Exploring Data through Dynamic Shape Displays

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Abstract
Advances in shape-changing user interfaces have begun to make real-time physical interaction with data possible. Dynamic shape displays can render physical forms through an array of linear actuators, updating at interactive refresh rates, enabling rich direct manipulation. This paper reviews a number of design explorations in Dynamic Physical Data Visualization using Shape Displays that our research group has developed, ranging from visualizing medical data, to city mapping, and bar charts. Based on these design studies we provide new strategies for data visualization and annotation. Beyond these explorations, we look forward and outline exciting new possibilities for interactive physical visualization with shape displays.

Introduction
There has been a rich history of encoding information into physical objects and tools. These artifacts not only allow us to visualize this information, often they serve as mechanisms to aid computation [2]. An astrolabe can be set to show the positions of different heavenly bodies at different times of day, or different dates, or different latitudes (i.e. the astrolabe functions as a representation of information). But, an astrolabe can also serve as a computer to help to solve navigational tasks. Obviously, graphical material is an important means to visualization, but many researchers have

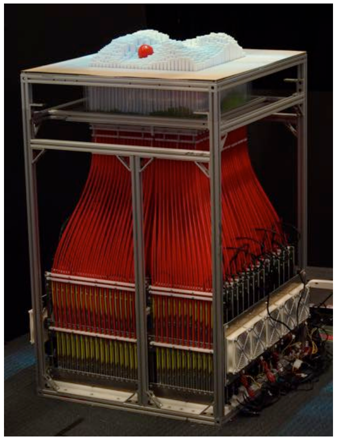

Figure 1. inFORM Shape Display

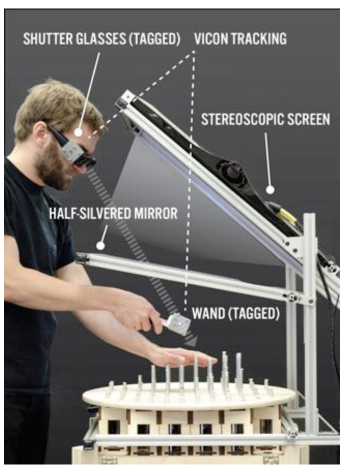

Figure 2. The Sublimate System, which combines spatial AR with a Shape Display

shown that the tangible aspects of visual information on paper help us think [7]. However, with the advent of digital computation we are beginning to rely more on solely digital information visualization because of it's flexibly to update and represent data in different forms dynamically.

Research in Tangible Interfaces has provided an alternative direction, allowing for physical manipulation of digital information. But most tangible interfaces are limited by the static nature of the physical world - they cannot keep up with the speed of digital computation. Shape-changing and deformable interfaces begin to change this equation, not only allowing for more complex interaction but also for physical form to be updated by digital computation, through motors, smart materials, or pneumatics. Now we can begin to explore Dynamic Physical Data Visualization, where interaction and representation of complex data sets can take place in the physical world. Though many shape-changing interfaces have been used to visualize information physically, Shape Displays, which use an array of linear actuators to create 2.5D shapes, are of particular interest because they can often display a wide range of forms, moving towards more generic shape output.

However, shape output is not enough. Dynamic Physical Data Visualization requires rich interaction techniques that make use of the physical affordances provided by shape displays. Our research group has been investigating new interaction techniques for a variety of shape displays we have built [1,4,5,6]. These new techniques leverage physical interaction, but also embrace interaction patterns from GUIs.

In this paper we hope to show a variety of examples of Dynamic Physical Data Visualization, suggest design patterns based on our experiences, and highlight open research directions in the use of shape display in visualization.

Related Work

Physical Data Visualization has long been around, but is only recently actively investigated in the HCI community. Many Tangible Interfaces have been developed to view, annotate and manipulate digital information, such as Illuminating Clay, which allowed landscaper designers to create physical models of landscapes and provided users with feedback from simulations of water run off, or erosion patterns [10]. In addition, researchers have shown that physical representation and tangible interaction can provide advantages in understanding complex data sets [12]. Although techniques for haptic data visualization have also been explored [8], much of the work in physical data visualization remains static or very limited in the type of information that can be displayed, such as Ambient Interfaces.

Dynamic Physical Data Visualization requires shape changing user interfaces. Shape displays enable more general topologies and greater degrees-of-freedom than other Shape-Changing Interfaces. Shape displays render physical shapes through the use of an array of actuators [3]. This physical rendering is often limited to 2.5D shapes due to the common use of linear actuators. However, less research has explored interaction and data visualization with shape displays. Previously, researchers have explored interfaces that can respond to the user's touch [11] and gestures [5].

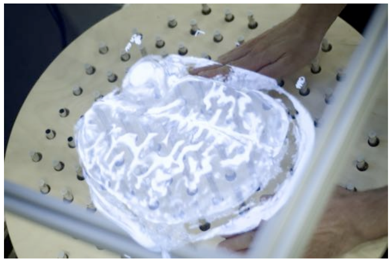

Figure 3. Using Sublimate to view and annotate volumetric medical data.

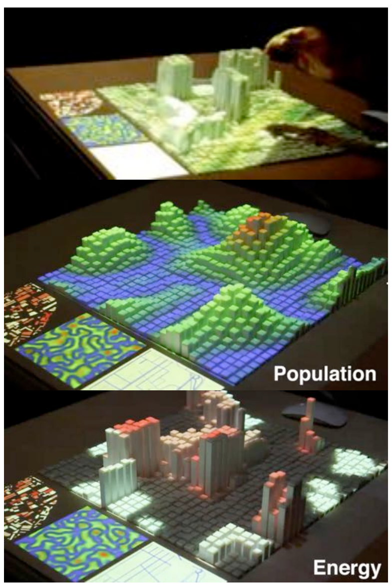

Figure 4. CityScape renders Urban Planning mapping data physically, allowing for physical annotation and 3D display. Different layers of the data can be made physical, such as building geometry, population data, and energy use, which can vary over the course of a day.

