Bringing clay and sand into digital design — continuous tangible user interfaces

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Tangible user interfaces (TUIs) provide physical form to digital information and computation, facilitating the direct manipulation of bits. Our goal in TUI development is to empower collaboration, learning, and decision-making by using digital technology and at the same time taking advantage of human abilities to grasp and manipulate physical objects and materials. This paper presents a new generation of TUIs that enable dynamic sculpting and computational analysis using digitally augmented continuous physical materials. These new types of TUI, which we have termed 'Continuous TUIs', offer rapid form giving in combination with computational feedback. Two experimental systems and their applications in the domain of landscape architecture are discussed here, namely 'Illuminating Clay' and 'SandScape'. Our results suggest that by exploiting the physical properties of continuous soft materials such as clay and sand, it is possible to bridge the division between physical and digital forms and potentially to revolutionise the current design process.

1. Introduction

Despite the increasing availability of sophisticated forms of digital representation and analysis, many designers still value the use of physical models in the planning and design process. Contemporary architect Frank O Gehry, for instance, often uses physical models (which are later digitised) in the early stages of design explorations. Automobile designers work extensively with physical, tape and clay models, even if they have access to sophisticated curved-surface modellers.

On the one hand, there is great efficiency in representing physical structures with physical, tangible media, since they only differ in scale and/or material from the final outcomes. Physical models offer the user an intuitive understanding of complex geometries and physical relationships that are difficult or indeed impossible to describe with pixels on a flat computer screen. They better support rapid ideation and form giving (dynamic sculpting), especially in the initial (upstream) phase of design. Also, they support collocated collaboration better than most existing computational media.

On the other hand, computer-based models, while commonly being limited to 2-dimensional visual representations, offer many advantages over physical models. The dynamic qualities of the screen allow computational systems to represent entities or forces that change over time. They offer a vast increase in the efficiency of production, reproduction and distribution via the Internet. They also offer the ability to work directly with numeric data and at accuracies that far surpass the tolerances of most physical models. In general, they are more suitable for the final (downstream) phases of design where greater precision and quantitative analysis are required.

As a result, a fracture appears in most creative processes — a disjunction between physical and digital forms of representation and analysis, especially between the upstream of exploratory design and the downstream of analytical design. This paper presents two tangible user interfaces (TUIs), namely Illuminating Clay and SandScape, that aim to bridge this fracture by creating a seamless interface between physical and digital design in the field of landscape architecture.

TUIs give physical form to digital information and computation, facilitating direct manipulation of representations. Our hypothesis is that utilising our physical abilities of grasping and manipulating materials can advance the design process, enable deeper learning, and increase collaboration among designers and technologists [1].

Until recently, most TUIs, such as 'Urp' (urban planning workbench [2]), were designed to address the relatively structured downstream aspect (final phases) of the design process based on discrete object-oriented representations allowing rich representations of semantics and the reconfiguration of spatial relationships among discrete objects. However, such a discrete object-oriented approach has a serious limitation in that it does not support the form giving that is critical in the initial (upstream) phases of the design process. In order to go beyond this limitation and support rapid sculpting with real-time computational analysis, this paper presents new forms of TUIs, which we have termed 'Continuous TUIs'.

Users of Illuminating Clay and SandScape alter the topography of a clay/sand landscape model with their hands while the changing geometry is captured in real-time by a ceiling-mounted laser scanner or IR (infra-red) light sensing technology. A depth image of the model serves as an input to a library of landscape analysis functions. The results of this analysis are projected back into the workspace and registered with the surfaces of the model.

In the next sections we describe a scenario for which our approach has been developed and we review past work that has taken a similar approach. We describe our system architecture and highlight specific technical issues in its implementation. We conclude with a discussion of the benefits of the system in combining the tangible immediacy of physical models with the dynamic capabilities of computational simulations. This suggests that digitally augmented continuous physical materials have the potential to change the current design process — integrating physical form giving and computational analysis into one single process rather than separated ones.

2. Application domain — landscape design and analysis

2.1 Scenario

A geo-science 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 projections change on 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 on to the model. Based on the projected colour map, the student gains an intuitive sense of slope and likely water velocity.

The above scenario is an example of how Illuminating Clay can be used in landscape design and analysis by simulating dynamic forces by projecting computational representations directly on to the model landscape (Fig 1).

Fig 1 Illuminating Clay in use — digitally augmented clay model of landscape provides the input/output for GIS (Geographic Information System) simulations.

2.2 Landscape design — physical and digital models

The fracture in the process of design that was highlighted in the previous section is most evident in the context of landscape architecture. There, professionals regularly experiment with clay or sand models to explore complex 3-D terrain geometries quickly and synthetically. On the other hand, they rely more and more on numerical analyses to assess the efficiency or inadequacy of their designs. Illuminating Clay and SandScape bridge this fracture by creating a seamless interface between the physical and the digital for landscape architects.

