PHOXEL-SPACE: an Interface for Exploring Volumetric Data with Physical Voxels

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Abstract

Three-dimensional datasets (voxel datasets), generated by different types of sensing or computer simulations, are quickly becoming crucial to various disciplines - from biomedicine to geophysics. *Phoxel-Space* is an interface that enables the exploration of these datasets through physical materials. It aims at overcoming the limitations of traditional planar displays by allowing users to intuitively navigate and understand complex 3-dimensional datasets. The system works by allowing the user to manipulate a freeform geometry whose surface intersects a voxel dataset. The intersected voxel values are projected back onto the surface of the physical material to reveal a non-planar section of the dataset. The paper describes how the interface can be used as a representational aid in several example application domains, overcoming many limitations of conventional planar displays.

Categories & Subject Descriptors: B.4.2 [**Input/Output Devices**] B.m [**Miscellaneous**] E.1 [**Data Structures**] E.2 [**Data Storage Representations**] J.2 [**Physical Sciences and Engineering**] J.3 [**Life and Medical Sciences**]

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1 SCENARIO

A trainee neuro-surgeon and an expert in brain tumor analysis stand in front of a physical clay model of a patient's head and discuss the surgical trajectory of a proposed operation. The trainee adds or removes material from the model and as she does so graphical information describing the interior of the brain is projected onto the newly revealed surfaces. The tumor expert points out critical regions that should be removed in the operation and to some blood vessels, while the surgeon familiarizes herself with the spatial relationships of the surrounding tissues.

Having discussed and rehearsed the procedure in these ways the trainee is ready to help in carrying out the operation a few hours later.

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2 INTRODUCTION

In many fields of science and engineering there is a need to represent and understand volumetric information. This data can be obtained from a variety of scanning and sensing techniques, such as seismic and electric explorations in geophysics and - in the medical field - Computed Tomography (CT), Magnetic Resonance (MR) or Time Domain Reflectometry (TDR). It can also be generated by computational simulations, using finite element analysis such as Computational Fluid Dynamics (CFD) techniques. However, the scale and spatial complexity of these kinds of data structures, both sensed and simulated, has raised challenging questions about how to best visualize and understand them.

Our system, named *Phoxel-Space*, combine positive aspects

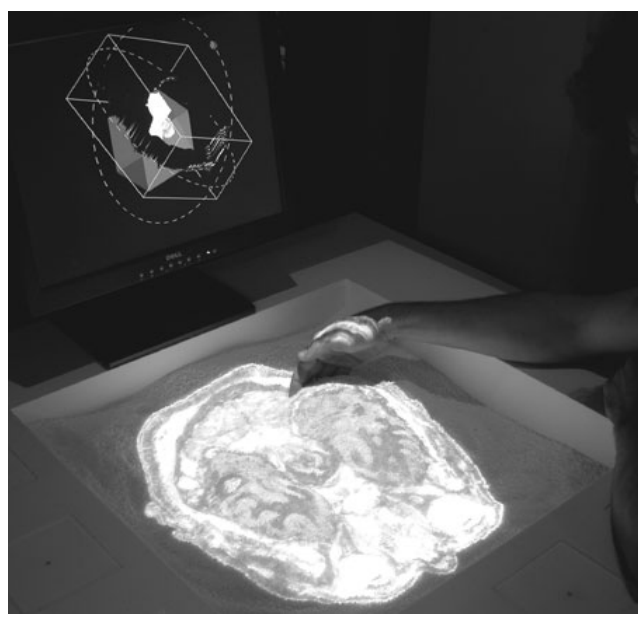

Figure 1. *Phoxel-Space* allows the exploration of voxel datasets through the use of physical materials. The photo shows a non-planar section through a dataset of a human brain.

Our system, named *Phoxel-Space*, combine positive aspects of two traditional ways of exploring 3-dimensional datasets: 2-d displays and physical models. A 2-d display enables a high degree of flexibility. It allows the exploration of all forms of data, but as a result it cannot convey physical properties of the information displayed such as texture, hardness, etc. Physical models, however, convey all spatial properties of the data, but are domain-specific. *Phoxel-Space*'s attempt to combine both formats creates an interface that functions flexibly somewhere between a conventional display and a physical model. It is a display that adapts itself to the physical properties of modeled data.

