ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers

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ABSTRACT
This paper presents ShapeClip: a modular tool capable of transforming any computer screen into a z-actuating shape-changing display. This enables designers to produce dynamic physical forms by 'clipping' actuators onto screens. ShapeClip displays are portable, scalable, fault-tolerant, and support runtime re-arrangement. Users are not required to have knowledge of electronics or programming, and can develop motion designs with presentation software, image editors, or web-technologies. To evaluate ShapeClip we carried out a full-day workshop with expert designers. Participants were asked to generate shape-changing designs and then construct them using ShapeClip. ShapeClip enabled participants to rapidly and successfully transform their ideas into functional systems.

Author Keywords
Shape-changing Displays; Actuated Displays; Shape Displays; Reconfigurable; ShapeClip; Tool;

ACM Classification Keywords
H.5.3. User Interfaces: Graphical User Interfaces, Input devices and strategies, Interaction Styles.

INTRODUCTION
Actuated shape-changing displays transform our interactions with technology by exploiting perceived affordances inherent in physical form [9, 22]. However, despite being a powerful technology with transformative potential [9, 18, 31, 32] such systems are still too difficult to construct and deploy, even for those with the essential, highly specialist, technical skills. These barriers prevent those with different expertise (e.g. designers) from engaging with shape-change and thus iteratively evaluating and improving it as a community. We argue that creating and deploying applications and motion designs for shape-change should take hours, not weeks.

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Figure 1: ShapeClip in 4 different configurations deployed on a Microsoft SUR40.

To overcome these barriers, we present *ShapeClip*: a modular tool capable of transforming any computer screen into a z-actuating shape-changing display (Figure 1). By significantly lowering the cost, complexity, time, and skills required to develop shape-changing displays we are able to engage a wider community of non-technical designers. ShapeClip displays are composed of multiple shape-pixels or '*clips*' that actuate when placed on standard displays (Figure 1). Clips can be re-arranged into different topologies, added and removed at runtime, and support varying degrees of scale and density. Battery powered clips enable portability, and a graphical control system removes the need for control circuitry whilst encouraging designers to quickly evaluate shape-change in different configurations.

To evaluate ShapeClip and learn from its strengths and limitations, we organised a full-day workshop and invited seven experienced designers to participate. During the workshop participants proposed and constructed six shape-changing prototypes, with the option to collaborate and use a range of materials (e.g. fabrics, cardboard, plastic, etc.). We focused our analysis on determining if participants were able to immediately 'pick up and construct' their ideas and leverage existing design skills and familiar tools. All participants successfully constructed one or more functional prototypes and reported spending more time on design than shape changing implementation. Post-session feedback also provided insight into strengths, limitations, and important features for expanding the range of shape-changing toolkits.

The paper is structured to draw out the foremost contributions:

1. **Concept and Implementation:** The open-source concept, design, and implementation of hardware, software, and firmware applied to a range of actuators and performance tested on a range of displays.
2. **Capability Demonstration**: A description of the key capabilities and validation that they operate together in a cohesive manner through five demonstration applications.
3. **Workshop Findings**: Evaluation of the suitability for adoption by designers leveraging their ability to use existing skills to implement their ideas, and lessons learned that can inform future toolkit requirements.

RELATED WORK

Prototyping tools in HCI and computer science are strong drivers of experimentation and innovation [11, 12, 14]. The design of ShapeClip is guided by the study of tools that support user innovation [17] in concert with the unique requirements of the shape-change research community. Effective tools allow end-users to quickly and inexpensively explore new designs, reduce the cost/risk of failure, and allow use in a flexible and reconfigurable manner that can be easily deployed.

The Range of Shape-Changing Displays

Shape-changing displays are visual output surfaces that support dynamic physical reconfiguration. Coelho et al. [7] review the design space of self-actuating shape-change, categorising devices by their materially or surface properties and Rasmussen et al. [31] by their topological form, transformation, and interaction. Displays' geometry can be described using 'shape-resolution' [32].

The community has explored a range of self-actuated shape-changing device forms. InFORM [9], Lumen [30], Feelex [19], and Relief [25] provide various scales and densities of z-actuation with either top-projected visuals or coloured bars. Portable and mobile form factors have also garnered significant attention. Tilt Displays [1] added tilt to z-actuated OLED displays to a tablet-sized device, Hemmert explored tapering [15] and weight-shifting [16] phones, Morphees [32] explored a range of advanced material implementations, MorePhone [10] added SMA's to a thin-film e-ink display for corner-bending notifications, and Dimitriadis et al. [8] evaluated volume expansion, protrusion and corner-bending for in-pocket mobile notifications. Surflex [6] used SMAs embedded in foam, and BubbleWrap [2] enclosed actuators in fabric, to explore the design of programmable surfaces. Pneumatics [13] and microfluids [5] can produce on-demand buttons on touch-screens. Sublimate [24] addresses the challenge of combining high-resolution visuals and high-resolution physical output through augmented reality. Within this range, ShapeClip focuses on providing the most prominent form, z-actuation, whilst supporting dynamic scales, densities, topologies, and runtime reconfiguration.

Towards Prototyping Support for Shape-Change

The community has amassed a range of implementations that explore the design space of shape-change. However, significant challenges remain in their construction, restricting accessibility to non-technical audiences. A primary challenge is reducing the complexity of mechanical components and control systems. These factors currently limit physical resolution[1] and changes in scale and configuration require significant re-assembly.

One approach to overcome this complexity is to use existing display technologies to communicate in parallel with multiple components placed on a screen: Sugimoto et al. [34], Hairlytop [26, 28], and HamsaTouch [21] have shown how this is possible. Of these, the closest to ShapeClip is HairlyTop [26, 28] which uses changes in display brightness to simultaneously control multiple 'smart hairs' made from SMA wire. ShapeClip extends this approach with a digital circuit and adopts LDRs rather than photodiodes for increased information bandwidth. HamsaTouch [21] shows how display images can be directly converted into tactical feedback to achieve a tactile visual substation system. WebClip [23] shows how two-way serial communication can be achieved on touch screens.

