner and reflective of the visible spectrum, as explained in Piper et al. (2002). However, our tests showed that from a distance of 2 m and with an operating volume of approximately 0.5 x 0.5 x 0.5 m, a more simple arrangement could be used, with the projector and the scanner positioned alongside each other, as shown in Figure 2. In this case, the scanned and projected rays can be considered to originate from the same source.

The laser scanner provides a high degree of accuracy (less than 1 mm) and allows any opaque non-reflective material to be used as a modeling medium. Therefore, most objects in the designer's workspace can be used as a geometric input – including the user's own hands, pieces of paper, cardboard, foam, plastic or other *objets trouvés*. The Minolta™ Vivid-900™ laser scanner, however, may be too expensive for widespread use. This led us to investigate more affordable alternatives, such as *SandScape*.

The *SandScape* configuration is based on a box containing 1 mm diameter glass beads lit from beneath with an array of 600 high power infrared LEDs, as shown in Figure 3. Four IR mirrors are placed around the LED array to compensate for the uneven radiance distribution on the boundary. A monochrome infrared camera is mounted 2 m above the surface of the beads and captures the intensity of light passing through the volume. The intensity of transmitted light is a function of the depth of the beads and a lookup table can be used to convert surface radiance values into the surface elevation values.

The system has been calibrated to work with a specific bead size and the optical properties of the material used (absorption and scattering coefficients) are critical to its successful functioning. Owing to the exponential decay of the IR light passing through the glass beads (or any other material) the intensity at the top surface can vary greatly and sometimes exceed the dynamic range of the video camera. This problem can be solved by taking several images with different exposure times and combining them to recover the effective radiance of the scene, as explained in Debevec and Malik (1997).

SandScape is less accurate than *Illuminating Clay* (our initial tests show an error of 5mm, compared with 1 mm with the Minolta laser scanner) and also material-dependent: no other material than glass beads can be used prior to time-consuming testing and calibration. However, it has the advantages of higher speed (in principle it would be possible to reach 6 frames per second), and an affordable implementation (an order of magnitude lower than the laser scanner).

4.2 Tangible Workbench

The physical landscape model which acts as an input/output interface is placed at the center of the worktable. A library of GIS analysis functions are projected as thumbnails around it (Figure 6). Users can select one of the analysis functions by clicking the corresponding thumbnail, prompting the computer to display results in full size on the physical



Figure 4 The tangible worktable comprises a landscape model, which is augmented by computer projections. In the *Illuminating Clay* case, any object from the user's environment can be used for including the user's own hands, pieces of paper, cardboard, foam, plastic or other objets trouvés

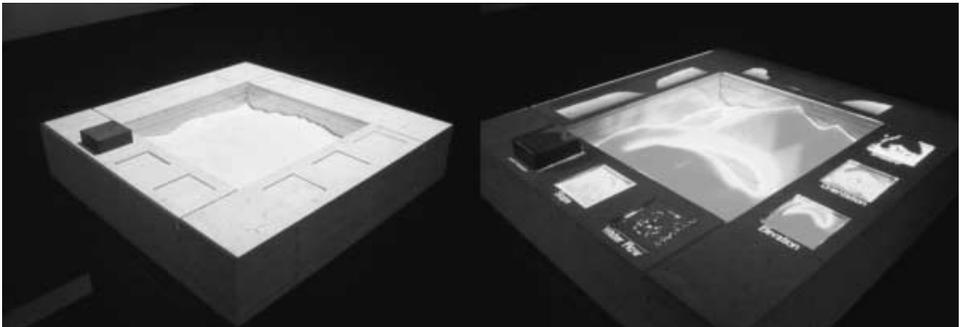


Figure 5 The tangible worktable in the *SandScape* system. The geometry of the landscape model is defined using glass beads

landscape model. The other thumbnails remain active and are updated in real time with changes of the model, so that users can have a glimpse of the results of different landscape analyses before choosing which one to project in full size. Besides the thumbnails, two cross profiles are also projected on the worktable, helping users understand the 3-D geometry of the terrain.