3 PREVIOUS WORK

Physical models have long served as an effective and intuitive means for representing and studying complex spatial structures. For example, medical students use anatomical models to learn about complex biological structures. Geophysicists build physical terrain models to better their understanding of the earth's crust. Digital technologies offer a powerful new alternative to these kinds of physical models. Numerous research and development projects have discussed interfaces that allow the interpretation of datasets and digital models of spatial structures.

In this section we will describe current approaches to the design of interfaces that aid in the exploration of 3-dimensional datasets. These are: Graphical Interfaces, Virtual Reality Interfaces, Augmented Reality Interfaces and Tangible Interfaces.

a) *Graphical Interfaces*. Traditional graphical interfaces define a 2-dimensional cutting plane through a 3-dimensional dataset and display the results as a 2-dimensional cross section. A number of software packages exist, some of which are freely available on the Internet (see for instance [16] and [4] which have been developed in the framework of the Visible Human Project®). Although these methods allow users to view precisely defined cross-sections, they are limited because of the planar display system they adopt.

   3-dimensional volume rendering techniques have been developed to allow the graphical rendering of volumetric data. In order for this technique to work effectively, the data usually must be manually or computationally segmented into different regions. For example, in biomedicine a dataset of human anatomy may be divided into regions of muscle, fat or bone. In this way a user is able to adjust the relative opacities of different tissue types to reveal information that might otherwise remain occluded. 2-dimensional cross sections can be combined in perspective views to build up a better visual understanding. A review of volume rendering techniques can be found in [13]. While volume rendering was originally developed for applications in the biomedical sector (see [7]), it is increasingly being applied in other fields where the visualization of 3D datasets is of critical importance. These include Computational Fluid Dynamics [20], atmospheric studies [12], fire engineering [21], geophysics, and geology.

   Although 3-dimensional volume rendering techniques offer significant improvements over 2-dimensional planar representations, they are still limited in that they rely on illusions of perspective and lighting to convey spatial information. In order to build up a more holistic understanding of a dataset, users must correlate multiple images from different viewpoints.

b) *Virtual Reality Interfaces* aim to create the illusion that users are immersed in a computer-generated virtual environment. Head tracking devices combined with binocular graphical displays create the illusion of real objects that exist in the same space as the user. Position tracked gloves and tools allow a degree of interaction with the virtual scene. The value of virtual reality is that data can be explored as if it existed in the same space as the user. Instead of viewing images of spatial information users can interactively explore immersive computational representation.

   Although these techniques have existed for a number of years their application in scientific or industrial visualization is relatively recent. One example, developed by Mercedes and AT&T, consists of a position tracked LCD screen that allowed users to interactively explore un-built car interiors. (The system is now commercially available from Virtual Research Systems). Immersive projection environments are also available for 3-dimensional visualization, both in the scientific realm ([23]) and industry. The Virtual Windtunnel project at NASA, [1] and [2], uses immersive VR to create a virtual wind tunnel, where users can interact with computationally generated 3-dimensional flow fields by releasing virtual wind tracers using position tracked gloves. Also, the Phantom Arm [14] has been developed as a device that can represent computationally defined material properties and has been used to demonstrate a number of potential applications in the interactive visualization of anatomical models [3].

   While VR techniques have many advantages in allowing a spatial understanding of 3-dimensional representations, they are limited by the lack of physical interaction. They can also be highly disorienting due to slow update rates and low visual resolution. In addition the head mounted displays, and position-tracked gloves are often cumbersome to use and lack the intuitive believability that would make such systems more useful on an every day basis.

c) *Augmented Reality Interfaces* superimpose supplementary information on real world objects, creating the illusion that virtual and real objects coexist. For example Grimson, et al., ([9], [10]) at the MIT Artificial Intelligence Lab report on Augmented Reality visualization where internal brain tumor and ventricle structures can be calibrated with and overlaid directly on the patient, allowing a surgeon to orient a given procedure.

d) *Tangible Interfaces* seek to make use of natural human means of understanding through the manipulation of physical objects and materials. Some, such as [15], have developed techniques to segment and visualize volume data using physical models (produced with solid freeform fabrication equipment). Ken Hinkley's et al. interface for neurosurgical operations ([11] and [8]) allow the user to understand the complex geometries of the human brain through the manipulation of real world props representing a given brain data set and a cutting plane. MIT Media Lab has also developed a number of innovative systems that could be developed to aid in the process of visualizing 3D datasets (see [17], [19] and [22]).