Although requiring a screen suggests that designers may only work with a fixed flat surface, display devices are available in a variety of sizes and shapes that make the concept applicable to a range of scales (i.e. large LCD screens through to small wearable devices). In the near future OLED technology promises bendable displays [10] and projector-based control could support multiple devices over wider areas on non-planar surfaces [27, 33]. ShapeClip steers designers away from monolithic system architectures that limit on-the-fly re-configurability and transference to other application scenarios. Follmer et al. summarise the current state of design: "*Most current shape-changing interfaces that address on-demand affordances provide a specific transformation, which limits their use for general purpose UIs and 3D interaction*" [9].

CONCEPT

The goal of ShapeClip is to remove complexity from the process of building shape-changing displays and re-focus effort on design of applications rather than engineering.

This is achieved through the removal of hardware barriers: (1) engineering complexity, (2) fixed actuator arrangements, (3) control circuitry, (4) low failure tolerance, (5) large build-footprints and, (6) scalability challenges. Interactive motion designs can be produced with no programming knowledge, embedded firmware, cross-platform support, or software tools.

[1] MIT's inFORM [10] provides the highest resolution to date with 30×30 actuated pixels.

Figure 2 illustrates the components needed to construct a ShapeClip display. *Clips* are placed on a *control surface* (i.e. LCD Screen). Light Dependent Resistors (LDRs) in each Clip sense changes in screen brightness to adjust actuation height and output color. Touch events can be 'forwarded' to capacitive surfaces using thin wires run down the length of the Clip to copper tape on the base.

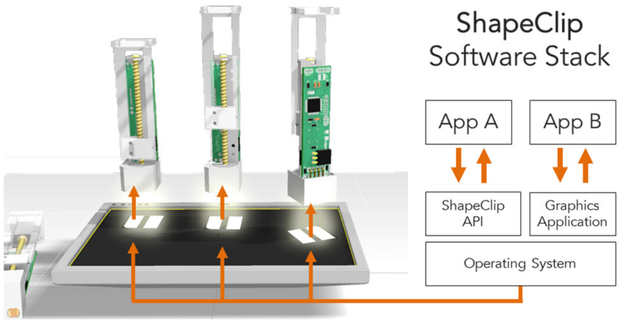

Figure 2: ShapeClip display hardware and software components (not to scale).

This approach enables individual Clips to be added, removed, repositioned, and re-oriented at runtime. A small, light, design allows several Clips to fit onto small screens (e.g. phones and tablets) and many to pack onto larger displays (e.g. televisions and touch surfaces). Clips can be *augmented* with different covers/casings to change their appearance or interactive qualities (i.e. hard or spongy to the touch). It is also possible to place Clips into *assemblies* that add new functionality through the combination of clips (e.g. tilting).

The light based control approach allows program code to be replaced entirely with graphics animations—making it accessible to non-programmers and children. Those with programming experience can control the Clips with a provided JavaScript API. Advanced users may edit the Clip firmware directly. The modularity of ShapeClip removes the need for fixed hardware configurations, and a graphical control system replaces complex bespoke circuitry with a system that can quickly adapt to configuration change. These features ease the prototyping phase as they enable quick iteration over different application ideas.

IMPLEMENTATION

To validate the ShapeClip concept we fabricated 100 Clips. All of the resulting outputs (hardware, firmware, web-graphic API, and applications) are made available[2] under the MIT license.

Clip Hardware

Standard Clips are constructed from a bespoke circuit board containing an ATmega328p (compatible with the Arduino tool chain), two LDRs, a stepper motor (as used in DVD drives), a corresponding 3D printed base, and a WS2812B LED for RGB color output. For interactivity, Clips are able to forward touch events to capacitive screens using copper tape and thin wire, or stream data from an optional force sensor attached at the top. Heads and bases tailored to suit different applications can be attached to the motor or screwed onto the actuator. It is also possible to change the actuator to support other kinds of shape-change (i.e. rotary, pneumatic). This is achieved using auxiliary output pins that support standard control slide potentiometers and servos (Figure 3). A separate pin in the power connector supports different motor voltages.

Each standard Clip weighs ≈30g, and is 20×20×80mm when closed, and costs ≈USD$15. The selected stepper motor has 60mm of travel. Under stress, individual Clips draw between 60–540mA at 5V, enabling small groups to be powered via USB. To power larger numbers, our designs specify appropriate power supply requirements. An independent on-board power circuit separates motor voltage from logic in order to increase the travel speed above the standard 80mm/s. Clips are 'clipped' together with pin connectors that double up as a power transmission method. To enable portability, an accompanying LiPo battery pack can continuously actuate a Clip for ≈30mins.

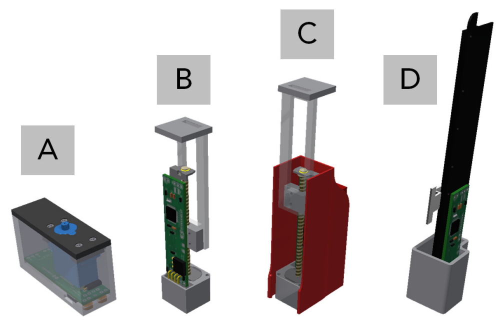

Figure 3: Different Clip actuator configurations. (A) SG90 Servo, (B) Standard Clip, (C) Standard Clip + Battery Pack, and (D) MD100AM2BF motorized slide potentiometer.

