A Shape-Shifting Wall Display that Supports Individual and Group Activities

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ABSTRACT

We contribute a shape-shifting wall display that dynamically changes its physical shape to support particular individual and group activities. Our current prototype comprises three vertical slim screens, each mounted on a mobile robot. Different shapes are created by controlling the position and angle of each robot. Examples include: (1) a flat wall display for collaboratively sharing visual content; (2) three separated screens for individual work; (3) a concave screen that provides a more immersive and private experience; (4) a convex screen that supports a mix of individual and group work, (5) tilted screens, and others. Shape-changing is controlled explicitly or implicitly. Explicit control occurs when a collaborator indicates a desired shape via a hand gesture. Implicit control occurs when the system infers a change in the group's context, e.g., as determined from a change in the screen's contents, or by monitoring the spatial relations between participants around the display (via proxemics and F-formations). Several interaction scenarios illustrate how a shape-changing display is used in practice.

Author Keywords
Shape-changing displays, robotic displays, proxemics interaction.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces, Interaction styles.

INTRODUCTION
The research focus on single and multi-display design has tended towards their hardware construction and their interactive capabilities. Yet the physical placement of these large displays within the workplace is also critical: a display's location and orientation within a room and its features, and its positioning relative to other displays, can afford or inhibit individual and collaborative activities [3,5,7,12-17,22-26]. This is why other domains, such as interior design, architecture, and furniture design, pay considerable attention to designing efficient and comfortable workplaces. Even so, displays are typically anchored to a location, or are unwieldy to move, thus creating a fairly static environment that reflect a single expectation of use.

The issue is that people can change their activity from moment by moment. A given multi-display configuration appropriate for one activity may not be a good match for the next activity. For example, a group of collaborators arranged semi-circularly in an F-formation [15] would likely want a common display in the shared space immediately in front of them. Yet if that group then transitioned to individual activities involving personal tasks, each person would likely want their own separate display to avoid interfering with one another. Individuals may even want these displays angled away from one another to afford privacy or minimize distraction.

One simple remedy is to allow people to manually move displays to fit their activities. This is already afforded by various non-digital displays that can be easily re-arranged. Examples include mobile whiteboards, paper flip boards and even foldable screens. Manual repositioning also exists within the digital realm, usually by mounting displays on display arms or pedestals, as will be discussed in the Related Work section.

Another possibility – and the focus of this paper – is a shape-changing display that *automatically* changes its physical shape or screen arrangement to support the collaborative or individual contexts of people's activities. While shape-changing interfaces are an emerging area within HCI, its research currently emphasizes surface deformation of a small display into a 3D shape [1,6,9,20] *vs.* large display reconfiguration. While the entertainment industry has developed several impressive shape-changing displays ([2,21]: see Related Work), their focus is on supporting interactive performances rather than work activities.

To this end, we contribute a shape-shifting wall display that dynamically changes its physical shape to support particular individual and group activities. Shape changes are triggered either explicitly through gestural commands, or implicitly by the system monitoring and matching the shape to best fit the physical position of group members and/or the screen contents.

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RELATED WORK

While there is relatively little prior work on multi-display environments that can autonomously reconfigure themselves, other work is available that informs this area.

Manually Repositioning Displays

Various multi-display environments include displays that can be manually repositioned. One example is ConnecTable, a horizontal display atop a custom wheeled pedestal [24]. When two people abut ConnecTables together, their interfaces are fused to enable collaborative interaction. Another example is the Chained Display [13], a public display consisting of six connected vertical Plasma displays, each mounted on a pedestal. Its creators manually reconfigured them into various arrangements (e.g., flat, circular, hexagonal), and found that particular arrangements significantly impacted people's interactions with it. While these and others works (e.g., [22]) support the idea of display re-configuration, our work differs in that it goes beyond manual movement.

