PolySurface: A Design Approach for Rapid Prototyping of Shape-Changing Displays Using Semi-Solid Surfaces

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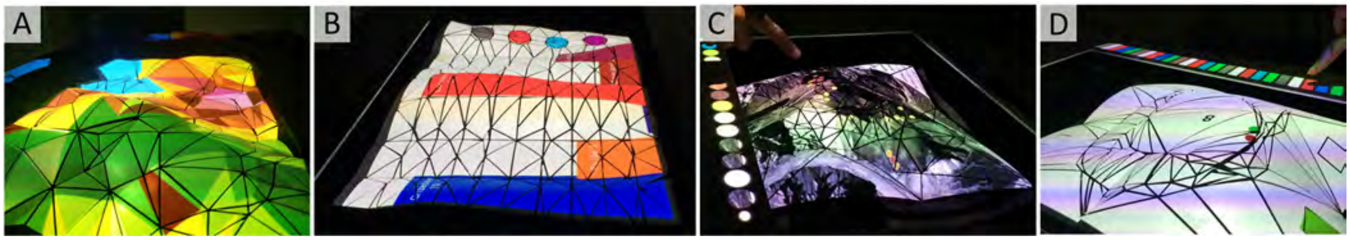

Figure 1: Interactive shape-changing displays developed with PolySurface: A) a physical terrain model used for design session demos; B) physical bar-chart interface designed by P1; C) physical volcano modeling by P2; (D) interactive physical display to model eye-tracking data by P3.

ABSTRACT

We present a design approach for rapid fabrication of high fidelity interactive shape-changing displays using bespoke semi-solid surfaces. This is achieved by segmenting virtual representations of the given data and mapping it to a dynamic physical polygonal surface. First, we establish the design and fabrication approach for generating semi-solid reconfigurable surfaces. Secondly, we demonstrate the generalizability of this approach by presenting design sessions using datasets provided by experts from a diverse range of domains. Thirdly, we evaluate user engagement with the prototype hardware systems that are built. We learned that all participants, all of whom had no previous interaction with shape-changing displays, were able to successfully design interactive hardware systems that physically represent data specific to their work. Finally, we reflect on the content generated to understand if our approach is effective at representing intended output based on a set of user defined functionality requirements.

Author Keywords

Interactive Shape-Changing Displays; Fabrication Approach; Data Physicalization;

ACM Classification Keywords

H.5.2. User Interfaces: Graphical User Interfaces, Input Devices and Strategies, Interaction Styles, Screen Design.

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INTRODUCTION

Interactive shape-changing displays enable the dynamic representation of data and information through physically reconfigurable geometry. Over recent years, the research community has proposed numerous prototype systems [26] that have explored a variety of shapes, forms, interactions, and implementation techniques. Despite the potential for enhancing the capabilities of information representation, there are still accessibility challenges faced by the field.

Firstly, there is a limited number of tools and methods to enable end-users, with minimal resources, to directly author physically reconfigurable interfaces [15, 33]. Currently, domain experts cannot engage with novel physical representations of their data as they do not have the necessary tools or skillsets to directly design and create shape-changing displays based on their specifications. The need to create more accessible approaches and tools for fabricating shape-changing displays is highlighted in current research [8, 32]. To overcome this challenge, we propose a design and fabrication approach for shape-changing displays with low implementation costs, technical simplicity, and accessibility compared to resource intensive demands needed to develop existing systems.

Secondly, the majority of current shape-changing displays are one-off prototypes that are either restricted to linear pin-based [12, 17, 21, 23] or continuous surface outputs [6, 29, 35]. These hardware systems limit the forms of data and information encoded within them due to the lack of resolution and dynamicity in the surface configurations, for both static and motion based representations. Complex polygonal structures, meshes, or curved contours are difficult to construct. Our low cost implementation method, PolySurface, combines the benefits of pin arrays and cloth. The combined flat solid surfaces and elastic material used in PolySurface enhances the design space for shape-changing displays due to its capability to represent more complex physical structures, such as curved contours, in comparison to traditional shape-changing displays.

Our approach enables users from a range of domains to design and construct interactive shape-changing displays based on their own input data. This can take many forms: photographs, graphics, Comma Separated Values (CSVs), topographic models etc. Our approach decreases the number of actuators needed whilst showing more complex content and structures than pin-based or continuous fabric displays.

The PolySurface approach consists of six steps: (1) Data Segmentation: input data and interface designs are digitally segmented to generate a polygonal mesh of the semi-solid surface; (2) Fabrication: the polygonal mesh is laser cut on a thin solid material such as polypropylene; (3) Assembly: the polygonal mesh is attached to durable spandex to allow elasticity; (4) Visualization Design: establish visual interface features. (5) Height Design: identify variables from the data to represent surface movement and position actuators below the display; (6) Interaction Control: implement interactive features of the display (e.g. buttons, hover control, gesture recognition).

To validate our approach and demonstrate its wide accessibility, we conducted three design sessions with participants from separate domains. Each participant designed their own domain-specific shape-changing display. To understand the effectiveness of their data representation, participants were then encouraged to showcase their prototype shape-changing display to an audience in their domain or to a novice.

All participants successfully designed and discussed their interactive shape-changing displays. From the evaluation meetings and showcases we saw that PolySurface enables the simplification of complex data and information by enhancing user engagement. To summarize, the primary contributions of our work are:

1) *Conceptual approach* for designing and developing shape-changing displays using dynamic polygonal surface structures.
2) *PolySurface* as a low cost implementation method for rapid high fidelity prototyping of shape-changing displays and interactive interfaces.
3) *Three case studies* where participants, from different domains, generated interactive shape-changing displays based on datasets provided from their work.
4) *Discussion* of design sessions observations that identify key design requirements, limitations, and research challenges for designing and fabricating shape-changing displays and interfaces.