Clip Firmware

The Clip firmware samples pixel brightness and converts it into control signals for the actuators and RGB LED. If needed, users can select different modes that optimize for different requirements (i.e. trade speed for precision):

Height Mode (default): Both LDRs are used to sample height, RGB output is disabled. This mode is useful for orientation independent applications and can be driven purely by graphics. Samples are analogue (every 10ms). This mode continues to operate if an LDR is damaged.

Sync Pulse Mode: One LDR samples height, whilst the other looks for a regular sync pulse (Figure 4, top). This is used as a timing signal so that RGB values can be sampled at appropriate offsets (typically 200ms apart). This method can reliably update the RGB LED just over once per second without compromising stability.

[2] https://github.com/LUHCI/ShapeClip

Serial Mode: Both LDRs are used to transmit arbitrary digital data to the Clip using a tri-state auto-adjusting differential transmission method (Figure 4, bottom). One parity bit and two stop bits provide error checking and can achieve a stable transmission rate of ≈9.8 bits/s. A simple protocol layer interprets height and color changes, but is significantly slower than the other analogue modes. It is useful for advanced users who require reliability when extending the Clip firmware or hardware. The use of differential light levels means it can run concurrently with the other modes without interrupting their operation.

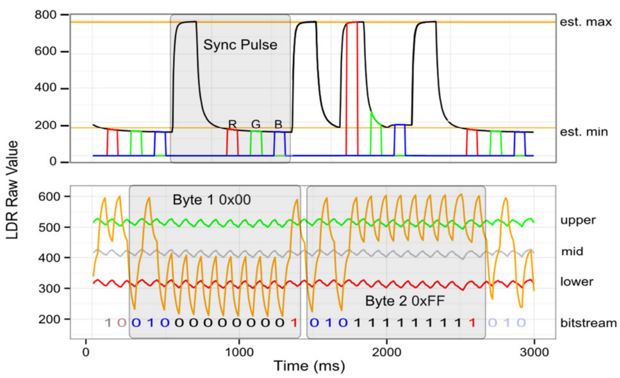

Figure 4: Sync Pulse LDR behavior showing RGB samples (top). Serial-over-screen LDR behavior showing two bytes: 0x00 and 0xFF (bottom).

End User Development

In support of non-programmers, motion designs can be created using well known graphics packages such as Adobe Illustrator, Photoshop, Microsoft PowerPoint, and MSPaint. As ShapeClip is not restricted to any particular software package, users are free to work with the tools they are familiar with. Interactivity can be direct (i.e. next slide when a clip is touched) or simulated via wizard-of-oz using a multi-monitor system. For programmers seeking greater control, a web-graphic based API (HTML5, CSS, and JavaScript) wraps common and advanced functionality. This API has the ability to encode serial messages into the on-screen graphics using the methods described above. It also contains a WebSocket-to-Serial bridge (for Clip profiling and debugging from within the browser), and a Clip arrangement tracker compatible with the Microsoft Surface SUR40 that detects topologies at interactive rates.

This approach to end user development make it easy to test motion designs immediately without re-compilation, enables Clip operation across multiple devices and platforms, and easily integrates rich graphics, multimedia, and traditional UI components into ShapeClip applications.

System Performance

The primary technical challenge was achieving screen-based communication that worked reliably across a wide variety of consumer displays and devices. Our approach is influenced by the limitations of commodity screens (low screen fill/refresh rates, varying brightness and contrast levels) and the sensing characteristics of the LDRs (≈66ms response time to recognize a 0%–100% brightness transition). Many displays are gamma-corrected to optimize for human perception; creating artifacts in the transmission process (Figure 5). To correct for this without affecting the visual appearance of surrounding graphics, a profiler application compares expected LDR values against actual LDR samples for specific displays; reducing the error to a negligible value.

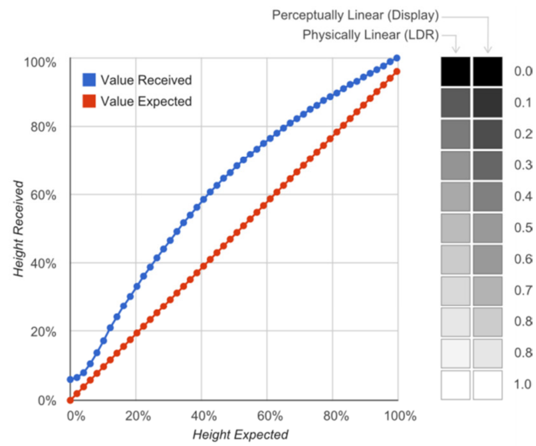

Figure 5: Expected vs received LDR analogue values (left). Illustrated mismatch between 'perceptually linear' display luma and 'physically linear' LDR samples (right).

ShapeClips successfully operate without profiling on a wide range of consumer displays. We specifically tested them on: an iPad mini (Gen 1), Microsoft SUR40, Microsoft Surface Tablet, Nexus 5, Samsung Galaxy SII, and a various Dell monitors (LED, LCD, and IPS).

To enable bi-directional communication between Clip and screen, we implemented an in-circuit representation of the human-body-model [20] and the method described by Kubitza et al. [23]. Although these worked individually, we were unable to reliably communicate with multiple Clips. As an alternative, we support interactivity through capacitive forwarding, resistive pressure, and serial-streamed force sensing on selected Clips.

CAPABILITY DEMONSTRATION

ShapeClip provides nine capabilities that facilitate different rapid prototyping scenarios. In order to validate these operate cohesively, we implemented five scenarios to cover a range of requirements (Table 1).

Portability: By combining battery-powered Clips with a mobile device it is possible to produce portable shape-changing displays. Figure 6H shows a portable augmented magazine, with ShapeClips assembled on an iPad.

Interaction: Beyond capacitive forwarding, Clips can be made to react to gesture (i.e. depth camera data), force, or signals from an external data source.