The interface that we describe in the following section is an attempt to build on the lines of research outlined in c) and d) above by developing an interface to 3-dimensional datasets that combines different benefits from a number of these systems.

4 PHOXEL-SPACE SYSTEM

Users of the *Phoxel-Space* interface are able to physically interact with voxel data, otherwise referred to as *Phoxels* (Physical Volumetric Pixels). The following section describes how our system uses the surface geometry of a physical material to define a cross section surface that passes through a given voxel dataset. The values in the dataset that are intersected by this surface geometry are projected back onto the surface of the physical material. This allows users to easily define the exact location and geometry of cross sections through any desired voxel dataset and interactively view the results. The system is comprised of the following key components:

a) *Physical modeling material*. This material is used to define a geometry with which to intersect the voxel dataset. An arbitrary range of materials (such as clay, plasticine, glass beads, cubic blocks, etc.) can be used for this purpose depending on the type of voxel data to be explored as explained in a later section. Material choice is only limited by having to provide a suitable surface for data projection.

b) *A Dataset in Voxel Format*. This dataset is the source of information to be explored using *Phoxel-Space*. The voxel (Volumetric Pixel) format is an array of point values arranged in a regular 3-dimensional grid. These voxels are assigned an RGB value for graphical visualization and, if required, an additional Alpha component defining their opacity. As described in the introduction, voxel datasets may be generated using sensing technologies (such as MRI or CTI) or by using computational simulation methods (as is the case in CFD). Voxel data is often pre-segmented, either manually or computationally, to allow the easy separation of different regions in a given voxel dataset.

c) *3-dimensional sensor*. A 3-dimensional sensor is required in order to capture the surface geometry of the physical modeling material. This sensor must ideally be capable of capturing changes in the surface geometry in real-time allowing interactive exploration of the given dataset.

d) *Computer*. A computer is used to store the voxel dataset, control the 3-dimensional sensor, process the 3-dimensional sensor output and render the voxel values that are intersected by the physical surface geometry.

e) *Video projector*. The video projector projects the voxel values rendered by the processor back onto the surface of the physical modeling material. The video projector must be precisely calibrated with the 3-dimensional sensor to allow projected voxel values to correspond with points of intersection on the surface geometry. The type of projector used is partially dependent on the 3-dimensional sensing technique as described below.

The system functions as follows. The surface geometry of the modeling material is captured in real time by the 3-dimensional sensor and intersected with the voxel datasets. Results of the intersection are then projected back on the modeling material, allowing users to physically browse through 3-dimensional data.

5 EXAMPLES OF VOLUMETRIC DATA ANALYSIS

We illustrate here some example applications that we have developed with *Phoxel-Space*.

5.1 Medical Analysis Using Malleable Material

Students are conventionally taught about the complex structure of the human anatomy using diagrams, photographs, models, 3-dimensional visualizations, video clips and cadaver dissections. Each form of representation is valuable in a different way. A diagram can clearly depict certain abstract properties of the brain but lacks the physical detail of a photographic image that can record a specific state. Physical models convey spatial relationships but lack flexibility in how they are viewed. Volume renderings allow examination of particular case data, but they rely on being understood as 2-dimensional visual information. Cadaver dissections allow students to become familiar with the properties of real anatomical tissues and spatial relationships but they do not allow for the demonstration of a particular state and it is a destructive process of great expense.