Projected results of the analyses use a colormap, which can be interactively modified using a simple GUI. More precise quantitative information on the projected analysis can also be displayed as digital icons on the landscape model. For example, placing a digital icon on the landscape surface by dragging the mouse prompts the numerical value of the simulation at that location to be shown, such as "Slope: 64%", "Shadow: Yes", or "Aspect: South".

A vertical screen is also placed on the side of the worktable, in order to display a 3-D perspective view of the landscape Figure 6. Users can use it to visualize real-time fly-through animations at human eye level. The perspective view complements the physical landscape model, by providing a virtual experience that is similar to that that a human would have while moving through the landscape. The vertical screen addresses the old problem of the difficulty of imagining a real landscape while working on scale models,

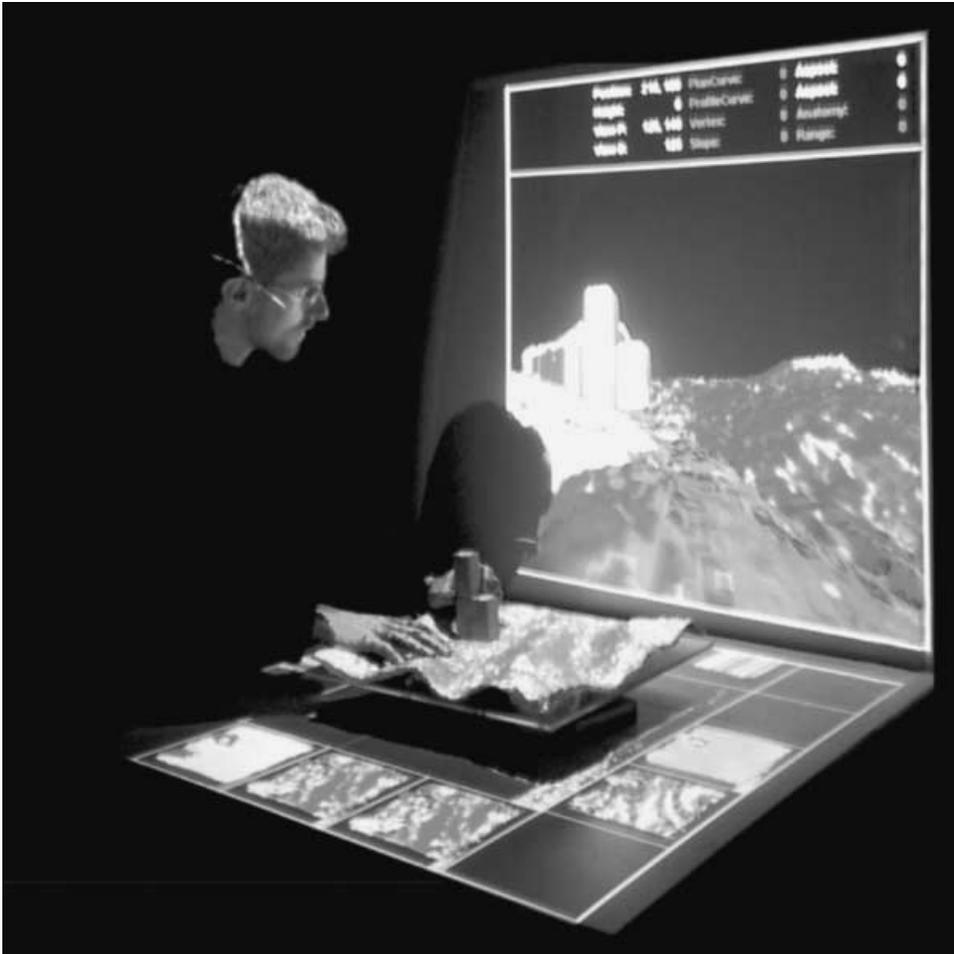


Figure 6 A vertical screen, next to the worktable, provides users with a virtual view of the landscape at human eye level (the image shows *Illuminating Clay*)

which was once solved with the use of modelscopes. In addition to geometrical information, the 3-D view is texture-mapped with the results of the GIS simulation and is updated in real-time.