Variable Scale: No limits are imposed on the size of the control-display surface, including the number of Clips that can be placed on it.

Variable Topology and Density: ShapeClip displays do not require a fixed arrangement; allowing users to place and reconfigure Clips at-will. Density is limited by the physical Clip size and available screen space. Topology is limited by line-of-sight to the control surface.

Variable Orientation: Clips can be re-oriented locally (i.e. turned to face a user) or globally (i.e. moved as the display moves). When operating in sync-pulse mode local orientation interrupts operation. It is possible to operate a ShapeClip display on its side or upside-down.

Hot-swappable: Like all mechanical systems, Clips are subject to mechanical failure. Should a Clip fail, it can be easily replaced on-the-fly, without stopping the software or hardware (if not part of a shared power rail).

Augmented: Clips may have additional materials added to change appearance (i.e. covers, casings) or interactive capabilities (e.g. force sensor). Augmentations can apply to individual Clips or to groups (i.e. a top-mounted deforming membrane).

Assemblies: Clips can be arranged into assemblies which achieve specific objectives (e.g. tilting, stacking, pushing, levering). Specific 3D printed bases are also available that hold Clips at different angles to achieve expanding volume style deformation.

Capability / Scenario	Portable	Interaction	Variable Scale	Variable Density	Variable Topology	Variable Orientation	Hot Swappable	Assembly Based	Augmented
PortableClips	✓	✓				✓	✓		
LensClips			✓	✓	✓	✓	✓		✓
PaintClips					✓	✓	✓	✓	✓
TangibleClips		✓	✓			✓		✓	✓
ForceClips		✓					✓	✓	✓

Table 1: Map of capabilities to application scenarios.

Scenarios

LensClips create a shape-shifting magic-lens [3] that visualizes population density over a map. It demonstrates variable densities and topologies by running the same application code on a SUR40 and a tablet PC. On smaller displays (Figure 6A) a user places Clips in interesting locations to 'physicalise' population. On larger displays (Figure 6B) the user moves a lens (clips in a grid assembly that can be moved as one) to reveal trends.

PaintClips allow users to define motion behaviors by drawing them on an interactive surface. This example shows a teddy bear (Figure 6C) whose arms wave as a child moves her across the display. A 'fill' tool is used for rapid state changes and a gradient tool is used for subtle changes or slower movements.

ForceClips demonstrate Clips used in an (8×6=48) array to create a large shape-display that reacted to force (Figure 6D, Figure 6E). A spandex sheet was spread across the clips. A FingerTPS[3] pressure sensing glove made the table react to different interaction pressures across a continuous surface.

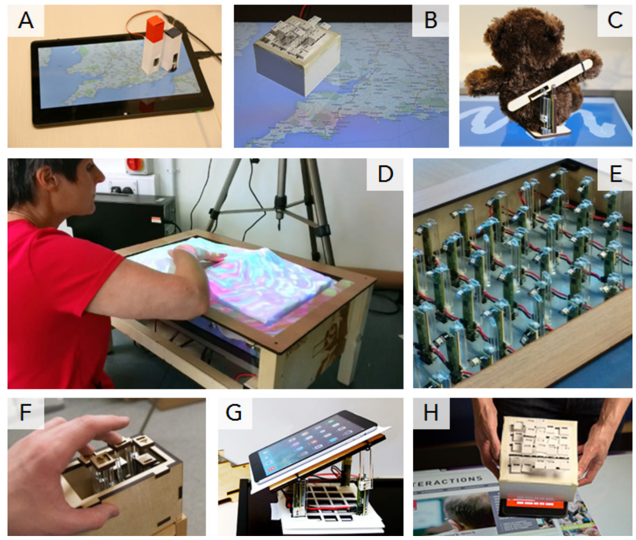

Figure 6: Montage of scenarios that demonstrate capabilities of ShapeClip. Photographs are described inline.

TangibleClips demonstrate augmenting physical objects with Clips. Clips are used to prototype a shape-changing TV remote control embedded within a sofa; controls appearing when required (Figure 6F). A smartphone provided a compact control surface. Additionally, four Clips are used to create a Tilt Display [1] inspired assembly that re-orients an iPad in response to gestures detected by a Microsoft Kinect (Figure 6G).

PortableClips is a magazine based data-visualization that renders on-screen bar-charts as physical data on a tablet (Figure 6H). Clips are attached to the device on-the-fly as appropriate content becomes available. They are secured by a laser-cut template. Users can perform touch interactions on the chart to inspect specific values.

EVALUATION WORKSHOP

To evaluate ShapeClip's suitability for adoption within the designer community, we wanted to determine whether designers with diverse skillsets were able to seamlessly 'pick up and construct' their own shape-changing ideas; leveraging existing skills and familiar tools.

Workshop Format

We organized a full-day workshop and invited seven experienced designers to lead the construction of multiple

[3] http://www.pressureprofile.com/finger-tps

shape-changing display prototypes. The day was divided into four stages: (S1) introduction to ShapeClip and shape change generally, (S2) ideation and concept design, (S3) rapid prototyping, and (S4) reflections and feedback.

During the ideation stage (S2), participants were asked to brainstorm ideas for shape-changing technology, and record their ideas on post-it notes on a large wall. For half of the session, we used fast paced (30sec) themed idea generation via a verbal stimulus. During the construction stage (S3), participants constructed their ideas from the previous session. They were welcome to form new ideas or implement multiple prototypes. A range of materials were provided to assist construction, such as fabrics, plastic, wood, Lego®, cardboard, tablets, interactive surfaces, projectors, and 3D-printed baseplates with various shapes and angles for the Clips The final session (S4) involved a reflections period during which participants were asked to identify the strengths and weaknesses of ShapeClip, the problems they encountered, ideas for enhancements and future explorations, and to describe how closely their prototype matched their intended outcome.