RELATED WORK

The exploration of shape-changing displays, surfaces that support dynamic physical reconfigurations, is emerging as a prominent area in HCI. The majority of these devices can either be user-deformed or self-actuated, and are mainly used as input or output for data representation [26]. Poupyrev et al. [24] presents an overview of actuation mechanisms and techniques for physically reconfigurable user interfaces. Coelho et al. [5] survey smart-materials used for shape displays. The majority of existing shape-changing displays consist of an array of solid actuation pins [12, 17, 19-21, 23] or deformable surface material [6, 29, 35, 37]. These hardware systems can limit the physical representations of complex polygonal structures, meshes, or curved contours due to lack of resolution and dynamicity in in surface configurations.

PolySurface combines a flexible surface with solid elements to reduce the actuation requirements (enhancing non-technical user engagement) and provides polygonal structure rendering. Examples such as HypoSurface [7] also provide this combination, but not with the purpose of reducing the barrier to adoption outside HCI.

Elastic Deformable Displays

Troiano et al. [34] explore interaction scenarios and gestures for elastic user-deformable surfaces without actuation. They list a range of user-deformable devices with haptic feedback in addition to materials and gestures used for applications such as multi-layered data visualizations [22], and 3D modelling. These devices enable simultaneous visual and haptic feedback by using a transparent flexible sheet in front of an LCD [16], or using rear-projection [36]. Users can also explore multi-dimensional data using ElaScreen [38]. TableHop [29] presents a new actuation approach for creating a dynamic surface display that combines the advantages of user-deformable and self-actuated fabric displays. Our work extends current research by combining the dynamicity of elastic display surfaces with semi-solid polygonal segmentations. This allows more complex deformations to be represented in physical space with greater elevated movement. The semi-solid segmentations on PolySurface act as hinge joints to elevate more complex polygonal structures, such as curved contours, that are difficult to represent on current shape-changing displays.

Mechanical Pin-Actuation Displays

Pin actuators are commonly used for constructing shape-changing display. These hardware systems provide enhanced sensory abilities such as haptic feedback, physical affordance, scalable form-factors, and three dimensional interactions. FEELEX [18] was one of the earliest shape displays that combined haptic sensations with computer graphics on a table-top. Sublimate [20] combines the transition of motorized actuators to represent physical shape output together with 3D spatial graphics to explore computational transition between these two states.

inForm [12] provides dynamic physical affordance by table-top deformation. The hardware system consists of a 30x30 grid of motorized pins for height actuation and provides illumination with overhead projection. A depth-camera positioned at the top of the display enables interaction. TRANSFORM [17] combines 3 embedded inForm shape displays, each consists of a 24x16 grid of motorized pins (total 1,152 pins).

Taher et al. [33] developed EMERGE, a hardware system that generates dynamic physical bar charts on a table-top. They explore new direct interaction techniques with a shape-changing display. Their system consists of a 10x10 array of motorized sliders. Each motor is attached to a plastic rod with a dedicated color LED for visualization without occlusion.

Relief [21] is an actuated table top display that explores gestural interaction for rendering dynamic 3D surfaces. It is actuated by an array of 120 commercially available motorized pins. These pins can also be covered with a Lycra cloth to create a continuous smooth surface to create an elastic deformable display. PolySurface extends the duality of this system by using a semi-solid surface to render more complex polygonal meshes and curved structures. We reduce the number of actuators, to only areas of the display that require height elevation, to further engage non-technical users.

ShapeClips [15] enable rapid prototyping of physical forms with minimal programming skill. Together with an LCD screen can create 3D surface displays with dynamic physical forms. We utilize the open source modular nature of ShapeClips to allow users to place actuators anywhere below the surface of their shape-changing displays that requires height elevation.

Other Actuation Mechanisms

Harrision and Hudson's [16] visual display elevates deformable physical buttons and other interface areas with pneumatic actuation. An infrared camera behind the display enables multi-touch input and visualization through rear projection. Stevenson et al. [30] present an inflatable hemispherical multi-touch display where curvature changes dynamically between flat or dome. Follmer et al. [11] explores jamming of granular particles applied to malleable and flexible interfaces. Yao et al. [37] present a range of shape-changing interfaces that actuate by pneumatic soft composite materials. Direction and angle of deformation is controlled by constraints through pre-programmed material structures.

Coelho and Zigelbaum [4] explore properties and limitations of Shape Memory Alloys (SMA). They fabricate four design probes to further understand parametric design and motion transitions using SMA for shape-changing interfaces. Qi and Buechley [25] present examples of SMA self-actuated paper/origami for physical notification output and animation. Morphees [27] are flexible mobile devices that adapt their shape on-demand to depending on an application scenario.

Semi-Solid Surface Design

3D fabrics combines light elastic textiles with a more rigid support to form more dynamic three-dimensional structures. Mika Barr's "3D Fabrics" [3] enable folding and fracturing of a flat textile pattern into a three-dimensional structure. Similarly, Elisa Stozyk designed "Wooden Fabric" [31], a material that is half-wood half-textile. These dynamic wooden surfaces are can be manipulated by touch due to their semi-sold material properties. We expand on these design techniques and presents semi-solid polygonal shape-changing surfaces that dynamically reconfigure based on user input.