Phoxel-Space can be used in the planning of surgical operations in non-regionalized anatomies such as the brain and the colon. Currently, the technology can be used to

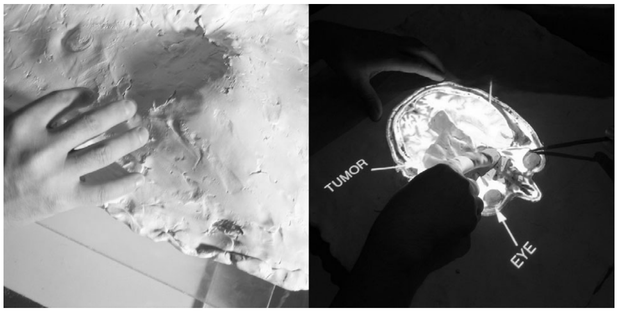

Figure 2. Malleable clay material used to define a freeform cross section through a brain data model

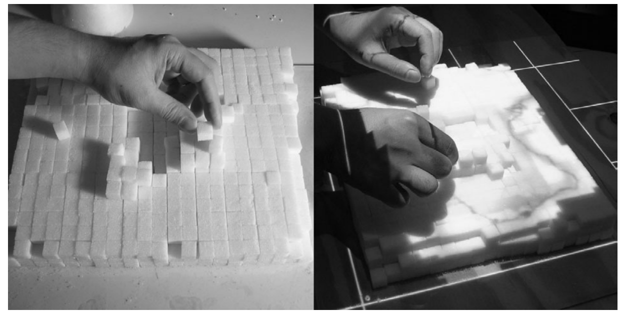

Figure 3. Modular blocks used to explore the seismic velocity below Australia to a depth of 55km

instruct students, but could in the future be fine-tuned to enable use for planning an actual surgical procedure. While visual renderings and MRI cross sections greatly aid in such surgical planning, *Phoxel-Space* offers the potential for surgeons to non-invasively explore living anatomical regions in 3 dimensions.

In the first example, plasticine, a malleable and fine-grain material, is used to define a freeform cross-section surface onto which an anatomical dataset of the brain, captured using MRI, is projected. The surgeon is then able to alter with great precision the form of this cross section surface, thereby revealing the precise spatial boundary between, for example, tumor-affected regions and normal tissues. This spatial understanding would be extremely difficult to convey via other media and could facilitate the planning of surgical operations.

There is a limit to the complexity of the surface curves that users can define when they must create the desired surface out of a physical material. Various conformal mapping algorithms (e.g. flattening algorithms) can be used to reduce the spatial complexity of the 3-dimensional data, thus allowing the analysis of complex geometry textures on a simpler geometrical surface.

In the second example, areas suspected to be tumors are highlighted on a non-distorted flattening map of a colon segment. The complex shape of the colon has been simplified to match the complexity of the surface of the sand, so that rapid and accurate browsing of this complex shape is made possible.

5.2 Seismic Velocities with Block Modules

As in biomedicine, the field of seismology requires a sophisticated understanding of spatial relationships, in this case within the volume of the earth. The example below shows how *Phoxel-Space* can be used to explore the seismic velocity within the Australian plate, recorded using a network of geophones laid out across the continent. The model reaches a depth of 55km and discrete blocks (sugar cubes) are used in this example to represent a 5km depth and a surface area of 50 x 50km. The geoscientist can add or remove these blocks to reveal regions of equal seismic velocity, gaining a clearer understanding of the 3-dimensional composition of the earth's crust.

5.3 CFD Simulation with Continuous Material

While the examples given so far rely on the exploration of 3-dimensional datasets captured from the physical world, it is also possible to use *Phoxel-Space* to gain better understanding of computer-generated datasets, such as those obtained with Computational Fluid Dynamic (CFD) simulations. In the example below a physical model airplane is half submerged in the volume of glass beads used in configuration II. The model is calibrated with a 3-dimensional CFD simulation of air temperature around the airplane geometry and as the glass beads are removed, the varying temperatures around the plane are represented as a color map. As with the anatomical example described above, this interface approach allows the user build up physical geometries of regional boundaries or contours.

Figure 4. Glass beads to explore a cross-section of a CFD simulation of air temperature around an airplane fuselage

6 SYSTEM SETUP

We have assembled two configurations of the *Phoxel-Space* system shown in figures 3 and 4 below. The primary difference between them is in the 3-dimensional sensing method used. Configuration I was developed first, and proved very reliable and accurate, albeit rather expensive. Configuration II was developed at a later stage as a more affordable alternative. It has, however, some limitations.