An attempt toward tangible purity led us to develop a version of *SandScape* where even the choice of the algorithms is made by moving tangible objects (blocks of travertine which are tracked along with the landscape modifications). While this approach is conceptually interesting and could lead to the tangible interfaces of tomorrow, we have found that in terms of usability, given the large number of GIS parameters involved, it is better to stick to a GUI and to its standard inputs (mouse, keyboard).

4.3 GIS library

We have developed a small library of landscape analysis functions, written in C++, such as slope, shadow casting, local drain direction, etc. They are standard algorithms in the



Figure 7 A number of different GIS analysis functions can be selected from the thumbnails around the worktable. From left to right: height, aspect, and shadow casting



Figure 8 Using *Illuminating Clay* in teaching at the Massachusetts Institute of Technology, Department of Urban Studies and Planning (course 11.304, Professors Eran Ben-Joseph, Hiroshi Ishii, and Carlo Ratti, Spring Semester 2002)

GIS literature, and will not be discussed here (for more references, see Burrough and McDonnell 1998).

This list is preliminary and could be easily expanded. Our aim has been simply to give a proof of concept of the potential of TUIs applied to GIS. However, we have deliberately kept the system architecture open, so that different functions could be plugged in and out. Both *Illuminating Clay* and *SandScape* have been developed in the C++ environment (with extensive use of the graphical library OpenGL) and each of the analysis functions has been kept as a module. This makes our systems very flexible and would allow them to be interfaced, for instance, with the GRASS open source GIS (Neteler and Mitasova 2002).

5 Discussion

Having briefly described the architecture of *Illuminating Clay* and *SandScape*, we should address the following question: what could be the advantages of using TUIs in GIS? This

section lists our preliminary findings, based on our use of the system and on the feedback that we have received from a number of students and professionals, both experts and non-experts, in the past months. The next step would be to carry out a comprehensive usability study, based on principles developed in the human-computer interaction community, to assess the comparative strengths of TUIs versus other types of GIS interfaces.

5.1 Free-form geometric modeling

SandScape offers an intuitive alternative for modeling free-form 3-D objects, such as landscape models. A DEM is generated in near-real-time according to the changing geometries of a clay or sand surface, and used to feed computational simulations. This approach allows users to quickly create and understand highly complex topographies that would be difficult to deal with using mice and keyboards in conventional CAD tools (because of time issues and inaccuracy). In addition, unlike other approaches in TUIs, our systems do not rely on tagging, tethering or demarcation, but simply use the geometry of objects on the worktable as input. *Illuminating Clay* and *SandScape* seem to open a new perspective not only to GIS but also to TUIs: they have given rise to considerable interest in the human-computer interaction community and could be defined as ‘continuum interfaces’, using the surface of a continuous workspace as input and output.

5.2 Integrating physical and digital representations

Even in an age of increasingly sophisticated forms of digital representation, designers still make use of physical models. Landscape architects, for instance, keep on working with clay or sand models to quickly and synthetically explore complex 3D terrain geometries. On the other hand, they rely more and more on numerical analyses to assess the strengths and weakness of their designs. This produces a fracture in the creative process – a disconnect between physical and digital forms of representation and analysis. *Illuminating Clay* and *SandScape* bridge this fracture by creating a seamless interface for landscape architects. The latter can change the surface of a sand model as if they were changing the topography of terrain, and see the results of this action projected back on the model – be they interested in the flow of water, the casting of shadows or the slope of land. This would result in a streamlined process of design.

