Changing the Appearance of Physical Interfaces Through Controlled Transparency

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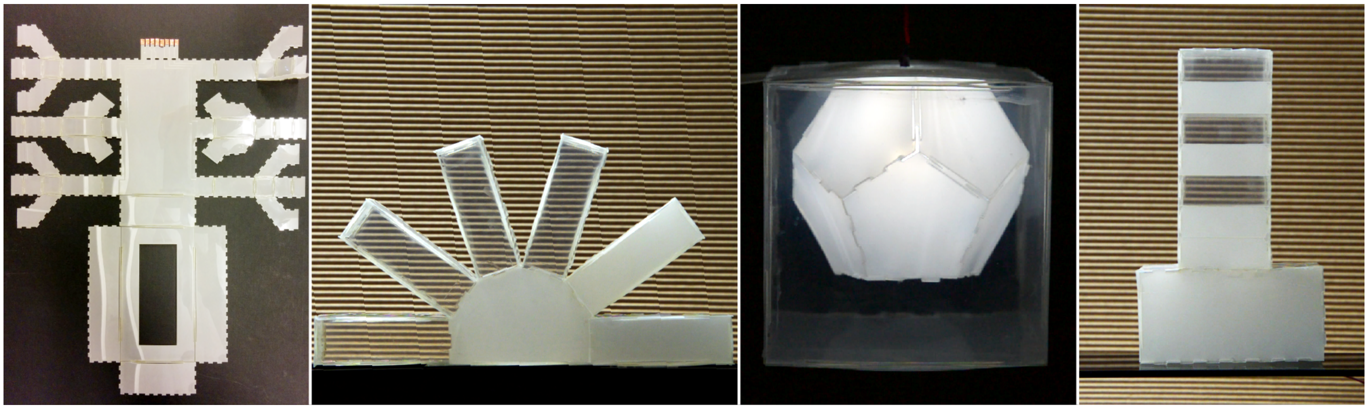

Figure 1. We create physical interfaces which alter their appearance through controlled transparency. This is achieved by cutting and folding objects from a single sheet of transparency-controlled material (*left*). Parts of an interface are controlled individually, resulting in *the illusion* of changed shape. We demonstrate multiple examples, such as a notification indicator (*2nd left*), an appearance changing lamp (*3rd left*) and a physical progress bar (*right*).

ABSTRACT

We present physical interfaces that change their appearance through controlled transparency. These *transparency-controlled physical interfaces* are well suited for applications where communication through optical appearance is sufficient, such as ambient display scenarios. They transition between perceived shapes within milliseconds, require no mechanically moving parts and consume little energy. We build 3D physical interfaces with individually controllable parts by laser cutting and folding a single sheet of transparency-controlled material. Electrical connections are engraved in the surface, eliminating the need for wiring individual parts. We consider our work as complementary to current shape-changing interfaces. While our proposed interfaces do not exhibit dynamic tangible qualities, they have unique benefits such as the ability to create apparent holes or nesting of objects. We explore the benefits of transparency-controlled physical interfaces by characterizing their design space and showcase four physical prototypes: two activity indicators, a playful avatar, and a lamp shade with dynamic appearance.

Author Keywords

dynamic appearance; transparency control;

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INTRODUCTION

Shape-changing interfaces adjust their physical shape to match users' desires and needs, for example for fulfilling functional or hedonic aims. Current devices such as shape-changing mobile phones (e. g. [9, 40]) or shape displays (e. g. [35, 23, 8]) are limited in the rate of change as well as the type of possible changes: speed is limited by physical constraints of the actuators; topological changes (e. g. creating holes) are difficult due to the limited ability of motorized interfaces to shrink in volume.

In this work, we introduce *transparency-controlled physical interfaces*. These interfaces change their *appearance* (i. e. perceived shape) by changing their transparency. This enables toggling the visibility of parts of objects for communicating information or for hedonic purposes. Transparency-controlled physical interfaces enable the *illusion* of changes in shape, volume, or the appearance of holes, as well as nesting of objects. Appearance changes rapidly (with our current implementation ~8 ms to turn transparent; ~80 ms to turn opaque) and does not involve any mechanically moving parts.

Prior work changed the optical appearance of interfaces through different types of augmentation such as see-through augmented reality [22] or projection mapping [27]. These approaches require tracking of a user's location for perspectively correct rendering of contents (e. g. the background) onto objects. Our approach requires no instrumentation since the ability for optical change is built into the device.

While transparency-controlled physical interfaces change their appearance (i. e. *simulated* shape change), they do not exhibit any dynamic tangible qualities. We see them as complementary to current shape-changing interfaces whose physical shape truly changes. We argue that by focusing on dynamic physical *and* optical properties, the space of possible interactions can be expanded. Transparency-controlled physical interfaces are well suited in situations where no tangible qualities are needed (e. g. user is distant to the device) and enable features challenging to achieve with other technologies such as creating apparent holes or nesting of objects.

We create appearance changing devices by laser cutting the desired shape from a single sheet of polymer-dispersed liquid crystal (PDLC) switchable diffuser. This material transitions between opaque and transparent rapidly when voltage is applied and requires very little energy. To create 3D objects, we cut and fold the switchable diffuser in an origami-like manner. We include hinges that support arbitrary angle bends to avoid breaking the electrical connection between individual faces.

Our aim is to create objects that are seamless and require no physical support such as frames, or additional wiring. We eliminate the need for external frames by incorporating snap-fit connectors into the design of the optically dynamic 3D elements. To control individual parts of an interface, we route voltage through channels that are engraved in the switchable diffuser. Engraving and cutting are performed in a single fabrication step. Manufacturing an object only requires laser cutting its shape, folding and connecting to a standard flat flexible cable (FFC) connector. No wiring or soldering is needed.

We demonstrate a semi-automatic method for creating transparency-controlled physical interfaces. Our software analyses a given crease pattern and automatically adds hinges and snap-fits. When the user positions the connector, our software automatically adapts snap-fits and hinge patterns. Creating individually controllable parts is done by marking the respective areas and drawing paths for routing.