> **Configuration I** uses a commercially available triangulation based laser scanner (*Minolta Vivid 900*) to capture the surface geometry of the physical modeling material. The laser scanner is calibrated with a video projector above the physical modeling

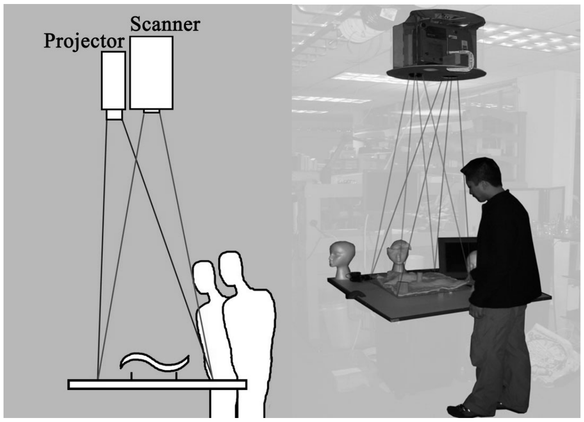

Figure 5. *Phoxel-Space* Configuration I, showing the laser scanner, the projector and the table where users interact with a malleable material

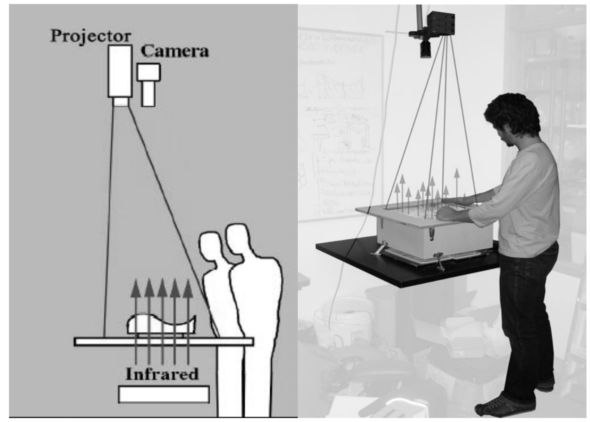

Figure 6. *Phoxel-Space* Configuration II, showing the IR camera, the projector and the table where users interact with a malleable material

material. This calibration ensures that spatial coordinates captured from the surface of the material correspond precisely with projected voxel values. The scanner/projector pair is housed inside an aluminum casing at a height of approximately 2m above the surface of the modeling material.

The *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 write a control script to repeatedly scan the surface of the material. This control script allows 240x240 point values to be captured every 0.3 seconds, resulting in a method for near-real-time 3-dimensional surface capture. This scanned data output is re-sampled into x, y and z coordinates and then finally intersected with the 3-dimensional dataset.

The laser scanner provides a high degree of accuracy and allows any opaque non-reflective material to be used as a modeling medium. However, it may be expensive for widespread use and therefore led us to develop an ad-hoc hardware system, which is described below.

Configuration II uses an IR based system to take advantage of real-time video capture rates. A box containing a volume of 1mm diameter glass beads is lit from beneath with an array of 600 high power infrared LEDs, as shown in figure 4. Four IR mirrors are placed around the LED array to create an infinite plane of uniform radiance. A monochrome infrared camera is mounted 2m above the surface of the beads and captures the intensity of light passing through the volume. The intensity of transmitted light is proportional to 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 exceed the optical intensity range of the video camera. The solution is to take several images of differing exposure time and combine these to recover the effective radiance of the scene, as explained in [5].

This process is less accurate than the use of the laser scanner. Another limitation is that this approach is material-specific and each material requires time-consuming testing and calibration). However, the system has the advantages of high speed (it is possible to reach 10 frames per second), low cost (an order of magnitude lower than the laser scanner) and it is still sufficiently accurate for a number of useful applications.

Interference with the scanning and projection process may result from the user placing his hand within the scene to manipulate the geometry of the modeling material. This problem can be partially eliminated by applying a removal algorithm with image-processing techniques or a simple toggle switch. However, we decided to maintain the possibility of scanning and projecting on the user's hands as they offer an additional means for exploring voxel datasets. For instance with configuration I, a user can tentatively position his hand in *Phoxel-Space* and use it as surface for intersection and projection. Once a region of interest is discovered, the modeling material can be used to build up a more permanent surface.