5.3 Improving collaboration and communication

Landscape architecture, as well as urban and other types of design, requires the collaboration of a numbers of specialists. These include earth engineers, water engineers, agrarian managers, land economists, transport engineers – to name just a few. In the current process of design the collaboration happens at different stages, without much direct and synchronous interaction. Designers work on physical models and topographic maps; engineers rely on the computer programs for mathematical analysis of the intended design; project managers use photos, physical models, and paper reports to discuss different options with their clients. *Illuminating Clay* and *SandScape* provide a common platform for collaboration, centered on the table workspace. Numerous representations and analyses can be combined in a single design environment, potentially offering a greater cohesion between different specialists and streamlining the process of design.

In addition, *Illuminating Clay* and *SandScape* seem very valuable platforms to communicate design decisions to non-experts, allowing them to become involved in the design process. In practice, rough 3-D study models are often used to work with community groups and lay clients, since people understand three-dimensional representations more easily than drawings. In addition, most people feel comfortable manipulating clay and sand to test their own scenarios; it requires no special skill. With *Illuminating Clay* and *SandScape*, such manipulations allow non-experts to interact with sophisticated GIS data alongside professionals, both empowering them to participate and potentially streamlining the process of public design and decision-making.

5.4 Preliminary usability results

In a similar sense, *Illuminating Clay* and *SandScape* have been used in teaching a class at the Massachusetts Institute of Technology, Department of Urban Studies and Planning, during Spring Semester, 2002 (course 11.304, taught by Eran Ben-Joseph, Hiroshi Ishii and Carlo Ratti; more information can be retrieved on the Internet from MIT OpenCourseWare – see <http://ocw.mit.edu/> for additional details). The shared perception has been that they simplified the teaching, making the very principles of site planning more accessible to students. Basic concepts, such as the definition of contour lines or the meaning of local drain direction, become immediately evident when explained on the physical clay or sand model (Piper 2002).

More rigorously, a preliminary usability study on *Illuminating Clay* has been conducted at the same time of the class, as reported by Shamonsky (2003). This involved students as well as professionals, with experience ranging from 0 to 30 years, divided into small groups. They were given a short-term design problem consisting of establishing sites for two buildings on a one-acre lot, using three different tool sets: *Illuminating Clay*, clay, and paper. Tool sets were alternated amongst the participants, as well as maps of three different parcels of land. Subjects were videotaped during their design activity, in order to collect quantitative data such as time spent on different tasks, verbal transcripts, and visual records. Furthermore, they were interviewed after they had performed the task.

Results showed that *Illuminating Clay* allows designers to easily rough out a concept. On average, a higher number of *what-if* iterations were performed, compared with more traditional tool sets (clay, paper). Furthermore, the seamless interface between digital and physical representations made the design process more informed; feedback from subjects showed that they could come to decisions with more confidence. Finally, everyone commented that *Illuminating Clay* promoted communication, making it simpler to express ideas and discuss them with others. Twelve out of twelve subjects commented that it was a better presentation tool than a physical model or a GUI, especially for complicated presentations. For more details, refer to Shamonsky (2003).

6 Conclusions and Future Work

This paper describes how Tangible User Interfaces (TUIs) – an emerging concept in human-computer interaction – could be applied to GIS. The architecture of two systems, namely *Illuminating Clay* and *SandScape* has been described and their potential use in GIS discussed. Both systems use simple landscape models as input/output. Users interact

with these models, while a sensing device captures their geometry in real time and a computer projector sends back the results of selected GIS simulations.

Both systems have been developed as simple human-computer interfaces. A preliminary library of basic GIS functions has been included to demonstrate their usability. However, their architecture, developed using the C++ programming language, has been kept open to allow interfacing with wider libraries of GIS algorithms, such as those contained in GRASS. We are planning to work on this aspect in the coming months, to make our interfaces truly usable in the practice and teaching of landscape architecture.