We present four physical interfaces demonstrating our concept. We describe two different appearance-changing activity indicators: a vertical volumetric progress bar and a flower-shaped notification indicator with actuated leaves. By toggling individual parts, progress can be indicated, or certain appearances can be generated for hedonic purposes. We also present a playful bug-shaped avatar, with legs reacting to displacement and exhibiting apparent motion. The switchable diffuser wraps around and extends a computer mouse for creating the desired shape with included displacement measurement. Lastly, we created a dynamic lamp shade with 3 different appearances, shaped like a cube, a dodecahedron or a cone, nested within each other. These shapes can be toggled based on user's hedonic desires or for notifications.

Contributions

- We provide a conceptual addition to conventional shape-changing interfaces through transparency-controlled physical interfaces. We explore the design space of these interfaces to outline their benefits and challenges.
- We demonstrate a simple production process for creating 3D transparency-controlled physical interfaces through origami-like folding, with electrical routing being included in the created objects. They require no additional mounts or wiring and consume little energy.
- We present algorithms for semi-automatic generation of 3D transparency-controlled physical interfaces based on a given crease pattern.
- We showcase four physical interfaces demonstrating the versatility of our concept.

RELATED WORK

Changing optical apperance

Projection mapping allows changing the perceived shape and texture of objects through projected graphics. Raskar et al. [36], as an early example, developed Shader Lamps, which virtually enhances 3D objects through projected textures. In general, this is referred to as spatial augmented reality (cf. [2]). Inami et al. [14] used retro-reflective projection for camouflaging objects. Iwai and Sato [17] rendered objects on a desk transparent by projecting underlying contents onto them. Projection mapping requires calibration and background compensation (e. g. [10]). Furthermore, to create 3D effects that work for more than one viewpoint, the position of a user has to be tracked. This, however, usually only works for a single user. These techniques are used for example to increase immersion (e. g. [19]) or in installations (e. g. [4]).

Besides projection mapping, researchers changed the optical appearance and properties of objects with a variety of other techniques. Alexa and Matusik [1] fabricated objects with different microstructures that yield appearance changes under different viewing angles. Schüller et al. [41] created viewport-dependent bas-reliefs. Olberding et al. [32] created PrintScreen, which can be used for augmenting objects with printed displays. Furthermore, there is a large body of work on controlled surface reflectance (bidirectional reflectance distribution function, BRDF, e.g., [7, 13, 28]). This allows creating objects with dynamic surface properties.

In contrast to our work, most aforementioned approaches are not able to render an object transparent. Simulating transparent surfaces with projection mapping requires techniques such as projecting a video of the environment onto the object. Even then, though, image quality (e. g. contrast, latency) would potentially be too low for creating a high quality illusion of transparency. Our approach does not require any instrumentation or tracking, since it allows altering an object's transparency independent of viewing position, and also does not require any image representation of the background.

Shape-changing interfaces

Shape-changing interfaces alter their physical shape for fulfilling a variety of aims, such as functionality (e. g. communication [12], dynamic affordances [8]), hedonic aims (e. g. aesthetics [46]), or for exploration (cf. [16, 38]). Different strategies have been used to achieve these aims. With PneUI [46], the shape of objects is altered with pneumatics for functional (e. g. a game controller) or hedonic aims (e. g.

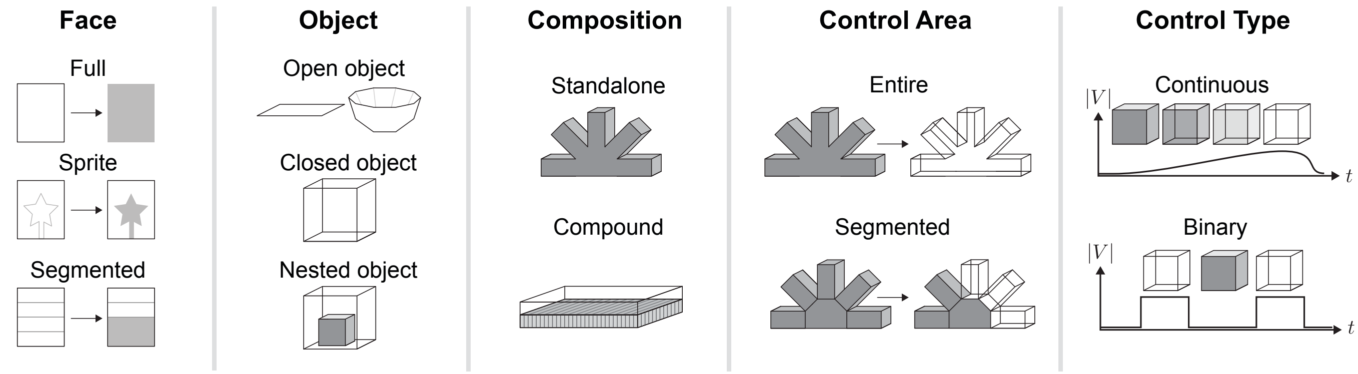


Figure 2. Design space for transparency-controlled physical interfaces. Gray areas indicate opaque state, dashed areas indicate external objects.

shape-changing lamp). Shape displays can be used as input and output devices as well as for remote collaboration and telepresence (e. g. [35, 24, 8]). Olberding et al. [31] created shape-changing devices with printed electronics through folding. With Shutters, Coelho et al. [3] created holes in a surface for applications in architecture using shape-memory alloys. For other technologies (e. g. motorized interfaces, pneumatics), creating holes is challenging to achieve (cf. [38]).

In previous work, we proposed an approach combining physical and optical changes. We enriched shape-changing interfaces with spatial augmented reality for extending the space of appearances of actuated interfaces [27]. This work also aims at creating interfaces that can dynamically alter their appearance. Our work focusses on the *illusion* of altering an object's appearance. Dynamic behavior is purely optical, yielding no dynamic tangible qualities. This makes our approach suitable e. g. for distant interaction and complementary to work on existing shape-changing interfaces.