Participants were free to use any tools they wished, collaborate, and form groups. This approach aimed to create an ecologically valid environment that reflected processes found in a typical design studio setting [4], rather than isolating participants in a controlled environment. Questionnaires were provided at the start and end of the workshop. The entire workshop was recorded with audio and video to document processes and physical outcomes.

Participant Demographics

The workshop consisted of seven participants within the age ranges of 18–44 (µ30 years). All participants were formally trained in one or more design domains, predominantly: (P1) graphic design and advertising, (P2) sound and multimedia, (P3) UX design and digital fabrication, (P4) materials, (P5), cartographic design, (P6) graphics and multimedia, (P7) audio-visual engineering. Six participants had previously seen demonstrations of shape-changing technology, but had no previous direct interaction experience. All but one (P5) indicated more experience with graphics and media visualisation than programming.

Brainstorming

The brainstorming stage resulted in a diverse range of shape-changing applications. Of the 86 ideas generated, 88% were technically feasible for ShapeClip in its current state. The domains included, but were not limited to: augmented living (12), public transport (11), graphic design (11), gaming (9), wearables (8), concerts (8), sports (6), aviation (6), and advertising (6). While many ideas were technically feasible, others were beyond the practical scope of ShapeClip or already existed (e.g. adaptable landing gear and wings on an airplane).

Prototype Construction

Several functional shape-changing prototypes were developed during the workshop (Figure 7), including: two physical sound equalizers, a dynamic terrain elevation map, a shape-shifting advertisement, a portable exposure analyser, and a shy robot concept. The motivation behind each prototype tended to mirror the experience background of the participants who created them.

Sound Equalizer

Participants P3 and P7 collaborated to construct a graphical equalizer using a row of eight Clips (Figure 7D). They used the Processing library to detect input sound through a microphone and converted the frequency values into colour brightness levels (i.e. higher frequencies would drive a ShapeClip up and vice versa). The Clips were mounted on top of an LCD display (connected to a laptop) that displayed eight circular pads that were positioned beneath the Clips. P3 and P7 spent approximately 2 hours to complete the prototype.

P2 also developed a sound equaliser but adopted an approach that did not involve programming (Figure 7B) and used battery packs so that he could test it around the room. This involved downloading a frequency analyser application that visualized the frequency as a white wave on a dark background. He placed 10 Clips in two rows on an LCD display connected to his laptop. The movement of the wave controlled the heights of the Clips; the first row detected high gain and the second row detected low gain. This was achieved in approximately 30 minutes.

Dynamic Physical Elevation Map

Participants P5 and P6 constructed a display that rendered graphical terrain and physical elevation using a mixture of projection and Clips placed on an SUR40 (Figure 7C). A greyscale height map was produced using QGIS[4] and then overlaid onto an interactive map created using Leaflet.js[5]. A grid of 4×4 Clips (300×230mm) was placed on top of this and covered with a sheet of white spandex material to create a continuous surface between the actuators. The corresponding graphical terrain (i.e. roads, lakes, etc) was projected on top of the material. Using the computer arrow keys, the projected terrain would shift in alignment with the map, and the Clips automatically adjusted to show corresponding elevation. Constructing this prototype took approximately 2 hours.

Shape-shifting Advertisement

P1 constructed a poster that displays an actuating question mark (Figure 7G). Her aim was to draw attention from passers-by through movement and enable users engage with the content by feeling parts of the poster. P1 used

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[4] QGIS: Open source Geographic Information System http://www.qgis.org/

[5] JavaScript library for producing interactive maps. http://leafletjs.com/

graphics from a previous project and arranged Clips into a question mark shape on an LCD screen. Lego® was used to build up the sides of the monitor to the closed height of the clips, and a poster sheet was attached over the top that would be raised in different areas as the clips actuated. The movement of the Clips was controlled through Adobe Photoshop (Figure 7F) and a brightness control slider on the connected laptop. The moving poster took approximately 1.5 hours to complete.

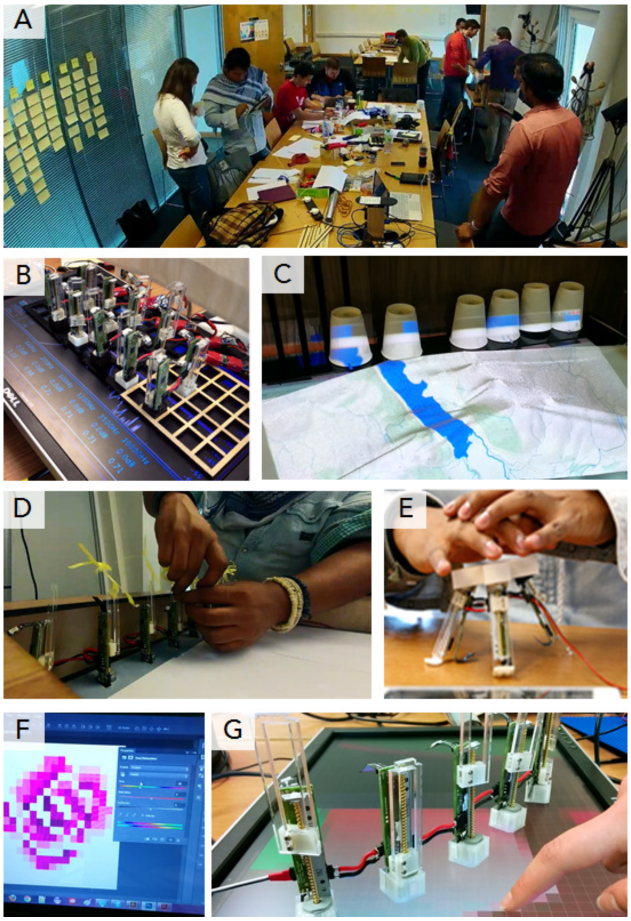

Figure 7: The workshop setting (A), a shape-changing sound equalizer (B), a terrain map that shows elevation data (C), figures being attached to another sound equalizer during construction (D), a shy robot concept (E), and graphical software used to create a digital poster (F) and the poster in development (G).