While a comprehensive study, in terms of usability, of the advantages of TUIs in GIS has not yet been carried out, preliminary results obtained during a class at MIT are very encouraging. In addition, our systems have been tested so far by a variety of people, experts and non-experts, including sponsors who regularly visit our lab. Results suggest that they are very intuitive interfaces to work with and can facilitate collaboration between landscape architects and experts. They also seem to promote the involvement of lay people in the design process.

In addition to improving collaboration between a group of people present at a certain physical location, in the future they could allow distributed collaboration – whereby people in different parts of the world work together on the same problem. A simple implementation could be accomplished by synchronizing the projected outputs, without affecting the physical models. A major advantage, however, would be if also the physical models were reacting together – i.e. if a change made by, say, a landscape architect in Boston on his clay model would affect a similar model placed in London. Technology is rapidly emerging that could allow these types of operations, via a fully actuated surface (see for instance Pangaro et al. 2002). This would create a symmetrical situation in the control loop, allowing both the computer and the users to modify the clay or sand model – a big step forward in terms of working seamlessly with the worlds of bits and atoms.

Acknowledgements

We would like to thank Assaf Biederman, who has been one of the major driving forces behind the development of *Sandscape*. Without him and our team of ‘illuminators’ the projects described in this paper would have remained in our imaginations. In particular, we would like to thank Bryan Blumenkopf, Ken Goulding, Saro Getzoyan, Jason Hickey, Kartik Lamba, Aaron Mihalik, Alexander Mekelburg, Ishan Sachdev, and Bo Zhu. Dorothy Shamonky has provided key insight on the usability of *Illuminating Clay* and its impact on design. We would also like to acknowledge William Mitchell, former Dean of the MIT School of Architecture and Planning, for his enthusiasm and generous support in the purchase of our laser scanning equipment and Professor Eran Ben-Joseph for his thorough feedback and many inspiring discussions.

References

- Agrawala M, Beers A, and Levoy M 1995 3D painting on scanned surfaces. In *Proceedings of the Symposium on Interactive 3D Graphics*, 9-12 April, Monterey, California
- Appleton K, Lovett A, Sünnerberg G, and Dockerty T 2002 Rural landscape visualisation from GIS databases: A comparison of approaches, options and problems. *Computers, Environment and Urban Systems* 26: 141–62