Developments in high-resolution commercial satellite photography, global positioning systems, digital image processing, database management, and the globalisation of information sources in general have led to a vast wealth of information available to contemporary landscape architects and engineers [3]. High-resolution topographic maps, information on soil types, population densities, variance in vegetation species and so forth are routinely used. Also, there have been parallel developments in the methods with which to analyse and model such data, giving designers and engineers the ability to predict the results of their design decisions through computational simulation.

Despite this progress, there has been relatively little development in the user interfaces through which landscape-based information is represented and manipulated. Most 3-D renderings and simulations are still viewed on computer screens that lack the more intuitive 3-D analysis provided by physical models. The systems presented here aim to address this limitation.

Also, our interfaces aim to promote participation and collaboration in design. Landscape architecture and engineering often occur over large areas and require the input of a great number of specialists. These may include geologists, hydrologists, soil scientists, land economists, transportation engineers and land use lawyers.

Furthermore, large-scale interventions inevitably affect large numbers of people living on or near a particular site. It is therefore critical for the designers and planners of such projects to communicate their vision to the local stakeholders. It is even more important that the tools used for the planning of such areas allow the various specialists and lay members to participate in a collaborative design process.

Also, if our aim is to let the public become more involved in the planning and design of physical spaces, better methods and tools have to be developed. Ideally, these tools would communicate changes that are proposed so that non-design professionals could easily understand the impact of the proposed changes. These systems could be used not only as tools for design professionals but also as an interactive application to enrich communication and learning within the design process. The integration of such envisioning tools into decision-making will allow for better professional judgements while incorporating stakeholders' expectations.

2.3 Context — evolution of user interfaces for GIS

In recent years, an increasing effort has gone into the design of user interfaces for GIS. This section summarises their evolution as a context for our research on TUIs.

First-generation line-driven GIS interfaces have rapidly become obsolete for certain operations, due to their inability to cope with new algorithms for spatial analysis and complex 3-D modelling. According to Cartwright et al [4]: '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, among others, by Elvins and Jain [5]: '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 Visualisation: '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' [6].

one of the goals is to introduce a novel approach to GIS interfaces

Also, Oviatt and Cohen [7] argue for the introduction of a 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 [4].

- Graphical user interfaces (GUIs)

  Most first-generation line-driven command GIS have now been integrated with or replaced by GUIs. Estalrich and Trilla [8] report on this having happened with GRASS (Geographical Resources Analysis Support System) [9], 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 [5]. 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 3-D forms.

- Virtual environments (VEs)

  A VE is defined as 'a computer-generated, interactive, 3-D environment in which a person is immersed' [10]. With GIS acquiring powerful 3-D output capabilities, the use of VEs is receiving an increasing amount of attention from the scientific community [11]. For instance, Kumaradevan and Kumar [12] describe how a VR interface could be used for distributed GIS. Koller et al [13] 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 [14] 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 getting lost in virtual spaces that adopt unfamiliar distances, speeds and levels of detail [4]. Also, the power of VEs as output devices must be balanced against their unsuitability as input systems. Cognitive and usability issues in using VEs for GIS are discussed, among others, by Slocum at al [15].

- 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 [16], whose system allows the retrieval of information from a database by clicking on real objects on a live video image (for instance, clicking on a building on a live urban video prompts information to be displayed such as name, address, direction and distance from viewpoint). Ghadirian and Bishop [17] report on a similar system developed for monitoring environmental change, while Pasman et al [18] address some technical issues in accurately overlaying virtual information on real-world views.

- Other interface techniques

  Systems such as the Phantom Arm [19], when combined with virtual environments or holography, allow for highly convincing interactions. Agrawala et al [20] have developed methods for painting directly on the surfaces of complex 3-D geometries while Raskar et al [21] and Bandyopadhyay et al [22] have looked into possibilities for animating computational projection and highlighted some of the difficulties that arise when projecting from multiple sources.

One of the goals of our research is to introduce a novel approach to GIS interfaces, based on recent developments in TUIs. Giving physical form to digital information and computation, TUIs make bits (digital information) directly and collaboratively manipulable [1]. TUIs are increasingly accepted as an alternative paradigm to the more conventional

GUIs [23] because of their advantage of spatially multiplex direct interactions with computational models.

The development of TUIs dates back to the early 1980s, when Frazer explored different approaches to parallel physical/digital interactions with his 3-D data input devices [24]. Since then, there has been a number of impressive developments — Wellner's [25] digital desk illustrates the efficiencies of augmenting paper-based office production with digital tools and methods for storage.