7 THE GUI NAVIGATION INTERFACE

Phoxel-Space was initially developed as a rigorously tangible interface, in that the only interaction allowed to users was the manipulation of the modeling material. Repeated tests and extensive use of the system, however, suggested to us the possibility of adding a Graphical User Interface (GUI) to it, in order to address the following aspects:

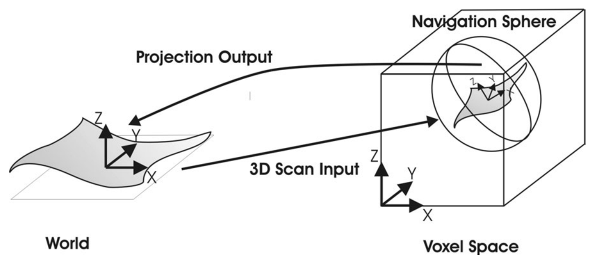

Figure 7. Transformation between world and voxel coordinate systems

a) The need for rescaling the portion of the dataset mapped onto the modeling material, enabling zoom in and zoom out capabilities. This need was felt strongly by professionals in the medical disciplines. (The overall planning of an operation is often followed by the smaller scale examination of the condition of tiny blood vessels);

b) A system for quickly switching between different and far apart areas of the dataset. This process was initially tedious, as it required the dislocation of large amounts of modeling material to expose the desired part of the dataset (for instance, if a user wanted to browse the bottom level of an MRI scan, while the surface is mapped to the top of the scan);

c) A method for rotating and translating the dataset in more convenient ways. For instance, it seemed useful to have the ability to see and explore a brain scan from the top, or from the bottom and from the side.

Based on the above requirements, it seemed that *Phoxel-Space* would benefit from the addition of a GUI navigation interface, enabling translation, rotation, and rescaling. This addition in turn prompted us to create a self-monitoring display to prevent disorientation during zooming, rotation, and translation.

In order to address these points, a software navigation interface was developed to complement the free-form physical browsing mechanism. This permits navigation through the whole 3-dimensional dataset, while the physical material allows detailed 3-dimensional browsing.

The navigation system is based on the definition of two separate coordinate systems, the 'world system' for the physical interface, and the 'voxel system' for the 3-dimensional datasets. A scanner/projector matrix is used for coordinate transformation from one system to the other (Figure 7).

A navigation sphere represents the transformation from the world system to the voxel system. The sphere is conformed to the physical surface along with the circular sections. When rotated, translated, or scaled using mouse interaction, it transforms the corresponding surface inside the voxel data set. An additional LCD display is used to show the perspective view of the voxel data set as well as the location and orientation of the cutting surface inside it (Figure 1).

8 DISCUSSION

8.1 3-D Capture and Projection

Our system configuration is limited in several areas. Since we are using a single sensing mechanism (either a scanner, as in I, or a video camera, as in II), the system is limited to a single point of view. While this may be adequate for many applications, it only provides depth information on the model surface as a, so-called, 2.5-dimensional surface scan. A full 3-dimensional scan might be desirable for more complex geometries such as airplane fuselages or other industrial applications. In the future it may be possible to use a real time multiple input system for this purpose.

In a similar manner, the single source of data projection means that it becomes increasingly difficult to project on surfaces as they approach 90° to the working plane. One solution would be to use multiple projectors in order to fully illuminate a given 3-dimensional model, as explained by [18].

8.2 Modeling Materials

As demonstrated by the variety of modeling materials used in the different applications, there is no single material that can combine the benefits of easy mouldability, rigid form, discrete elements or modular blocks. In the future, new hybrid materials might be developed to combine these kinds of properties in one or more materials. In addition, the development of a material that could dynamically respond to a computational input would allow the representation of precisely controlled surface geometries making *Phoxel* representations less labor intensive and perhaps providing an additional channel for haptic interaction.

It should also be noted that different geometric and physical properties of the modeling materials have an effect on the process of exploring and understanding 3-dimensional datasets. It is important to match the granularity of the modeling material to the grain size or resolution of the data. The sand bed, for instance, provides a continuous browsing medium without particular spatial constraints. It allows the free movement of *phoxels* and can therefore be considered a malleable display in 2.5 dimensions. It departs from the domain of traditional displays by introducing non-linear shapes that can take on many of the physical properties of the explored 3-dimensional data. Conversely, sugar cubes add constraints to the patterns of voxel addition and removal, allowing only certain orthogonal geometric transformations. Extrapolating along the same lines, a system could be imagined where the browsing elements are composed of large discreet objects that can be added or removed in predefined ways - such as a brain model whose components represent the segmented anatomical elements. Such a system would clearly add to the immediate and semantic understanding of the dataset exploration, although it would be very limiting in terms of flexibility. It would require tedious prototyping and calibration of the model with the dataset and would not allow the exploration of surfaces inside each object.