Displays for Individual and Collaborative Tasks

Numerous studies examined the impact of various display configurations on individual and group interaction and activities. Examples include the interplay between personal displays and a large shared display [26], and the effect of a display's tilt-angle [10]. Others have considered display strategies for *mixed focus collaboration* [7], where people pursue individual work while monitoring what others are doing so they can fluidly transition into group work. Examples include PiVOT [12] and Permulin [14]: both provide a single tabletop display that can present different views to its viewers. [5] describes middleware that allows different views across a multi-surface environment. [3] suggests that different physical layouts of multi-monitors (a flat or curved arrangement) can support different collaborative scenarios. These efforts confirm that particular individual and collaborative activities are best supported by a matching display configuration.

Displays that Change Content in Response to the Spatial Relations of its Users

Various displays dynamically change their content (rather than their shape) to best fit the changing spatial relationship between people and the displays that surround them. This is called *proxemic interactions* [16,25], which is in turn based upon the social theory of *proxemics* [8]. For example, if a person faces towards the display and approaches it (signifying increased interest and engagement), the display will provide providing progressively more detail [16,25]. As another example, when people orient and move their personal displays towards one other, the interface changes to afford easy information transfer [16]. Another approach uses the social theory of *F-formations* to infer group membership. For example, [15] matches cross-device interaction with particular F-formations, e.g., when people stand in a side-by-side F-formation, they can fluidly share visual content by tilting one device towards the other device. E-conic [17] also uses the spatial relations to provide distortion-free content to users when using multi displays placed at different locations and angels.

Our work also monitors the spatial relations between people and displays, but differs in that it also uses that information to infer a display's physical shape (and optionally the content) that best matches the group's individual and collaborative contexts.

Shape-Changing Shared Displays and Robotic Displays

While some small shape-changing displays exist [1,20], there are very few examples of self-actuated large shared displays that can change their physical shape. TransformTable is a digital table that can change the shape of its single display, e.g., from round to square [23], where it can infer its shape from situational contexts and from the displayed matter. Our work differs, as we consider multi-display configurations.

The use of robotic displays is being explored for example in telepresence systems [4]. The entertainment industry has developed several quite sophisticated shape-changing multi-display systems to support interactive performances [2,21]. They typically exhibit a rapidly moving array of displays, each mounted on an industrial robot, where the projected contents are animated to fit the display movements, e.g. to physically enhance the 3D nature of its content [21], and to react to a performer's actions [2]. These products are inspiring, as they illustrate both the potential and the beauty of robot-controlled shape-changing displays in an artistic installation. Our work is based on the same technical approach (using robots to reposition displays). However, it differs as our goal is to consider and support particular personal to collaborative interactions within the workplace.

IMPLEMENTING A SHAPE-SHIFTING DISPLAY

Our prototype, illustrated in Figure 1, comprises three vertical slim screens (61 x 150 cm for each). Each screen is mounted on a mobile Roomba Create robot. Each screen also has 3D markers atop of it. Thus the position and orientation of each screen is controlled by maneuvering the robot, where a tracking system accurately tracks the position of each display as it is moved via its markers. People also wear markers, which allows the system to track their spatial location relative to the display and to each other. People's input gestures (described later) are recognized via a Kinect placed above the display.

As screen positions and orientations change, visual content (image-scrapped from a host computer's display) is adjusted continuously and dynamically via projection mapping. This is done to remove distortion (resulting from tilt and distance changes), and to map content to individual screens and/or to the collective screen as a whole.