PolySurface is a design and fabrication approach to engage non-technical domain experts in utilizing shape-changing displays. It builds on the design and learnings of many previous shape-changing displays to provide non-technical experts with an effective and rapid prototyping process. In this sense, the produced surfaces are intentionally similar to previous displays as these demonstrate current best-practice.

DESIGN AND FABRICATION APPROACH

The overarching goal of this work is to develop an approach for rapid prototyping high-fidelity dynamic shape-changing displays with interactive capabilities. In order to develop a more generalizable contribution, we focused on reducing the design and construction time and technical requirements needed to design and generate these dynamic physically reconfigurable hardware systems.

Our approach utilizes both actuated pixels, where each actuator keeps to a flat solid state, and an elastic material that extrudes smoothly from the surface of the shape-display.

Conceptual Approach

To facilitate engagement with end-users our approach has two key design features: (1) Allow end-users to generate dynamic display surfaces using a diverse range of input data; (2) Reduce display construction and implementation complexity by using pre-existing toolkits and minimal hardware. We developed a six-step process (Figure 2) that incorporates these design features.

Figure 2: Breakdown of conceptual approach.

This process is based around the idea of semi-solid surfaces: surfaces that consist of solid components (laser cut polypropylene) fused onto a flexible sub-surface (spandex). By correctly segmenting input data we can produce templates that maximize continuous surfaces (to reduce the required number of actuators) and provide sufficient flexibility to allow height control where required.

Our approach has three key advantages for shape-changing displays: (1) Only areas that require height elevation are segmented and cut, significantly reducing the number of actuators required; (2) It can produce areas of continuous surface not currently possible with pin-arrays; (3) Development time is significantly reduced for high-fidelity prototyping. The key trade-off is the reduced generalizability of the shape-changing surface if the initial input data is coarse. To validate and test our conceptual approach we developed PolySurface, an implementation of the design and fabrication of semi-solid surfaces.

PolySurface: Implementation of Approach

We developed an approach for fabricating semi-solid surfaces that consists of laser cut flat polygonal meshes that are attached to a durable spandex material. A minimal number of actuators are placed below the semi-solid surface to enable elevation of selected polygonal areas. We believe this process enables rapid creation of more complex shape-changing representations and greater accessibility to non-technical users.

Step 1: Data Segmentation

This process outlines all of the vertices necessary to allow actuation. Firstly, we map the users' data or interface designs onto a polygonal segmented surface ready for fabrication. To do this, we capitalize on the wide range of segmentation algorithms already available. Image data can be segmented using a number of geometric algorithms (e.g. General Triangulation [13], Straight Skeleton [9], Voronoi Diagrams [2]) which are available open source and via online web applications [10]. For numerical data (x, y), we use the Delaunay Triangulation [28] segmentation algorithm that generates polygonal meshes. This algorithm ensures each data point is a vertex on the mesh plane of the semi-solid surface. For outline designs, such as interfaces or architectural plans, we use plane segmentation in illustrator graphics software (Figure 3).

Figure 3: Segmentation process of a contour map.

Step 2: Fabrication

Secondly, we must produce a physical representation of the segmented surface (Figure 4B). Once the digital surface is designed (Step 1), we laser cut it based on a set of guidelines detailed below. We use lightweight polypropylene (0.8mm depth) for laser cutting the polygonal mesh. We recommend that any small polygons (less than 10mm diameter) are merged into adjacent larger polygons to ensure anything smaller than 10mm is not deformed by the laser cutter as polypropylene material has a low melting point. A gap of at least 1mm between each polygon is advised as it ensures fluid flex and fold motion of the surface. This mesh is then attached to black bidirectional (x and y axis stretchable) spandex for fluidity and elastic support (Figure 5).

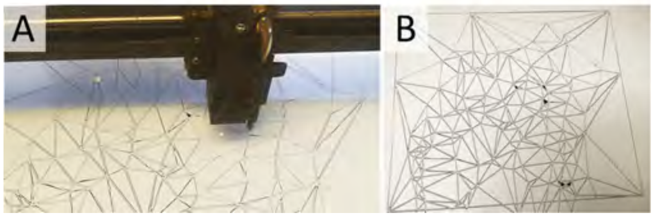

Figure 4: (A) Laser cutting polypropylene sheet (0.8mm depth) and (B) fabricated polygonal surface.

Step 3: Assembly

To ensure that all of the polygons stay intact and in the right position we overlay strips of tape over the mesh before removing it from the laser cutter bed (Figure 5A). This ensures no parts are lost or move position. We remove the cut outline surrounding the mesh (Figure 5B) and super glue the entire surface as onto stretchable spandex (Figure 5C) to provide the flexible sub-surface. To reduce visibility of lines on the surface we recommend using the same color material for both the Spandex and the solid segments. Figure 5D Shows the tape overlay removed once the surface is secured. The surface is then inserted into an enclosure (750 x 450 x 210mm) which also contains actuators and horizontal screen.