Special note should be made of the 'Urp' system developed by Underkoffler and Ishii [2], 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 [26], 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. Key idea — clay and sand as input/output

In order to introduce TUI concepts to GIS interfaces, we propose to use conventional modelling materials, such as clay and sand. They are digitally augmented and act as input/output for landscape design. Their tactile richness makes them pleasing to touch and easy to manipulate. These materials allow freeform landscape modifications in an immediate way, as noted by Massie [27]: '… 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 modelling packages to create within a 3-D digital domain'. In particular we aim at constructing a tangible interface that:

- would be self-explanatory and easy to interact with — as Cartwright et al [4] 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 has often been the case with past discrete object-oriented 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) in the upstream and GIS analysis in the downstream of design,
- 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, and thus, in this sense, it should promote participatory design, engaging the public in the landscape architecture discussion [28], and be particularly suited for teaching.

4. System architecture

Both Illuminating Clay and SandScape are based on the same principles, although they differ in terms of implementation. Users interact with a landscape model made of clay or sand. The geometry of the model is continuously sensed with one of the techniques described below. Sensing output is passed on to 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 happens in near-real-time (approximately one second per cycle).

4.1 Sensing technology

The two configurations of the system, Illuminating Clay and SandScape, are shown in Figs 2 and 3. The primary difference between them is in the 3-D sensing technologies used. Illuminating Clay was developed first, and proved very reliable and accurate, albeit rather expensive. Its preliminary set-up was described in Piper et al [29], although it has been extensively modified since. SandScape was 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.

4.1.1 Illuminating Clay sensing technology

Illuminating Clay uses a commercially available triangulation based laser scanner (Minolta Vivid-900^{TM} [30]) 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 co-ordinates of the surface of the model correspond precisely to the projected image co-ordinates. The scanner/projector pair is housed inside an aluminum casing at a height of approximately 2 m above the surface of the modelling material.

The Minolta Vivid-900^{TM} was designed to perform single scans of static objects and scenes. In order to capture changes in the surface geometry of the modelling material in real time, it was necessary to modify the scanner controls using the Minolta Software Development Kit (SDK). 320×240 point values are scanned every 1.2 sec resulting in a near-real-time surface capture. Scanned data is re-sampled into x, y and z co-ordinates and then converted into a well-established GIS format — the digital elevation model, a grid 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 [29]. However, our tests showed that from a distance of 2 m and with an operating volume of approximately $0.5 \times 0.5 \times 0.5$ m, a simpler arrangement could be used, with the projector and the scanner positioned alongside each other, as shown in Fig 2; in this case, the

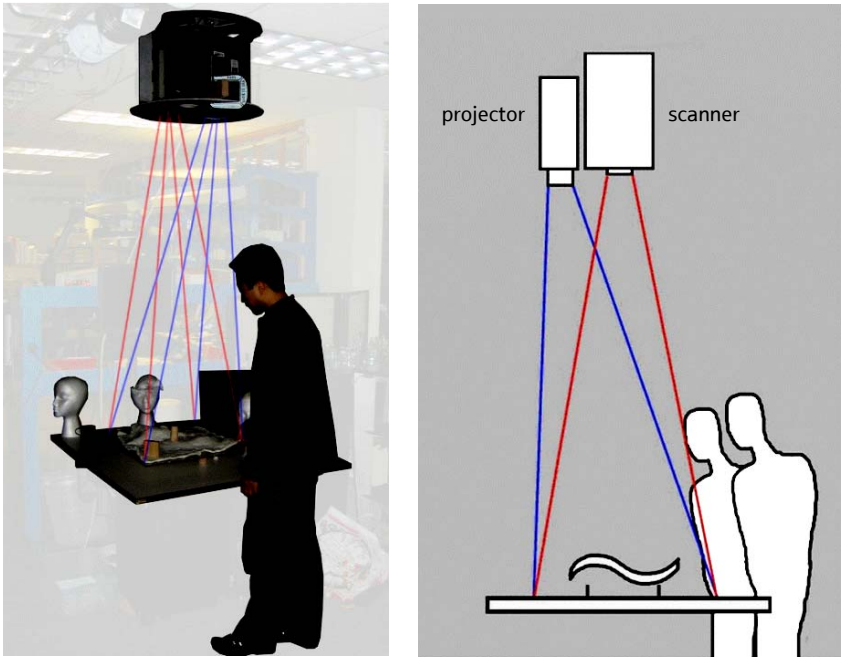


Fig 2 Illuminating Clay system — this system uses a commercial Minolta Vivid-900™ laser scanner to capture the geometry of the clay model.

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 modelling medium. Therefore, most objects in the designer's workspace can be used as 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 expensive for widespread use. This led us to investigate more affordable alternatives, such as SandScape.