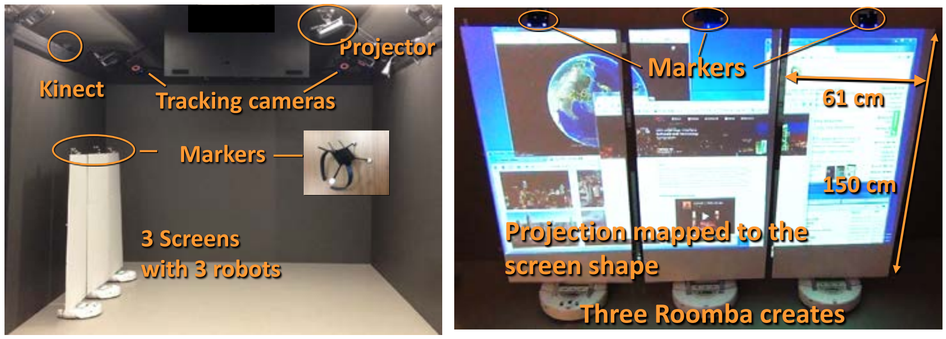


Figure 1 Prototype implementation

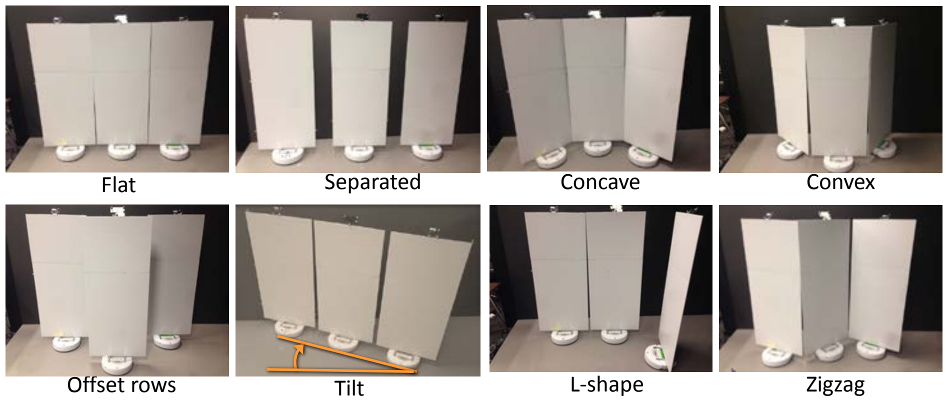


Figure 2 Shapes of the wall display

Due to the small projection area of the single projector (Figure 1) we currently use, our prototype is currently shifting between relative angles of either ±0°, ±30° or ±45° for its flat, concave and convex conditions, and is allowing up to 22cm physical gaps between its screens. However these values can be easily revised by changes to the robotic movement patterns, or via different projectors settings.

Our control software communicates with the robots via Bluetooth, and with the tracking system and Kinect through TCP sockets at 100Hz. Our projection mapping program is implemented atop of openFrameworks [18] at 30 fps. People interact with the displayed content via a controller, such as a wireless mouse or smartphone. As projection mapping onto moving displays is difficult, we suppress display updates during shape-changes by using static screen snapshots captured just before movement starts.

Design Elements

Shape-shifting displays are heavily influenced by several design elements. This can affect how they fit into the workspace and how they adapt to intended uses.

First, the number of individual screens and their sizes are important. The more screens, the more shapes possible. Our prototype uses three modest-sized screens. This is sufficient for now, as we can create various interesting shapes (Figure 2) that we believe appropriate for individual and small group interactions (1-3 people).

Second, the way multiple screens are connected can constrain what is possible. For example, Chained Display [13] and other small shape-changing displays [1,6,9] physically connect screens with hinges to create a single screen whose curve can be altered manually. We use unconnected screens, each controlled separately. This allowed us to explore a variety of screen arrangements ranging from one continuous screen to three individual screens.

Third, the robot's ability to move affects the screen shapes possible and the flexibility of their movement. We currently use Roombas, a low-cost differential two-wheeled robot, where the screens are fixed perpendicularly atop of them as in Figure 1 (left). This allowed us to create various configurations of perpendicular displays by horizontally moving and rotating the robots across the floor.