Shy Robot

P4 explored a playful interaction concept by attaching four Clips to a 3D printed baseplate and turning it upside down such that the Clips behaved as limbs (Figure 7E). As a user's hand was hovered over the device, the Clips contracted due to the reduction in light intensity. They then quickly expanded again once the user removed their hand. This created an effect of "shyness". This concept was realized within minutes, as it was simply a case of attaching the Clips to pre-fabricated baseplates and powering them on. It was an unexpected use of the technology (using the LDRs as presence sensors) and stimulated discussion about use of other types of sensor.

Portable Exposure Analyser

Within minutes of the prototyping session starting, P2 produced a portable Clip attachment for a DSLR camera that indicated the exposure setting to the user whilst allowing them to continue looking through the eyepiece. This approach exploited the light sensing capability of the LDRs. Realizing this concept involved simply using tape to attach a Clip to the eye-piece of a digital camera.

Analysis

The overall reception of ShapeClip was positive (Figure 8). All participants agreed that the technology was easy to understand and work with. Deeper analysis of post-hoc feedback confirmed many of ShapeClip's expected strengths (i.e. simplicity, non-technical control, modularity, variable topology) and exposed areas for immediate improvement that we had not initially considered as significant (i.e. expanded range of end-adaptors and input sensors).

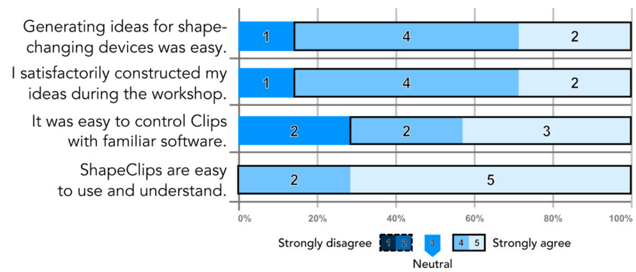

Figure 8: Responses to post-session feedback questions.

Controlling Actuation

All but one participant (P4) agreed or strongly agreed that they were able to satisfactorily construct their ideas within the prototyping session. A wide array of tools were used to control the Clips, including web browsers, Adobe Photoshop, Processing, sound visualisation, and simply blocking natural light. No participants indicated that they could not satisfactory control the Clips. Their comments included:

"It was a really good idea to use colour as an input variable as I didn't even need to use code to control the system" – P1.

"Implementing the idea was simple enough. I need a grid to put the ShapeClips in and a screen to connect my laptop" – P2.

"Easy to control because you are not locked in a set of tools. You can use anything from Scratch to PPT [Microsoft PowerPoint]" – P7.

Extension with Materials and Assemblies

Participants typically used familiar software and hardware tools in order to configure the ShapeClips. For instance, P5 used GIS software and P1 used graphic design packages. Hardware used included attaching materials like fabrics, cardboard, plastic, and Lego® to the Clips. P6 attached a sheet of fabric to the top of 16 Clips using cardboard and two-sided adhesive pads. In the post-hoc feedback four participants indicated better attachments would have assisted their process; suggesting Velcro® and Lego® connectors. Six participants stated that most of their time was spent on the design process of their prototype (i.e. creating the applications, attaching materials), rather than the control of shape-changing hardware components:

"We probably spent half the time on data and software, and half trying to attach some spandex to the shape clip matrix" – P5.

"Very little [time spent on ShapeClip] - mostly the time was used to create the [equalizer] visualization" – P3.

Participants particularly liked that ShapeClip did not require technical expertise and it was clear that no significant technical learning curve impacted the process. The main confusion stemmed from the power cable orientation being initially unclear. However, P1, P2 and P4 all independently worked out they could chain the Clip power connectors to create arrangements.

Modularity and Flexibility

We observed the participants freely repositioning and moving the Clips, experimenting with different densities and layouts. The modular nature of the Clips led them to be shared between different groups in the session. For instance P3 and P7 started with two rows of eight Clips for their equalizer, but later changed it one row of eight. P5 and P6 encountered a faulty Clip whilst setting up their terrain mapping prototype. The faulty ShapeClip was easily replaced by the two participants:

"The modular system works well. One module broke but was easy to replace" – P6.

The post-workshop reflections also evidenced the value of modularity and flexibility through the number and range of prototypes developed in a short space of time featuring different configurations and control mechanisms. This strengthens the argument for modular and flexible approaches to actuation in shape-change prototyping toolkits.

Size and Resolution

The constructed prototypes ranged from using individual clips through to grids (4×4=16) and rows (8×2=16). P5 expressed an interest in using more of the Clips at a later date to continue development of their terrain map. Beyond construction cost (which was not a factor in this study) the main complexity for increasing resolution was powering more ShapeClips. Without prompting, participants sought out more Clips to expand their displays size or resolution. Doing so did not require modifying their underlying design architecture. To support a larger Clip layout, P2 reduced the resolution settings of his computer to that the visualization covered a larger physical space. This suggests that it might be prudent to provide desktop application software that can selectively scale regions of a display, perhaps by applying a contrast filter.

Limitations and Suggested Improvements

During the workshop one ShapeClip failed due to a mistake with wiring. Although additional durability testing and refinement of the power connectors is required, we are confident that Clips are structurally robust and suitable for rapid prototyping. Towards the end of the workshop participants remarked on the heat generated by the motors after extensive use. We aim to address this issue in the future with more durable motors.