4.1.2 SandScape sensing technology

The SandScape configuration is based on a box containing 1 m diameter glass beads lit from beneath with an array of 600 high-power infra-red LEDs, as shown in Fig 3. Four IR mirrors are placed around the LED array to compensate for the uneven radiance distribution on the boundary. A monochrome infra-red camera is mounted 2 m above the surface of the

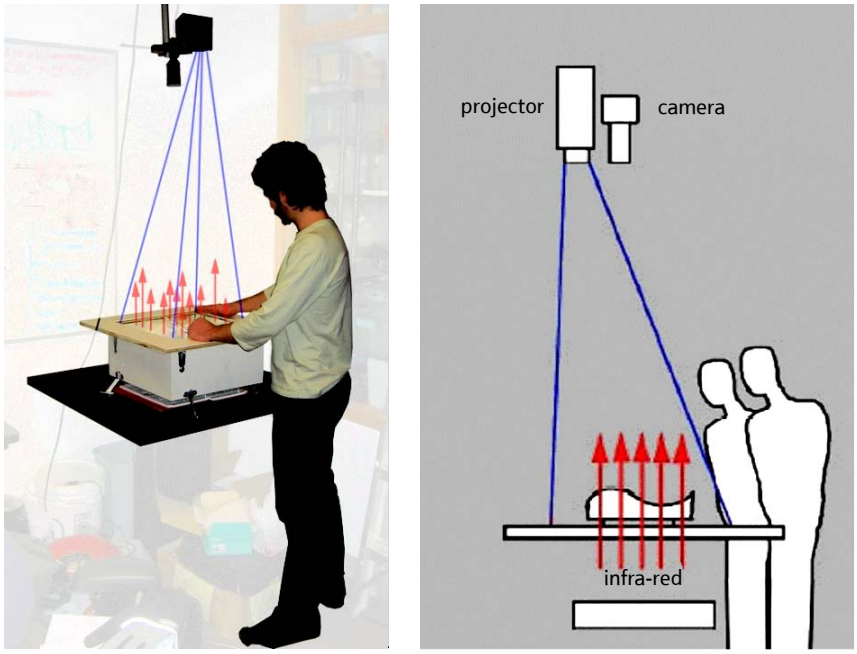


Fig 3 SandScape system — this system was developed as a more affordable alternative to Illuminating Clay. The geometry of the landscape model is captured with a sensing technology based on the measurement of infra-red light transmitted through a bed of glass beads.

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 look-up table can be used to convert surface radiance values into 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 [31].

SandScape is less accurate than Illuminating Clay[1] and also material-dependent — no material other 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 being an affordable implementation (an order of magnitude lower than the laser scanner). This system was exhibited as an interactive art installation at the Ars Electronica Center, Linz, Austria, from September 2002 until August 2004.

[1] Our initial tests show an error of 5 mm, compared with 1 mm with the Minolta laser scanner.

4.2 Tangible worktable

The physical landscape model that acts as input/output interface is placed at the centre of the worktable (Figs 4 and 5). A library of GIS analysis functions is projected as thumbnails around it. 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 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 (Fig 4).

Projected results of the analyses use a colour map, 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 for video projection or an LCD screen is also placed on the side of the worktable, in order to display a 3-D perspective view of the landscape (Fig 6). Users can use it to visualise real-time fly-through animations at human eye level. The perspective view

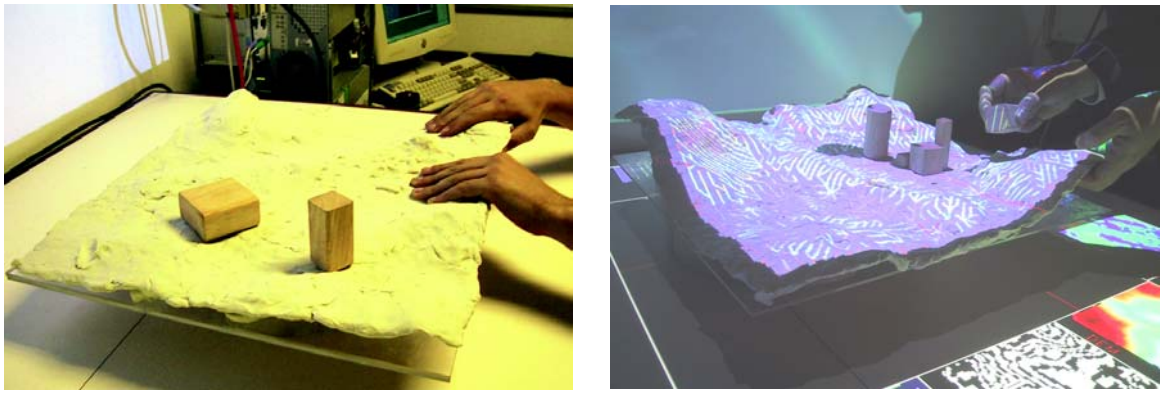


Fig 4 Tangible worktable for the Illuminating Clay system — the tangible worktable is comprised of a landscape model, which is augmented by computer projections (water flow simulation). In the Illuminating Clay case, any object from the user's environment can be used as an input/output mechanism, including the user's own hands, pieces of paper, cardboard, foam, plastic or other *objets trouvés*.