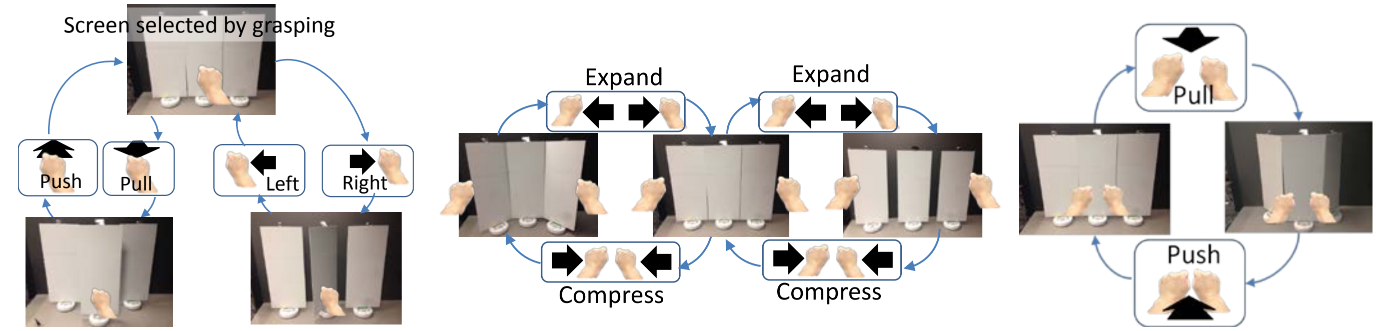
EXAMPLE SCREEN SHAPES

We created several 'stock' screen shapes as a starting point, where the system can easily switch between these shapes (Figure 2). These include flat, separated, concave, convex and other shapes, where we believe that each shape have unique features appropriate for particular individual and group activities. A few examples are detailed below, and are illustrated in the video figure.

Flat wall sized displays (Figure 2, top left) are appropriate for many purposes. Uses include a video viewing, serving as an ambient information wall viewable at a distance, or as a medium for collaborative data exploration by a group.

Separated displays (top mid-left) support one or more people pursuing individual tasks on individual screens. The gaps between the screens emphasize the separation between tasks or users. Each screen's angle can be further altered to emphasize or minimize this separation. All affect the perception of these screens as personal or private areas, as well as how one person can glance over to see what others are doing.

Concave connected displays (top mid-right) provide a somewhat physically shielded workspace for a more personal or private user experience. It is also appropriate for immersive content (e.g., games).