Transparency and transparency-control

In HCI, transparency and transparency control have so far mostly been used for display technologies as well as for architectural purposes. Transparent displays such as Clearboard [15], the work of Olwal et al. [33, 34] on Fogscreens, SpaceTop [21], HoloDesk [11] and Facingboard [25] focussed on interaction, communication and collaboration. With Tracs, we introduced the idea of transparency-controlled see-through displays [26], controlling the transparency of specific areas of a see-through display. Rekimoto [39] developed programmable physical architecture, where areas of a wall can be toggled between transparent and opaque. Danninger et al. [5] created Attentive Office Cubicles, which change their state from opaque to transparent when users on both sides of a cubicle choose to interact with each other. Kakehi [20] created ”transmart minispaces”, an installation that resembles a multi-layer display. In this paper we focus on creating transparency-controlled objects rather than displays or architecture.

In our work, we use switchable diffuser as our technology of choice to demonstrate the capabilities and potential of transparency-controlled physical interfaces. The material's ability to change transparency has priorly been exploited by a variety of work, such as Attentive Cubicles [5], Squama [39], Tracs [26] and SecondLight [18].

TRANSPARENCY-CONTROLLED PHYSICAL INTERFACES

In this section, we describe the design space of transparency-controlled physical interfaces. We take inspiration from previous work on shape-changing interfaces [27, 30, 38, 40] and non-traditional displays [32].

We develop the design space with respect to materials such as switchable diffuser, which means objects are composed of individually controllable planar pieces. While our implementation focuses on objects created from switchable diffuser, we believe the design space generalizes to other technologies that allow rendering parts of an object transparent, such as flexible transparent displays. Therefore, we consider our design space as largely technology agnostic. It aims at providing insights into capabilities and potential challenges of transparency-controlled physical interfaces.

We identified five dimensions that serve as a foundation for designing transparency-controlled interfaces, see Figure 2, i. e. face, object, composition, control area, and control type.

Face

A face is an individual side of a transparency-controlled object that can change its overall transparency. Objects are typically composed of multiple faces. Groups of faces can be controlled simultaneously.

By including iconic shapes in a face, predefined *sprites* can be toggled, shown in Figure 2 and Figure 3. Thus, not only the appearance of an object but also icons on the surface can be used for communication and information. Sprites can also be used to render apparent holes (e. g. users can see through the engraved star in Figure 3).

Furthermore, a face can be visually subdivided by *segmenting* it. Thus it can appear to be smaller or larger (as shown e. g. in Figure 1, 2 and 5), depending on the state of the segments.

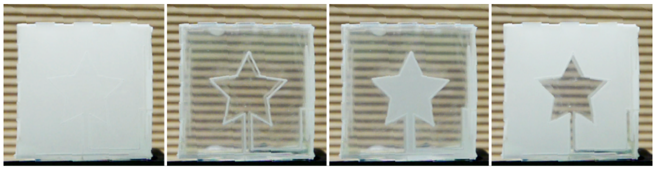


Figure 3. A cube with an engraved sprite (star) in all 4 possible states.

Object

Objects are typically composed of multiple faces. We distinguish between 3 types of objects.

Open objects

Open objects do not enclose a volume, e. g. planes or the open bowl illustrated in Figure 2. Switchable diffuser, in its original shape, is a planar sheet with limited bending capabilities. It can be used as-is and included as individual surfaces in other physical interfaces (as *compounds*, discussed below). Open objects also allow creating transparency-controlled objects that serve as *containers*. For example, a transparency-controlled medication box could turn transparent at specific times to remind users about taking their medication.

Closed objects

Closed objects enclose a volume, e. g. the cube in Figure 3. We create 3D objects through cutting and folding, which allows us to create relatively complex transparency-controlled objects (e. g. our flower-shaped progress indicator consists of 41 individual faces). The complexity of the objects with our current origami-like manufacturing process is limited by a minimum size of planar pieces. Keeping manufacturing in mind, folding objects with a side length smaller than 1 cm is challenging and the hinge patterns cut in the material decrease visual quality. Furthermore, while it is theoretically possible to create highly complex shapes through origami (cf. [6, 45]), human folding capabilities are typically limited. Objects can also include hingeless bends if supported by the material.

Nested objects

One key feature of transparency-controlled objects is the ability of *nesting*: Smaller objects can be included *within* larger ones and revealed through toggling the enclosing object's transparency. This is typically not available or challenging to achieve for other types of physical interfaces. Figure 4 shows an example of three nested cubes. Nested objects can be used for switching between appearances (e. g. between a cube and an enclosed pyramid), e. g. for representing iconic shapes. For us, while a nested object appears to be composed of multiple objects, they share the same surface since they are created from a single sheet of material. Thus, we see them as an addition to open and closed objects.

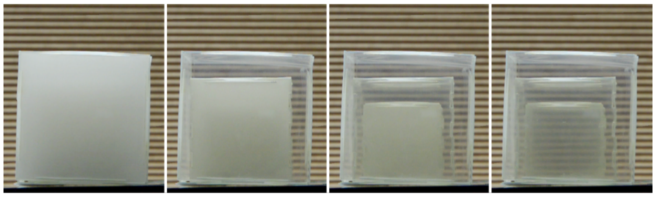


Figure 4. A nested object consisting of three cubes.

Composition

We refer to a composition as the final transparency-controlled interface, which is built from one or more faces and can be described as open, closed or nested. A composition can be created purely as transparency-controlled interface (*standalone*), or as a *compound*. A compound is a regular object (physically static or dynamic), enriched with one or more transparency-controlled objects.

One example of a compound composition is the actuated mobile phone shown in Figure 5. We adopted interactions typical for these devices (e. g. actuated flaps for notification, cf. [9, 40]) and extended it with a segmented transparency-controlled top surface. Including transparency-controlled segments into objects allows rendering features such as holes, for example for applications such as tracing objects underneath a device (e. g. Glassified [43]). By controlling the transparency of parts of a compound object, interior parts can be hidden or revealed (e. g. for privacy or hedonic purposes), or users can see through objects. This enables applications such as teaching mechanical functionality by revealing the inside of a priorly opaque device.