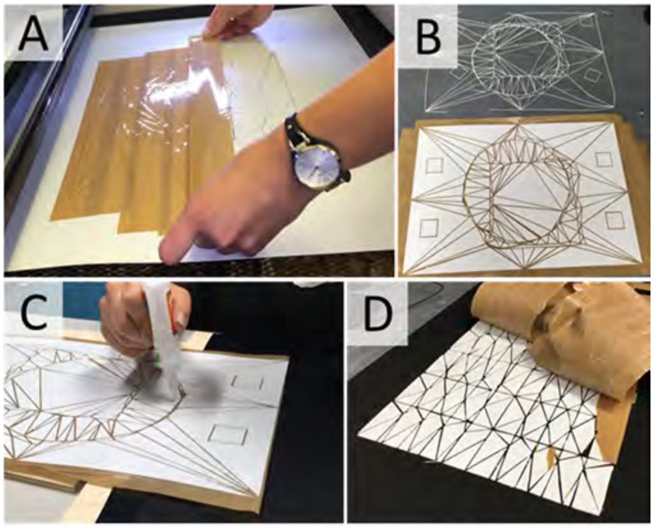

Figure 5: Securing shapes on surface (A); Removing spacing guides (B); Gluing surface to Spandex (C); Removing tape (D).

Step 4: Visualization Design

We then establish the correct position of visualizations by projection mapping the basic digital outline of the surface design onto the physical semi-solid surface (Figure 6A). Interactive visualizations are implemented using HTML webpages and are not restricted in diversity. An example of volcano visualizations is shown in Figure 6B.

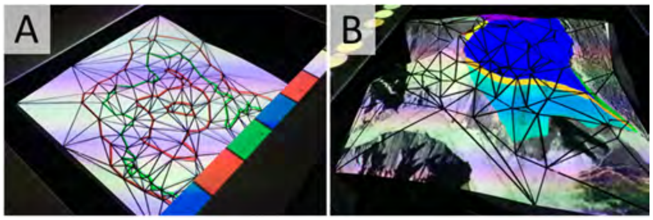

Figure 6: Map projection onto surface (A) and frame from volcano vocalization (B).

Step 5: Height Design

We generate physical reconfigurations of PolySurface by mapping variables, such as numeric variances, from the given data to represent elevation states. We use ShapeClip modules [15] for height actuation as they are cheap and easy to control, with light-intensity output from the monitor directly regulating actuator height above (Figure 7A).

ShapeClip placement is customizable, depending on the input data, and is not limited to a grid. The monitor, underneath the actuators, shows a HTML webpage that uses Bitmap greyscale animation frames for elevation control (Figure 7B). To determine accurate actuator position, we recommend observing where the greatest white and grey light-intensity variance occurs on the monitor. These areas directly map to the highest frequency of movement on the physical display. Positioning the actuators on these areas of the monitor guarantees most accurate height elevation on the semi-solid surface above.

Using our custom JavaScript functions, a user can simply design a set of Bitmap frames where the color of each pixel directly corresponds to movement for a designated actuator. Elevation controls can be translated directly from user's input data. We automatically scale custom data to fit grayscale RGB values (0-255).

Figure 7: Actuators in specific positions on an 8x6 grid above flat monitor (A); Height control webpage underneath (B).

Step 6: Interaction Control

To enhance engagement with the display users can add interactive elements such as hover or buttons directly on the dynamic surface (Figure 8A-B) or on the side of the enclosure (Figure 8C). A wide range of interactions can be implemented by using a depth camera positioned above the surface. Pre-designed code snippets were used with an open source toolkit [14] to enable interaction with the dynamic surface and enclosure.

The toolkit uses simple HTML webpages and client-server communication. Interaction is not limited to a depth camera and other forms of input, such as keyboard, can also be used.

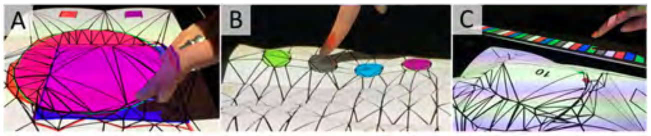

Figure 8: Hover interaction for shape selection (A); Interactive buttons on surface (B); Button on side of display enclosure (C).

DESIGN SESSION METHODOLOGY

The goal of the design sessions is to understand whether our approach to shape-changing interface design is: (1) Appropriate to engage non-expert users; (2) Able to generate surfaces suitable for use and demonstration in a variety of application domains; (3) Efficient for rapidly developing high fidelity prototypes.

Participants attended in two sessions: (1) Design: to bring along their dataset, specify requirements for the display, and design the surface, actuation, and interactions; (2) Evaluation: to assess the produced surface for its effectiveness in their domain, and where possible, to demonstrate it to other domain experts or a novice.

We conducted design sessions with three separate participants to explore content generation using our approach for fabricating shape-changing displays. We limited this study to three participants to allow us to work closely with each participant and the unique datasets they provided. Each participant was allocated a week-long slot to enable significant depth in the sessions and analysis.

Meeting One: Design

The first meeting was designed to last at most two hours and aimed to establish the surface design based on the participant's requirements. The participants were asked to bring along a sample of data they use in their everyday work. This could range from, but not restricted to: generic (x, y) data, more complex numeric representations (x, y, z), bar charts, as well as graphics, plan designs, sketches (hand drawn or digital), interface/web designs etc.

Each participant was shown a presentation overview of the project at the start of the first meeting. We showed video examples of existing shape-changing displays and a live demo of two applications generated using the PolySurface approach. The first application was a video player (dynamic user interface) with interactive height and visualization control on the surface. The second example was a dynamic terrain map (Figure 1A).

The researcher provided detailed instructions and walked the participant through the design process. This meeting consisted of the design tasks in the PolySurface approach (Figure 2) and listing a set of requirements the device must perform to successfully function. We used the requirements to help assess the effectiveness of the resulting display. Once the participant was satisfied with the designed surface (both physical and visual), elevation design, and height and interaction control, we laser cut (Figure 4) and assembled the device (Figure 5). Participation in the fabrication, assembly, implementation of height design and interaction was optional. Contextual inquiries were performed throughout to understand each participant's thoughts and impressions.