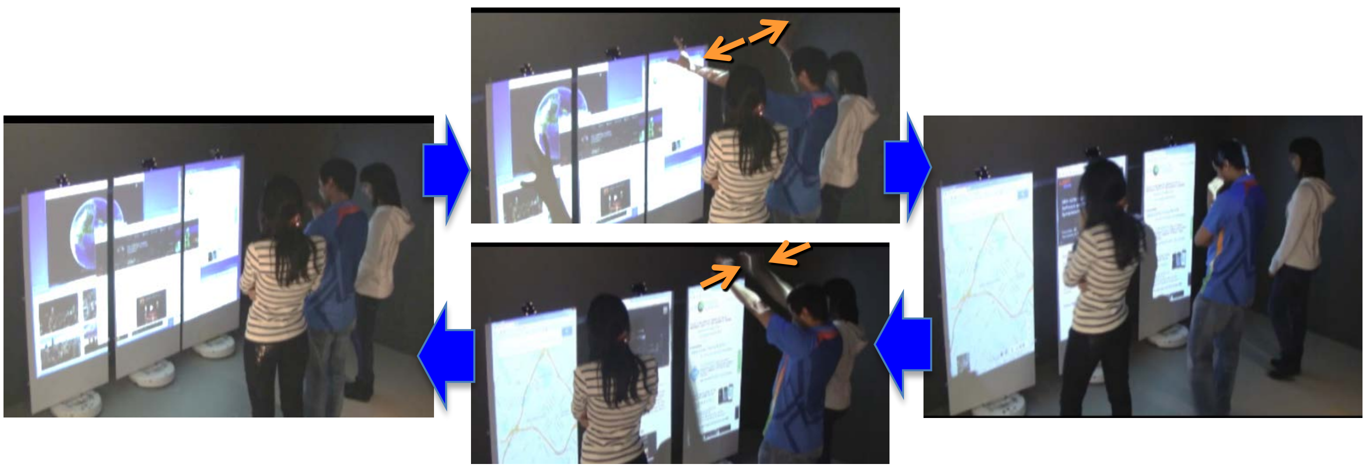


(a) Screen selection by grasping and position and angle controls by gestures

(b) Between concave, flat and separated shapes

(c) Between flat and convex shapes

Figure 3 State transition model of gesture-based shape control

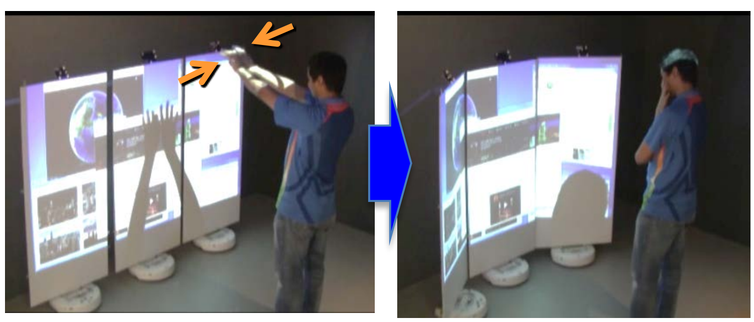


(a) Collaboration

(b) Expand (upper) and Compress (lower) gestures

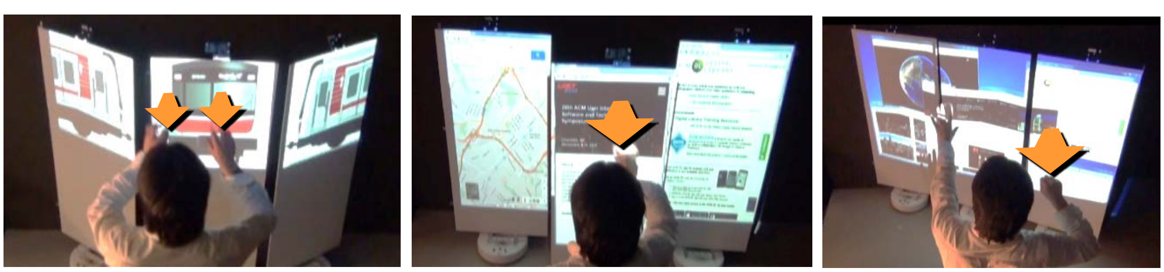
(c) Individual tasks

Figure 4 Application scenarios of explicit shape control trough gestures in individual and collaborative activities.



(a) Compress gesture

(b) Private workspace



(c) Convex shape

(d) Offset rows

(e) Tilt display

Figure 5 Explicit screen shape control through gestures

Convex connected displays (top right) are suitable to visualize volume data from three different camera points [19]. Alternately, each screen can display different tasks, where users can perform individual work while monitoring others (called mixed focus collaboration [7]).

Other shapes are possible (bottom row)**.** *Offset rows* may show primary work on the foreground screen and peripheral work on the background screens. *Tilting* can display distortion-free images to users at any directions. *L-shapes* and *zigzag* shapes can be customized to particular settings, such as public displays of posters or advertisements.

(a) Private view

(b) Wide content

(c) Volume data

(d) Immersive content

Figure 6 Implicit shape control inferred from screen content

INTERACTION TECHNIQUES AND USAGE SCENARIOS

While shape-shifting displays are interesting, their power comes from how shape-shifting is done in reaction to user actions and tasks. We developed several explicit and implicit interaction techniques that controls screen shapes, illustrated below through various interaction scenarios.

Explicit Interaction through Gestures

We allow users to explicitly control the display shape. While this could be done through various means (e.g., commands on a smart phone), we concentrated on gestural commands as a better fit: a person invoking a shape change doesn't have to touch the display or go through an intermediary device, and gestural actions are easily seen by other collaborators. All gestures consist of grasp-move-release action, each recognized by the Kinect above the display.

Example gestures are illustrated in Figure 3. A person selects a single screen by a one-handed grasping gesture made in front of it (3a), or all screens by a similar two-handed grasping gesture. Individual screens can be pulled, pushed or tilted via a corresponding single-handed *pull*, *push* or *tilt* gesture (3a). All screens can be simultaneously controlled in the same manner when two-handed gesture is done. A person can also use a class of gestures to invoke the stock screen arrangements previously illustrated in Figure 2. The basic gestural form creates a more focused convex workspace when the hands are moved sideways towards each other (*compress* gesture), or a more separated workspace (continuous flat, separated flat) when hands are move apart each other (*expand* gesture) (3b). Similarly, a two-handed *push* or *pull* gesture in front of the central screen will switch between flat and convex shapes (3c).