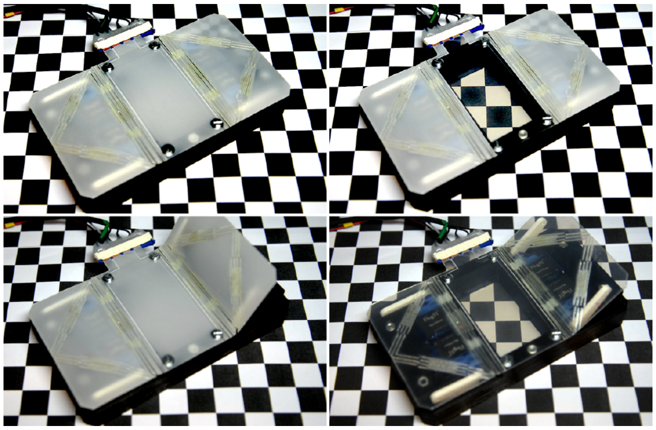


Figure 5. A shape-changing mobile phone with a transparency-controlled top surface (inspired by [37, 27]), modified to omit components in the center of the device; *top left*: base state, *bottom*: actuated state. Individual parts can be turned transparent (*right*).

Control area

We can control the entire surface of an interface, for example to reveal it only when needed. Furthermore, transparency-controlled interfaces with multiple controllable parts can be created for enlarging the space of possible applications and increasing expressivity (e. g. Figure 13). Controllable parts can be individual or segmented faces or larger areas (multiple connected faces) of an object. For nested interfaces, the individual objects can be toggled to reveal interior objects (e. g. as in Figure 15).

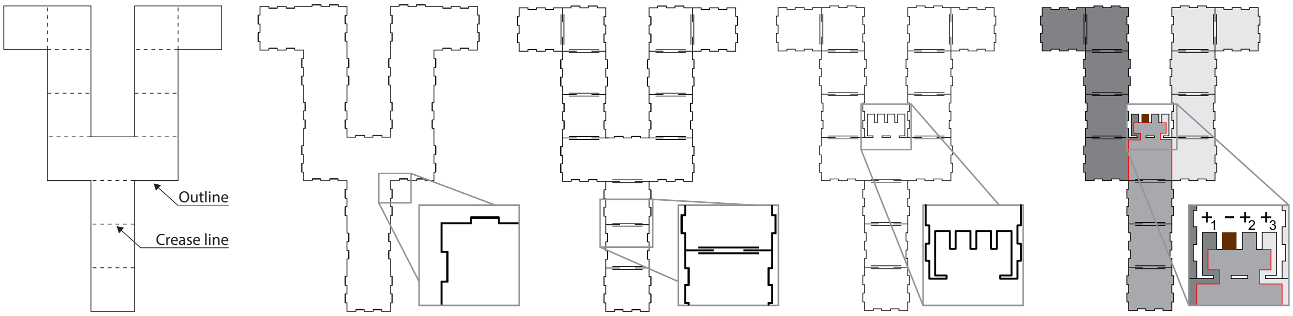
Control type

Binary optical change

Switching transparency-controlled physical interfaces can be performed very rapidly, since the change is purely optical. This enables effects such as apparent motion. Negative effects of mechanical motion such as oscillations around a target position are avoided. Such switching speeds can be exploited for different applications, e. g. fast reaction to changes in underlying data for data visualization.

Continuous optical change

Besides binary switching, transparency-controlled physical interfaces can change their appearance continuously and arbitrarily slow. This allows changing the appearance potentially even without users noticing it in their peripheral vision and can be exploited, for example, for unobtrusive peripheral display applications.



Input crease plan Snap generation Hinge pattern generation Connector Routing

Figure 6. Our process for creating laser cut plans for 3D transparency-controlled physical objects from an input crease plan (*left*). We generate snap-fits for connecting edges, and hinge patterns to allow for bending without breaking the electrical connection. Thereafter, the connector and the electrical routing is added. Red lines in the right image indicate cutting only one layer of ITO for separating the individually controllable surfaces. Gray areas indicate individually controllable areas. The resulting 3D object, a box with 3 controllable multi-face parts, is displayed in Figure 11, *right*.

IMPLEMENTATION

In this section, we describe the creation of transparency-controlled physical interfaces. Software and hardware are available as open source at *http://www.cg.tu-berlin.de/research/projects/transparency-controlled-physical-interfaces/*.

Base material and individually controllable surfaces

We use PDLC switchable diffuser (Kewei Films Non-Adhesive Smart Glass) for creating 3D objects. The material consists of two layers of transparent conductive film (indium tin oxide, ITO) with polymer dispersed liquid crystals in-between and an insulating layer on the outside (see Figure 7). In default state, switchable diffuser scatters incoming light and thus looks diffuse. When voltage is applied (60 VAC), it turns transparent (90% parallel light transmittance according to specification). We control switchable diffuser using custom circuitry (a combination of optocoupler and triacs, connected to shift registers). This allows for rapid toggling with low energy consumption (~10 mA/m^2 in transparent state, no power consumption in opaque state). Our current material exhibits switching speeds of ~8 ms to turn transparent and ~80 ms to turn opaque. PDLC, in transparent state, acts like a capacitor, resulting in lower switching speed from transparent to opaque. Different circuitry can decrease switching speeds (e. g. as in SecondLight [18] to 8.3 ms symmetrically). It can also be continuously controlled by varying the input voltage (e. g. applying 20 VAC results in less transparency than 40 VAC; approx. linear change). We control this through potentiometers in a voltage-divider circuit.