Participants felt that the ShapeClips generated too much noise and would benefit from being smaller, with faster actuation. This was in contrast to our initial expectations of demand for larger travel lengths. Better support for attaching materials was suggested via the inclusion of interchangeable caps and the use of Velcro®. Furthermore, motion-sensing, touch detection, and adding sound and direct replication of visual outputs (i.e. on-screen colour displayed on the RGB LED) were among functionality suggestions. This is because the sync-pulse approach to controlling the LDR was too complex.

A difficultly with the current Clip design is that the vibration of the stepper motor can cause a Clip to travel across the screen when not in a fixed assembly. When Clips are tightly packed there is a risk of actuators snagging on their neighbors as a result of this movement. Future iterations will experiment with a lower center of gravity and different base materials (e.g. rubber). It may also be possible to exploit this property to create self-propelled tangibles.

DISCUSSION

Concept Validation

We evaluated ShapeClip and validated our design through implementation, application scenarios demonstrating its capabilities, and exposing the Clips to a full-day workshop with expert designers. The designers were able to use them to construct functional prototypes based on their own ideas and backgrounds. In terms of effectiveness as a prototyping tool we observe similarities to other foundational technologies that allow for a trial-and-error approach to design—reducing the costs of failure and enabling runtime adjustment to designs.

The workshop demonstrated that no programming knowledge is required to rapidly produce functional prototypes, motion designs, and thought-provoking effects. We believe this approach has the potential to enable people of all ages and skillsets to engage with shape-change. Combining shape-change with rapid-fabrication tools (i.e. 3D printing and laser-cutting) means that designs can be quickly iterated and easily transferred into presentation-ready systems.

Engaging with ShapeClip

ShapeClip is open source and designed for easy replication and extension. Its construction uses low-cost commercially available components and 3D printed structures. We found it possible to assemble 100 Clips in our lab in less than two weeks.

While developing our own ShapeClip based displays, the power of the graphical control scheme became apparent. Even as technical users, we would find ourselves using motion graphics to achieve our goals. The inherently spatially-connected design makes applications trivially simple to deploy, with both small and large numbers of Clips. The use of graphical tools as a programming and control environment was intuitive and allowed non-technical designers to implement their ideas without obstruction. We hope that this level of user-accessibility and the number of transformations / configurations / assemblies enabled by the modular nature of ShapeClip can be combined with other tools (e.g. Bosu [29]) to help to overcome the challenge of limited applicability of single-transformation in shape-change described by Follmer et al. [9].

Risks

ShapeClip is based on linear-actuation, as this is currently the most common type of shape-change present in the literature. However, there is a risk that this decision could restrict or influence decisions designers make when developing shape-change. The brainstorming session validated that ShapeClip did not restrict ideation. The flexibility of ShapeClip also means that other types of actuation (such as rotary motors) can be substituted. The open-source nature of ShapeClip readily invites other researchers and developers to build on the concept as new and different types of shape-change emerge.

We also note that the nature of our workshop may encourage use of ShapeClip in a playful manner. More advanced motion designs may require simulation and timing that are yet to be explored.

Future Development

Display-based Control: The use of LDRs for analog communication is sufficient for many applications, but is inherently subject to limited bandwidth and accuracy—in particular the update rate of the RGB LED was too slow and would likely see increased usage if it were as easy to control as the height. It may be possible to detect full 24-bit colour using LDRs with filters applied to block certain light colours.

Scalability: The graphical control system can drive as many Clips as can be packed onto a display. However, large floor or wall sized displays introduce new scale-based challenges. We intend to examine the potential for in-place firmware upgrades using serial-over-screen to flash thousands of Clips in parallel.

Motion Design Toolkits: Although ShapeClip is primarily a hardware-oriented toolkit, it simplifies the end user development of motion design by expanding the range of tools/methods available. There is a clear opportunity to extend this research with more effective methods for creating, simulating, and debugging physical motion designs. We hope that future toolkits can be adopted and extended for this purpose.

Integration with Construction Kits: To support rapid-prototyping, the workshop demonstrated the need for ShapeClip to support attachments that connect to various types of construction kits (e.g. Lego, K'nex, etc.). We intend to develop a range of 3D-printable base- and top-plate connectors that are compatible with these popular construction kits.

CONCLUSION

ShapeClip provides researchers and designers with the ability to prototype programmable physical forms by simply 'clipping' actuators to screens. We demonstrated the robust, flexible nature of ShapeClip through a series of application scenarios that demonstrate novel capabilities, and a workshop that evaluated its effectiveness when used by a range of real designers to implement their own ideas.

This work has helped to solidify the requirements for the design of shape-changing toolkits for designers. Such toolkits must easily integrate quickly and easily with existing tools and skillsets, be 'readily available' (i.e. immediately usable without detailed training), and even if complex APIs are provided, it's probable they will be subverted to better suit expertise.

ShapeClip is open-source and actively supported to encourage the wider community to engage with and improve upon its design; allowing anybody to turn a screen into a shape-changing display. It is our intention that the concept, open-implementation, and the results from our workshop will help encourage others to join an active and innovative shape-changing community.

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REFERENCES

1. Alexander, J., Lucero, A., and Subramanian, S. *Tilt Displays: Designing Display Surfaces with Multi-axis Tilting and Actuation*. in *MobileHCI '12*: ACM.
2. Bau, O., Petrevski, U., and Mackay, W. *BubbleWrap: A Textile-based Electromagnetic Haptic Display*. in *CHI '09*: ACM.