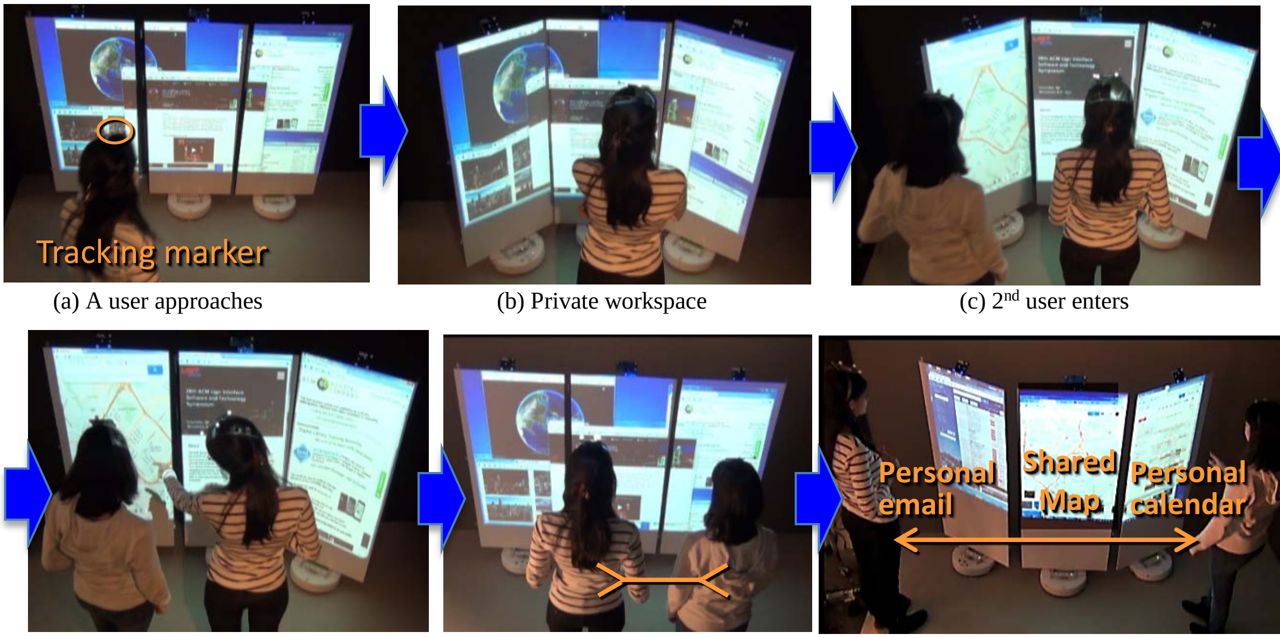
Figures 4 and 5 illustrate how this works in collaborative and individual scenarios. We see three people that are just finishing collaborating over a flat display (4a). One person invokes the expand gesture (4b upper) to split the display to support individual activities (4c). If they wish to move from individual to collaborate work, the compress gesture (4b lower) will bring the screens back together (4a). Figure 5 shows an individual usage situation. In (5a,b) a person wanting a somewhat more private setting uses the compress gesture to shape-shift the display into a concave form. Later, the person uses the pull gesture to form a convex shape for viewing 3D graphics (5c). This is followed by a one-handed push and pull gesture to create offset rows, where he can concentrate on foreground work on the front screen while still seeing background information on the other screens (5d). Finally, he tilts the screen so it can be viewable by an audience by using a combination of grasping (pushing) and pulling gestures (5e).

Implicit interaction techniques

Our second approach uses implicit interaction, where the screen shape changes proactively based on inferences made by the system. We focus on two contextual cues used by the system to trigger shape-changes: screen content, and the spatial relations of people around the display.