For applying voltage, the two layers of ITO have to be wired on the inside (ITO only conducts on the inside because of the isolating PET layer, see Figure 7). To create multiple controllable surfaces on a single object, we separate one ITO layer (top layer in Figure 7) and wire the resulting sides separately. The layer on the opposite side remains intact serving as a common electrode. This process is similar to Tracs [26], however, we eliminate additional wires through engraving routes directly in ITO. This simplifies production and improves the visual clarify of objects, since our method results in less constantly transparent areas than for Tracs. Furthermore, external wiring of nested objects is not always feasible.

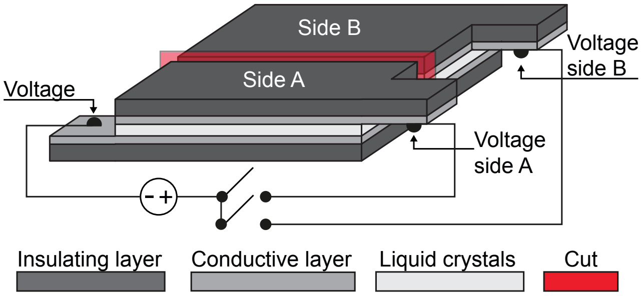


Figure 7. We separate individually controllable surfaces by cutting through one conductive layer. This allows us to control them separately, here side A and B. The cut (red) only goes through the top insulating and conductive layer, leaving the lower part (common electrode) intact.

3D objects from switchable diffuser

We decided to use an origami-like folding technique for creating 3D objects to avoid using external frames and to create objects that have few seams.

Folding

We describe our process as ”origami-like”, since classical origami starts from a rectangular piece of paper and does not allow additional cuts. Furthermore, we add snap-fit connectors to edges and partly disconnect individual pieces through cutting. This avoids overlapping faces (typical for traditional origami created from a single sheet), which would reduce the transparency of objects.

Processing

Processing to create a foldable 3D objects from switchable diffuser is a four step process, see Figure 6 for an overview. We describe the steps in the logical order of the processing pipeline. Processing starts with an input crease pattern, created in e. g. Adobe Illustrator or specialized software.

Snap connectors: We first alter the outline of the input crease pattern to include snap connectors. This is done automatically in our custom software, described later. The snap connectors allow for connecting faces after folding to obtain objects which do not require additional frames. Figure 8 shows the cut switchable diffuser with snaps as outline and the resulting folded cube.

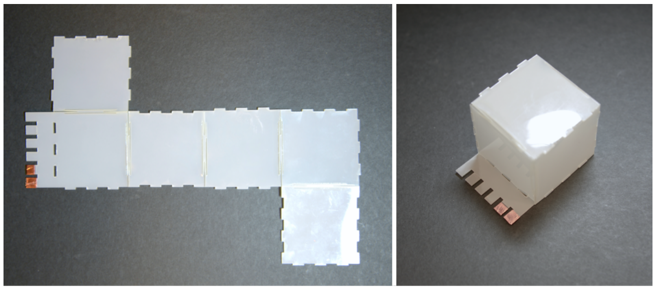


Figure 8. Left: laser cut folding pattern; right: the resulting object.

Hinges: In the next step, hinges are added, which are essential for creating foldable objects. The hinges are laser cut patterns (*hinge patterns*), yielding different bending properties. This solution was inspired by classical engineering, which refers to this as living hinge. If switchable diffuser is bent without cutting the hinge patterns, it exhibits large bending stiffness and the tension in the bend regions pushes the liquid crystals away, creating always-transparent parts. Further, the ITO layer is only $15\,\mu\mathrm{m}$ thin and sensitive to bending for radii smaller than $4\,\mathrm{cm}$ with angles $> 90°$.

To overcome this problem, we tested different hinge patterns, yielding different corner radii and bending stiffness, see Figure 9. A sharp edge is created with a single pattern consisting of 4 cuts (Figure 9, top left), which allows for arbitrary bend angles. Importantly, this pattern does not break the electrical connection in the ITO, since it relieves stress from the material. This allows creating 3D objects that retain their ability to change transparency. Other hinge patterns are used to create objects with different corner radii. We use patterns yielding low bending stiffness (Figure 9, *right*) for creating nested objects, which oftentimes require $180°$ bends with low bending stiffness.

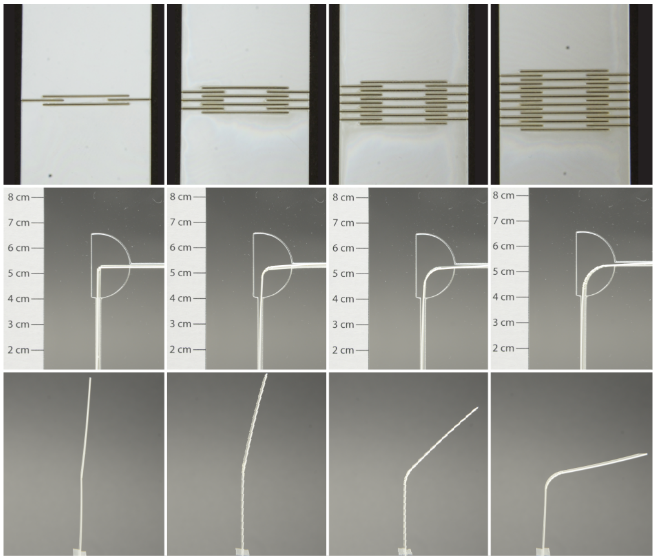


Figure 9. Corner radius (center) and bending stiffness (bottom) depend on the crease pattern (top).

Beside bend angle and radius, also the number of electrical routes has to be taken into account when designing hinges. Standard hinge patterns, as discussed above, only allow for a maximum of 2 routes. By further dividing hinges in multiple parts, more routes can be added, as illustrated in Figure 10.

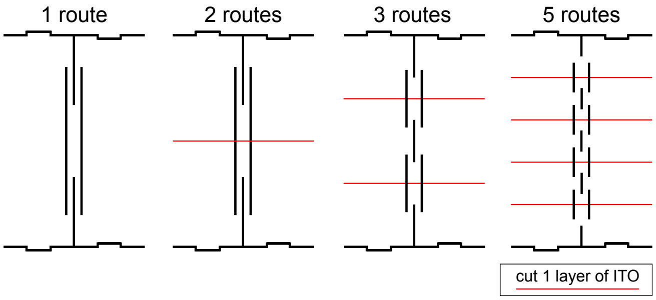


Figure 10. Crease patterns are adapted to number of routes. Each cut separates two individually controllable areas (or *channels*).