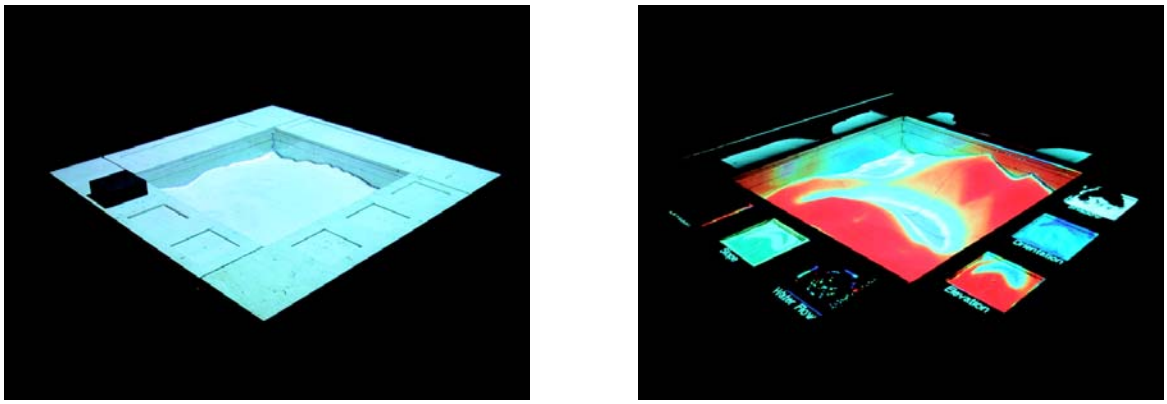


Fig 5 Tangible worktable for the SandScape System — the geometry of the landscape model is defined using glass beads.

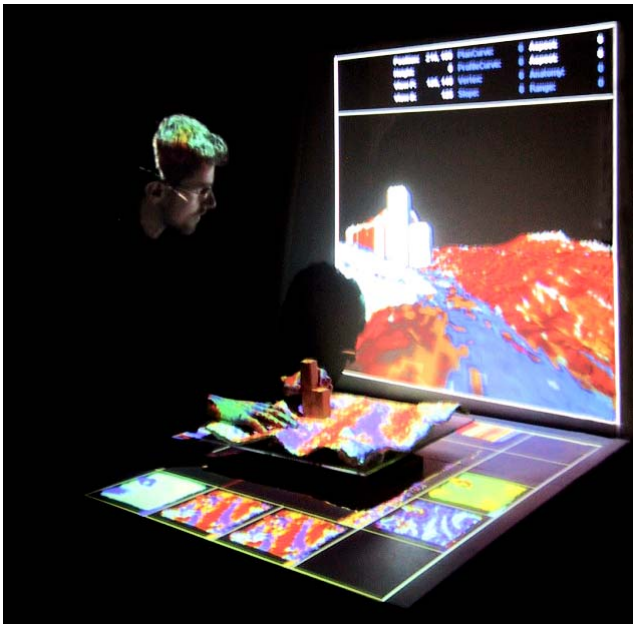


Fig 6 Vertical screen for Illuminating Clay a vertical screen next to the worktable provides users with a virtual view of the landscape at human eye level.

complements the physical landscape model, by providing a virtual experience similar to that which 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, which was once solved with the use of model-scopes. 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 Corian 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 standard input devices such as a mouse.

Illuminating Clay can operate on almost all projectable surfaces and requires no dedicated worktable. SandScape, on the other hand, requires a custom-built table to contain the glass beads, the electronics and LEDs used to emit the IR light, and the fibre optics that distribute IR light to various locations on the surface of the table and allow for the tracking of the Corian blocks. We designed a tabletop that houses both Illuminating Clay and SandScape, allowing the operation of the two systems through a single interface. The tabletop is shaped as a square torus ('square bagel') and holds 30 pounds of glass beads in the centre cavity (Fig 5). The glass beads are supported by a glass slab underneath which an array of 1600 IR-LEDs is placed. Fibre optics transfer light from the center cavity to the perimeter of the table and emit IR though six distinct locations on the surface of the table. Figure 6 shows the worktable for SandScape designed and implemented by Assaf Biderman.

4.3 Library of landscape analysis

We have developed a small library of landscape analysis functions, written in C++, such as slope, shadow casting, local drain direction. They are standard algorithms in the GIS literature (for more references, see Burrough and McDonnell [32]).