Shape control inferred from screen content

The system can monitor the content that is being displayed (e.g., by monitoring applications, tasks, and file types selected by the user), and automatically customize its shape to match that content. While seemingly unusual, our



(a) A user approaches (b) Private workspace (c) 2nd user enters

(d) Partial flat screen (e) Full collaboration (f) Individual and private tasks

Figure 8 Implicit shape control inferred from spatial relationships

premise is that particular screen shapes may best fit a given content.

Figure 6 illustrates several shape change scenarios that occur on particular content types. When a person's actions require a degree of privacy (e.g., display of a password entry dialog), the shape automatically changes to concave to discourage shoulder-surfing (6a). When the person selects a full-screen application with a wide aspect ratio, (e.g., a movie player) its form assumes a continuous flat shape to optimize his viewing experience (6b). When the person displays a volumetric visualization (e.g., showing side, front, side views) the screen becomes convex. This enhances the feeling of depth, and highlights that multi-perspective data is seen from three camera viewpoints (6c). When the person is navigating through 3D landscapes (driving simulators, 1st person shooter games), it becomes concave to create a more immersive experience (6d).

Shape control inferred from spatial relationships

The system can also monitor the spatial relations between people from each other and from the display. This is called proxemic interactions [16], where the system infers meanings from the positions of people. It also tracks which of two zones they are in: an ambient display zone where people may just be glancing at the display, and an interaction zone where people are close and thus likely to be interacting with the display's content (Figure 7). Within the interaction zone, the system detects F-formations [15,16]: the physical spatial patterns that people adopt when they engage in focused conversational encounters (e.g., side by side, face to face). While people's positions are currently tracked through head-worn tracking markers (Figure 8a), marker-less methods are also possible [16].

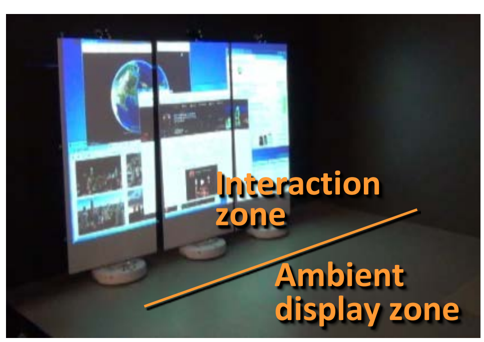


Figure 7 Proxemics zones

Figures 7, 8 and the video figure illustrate several shape change scenarios that occur when particular spatial relationships are detected. When no one is within the interaction zone, the display assumes a flat single shape so that its contents are viewable by passersby (Figure 7, 8(a)). When it detects a single person crossing into the interaction zone towards the screen's center (8a), it assumes a convex shape to reflect personal work (8b). This shape could entice user interaction, and will make the setting somewhat more private.

Figure 8c-f illustrate how the shape-shifting wall display supports mixed-focus collaboration. People may be pursuing a mix of individual activities while still monitoring what others are doing, up to fully collaborative activities where they are working together directly on a shared task [7]. Example mixed-focus collaborations include travel planning, competitive or cooperative gaming, brainstorming, and so on. To begin, when a second user enters the interaction zone and stands to one side (8c), the display flattens that part of it to afford a degree of collaborative viewing (8d). When people move closer together, the screen flattens completely as it assumes a purely collaborative task (8e). When they move apart to pursue individual tasks, the screen turns convex and separates somewhat. Shared content is on the middle screen (which both can monitor) while individual content is on the side screens (which creates a personal space). For example, Figure 8 (f) shows two people doing some travel planning. Both are accessing personal applications (email, calendar) on their own screens, while still seeing a shared map on the central screen. After that, they can easily come back to full collaboration by forming side-by-side in front of the display (8e). Next, F-formations can involve more than two people. For example, (and visually similar to Figure 4c), when three people stand somewhat apart from each other, the screen will separate as it infers each is pursuing individual tasks.

Figure 9 Stop gesture

Combinations

The system can also consider combinations of content-based and spatial-based mechanisms to provide more nuanced inferences. For example, if a movie is being displayed and people have stepped back into the ambient display zone, the system could infer that they are now watching that movie together and shape the screen accordingly.