Meeting Two: Evaluation

In the second meeting each participant was asked to evaluate the success of the final device produced based on a set of requirements they specified during meeting one of the study. To begin, the complete surface was demonstrated to the participant and they were walked through the set of interactions. Participants were then encouraged to explore their dataset and comment on the validity of the representation and any new insights, advantages, or disadvantages their shape-changing display provided. We conducted semi-structured interviews throughout each evaluation meeting to ensure the participant's thoughts and opinions were comprehensively audio and video recorded.

Display Showcase

When the participant had explored the prototype display and was satisfied that the functionality met their requirements, they were encouraged to showcase their shape-changing display to a small group or individual (either domain experts or novices). An informal group presentation and a short feedback session then took place to allow us to evaluate the effectiveness and engagement of the shape-changing prototypes developed.

POLYSURFACE DESIGN SESSIONS

To demonstrate the generalizability of our approach for designing and fabricating high fidelity shape-changing displays we conducted three design sessions. Each design session consisted of a two-hour design meeting followed by a one-hour evaluation session once the final display was developed. Participants also had the opportunity to showcase their shape-changing display to either domain experts or novices.

Based on the set of requirements defined in the first design meetings all three participants successfully developed shape-changing displays specific to their domain expertise (Figure 1B-D). During each meeting, the participant provided information on their domain-specific data and methods they traditionally use for presenting it. We detail findings and observations from the design and evaluation sessions below.

Demographic Background

We selected participants from a range to domains to ensure we had a wide variety of data samples to demonstrate the generalizability of our approach. We summarize their demographic profiles below (Table 1).

Age	Gender	Domain	Dataset Type
35-44	F	Accommodation Manager	Numeric & Text (Spreadsheet)
25-34	F	Volcanologist	Geographic Information Systems (GIS)
25-34	M	Eye Tracking Researcher	(x, y) co-ordinates (Spreadsheet)

Table 1: Participants' demographic information.

Participant 1

P1 is an accommodation manager and provided a spreadsheet detailing distribution of students in studio accommodation as well as their demographics. Their primary goal was to "*make the data visually easier to understand*". Based on the data sample provided we designed and developed a physical bar chart representing gender and nationality distribution across the six colleges they managed. The primary target-audience for this data representation are colleagues from the accommodation management department.

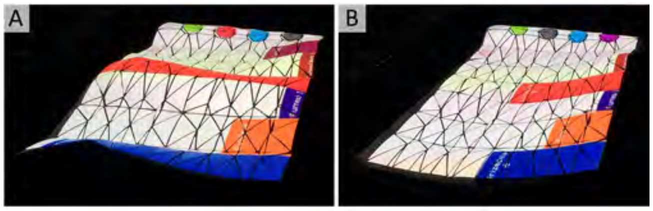

Figure 9: Example physical bar charts showing distribution of None-EU (A) and male (B) students across six colleges.

Design Session

We worked with the participant to establish which variable in the data sample would be best to represent using height and elevation variants. At first, P1 struggled with brainstorming ideas. We suggested examples of a physical bar-chart, a map of the accommodation, or a world height-map showing international distribution of students. P1 stated that the information provided is minimal in terms of creativity due to only a small data sample provided. The participant settled on the physical bar-chart as they were familiar with this style of representation.

Initially, P1 showed apprehension in the exploration of creative ideas for the display. When asked to sketch their design concept they indicated that they would prefer the researcher to do it for them. P1 became more comfortable once the bar-chart concept was established and then took over the sketching process. P1 did not initially think interaction with the display was necessary, but further discussion revealed the necessity of buttons to change data-sets. We attribute this apprehension to the novelty of the display modality and highlight the need for better methodologies to expose users to the potential of such displays (see Discussion).

Shape-Changing Display Description

The developed PolySurface is 355mm × 215mm and consisted of six vertical rectangles to represent each college membership and four circles on the right side for buttons (see Figure 8B). 14 actuators were positioned at various locations underneath the surface for elevation control. The full process, from design, to implementation took two days.

A user can press one of the four buttons to activate a physical bar-chart that represents either gender or continental distribution (female, male, EU, or None-EU) of students across six colleges in studio accommodation. In the height transition between each bar chart, elevation of the surface drops to minimal height and rises to appropriate levels to ensure the transition changes are obvious.

The high and low levels of the surface correlate to the number of people for each bar. The more data variation the more significant the dips would be. In this example, physical height is a direct representation of the visual display.

Evaluation Meeting

We presented this display to P1, who said that this information is easier to see and "*play around with as it is more visible than going through a lot of spreadsheets*". They stated that this representation would be easier to market as it was more visually appealing and interactive than traditional bar charts. They considered the display to be suitable for showing a 'snap-shot' of the data and its trends that can enhance audience engagement. They provide the example of using this for marketing purposes where complex data trends would be a lot easier to interpret and display rather than people going through figures and percentages. However, P1 commented that for their day-to-day work, this system is more sophisticated than needed. Although P1 did not showcase their display, they requested a video to show to colleagues.

Summary

P1 successfully designed a physical representation of their dataset. While the representation is familiar (a bar chart), this emphasized the need to help users think 'outside the box'. P1 appreciated the display for its communication and engagement potential to convey a 'snap-shot' of overall trends to senior management, in a public space and for educational purposes.