Connector: We add a ”connector” to the switchable diffuser (see Figure 8). The connecter is manually positioned by users in our custom software. The connector fits a standard FFC press-fit connector, thus no soldering is needed. Since the FFC connector conducts only from one side, we wrap conductive copper tape around the laser cut pins to control the individual parts of the object. This also increases the durability of the object's laser cut connector.

Routing: Routing includes both disconnecting specific faces from the overall object and adding channels, which are disconnected areas ranging from those faces to the connector. This is done by removing one layer of ITO, as described earlier. From a practical side, the channels which arise from cutting can be 1 to $2\,\mathrm{mm}$ thin. Routing is performed for creating segmented objects as well as for creating sprites.

Software

Our custom software assists users in converting input crease patterns to laser cut plans (see Figure 11). It automatically creates the snap outline and hinge patterns which are adapted to the routing. The software is developed in C++ with openFrameworks[1] for GUI and boost[2] for data structures and algorithms (e. g. boolean operations, polygon orientation correction).

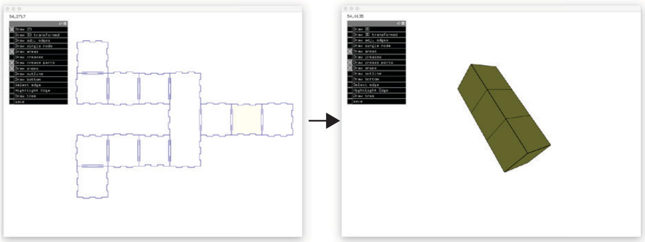


Figure 11. Our software converts a crease plan to a laser cut plan (*left*). It also features an automatic 3D preview of objects (*right*).

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[1] openFrameworks v0.9.0: http://openframeworks.cc/

[2] Boost C++ Libraries: http://www.boost.org/

Input

Our software takes a crease pattern as input (svg file). We opted for starting our processing pipeline after modeling the crease pattern, since there are specialized tools for creating origami patterns that feature semi-automated unfolding of 3D shapes (e. g. [31, 44]), as well as tools such as Adobe Illustrator with origami plugins (e. g. Boxshot Origami[3]) for preview that offer a rich set of controls. Our presented objects were modeled with Adobe Illustrator and Boxshot Origami.

The input contains an outline as well as crease lines, annotated as dashed stroke patterns (see Figure 6, left). By default, all crease lines represent bend angles of 90° in our 3D preview. Custom angles for individual crease lines can be specified by changing the name of the object's layer in Illustrator to the desired angle. The input includes an outline, which is a 2D polygon $S = (s_0, s_1, \ldots, s_{n-1}), s_i \in \mathbb{R}^2$. Further, it contains a list of creases $C = (c_0, c_1, \ldots, c_{m-1}), c_j \in \mathbb{R}^2 \times \mathbb{R}^2$, with each crease consisting of two points $\{c_{j,0}, c_{j,1}\}$ located on the outline $c_{j,k} \in S$ (see Figure 6, *left*).

Preprocessing

For creating the snap outline and the 3D preview, we first divide the outline into multiple areas (i. e. the faces of an object which are polygons enclosed by creases and the outline) based on the crease lines. These areas form a tree structure which we use for creating the 3D preview (hierarchical 3D transformation). Furthermore, this provides us with information which edges overlap when the object is folded. We use the available geometric information to determine areas.

For finding areas, we first visit all vertices s_i and sort all outgoing edges (including creases c_j) which contain s_i based on their outgoing angle. We then iterate through all crease endpoints $c_{j,k}$ and follow the outgoing edges (always taking the path of the smallest angle with respect to the incoming edge) until we reach the start point $c_{j,k}$, i. e. the path formed a cycle. This method gives us all areas (i. e. the edges of connected components) for the outline S and its creases C.

We use this information for generating a snap outline that alternates correctly between male and female connectors.

Snap outline generation

For generating the snap outline, we successively visit all edges e_i from S where $e_i = \{s_i, s_{i+1}\}$. Each edge is divided into an uneven number of sub-edges (3 to 7, depending on the length of the crease), which gives us a list of sub-edges of $e_i = (e_{i,0}, e_{i,1}, \ldots, e_{i,a-1})$. Each sub-edge of e_i is assigned to be either a hill or a pit, in an alternating manner. For hills, the sub-edge is shifted along the normal for a distance d. Pits are shifted in the opposite direction with the same distance. We chose d to be 1.2 mm, which approximately reflects the thickness of the switchable diffuser and allows for a good fit when snapping overlapping edges.

Next, we generate the overall snap outline with the aim of retaining corner positions to ensure good fit when folding an object. Each edge e_i is assigned to be hill-first or pit-first in an alternating manner, see Figure 12. A naïve approach would be to perform simple shifting of pits and hills. This, however, would shift the overall outline S, specifically on corner points (Figure 12, left), which negatively influences the folded object's fit. Thus, we change the snap generation to be *outline corrected*. For hill-first edges, only the sub-edges with pits are offset, whereas hills remain on the outline. Conversely, for pit-first edges, only hills are offset from the outline.