MANAGING ERRORS

Mistaken inferences will happen, which could lead to unwanted, and perhaps even annoying shape changes. Several methods can mitigate this [11].

Minimizing errors

The best way to manage errors is to minimize their number. One approach is to act very conservatively where the system may change its shape only when it has fairly convincing evidence that it has detected something warranting a shape change. It may also weight some shape changes more than others, i.e., shifting to unusual shapes would require more evidence. It may use timing and hysteresis constraints to minimize excessive screen changes, e.g., as may occur when people are rapidly moving around a display.

Explicit overrides of implicit actions

People should be able to easily override undesired shape-changes [11]. Our system provides for manual override by detecting a *stop* gesture (Figure 9), an open upright palm moved towards the screen during an implicit shape change.

DISCUSSION

The idea of a display that shape-shifts to support particular individual and collaborative activities is unusual, and thus could be met with some skepticism. Admittedly, this is early work. We have contributed a working proof-of-concept system that can shape-shift based on explicit or implicit user actions, but we have not yet studied the actual benefits of particular shapes over particular situations, nor have we verified that the implicit ‘rules’ followed by our system match people’s actual needs. As with many new ideas, shape-shifting displays will evolve, and our design knowledge will grow accordingly. We will certainly need to: study the nuances of shape-shifting design and strategies; test their actual use; and consider alternate implementations.

Yet the benefits of a shape-shifting display can be predicted from existing practices and works. For example, large concave screens are common as immersive screens, and some smaller ones are even sold commercially. Convex volumetric displays are afforded by cubic displays supporting multi-perspective data exploration [19]. As mentioned in the related work, others have explored manually reconfigurable modular displays of various shapes. For example, [9] used corner-to-corner shapes using dual tablets to facilitate collaboration. Reconfigurable Displays allow various quite large panels to be created by modular projection boxes e.g., 1x3 towers, 2x4 horizontal or vertical grids, L-shapes, etc. [22]. Commercially, there are myriads of wall displays comprising odd shapes (e.g., advertising walls, store-front displays, display rows, etc.). There is no question that both interest and deployment of differently shaped displays is growing. Our work just pushes it to the next step, where shape-shifting is done by the system in response to actual individual and group needs, rather than by a person manually moving and reconfiguring display components.

Our next steps will be to improve upon our own implementation. First, we will increase the number of screens, which involves a modified multi-projection system. This gives greater flexibility in the shapes possible and will also allow separated screens to have larger gaps between them, for example in order to form a box shape to visualize a volumetric data from four perspectives (i.e., front, two sides and back). Second, we will improve upon shape transition. While the screens movements are accurate, the movements possible are impacted by limitations in how we can maneuver our robot (i.e., its differential wheels means it takes three movement steps to separate screens), as well as the robot’s limited degrees of freedom (i.e., to perpendicular displays). We foresee an omnidirectional robot (e.g., [2,21]), perhaps with a controllable arm to carry actual flat displays and change their roll/pitch/yaw, as a feasible – and physically more stable platform (including more rigid screen support to avoid screen vibrations during movement) to rapidly and smoothly move the screens towards any location, direction and angle. Another possibility is to forego mobile robots, and to instead use a floor or ceiling mounted rail system that allows screens to be moved and rotated. This approach with the stable movement mechanizes could be helpful to minimize potential issues of projection for moving screens (e.g., focus length adjustment and arraignment of the projector).

Screen visualizations could also be improved by modifying our projection mapping so that animated content can be displayed even during the shape-changes. This can, for example, express motion cues that help users anticipate screen change intentions before its actual movement.

CONCLUSION

We contributed a shape-shifting wall display that dynamically changes its physical shape to support particular individual and group activities. Our first prototype comprises three vertical slim screens, each mounted on a mobile robot. We showed how we can transition not only between stock shapes (flat, separated, concave and convex) but other shapes. We provided scenarios of how particular shapes can potentially optimize individual, mixed-focus, and fully collaborative activities as well as content viewing. We illustrated three methods for triggering shape changes: explicit shape control based on gestural commands, and two implicit methods based on screen content and the spatial relations of users.

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