Participant 2

P2 is a Senior Teaching Associate (Environmental Science) specializing in volcanology. Their research looks into glacial volcanoes in Iceland from around 95,000 years ago. Their primary goal was to *"accurately and clearly represent the volcanic edifices and paleo-ice conditions in 3D"*. P2 provided a paper from field work conducted at Bláhnúkur (Torfajökull, Iceland). Their shape-changing display represents the predicted structure of the volcano before its eruption (95,000 years ago) (Figure 10) and the current morphology. The primary use of this data representation was for demonstrations to colleagues and novices.

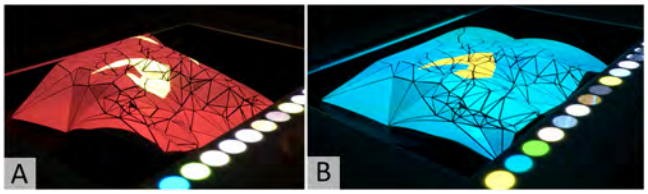

Figure 10: Physical state transition of volcano structure 95,000 years ago (A) and morphology with glacier overlay (B).

Design Session

Due to the complexity of their research, P2 came to two design sessions. The first meeting helped to develop an insight into the participant's domain and overall concept for the display design. Initially, P2 provided us with two papers with separate volcano models. We established Bláhnúkur as the volcano P2 was interested to recreate in physical form and outlined main functionality requirements.

During the second design meeting, we verified an accurate model of the PolySurface based on data from the Bláhnúkur paper. For visualization, P2 provided us with aerial photos, satellite images, contour map, and geological maps from geographic websites [1]. 2D images for structural representation was proven to be a limitation in P2's field:

"I cannot show everything in just one image which is a problem… it is impossible to get a photograph where you can see everything"

A contour map of the volcano was used as input for the PolySurface segmentation. P2 specified they wanted multiple images projected on their surface as this would help the audience differentiate between areas of the volcano through color as well as elevation. For interaction, we designed a simple button interface to transition between images provided by P2.

During the design sessions we established two limitations for 2D image analysis in P2's domain. The participant demonstrated this difficulty (Figure 11) to interpret data correctly from 2D images:

"I struggle with this image because optically when looking from the south, there is a valley, but actually it is wrong"

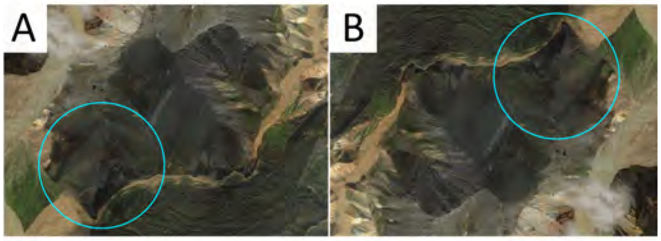

Figure 11: Comparison of the same aerial photo of Bláhnúkur volcano. Figure 11B is rotated 180 degrees. (Imagery ©2016 Google, DigitalGlobe, Map data ©2016)

Two limitations have emerged from P2's design sessions:

1. With aerial images, there is an optical illusion depending on view point angle.
2. With photographs of side view of volcano, it is impossible to see every side of the volcano.

For height design, we established three main states: (state 1) morphology before eruption, (state 2) morphology before eruption with glacier elevation, (state 3) current morphology of the volcano. Water sample data from their field work was used for height design and to physically represent the volcano model 95,000 years ago.

Shape-Changing Display Description

The assembled PolySurface is 310 x 273mm in size with 16 actuators situated below that control the elevation of three physical states. The full construction process, including fabrication, assembly, visualization and interaction control also took two days.

Interaction controls consist of 15 buttons that are projected on the top of the enclosure box. The first three buttons control height changes representing three morphologies of the volcano in the last 95,000 years. The other 12 buttons are transition between visualizations on the PolySurface. These visuals include: aerial photographs, satellite images, contour and topographic maps, and sampling location areas on the volcano surface.

Evaluation Meeting

For all three physical state changes P2 found PolySurface provided an accurate representation of the volcano's morphology. The semi-solid mesh surface clearly represented valleys and ridges to scale and these were also easier to differentiate compared to photo analysis.

The participant expressed interest in using this display for presentations of their research. P2 stated that using a shape display like this provides a better representation of a volcano:

"*You can turn your head and see the whole morphology and you cannot see all of the angles in a 2D image*".

Display Showcase

We asked P2 to present their interactive shape-changing display to a non-geologist. P2 walked through the display functionality whilst explaining to the non-geologist each physical state change with different visual backdrops. The non-geologist was able to clearly understand the main concept explained within 5 minutes and stated:

"F*or a non-geologist a shape-changing representation is much better to communicate and picture the whole thing"*

The direct interaction with the volcano structure and visualization also made it easier for P2 to explain their research. They felt this display is most appropriate for communicating their research to the general public. P2 and the non-geologist agreed that the added interactive features enhanced engagement with complex information.

Figure 12: P2 showing the none-geologist sampling points on the volcano.

Summary

P2 successfully designed a high fidelity reconstruction of a volcano by mapping pre-existing topography using a bespoke PolySurface. For P2 it is impossible to accurately visualize volcanos in 2D space. The dynamic polygonal mesh of PolySurface enabled a physical 3D representation of a range of angular structures comprising the volcano's valleys and ridges.

We established two limitations P2 has within their domain. Firstly, aerial terrain analysis is limited due to optical illusions based on rotation of images. Secondly, geologists are unable to represent a full model of terrain using solely 2D space. Our representation facilitated analysis by providing an additional (physical) information channel, reducing the confusion of optical illusions and overlaying additional (visual) data onto a physical terrain map.