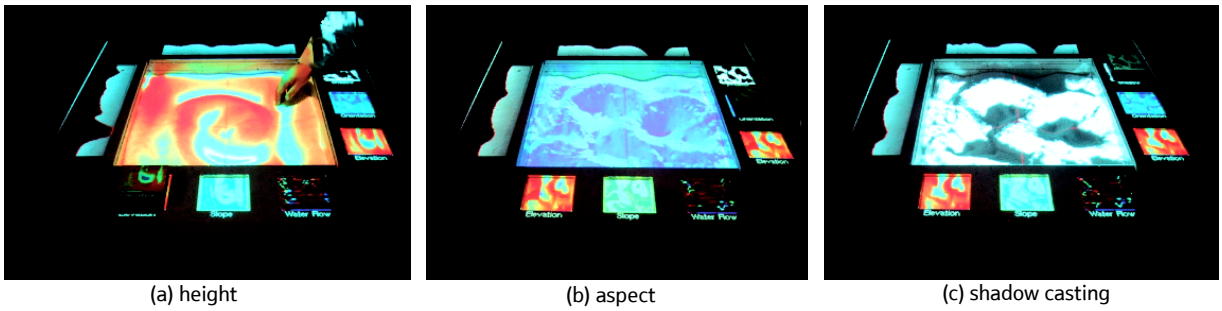
This list is preliminary and could easily be expanded. Our aim has been simply to give a proof of concept of the potential of TUIs applied to GIS. However, we have deliberately kept the system architecture open, so that different functions could be plugged in and out. Both Illuminating Clay and SandScape have been developed in the C++ environment (with an extensive use of the graphical library OpenGL) and each of the analysis functions has been kept as a module (see Fig 7). This makes our systems very flexible and would allow them to be interfaced, for instance, with the GRASS open source GIS [9].

4.3.1 Digital elevation model

As described previously, the output of the scanner is a range image that is converted into a DEM. In order to calibrate the system the unprocessed DEM is projected on to the surface of the model and scaled in order that each scanned point on the model corresponds with each projected pixel.

The DEM is the standard data format used in the geosciences to store topographical information. Its simple data structure — an array of regularly spaced elevation values — is conducive to numerous landscape analysis functions. Over the past decades a great number of algorithms have been developed for this format.

We have provided a small library of standard landscape analysis functions to demonstrate the potential for Illuminating Clay and SandScape. Some of these functions are described in the following sections.



(a) height (b) aspect (c) shadow casting

Fig 7 GIS analysis functions available for SandScape — a number of different GIS analysis functions can be selected from the thumbnails around the worktable — (a) height DEM, (b) aspect, (c) shadow casting.

4.3.2 Slope variation and curvature

A thorough understanding of the slope and curvature of landscape topography is extremely important in almost all landscape analysis. For example, slope gradients affect the positioning of roads, buildings, power-lines and so forth. The calculation of slope and curvature 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:

$$\nabla f = f'_x \vec{i} + f'_y \vec{i}$$

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 colour map ranging from red to purple, where the two extremes correspond to the maximum and minimum slope values (Fig 8).

4.3.3 Shadows and solar radiation

The DEM allows us to simulate the positions of shadows in the landscape (Fig 9). Shadow angles are calculated for a given sun position and are projected on to the model as a black and white image. By changing this 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. This kind of information may, for example, help the user to position crops, housing complexes, solar energy collectors and other sunlight responsive insertions in the landscape. These values can be integrated to form isolines, which can also be projected on to the model. The shadow algorithm was developed by Ratti and Richens [33]. A solar exposure algorithm is being adapted from the GRASS open source GIS library [9].

4.3.4 View-shed

It is often crucial to know the precise field of view from any given position in the landscape. This field of view is known as the view-shed and this landscape analysis can be performed by passing the DEM through an image-processing algorithm that generates the areas that are visible, based on a point in the model selected by the user. Applications are varied, from helping to decide the positioning of line-of-sight telecommunications devices (such as microwave transceivers) to the passage of routes that maximise or minimise views (scenic or smuggler's paths).

4.3.5 Least cost of passage

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 minimise the cost of passage. This cost can be calculated to take into account