3. Bier, E.A., Stone, M.C., Pier, K., Buxton, W., and DeRose, T.D., *Toolglass and Magic Lenses: The See-through Interface*, in *SIGGRAPH '93:* ACM: p. 73-80.
4. Bull, C.N., Whittle, J., and Cruickshank, L., *Studios in Software Engineering Education: Towards an Evaluable Model*, in *ICSE '13*. IEEE Press. p. 1063-1072.
5. Ciesla, C.M. and Yairi, M.B., *User Interface System and Method*. 2012.
6. Coelho, M., Ishii, H., and Maes, P. *Surflex: A Programmable Surface for the Design of Tangible Interfaces*. in *CHI '08 EA*: ACM.
7. Coelho, M. and Zigelbaum, J., *Shape-changing Interfaces.* Personal and Ubiquitous Computing, 2011. **15**(2): p. 161-173.
8. Dimitriadis, P. and Alexander, J. *Evaluating the Effectiveness of Physical Shape-Change for in-pocket Mobile Device Notifications*. in *CHI '14*: ACM.
9. Follmer, S., Leithinger, D., Olwal, A., Hogge, A., and Ishii, H. *inFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation*. in *UIST '13*: ACM.
10. Gomes, A., Nesbitt, A., and Vertegaal, R. *MorePhone: A Study of Actuated Shape Deformations for Flexible Thin-film Smartphone Notifications*. in *CHI '13*: ACM.
11. Greenberg, S., *Toolkits and Interface Creativity.* Multimedia Tools and Applications, 2007. **32**(2): p. 139-159.
12. Greenberg, S. and Fitchett, C., *Phidgets: Easy Development of Physical Interfaces through Physical Widgets*, in *UIST '01*, ACM. p. 209-218.
13. Harrison, C. and Hudson, S.E. *Providing Dynamically Changeable Physical Buttons on A Visual Display*. in *CHI '09*: ACM.
14. Hartmann, B., Klemmer, S.R., and Bernstein, M., *d. tools: Integrated Prototyping for Physical Interaction Design.* IEEE Pervasive Computing, 2005.
15. Hemmert, F., Hamann, S., Löwe, M., Zeipelt, J., and Joost, G. *Shape-Changing Mobiles: Tapering in Two-dimensional Deformational Displays in Mobile Phones*. in *CHI EA '10*: ACM.
16. Hemmert, F., Hamann, S., Löwe, M., Zeipelt, J., and Joost, G. *Weight-Shifting Mobiles: Two-Dimensional Gravitational Displays in Mobile Phones*. in *CHI EA '10*: ACM.
17. Hippel, E.v., *User Toolkits for Innovation.* Product Innovation Management, 2001. **18**(4): p. 247-257.
18. Ishii, H., Lakatos, D., Bonanni, L., and Labrune, J.-B., *Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials.* Interactions, 2012. **19**(1): p. 38-51.
19. Iwata, H., Yano, H., Nakaizumi, F., and Kawamura, R. *Project FEELEX: Adding Haptic Surface to Graphics*. in *SIGGRAPH '01*: ACM.
20. JEDEC/ESDA, *Electrostatic Discharge Sensitivity Test - Human Body Model (HBM) - Component Level*. 2012.
21. Kajimoto, H., Suzuki, M., and Kanno, Y., *HamsaTouch: Tactile Vision Substitution with Smartphone and Electro-tactile Display*, in *CHI EA '14*, ACM p. 1273-1278.
22. Klemmer, S.R., Hartmann, B., and Takayama, L., *How Bodies Matter: Five Themes for Interaction Design*, in *DIS '06*, ACM. p. 140-149.
23. Kubitza, T., Pohl, N., Dingler, T., and Schmidt, A., *WebClip: A Connector for Ubiquitous Physical Input and Output for Touch Screen Devices*, in *UBICOMP '13*, ACM. p. 387-390.
24. Leithinger, D., Follmer, S., Olwal, A., Luescher, S., Hogge, A., Lee, J., and Ishii, H. *Sublimate: State-Changing Virtual and Physical Rendering to Augment Interaction with Shape Displays*. in *CHI '13*: ACM.
25. Leithinger, D., Lakatos, D., DeVincenzi, A., Blackshaw, M., and Ishii, H. *Direct and Gestural Interaction with Relief: A 2.5D Shape Display*. in *UIST '11*: ACM.
26. Nojima, T., Ooide, Y., and Kawaguchi, H. *Hairlytop Interface: An Interactive Surface Display Comprised of Hair-like Soft Actuators*. in *WHC '13*.
27. Oguchi, R., Kakehi, Y., Takahashi, K., and Naemura, T. *Photonastic Surface: Pin Matrix Type Display Controlled with Light*. in *ACE '08*: ACM.
28. Ooide, Y., Kawaguchi, H., and Nojima, T., *An Assembly of Soft Actuators for an Organic User Interface*, in *UIST Adj. Proc. '13*. ACM p. 87-88.
29. Parkes, A. and Ishii, H., *Bosu: A Physical Programmable Design Tool for Transformability with Soft Mechanics*, in *DIS '10*. ACM. p. 189-198.
30. Poupyrev, I., Nashida, T., and Okabe, M. *Actuation and Tangible User Interfaces: The Vaucanson Duck, Robots, and Shape Displays*. in *TEI '07*: ACM.
31. Rasmussen, M.K., Pedersen, E.W., Petersen, M.G., and Hornbæk, K. *Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions*. in *CHI '12*: ACM.
32. Roudaut, A., Karnik, A., Löchtefeld, M., and Subramanian, S. *Morphees: Toward High "Shape Resolution" in Self-Actuated Flexible Mobile Devices*. in *CHI '13*: ACM.
33. Schmidt, D., Molyneaux, D., and Cao, X. *PICOntrol: Using a Handheld Projector for Direct Control of Physical Devices through Visible Light*. in *UIST '12*: ACM.
34. Sugimoto, M., Kodama, K., Nakamura, A., Kojima, M., and Inami, M. *A Display-Based Tracking System: Display-Based Computing for Measurement Systems*. in *ICAT '07*.