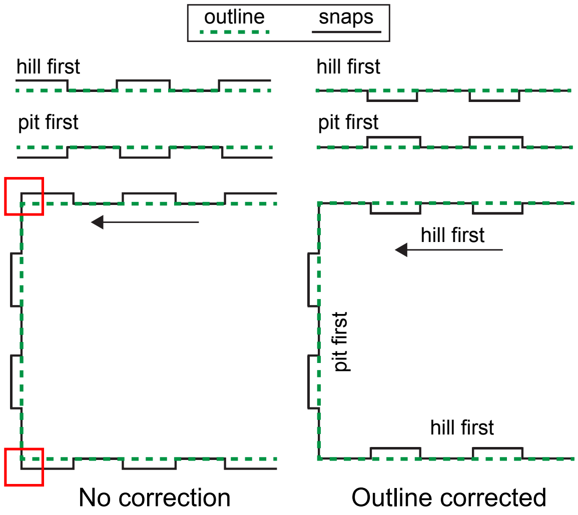

Figure 12. Without correction (*left*), the outline is shifted on corner points (marked with red squares), resulting in decreased fit when building objects. Outline correction (*right*) resolves this issue.

Hinge generation

The hinge patterns (illustrated in Figure 9, top) are created at the position of the crease lines. Initially, a standard hinge pattern (Figure 9, top left) with four cuts is created. Users then specify the position of the connector and indicate which areas they want to control by grouping faces. This allows us to automatically split hinge patterns according to the number of routes going through each hinge (see Figure 10).

Routing

We opted for a manual routing process, which basically consists of drawing paths on the crease pattern. This allows users to influence the optical appearance of routes, e. g. to be inconspicuous, *as well as* to create sprites on individual faces, based on the desired design. In the future, we would like to include automatic routing, e. g. as in Foldio [31].

APPLICATIONS

We built four prototypes to explore the potential of interfaces that can change their appearance through controlled transparency. All of them were built from a single sheet of switchable diffuser using our described technology. The prototypes serve as demonstrators for three different applications, i. e. as ambient activity indicators, as a playful moving avatar, and as a lamp shade with dynamic appearance.

Activity indicators

We created two different prototypes of ambient activity indicators, shown in Figure 13. Firstly, we built a vertical progress bar that is used for indicating activity (e. g. download progress). We also explored using it as an indicator of

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[3] Boxshot Origami plugin: http://boxshot.com/origami/

available hard disk space on peripherals such as USB drives. The amount of available disk space is indicated by the height of the indicator, i. e. little space used results in a lower height.

Secondly, we constructed a flower-shaped activity indicator. The individual leaves are toggled for indicating notifications. Furthermore, the appearance of the flower can be changed for hedonic purposes. When the indicators are not needed, they can be turned fully transparent, so that they effectively blend into the environment.

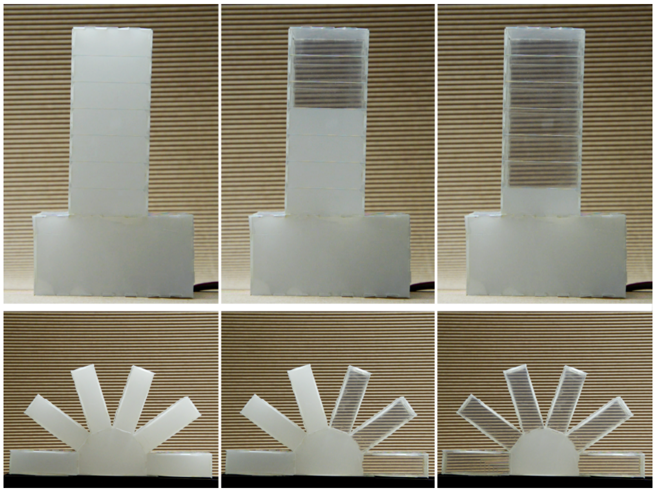

Figure 13. Our prototypes of progress and activity indicators.

Moving avatar

We created a playful bug-like avatar (see Figure 14). Its body is a cuboid with six legs, each of which can be controlled individually. We included a regular computer mouse in the inside of the avatar for tracking displacement. Groups of legs are turned opaque in sequence. By toggling the transparency of the legs in sync with tracked motion, the illusion of the avatar moving on the ground arises. This demonstrates that, although the avatar does not have any actuated or moving parts, its physical appearance can be extended by perceived motion.

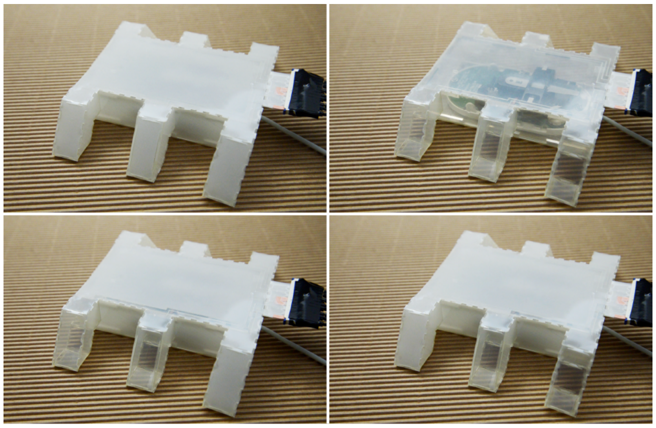

Figure 14. A bug-like avatar with transparency-controlled legs. Transparency of legs is toggled depending on the current velocity to create the illusion of motion.

Appearance-changing lamp

We created a lamp that can change its appearance. The lamp is a nested object composed of a cone inside a dodecahedron inside a cube, shown in Figure 15. All these layers can be individually switched or continuously controlled. This nesting of objects, as described earlier, is achieved by folding a single sheet of switchable diffuser. While it serves mostly hedonic purposes in its current state, it is easily imaginable to encode information in the different states. By rhythmically pulsing one of the layers, thereby effectively altering the lamp's perceived volume, users could be informed of notifications or activities happening in their environment.

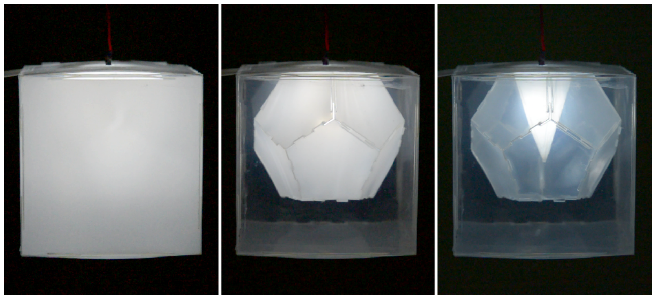

Figure 15. The appearance of the lamp can be switched between cube, dodecahedron and cone.