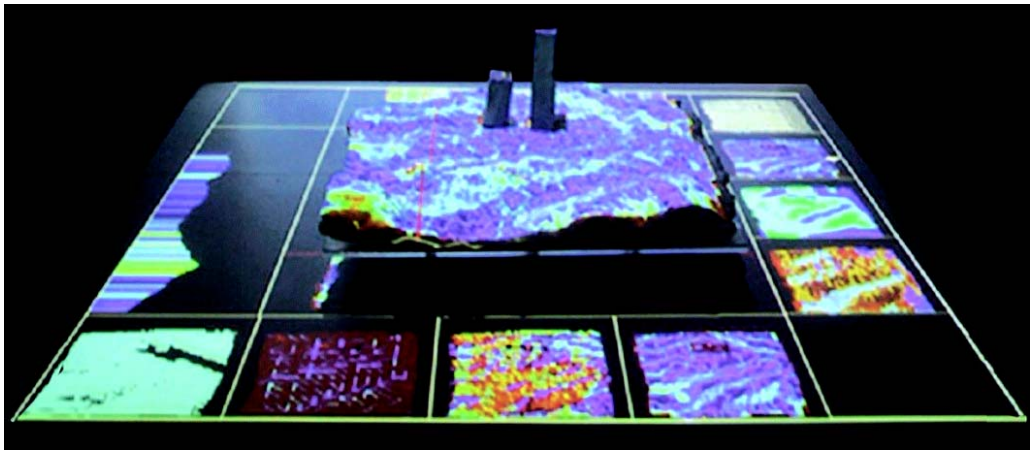


Fig 8 Slope variation in Illuminating Clay.

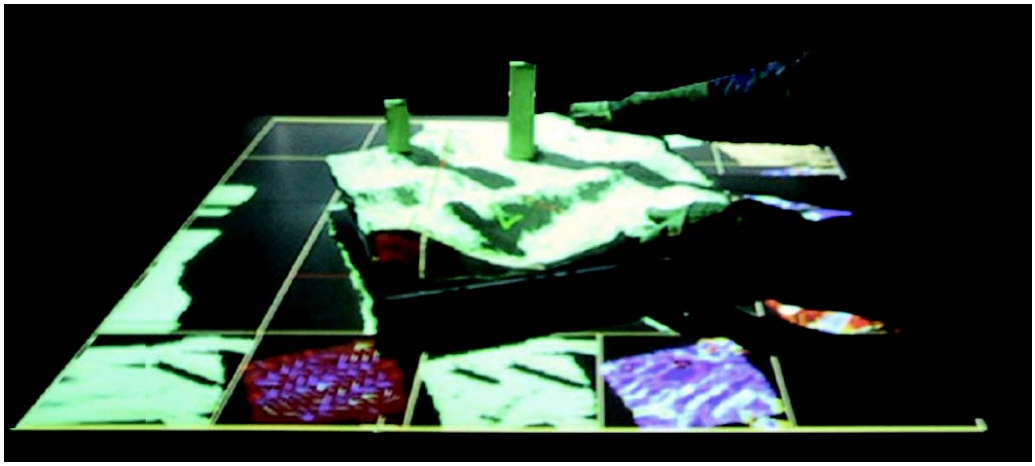


Fig 9 Shadows generated by an object placed in the workspace of Illuminating Clay.

different parameters such as the actual cost of construction or the cost in time taken to complete a particular route. In addition information relating to the necessary volume of cuts and fills on the landscape can be calculated and displayed in real time for the benefit of the user.

4.3.6 Water flow and land erosion

The representation of water flow and erosion in the landscape helps the user in siting housing complexes, dams, roads or other interventions while visualising the (often non-intuitive) consequences of these interventions. 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) in real time, while more sophisticated analyses are being adapted from the GRASS open source GIS library [9].

5. Discussion

Having described the system architecture and analysis functions of Illuminating Clay and SandScape, we should address the following question: 'What could be the advantages of using TUIs in landscape architecture?' 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. The next step would be to carry out a comprehensive usability study, based on the principles developed in the human-computer interaction community, to assess the comparative strengths of TUIs versus other types of GIS interfaces.

5.1 Integrating physical and digital representations

Illuminating Clay and SandScape have shown the potential advantages of combining physical and digital representations for landscape modelling and analysis. The physical clay and sand models convey spatial relationships that can be intuitively and directly manipulated by hand. This approach allows users to quickly create and understand highly complex topographies that would be difficult and time-consuming to produce with conventional CAD tools. We believe that this 'Continuous TUI' approach makes better use of our natural abilities to discover solutions through the manipulation of physical objects and materials.

At the same time the projected graphics give the user real-time feedback. While tracked physical models interfaced with a computer are not a novelty, we believe that Illuminating Clay and SandScape offer a new contribution, by using the continous surface geometry of the model itself to act as the input/output mechanism. In so doing we hope to give the projected information the same tangible immediacy as the clay material itself and allow quantitative data to support the intuitive understanding of the landscape.

5.2 Free-form geometric modelling

Illuminating Clay and SandScape offer an intuitive alternative for modelling 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, keyboards and conventional CAD tools. Also, unlike other approaches in discrete object-oriented 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 on GIS but also on TUIs by introducing the 'Continuous TUIs' category, which uses the 3-D surface of a continuous workspace as input and output.

5.3 Improving collaboration and communication

Landscape architecture, as well as urban and architectural design, requires the collaboration of a number 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, and sometimes without much direct and synchronous interaction. Illuminating Clay and SandScape provide a common platform for collaboration, centred 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 valuable platforms to communicate design decisions to non-experts, allowing them to become involved in the design process. In practice, 3-D models are often used to work with community groups and lay clients, since people understand 3-D representations more easily than drawings. Also, people often feel comfortable manipulating clay and sand to test their own scenarios as 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.