P2 showcased the display to a non-geologist who understood a complex research concept in a 5-minute demonstration. The non-geologist stated:

"This display summaries thousands years of history in just a few buttons"

Participant 3

P3 is a PhD researcher specializing in eye-tracking calibration. They provided data from their own study that compares eye tracking calibration effectiveness with a range of shapes. They wanted to show the comparison between two variables (target eye co-ordinates and actual gaze co-ordinates) through surface elevation on a timeline. Based on the data sample provided we developed a shape-changing display that physically represents this comparison variable using two interaction techniques (see Figure 13 example). P3 showcased their PolySurface display to a group of five colleagues (Figure 14) to gain insight of how the technology can be used to enhance data analysis and demonstrations.

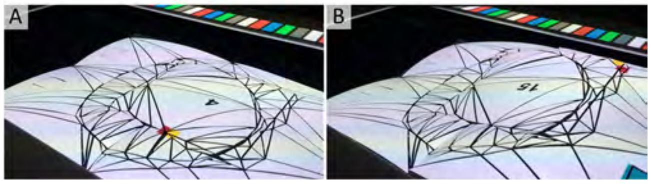

Figure 13: Difference represented between target and gaze on point on a line (A) and a corner (B) from square data sample.

Design Session

The spreadsheet supplied by P3 contained (x, y) co-ordinates for target eye location, actual eye gaze location, and the difference between them for a square and a circle samples. We used 30 samples from both the circle and square datasets. P3 traditionally uses 2D graphics, graphs and plots to represent their data. To enhance their current representation methods, they wanted to include interaction and visual features in their display.

P3 emphasized that the most important variable to represent was the offset between target and actual gaze co-ordinates. We agreed to use surface elevation to show this offset. P3 had the idea of using a slider to go through a timeframe to show "*evolution of that movement*" for their specific shapes.

P3 had the most comprehensive list of requirements. To be functionally successful their PolySurface display must: (1) Play the animation to see the different positions of both target and gaze coordinates; (2) See the difference (positive and negative) between coordinates using height; (3) Navigate around the animation; (4) Select on the animation line which points of the data set to activate; (5) Visualization must have different colors for the target and gaze points.

Shape-Changing Display Description

This PolySurface is 350 x 240mm in size and used 16 actuators. The display was designed and constructed within one week due to the high specification of functionality requirements listed. We developed two interaction techniques. Firstly, data from the square sample was represented using a chronological physical animation sequence when a user pressed the blue square on the bottom right of the surface (Figure 13). Secondly, sample data from the circle example was show through individual frames. A user can hover or press one of the 30 buttons projected on top of the display enclosure to select a specific indexed frame (see Figure 14 and Figure 8C). For height control, we automatically scaled P3's data samples to fit ShapeClip's grayscale RGB input values (0-255).

Evaluation Meeting

We presented this display to P3, who noticed there was sharp variation in height at the corners (Figure 13B) of the square whilst on the main lines (Figure 13A) were more flat. Both interaction features enhanced understanding of the preliminary data trends. Based on these observations P3 stated that this dynamic physicalization helped to verify their hypothesis regardless of the relativity small data sample:

> *"Now I know for sure from this square example that corners are problematic and in the circle example I can check that there are not that many changes."*

P3 noted that the segmented polygonal structure of PolySurface enhances slopes for each height actuation. Initially, the additional visualization of the data sample points aided differentiating between the square and circle examples. Individual frame selection enabled easy comparison between points on the timeline. The chronological animation sequence enabled clear insight into the overall trend of the data sample.

Group Showcase

P3 invited five colleagues from the eye-tracking research domain along to a showcase of their interactive shape-changing display. P3 showcased their PolySurface display, explaining the data representation and interactive features. P3 went into detail about the data trends that emerged from these representations (e.g. greater height variation in corners of the square). All group members were able to distinguish variation in height and come to the conclusion that corners is where gaze is lost due to sharp angles.

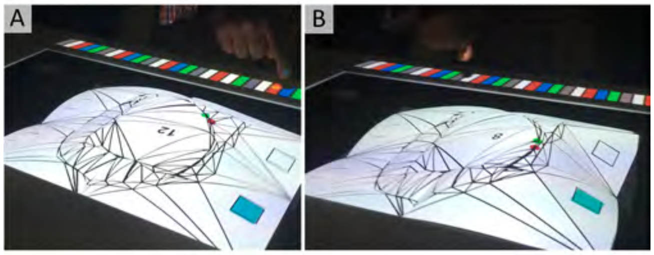

Figure 14: P3's colleague comparing elevation difference between circle frame 12 (A) and frame 8 (B).

One member questioned why distance of the gaze points was represented by height. P3 replied that eye-gaze offset is the most important variable in their data they thought it was the most appropriate to represent through elevation. Another colleague asked why distance between target and gaze points is not just visualized using the projector. P3 stated that having just the visualization does not clearly show positive and negative variation. Another member enquired about the possibility of adapting the display to show real-time data. This functionality could be easily implemented using visualization toolkits.

Summary

P3 successfully designed a shape-changing display which enables physical comparison between target and gaze position in an animated circle and square based on a timestamp log. We incorporated two interactive features to physically represent two separate data samples. Firstly, a user can play the full sequence of data points through a chronological animation (Figure 13). Secondly, show each data point through individual timeline frames. A user simply selects a specific frame by hovering or tapping their finger the top of the display enclosure (Figure 14).