8.3 Alternative Data Sets and Interactive Simulations

The applications presented in this paper illustrate how *Phoxel-Space* can be used to explore static 3-dimensional data. However, there is an increasing number of dynamic dataset sources available such as brain activity maps, CFD simulations, and astrophysical evolution models. Future work might include exploring the ways in which such dynamic data changes both spatially and through time.

All of the illustrated examples above rely on voxel datasets. While this format is the most commonly used (especially in the biomedical sciences in the forms of CT and MRI voxel data output), our interface could easily be extended to explore and interact with vector based datasets - datasets that contain vectorial information at each point in space and are commonly used in industrial engineering applications. Another future extension would be to include interactive simulation data. This would allow, for example, a car body designer to adjust the form of a physical model car while viewing the resulting changes in airspeed and aerodynamic properties.

8.4 Evaluation

While *Phoxel-Space* has a considerable potential in a wide range of fields, it has not yet been rigorously tested and compared with more convention methods of 3-dimensional dataset analysis. In the near future, we plan to use the system as a teaching aid in hope of finding additional useful directions for future research.

9 CONCLUSIONS: IMPROVED UNDERSTANDING OF SPATIAL RELATIONSHIPS

This paper has shown the value of *Phoxel-Space* in combining the benefits of physical and digital representations. The interface shares many of the advantages of standard GUI interfaces in allowing colored, layered, annotated and/or dynamic information to be represented to the user. As with GUI, different layers of information such as tissue types, solid objects or annotations can be invoked at will, offering a level of interactivity that is not possible using non-augmented 3-dimensional models.

However, unlike GUI methods which present 3-dimensional data as two-dimensional cross sections or, at best, perspective renderings, *Phoxel-Space* presents 3-dimensional data in its natural environment, allowing users to gain an intuitive understanding of complex spatial relationships through the natural mechanisms of human understanding (bioptical vision, position parallax and the tactile senses). These benefits are provided with a relatively simple and inexpensive hardware, without the need of tethering technologies such as tags, position-tracking devices, gloves or headgear commonly used in VR or AR environments.

The interface allows users to take advantage of the natural dexterity of the hands to quickly define cutting surface geometries of arbitrary complexity. These same geometries might take hours to define with the same level of control using traditional GUI methods. The interactive components of the system allow users to explore spatial relationships through the manipulation of a physical material. As with conventional physical models, this approach gives a tangible immediacy to 3-dimensional data representation. However, unlike conventional physical models, which are normally rigid and offer a limited scope for interaction, *Phoxel-Space* allows users to cut a section at any desired location in a voxel dataset and to explore the corresponding values in an array of volumetric data.

The illustrated examples have shown a range of modeling materials that can be used with *Phoxel-Space*. Each material has different affordances; some are more appropriate than others for different kinds of data exploration. For example, discrete element models are useful for demonstrating predefined regions, such as in the teaching of brain anatomy, while the plasticine is useful as means to discover the precise shape and location of unsegmented regions, such as the analysis of tumors. The modular blocks can be useful in representing predefined volumes, as in the geophysics example, and the glass beads are suited to the gradient geometries found in examples like the CFD simulation. These materials can be broadly classified by their relative grain size. While larger grain sizes better fit predefined, object oriented modeling, smaller grain sizes (as found in glass beads and plasticine) offer precise control over form and are therefore better suited to the understanding of unknown, undefined geometries. A possible taxonomy of materials seems to emerge, which could lead to a broader characterization of Tangible User Interfaces.

The representation of complex boundaries such as those between differing tissues, seismic velocity zones, archaeological elements, and equal fluid pressure regions, are difficult to comprehend using conventional methods. *Phoxel-Space* allows such analysis to be an easy and intuitive task. Furthermore, it allows multiple users to collaborate around the same model, providing a platform for discussion and shared understanding.

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