The role of these tools in fostering communication and collaboration, along with pluralistic planning and design processes, is one of the most important benefits offered by this new technology [34].

5.4 Preliminary usability study

Illuminating Clay has been used in teaching a class at the Massachusetts Institute of Technology, Department of Urban Studies and Planning, during spring 2002 (course 11.304, taught by Eran Ben-Joseph, Hiroshi Ishii and Carlo Ratti [35]). The shared perception has been that the system 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 directions, become immediately evident when explained on the physical clay or sand model (Fig 10).

In the design development phase, Illuminating Clay provided a benefit over conventional digital CAD platforms by allowing students to model their work physically with immediate results. In addition, in contrast to the standard computer interface where a single user has dominance over the creative space of the screen, the ergonomics of the tools allowed the entire design team to work simultaneously on a single scheme.

Fig 10 Illuminating Clay in use in the design studio — the Illuminating Clay system was used in teaching at the Massachusetts Institute of Technology, Department of Urban Studies and Planning [35].

The use of the TUIs enabled the students to achieve a consensus on the design solution while accommodating the opinions of all the individuals [36].

More rigorously, a preliminary usability study on Illuminating Clay was conducted at the same time of the class, as reported by Shamonsky [37]. This involved students as well as professionals, with an 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, ordinary clay, and paper. Tool sets were alternated among 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, visual records. Furthermore, they were interviewed after they had performed the task.

> the ergonomics of the tools allowed the entire design team to work simultaneously on a single scheme

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, many 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.

6. Conclusions and future work

People have developed sophisticated skills for sensing and manipulating our physical environment. However, most of these skills are not employed by traditional GUIs. TUIs seek to build upon these skills by giving physical form to digital information and computation.

This paper presents a new generation of TUI that enables rapid form giving (dynamic sculpting) and computational analysis in landscape architecture using digitally augmented continuous physical materials such as clay and sand. These interfaces differ from existing TUIs inasmuch as most of the latter were designed to be relatively structured tools for the analytic (downstream) level of the design process using discrete object-oriented representations — an approach that does not enable 'form giving' in exploratory (upstream) design processes.

We termed the new type of TUIs 'Continuous TUIs', as they offer rapid form giving in combination with computational feedback by exploiting the physical properties of continuous soft materials. In particular, two experimental systems were described, Illuminating Clay and SandScape, as well as their applications in the domain of landscape design. They both use simple physical landscape models as input/output for computational analysis/simulation. Users interact with these physical models, while a sensing device captures their geometry in real time and a computer projector sends back the results of selected GIS simulations on to the physical models. A library of basic GIS functions has been included to prove 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 the open source GRASS GIS library [9]. We are planning to work on this aspect in the coming years, to make our interfaces truly usable in the practice and teaching of landscape architecture.

While a systematic comparison of usability between TUIs and conventional GUIs still remains to be done, preliminary results

of the experimental use of Illuminating Clay are very encouraging. Illuminating Clay has been tested so far by a variety of people, experts and non-experts, including students in an MIT class and sponsors who regularly visit the Media Lab. SandScape was exhibited in the Ars Electronica Center (Linz, Austria) from September 2002 until August 2004, where it was one of the most popular 'interactive art' installations. Results suggest that these Continuous TUIs are intuitive interfaces to work/play with and can facilitate collaboration between landscape architects and experts. Also, they seem to promote the involvement of lay people in the design process.

A possible concern in using TUIs for design development and presentation could be their overemphasis on visual aspects. As one user noted: '… over reliance on TUIs could be problematic, i.e. we also need to think about social, political, and economic factors we cannot show on tools such as the Illuminating Clay. Also the Clay can distract from other effective presentation media such as drawings'. In other words, the emphasis on visual representation and the extensive use of reflex-based interactions — originally envisioned to be the key benefits of the TUIs — may discourage certain activities in design where deliberate and planned work is needed. The issue becomes which activities require the use of a more dynamic representation in the design process and which ones do not.

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Still, our research has demonstrated that bridging the division between physical and digital forms using materials with continuous physical properties has the potential to revolutionise the current design process by integrating exploratory form giving and computational analysis into a single process. Along with offering a missing link between the palpable and the digital, the promise of these new tools may be in shaping a plural planning process. The aforementioned innovations are really only the beginning of an ongoing revolution in design tools. As computing power has increased and the price of storage declined, the ability to put unique modelling tools at the fingertips of the users will increase further, giving individuals the power to understand and propose changes in their built environment. It is often said that democracy requires an enlightened republic. By promoting the communication that is critical to that enlightenment, TUIs can have a profound impact on the politics of planning and design.

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