- Bandyopadhyay D, Raskar R, and Fuchs H 2001 Dynamic shader lamps: Painting on movable objects. In *Proceedings of the IEEE and ACM International Symposium on Augmented Reality (ISAR 2001)*, 29–30 October, New York
- Buckley A R, Gahegan M, and Clarke K C 2000 *Geographic Visualization as an Emerging Research Theme in GIScience*. Washington, D.C., University Consortium for Geographic Information Science White Paper (available at http://www.ucgis.org/priorities/research/research_white/2000%20Papers/emerging/Geographicvisualization-edit.pdf)
- Burrough P A and McDonnell R A 1988 *Principles of Geographical Information Systems*. Oxford, Oxford University Press
- Cartwright W, Crampton J, Gartner G, Miller S, Mitchell K, Siekierska E, and Wood J 2001 User interface issues for spatial information visualization. *Cartography and Geographical Information Systems* 28: 45–60
- Coors V, Jung V, and Jasnoch U 1999 Using the Virtual Table as an interaction platform for collaborative urban planning. *Computers and Graphics* 23: 487–96
- Debevec P E and Malik J 1997 Recovering high dynamic range radiance maps from photographs. In *Proceedings of the Twenty-fourth Annual Conference on Computer Graphics (SIG-GRAPH'97)*, 3–8 August, Los Angeles, California
- Elvins T T and Jain R 1998 Engineering a human factor-based geographic user interface. *IEEE Computer Graphics and Applications* 18: 66–77
- Estalrich J and Trilla J 1998 GATAGRASS: A graphical user interface for using with grass GIS. *Computers and Geosciences* 24: 501–6
- Faust N L 1995 The virtual reality of GIS. *Environment and Planning B*22: 257–68
- Frazer J 1995 *An Evolutionary Architecture*. London, Architectural Association
- Germis R, Maren G, van Verbree E, and Jansen F 1999 A multi-view VR interface for 3D GIS. *Computers and Graphics* 23: 497–506
- Ghadirian P and Bishop I D 2002 Composition of augmented reality and GIS to visualize environmental changes. In *Proceedings of the Joint AURISA and Institution of Surveyors Conference*, 25–30 November, Adelaide, Australia
- Koller D, Lindstrom P, Ribarsky W, Hodges L F, Faust N, and Turner G 1995 Virtual GIS: A real-time 3D geographic information system. In *Proceedings of IEEE Visualization '95*, 29 October–3 November, Atlanta, Georgia
- Kumaradevan P and Kumar S 2001 Virtual Reality and distributed GIS. In *Proceedings of the 2001 GITA Annual Conference*, 4–7 March, San Diego, California
- Massie T 1998 A tangible goal for 3D modeling. *IEEE Computer Graphics and Applications* 18: 62–5
- Neteler M and Mitasova H 2002 *Open Source GIS: A GRASS GIS Approach*. Boston, MA, Kluwer
- Oviatt S and Cohen P 2000 Multimodal interfaces that process what comes naturally. *Communications of the ACM* 43: 45–53
- Pangaro G, Maynes-Aminzade D, and Ishii H 2002 The Actuated Workbench: Computer-controlled actuation in tabletop tangible interfaces. In *Proceedings of the Symposium on User Interface Software and Technology (UIST '02)*, 27–30 October, Paris, France
- Pasman W, van der Schaaf A, Lagendijk R L, and Jansen F W 1999 Accurate overlaying for mobile augmented reality. *Computers and Graphics* 23: 875–81
- Piper B, Ratti C, and Ishii H 2002 Illuminating Clay: A 3-D tangible interface for landscape analysis. In *Proceedings of the Conference on Human Factors in Computing Systems (CHI '02)* 20–25 April, Minneapolis, Minnesota
- Piper B 2002 The Illuminated Design Environment: A 3-D Tangible Interface for Landscape Analysis. Unpublished MS Thesis, Massachusetts Institute of Technology
- Raskar R, Welch G, and Chen W 1999 Table-top spatially augmented reality: Bringing physical models to life with projected imagery. In *Proceedings of the Second International Workshop on Augmented Reality (IWAR 99)*, 20–21 October, San Francisco, California
- SensAble Technologies 2003 Phantom Arm. WWW document, <http://www.sensable.com/>
- Shamonsky D 2003 Tactile Spatial Interfaces for Computer-Aided Design: Superimposing Physical Media and Computation. Unpublished PhD Dissertation, Massachusetts Institute of Technology
- Slocum T A, Blok C, Jiang B, Koussoulakou A, Montello D R, Fuhrmann S, and Hedley N R 2001 Cognitive and usability issues in geovisualization. *Cartography and Geographical Information Systems* 28: 61–75

- Takuma A, Shibasaki R, and Fujii M 1997 Development of new user interface for 3D GIS using mobile terminal. In *Proceedings of the Eighteenth Asian Conference on Remote Sensing (ACRS)*, 20–24 October, Kuala Lumpur, Malaysia
- Ullmer B and Ishii H 2000 Emerging frameworks for tangible user interfaces. *IBM Systems Journal* 393: 915–31
- Underkoffler J and Ishii H 1999 Urp: A luminous-tangible workbench for urban planning and design. In *Proceedings of the Conference on Human Factors in Computing Systems (CHI '99)*, 15–20 May, Pittsburgh, Pennsylvania
- Wellner P 1993 Interacting with paper on the DigitalDesk. *Communications of the ACM* 36: 86–96