DISCUSSION

Changing the appearance of physical interfaces through controlled transparency has a number of benefits when compared to mechanically-actuated interfaces. It is very fast and we do not believe that rapid changes would startle users. Since no mechanical parts are involved, transparency-controlled interfaces are less prone to wear and tear (life time specified as >10 years by manufacturer and we have not observed any wearout of hinges through repeated bending) or other mechanical challenges. They perform changes silently, and use very little energy. Our proposed interfaces allow performing changes that are typically difficult to achieve with shape-changing interfaces such as creating apparent holes (cf. [38]) or nesting. However, other challenges and limitations arise.

Tangible qualities

Foremost, since change is solely optical, no dynamic tactile qualities are present. This is one of the main benefits of shape-changing interfaces, and we sacrifice it for the aforementioned benefits. However, as we have shown in our example of equipping a shape-changing device with transparency-controlled parts (see Figure 5), the technologies are complementary rather than mutually exclusive. We believe our work provides researchers in the field of shape-changing interfaces with a new tool that can be beneficial in many situations, as showcased in our applications. By including materials with shape-changing properties (e. g. shape-memory alloys or hydrogels), we plan to combine the benefits of both worlds in the future. As an example, hydrogels as used in GelTouch [29] can change their viscoelasticity and simultaneously change from transparent to opaque. Switching, however, takes far longer than changing transparency with switchable diffuser. Furthermore, hydrogel needs to be sealed in compartments, increasing its (already high) production complexity. We plan to explore this technology in the future.

Base material & transparency

We use PDLC switchable diffuser because of its fast switching speeds and good visual clarity in transparent state. Electrochromic materials, as a potential alternative, require less voltage but typically exhibit longer switching times. Another alternative are LC shutters and transparent LCDs, which also require less voltage for state switching (3-5 VDC). However, since they do not allow for laser cutting or folding, they are less suited for creating 3D objects. Switchable diffuser is well suited for objects with dynamic transparency.

PDLC switchable diffuser, however, is prone to reduced transparency for oblique viewing angles. This could be resolved by using a different type of diffuser such as suspended particle devices, which use particles rather than liquid crystals, cf. [42, p. 14-26]. Nesting objects had a less deteriorating effect on perceived transparency, at least for the objects we tested (e. g. three layered cubes, resulting in 6 layers overall). Transparency decreased from 90% (1 layer) to approximately 50% (6 layers). We believe that future generations of switchable diffuser will have increased transparency (close to 100%), especially since the prime use case for this material are dynamic window blinds. Using switchable diffuser also allows us to not rely on external wiring for toggling of individual parts. By incorporating the separation of individual controllable parts directly in the manufacturing process of the switchable diffuser, we believe we will also be able to remove current artefacts originating from laser cutting.

Software

Our software currently automates generating the snap outline and hinge pattern generation. These are the most time consuming aspects when creating transparency-controlled 3D objects from a given crease pattern. While routing could be performed automatically (e. g. as in Foldio [31]), our manual process allows users to take visual clarity into account (e. g. not routing through the middle of a face) and allows for creating sprites. Routing is always a tradeoff between the number of possible individually controllable parts and visual clarity. The number of routes increases linearly with the number of individually addressable faces. Therefore, having a large number of faces on small objects potentially deteriorates visual clarity. Adding a higher degree of automation to our software, including different modes for manual and automatic routing, will be subject of future work.

Why transparency?

Applications like the progress indicator could be made with non-traditional display technologies such as PrintScreen [32], too. By changing the color for individual areas, progress indication could also be achieved. This would, however, always result in the perception of two or more distinct areas on the same object, depending on the current color configuration. We argue that by creating transparency-controlled objects, unwanted parts of the interfaces can be hidden. We envision that users always only see the parts of the object that are needed to resemble a specific appearance. Hidden parts blend into the environment. This strengthens the illusion of a specific appearance and avoids that users perceive multiple objects when there should really only be one.

Transparency-controlled physical objects share some of their capabilities with volumetric or stereographic displays. In contrast to these displays, however, transparency-controlled physical interfaces feature digital enrichment on an *object level*. This means that the optically dynamic elements are tightly integrated into objects, essentially forming their outer hull. Aforementioned displays typically are planar (stereoscopic displays), or spherical or cubic shaped (volumetric displays) and are used for general-purpose rendering of contents. While they have benefits in terms of display capabilities, they cannot be tightly integrated into other objects.

We think that our work is complementary to current work on dynamic physical interfaces. It offers benefits in speed, power consumption and ability to render certain features that can be a valuable addition to physically dynamic interfaces. Furthermore, transparency-controlled physical interfaces allow rapid toggling as well as continuously changing transparency of individual parts. This additional temporal dimension potentially offers a range of novel behaviors, such as smooth transitioning between nested objects. For mechanically actuated physical interfaces, change is always continuous, whereas our proposed interfaces allow switching between shapes in a discrete manner. We believe that these temporal aspects and their in-depth investigation would result in interesting future applications of transparency-controlled physical interfaces. Lastly, our objects do not incorporate sensing capabilities, therefore rely on technologies such as camera-based interaction or manual activation for input. By including sensing capabilities such as capacitive touch (e. g. through additional layers of ITO on the outside of the diffuser), we think a transparency-controlled physical interface can serve as both, input and output technology.

CONCLUSION

We presented transparency-controlled physical interfaces, which can change their appearance purely through optical alteration. We built prototypes of such objects from a single sheet of switchable diffuser through origami-like folding techniques. Individual parts of objects can be controlled separately by engraving necessary routing directly in the switchable diffuser, eliminating the need for external wiring. We believe our proposed method is complementary to mechanically actuated interfaces and offers unique benefits in switching speed, rendering capabilities (e. g. holes, nesting) and energy consumption.

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