The participant showcased their display to five colleagues. All group members were able to distinguish greatest height variation on the corners of the square example which verifies P3 research hypothesis. P3 described his shape-changing display as a tool for "*proving hypothesis and data trends*".

DISCUSSION

Our design session observations show that PolySurface enhances the rapid prototyping of high fidelity interactive shape-changing display with minimal hardware requirements. From the evaluation meetings and showcases we saw that all participants were able to successfully design shape-changing displays which were then constructed using our PolySurface approach. We identify and discuss key findings and limitations below.

Simplification of Complex Data

During the design sessions, we observed trends in designing minimal visual aids or labels. We saw all participants apply some form of data simplification when designing their shape-changing display. P3 wanted to see if the focus group could perceive data trends represented by their display without a comprehensive explanation. P2 explained the underlining representation to the non-geologist. Both the non-geologist and focus group members were able to understand the underlining concepts after an initial explanation. P2 also highlighted that experts from their domain focus on low level data specifics. Similarly, P1 noticed that they did not add axis labels to all four physical bar-charts. We established that additional visual aids are necessary to represent complex information and data.

The novelty of designing shape-changing and elevated features for displays resulted in lack of focus on visualizations. Further investigation is needed to understand if it is the medium that encourages data simplification or the toolset. We suggest that during the visualization design step, users are encouraged to carefully consider how they should use visual aids and labels in their design.

Insights Gained

The novelty of physically representing eye-tracking data encouraged focus group participants to think about their work from a new perspective. Pleasingly, our physicalization helped P3 to verify previously-unknown areas of focus in his dataset (the corners of square targets). Our novel approach for data representation helped to expose new insights.

Input Data Types

All participants used spreadsheets, databases, tables, plots or graphics to represent their data traditionally. Both P1 and P3 provided spreadsheets. P1 supplied a basic table containing numeric and text data. P3 normalized their numeric data into CSV format, which was used for segmentation and mapping elevation controls. P2 provided a copy of their paper and multiple images, photos, figures, and graphs to aid communicating their data. The combination of numeric data, aerial photographs, contour maps and topographical images aided the design and construction of their display. This wide range of data types shows that our approach facilitates the conversion of a variety of input data into shape displays.

Generalizability

Based on our observations, PolySurface has the greatest impact on low-frequency and contour-based geometric transformations. Landscapes and novel interfaces (P3) with curved and rounded outlines are best emphasized using the semi-solid characteristics of PolySurface – where small solid segments and dynamic folds emphasize more complex geometry. For high frequency geometric transformations such as bar charts, bare pin actuators may be more appropriate but this does increase hardware requirements.

Levels of Participation

Participation levels varied depending on confidence with technical capability and creative engagement with the data. P1 initially felt inadequate designing a shape display due to their unfamiliarity with this type of technology. As P1 became more comfortable with the design process they took over sketching. With guidance and support P1 was able to develop a simple physical bar chart representation. We observed that P2 and P3 were more engaged in the design process. Although their data samples were more complex, the additional time spent establishing their designs enhanced their engagement with our approach. To increase creative engagement in the design process, we propose developing a library of templates with adjustable features for numeric data types as an example. This would allow users to visualize their prototypes more clearly and adjust features as they see fit.

Reflection on Approach

Our aim was to develop an approach that reduced the technical entry-point for developing shape displays. Participants were able to efficiently design their own shape displays and showcase them to both colleagues within their domain and non-experts. All participants designed novel applications with practical uses that were engaging to users.

While participants were fully involved in the design sessions, none stayed to help with the fabrication step. Despite its widespread use in maker communities, laser cutting is still a niche skill that the majority of the population would not be confident to conduct independently. Further, while height-design was conducted by participants, interactive elements were implemented by a researcher. Even with toolkits, code snippets (and in future, drag-and-drop coding), this task cannot be performed independently by a non-technical user. More work is needed to bring the accessibility of interactive elements in these displays closer to non-technical users.

Our design sessions aimed to demonstrate examples of possible applications using a wide range of data from different domains. In future work, we aim to gain more insight into how participants would respond to current shape displays that use cloth material and bare pins in comparison to PolySurface.

Limitations

While our approach provides non-technical users with a route into shape-changing display design, it does suffer from some limitations. First, the approach still requires some technical input. The key area for improvement is in interaction design, where code-snippets need to be integrated into the system to easily implement buttons, and other interactions. In future, a visual code editor would allow non-technical users to be more engaged with this step.

Second, PolySurfaces are not as generic as large pin-arrays. This is a trade-off in implementation cost – our reduced engineering complexity results in reducing generalizability of the display. While users can input several datasets to design a complex semi-solid surface, this does not necessarily mean the surface can physically represent all datasets. Until generic shape-changing displays mature (both in terms of cost and accessibility), we believe that for most uses (public displays e.g.), PolySurface users will be happy with this generalizability trade-off. Currently, PolySurface actuator position is determined by the variance in height between frames. In future iterations of PolySurface an algorithmic approach will allow the user balance the number and placement of actuators and the output resolution.

CONCLUSION

We present PolySurface, a dynamic semi-solid surface, as a low-cost implementation method for rapid high fidelity prototyping of interactive shape-changing displays. Our design approach combines characteristics of solid actuation pins with the elasticity of cloth material to enable a more dynamic form of polygonal shape-changing surface. We demonstrate generalizability by allowing users, from different domains, to design interactive shape displays based on datasets from their own work. The combination of mapping data to physical surface reconfiguration, interaction features, and visualization enhances user engagement and understanding of complex data trends and information.

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