Visualizing and Manipulating Data Physically with Shape Displays

We have devolved a wide range of Dynamic Physical Data Visualization in the course of our research on interaction with shape displays [1,4,6]. Here we review some examples that demonstrate the utility of shape displays in this domain.

Volumetric Medical Data Exploration with Sublimate

Volumetric data is often hard to visualize. Doctors traditionally have viewed MRI or CT data layer by layer. Using Sublimate [4], volumetric medical data sets, such as MRI scans of a Brain, are rendered as 3D graphics that are spatially co-located with a physical shape. The user can browse this data through deformation to create a non-planar cross section through the volume. This interaction is similar to Illuminating Clay and Phoxelspace [10], but has the advantages of an actuated shape display, such as being able to save and load cross sections, or to define parametric shapes. The cross section can be conveniently flattened and moved computationally, while the user can intervene at any time by modifying its shape by hand. High-resolution AR graphics supplement physical shape output.

CityScape: Visualizing Urban Plans with inFORM

CityScape uses high resolution shape output [1] in conjunction with a large wall display, to allow urban planners to view and annotate city plans. Urban planners have traditionally built large physical models to understand a city. Shape displays allow this data to be updated in real-time, and change over the course of a day. The shape display shows a subspace of the map physically, and a user can pan around the scene using gestures, while direct touch provides annotation. The user can switch which different layers of visualization are represented physically (buildings, population data, or energy use).

Visualizing Math Equations with inFORM

Another use of inFORM is for math education, where students can visualize math equations that represent 3D surfaces physically. As users modify parameters of a equation, the physical surface changes form to represent it. By moving their hands on the surface, users can find local minimum and maximum easily. This is especially useful for the vision impaired.

Design Patterns

Allow for different modes of interaction and display

In our systems we try to make use of physical interaction for parameters that are spatially relevant. Gestures are often better suited to control more abstract and view oriented parameters.

Similarly, not all information is best represented physically. Some content makes more sense represented physically, while other information is best represented graphically. Consider allowing users to select the representation that works for them.

Consider the scale of data

One of the largest problems we have encountered is the bounds of a shape display’s z travel. Often 3D information will fit in the x-y plane, but will extend beyond the limits of the z plane. Should the object be cropped, squashed, or scaled? Not all data is easily represented on a shape display.

Take advantage of inter-material interaction

Because shape displays render not just points but surfaces physically, other objects can be placed on

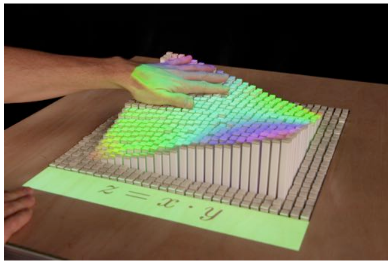

Figure 5. Representing 3D surface equations physically on inFORM.

them and the rules of physics apply to their interaction. Designers can leverage this: for example, a ball placed on a shape display will roll to the local minimum, such as in the Math Equation example.

Shape change can be surprising
In our studies with shape displays [4] and our informal observations we have noted that users can find rapid shape change jarring. When designing for Dynamic Physical Data Visualization it is important to not change physical form too quickly if users are directly touching the display.

Combine with graphics
Though the shape displays we have built are low resolution (only at most a kilo-pixel display), by combining these with higher resolution graphics we can achieve a higher perceived resolution. Projection Mapping on the surface or See-Through-AR are two approaches we have taken. These graphical techniques are especially helpful for annotation.

Looking Forward: Directions for Physical Data Visualization on Shape Displays

The limitations of current shape displays can allow us to consider exciting new directions to push shape output research.

Collaborative Physical Data Exploration
Shape displays could make it easier for remote collaborators to work together on a data set. We have begun to explore techniques for collaboration using shape displays [6]. Moving forward, how can two users at a distance both interact and manipulate the same physical data set? What are techniques for real-time shared annotation?

Degrees of Freedom of Shape Displays
Shape displays are limited by many factors that make rendering of certain types of 3D information difficult (overhangs, etc.). This also poses challenges for interaction, as users can currently only physically deform a shape display in the z direction. By increasing the degrees of freedom of output and input, richer interaction with data could be made possible.

New Form Factors
Current shape displays are limited by their rigid arrangement and large size. Users cannot hold them in their hands and move them to gain different views. In addition they cannot move or rearrange parts of the display to leverage spatial reasoning [2]. Modular shape displays could allow users to rearrange parts easily to compare different sections of a data set, as Jacques Bertin’s pioneering tabular visualizations allowed[9]. As opposed to 3D surfaces, shape displays could be made in a chain form factor allowing for displaying spark lines or other linear forms. Large numbers of small swarm robots could rearrange quickly to form physical scatter plots on a table surface. These different geometries would allow for different means of interaction.

Conclusion

In order to allow for interactive general purpose physical data visualization we must have interfaces and displays with dynamic form at interactive refresh rates. We have shown that shape displays can enable rich interaction with physical data visualization. In presenting our research in this context we hope others will explore further techniques for Dynamic Physical Data Visualization enabled by shape display.

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