Designing Line-Based Shape-Changing Interfaces

Envisioning a future in which shape-changing lines are woven into our daily lives, the authors explore a broad research space around line-based shape-changing interfaces, encouraging researchers and designers to further investigate this novel direction for human-computer interaction.

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Shape-changing interfaces have gained prominence in recent years in the field of human-computer interaction (HCI). These interfaces transform their physical shape to display information in 3D and adapt to user interactions. Researchers are exploring a variety of actuation techniques to realize the goal of creating physical interfaces that can transform into any kind of shape, inspired by pixels in screen-based displays. In addition, researchers have presented various types of shape-changing interfaces, composed of a variety of forms and geometric shapes,[1] including points,[2] surfaces,[3] and solids.[4] However, *lines* have not been explored in depth as a general form for shape-changing interfaces.[5,6]

Given the versatility of lines in various contexts and their adaptability in physical form (see the "Exploiting Lines" sidebar), lines have the potential to expand the interaction landscape of shape-changing interfaces. For example, the potential transformation capability of a line could be critical for shape-changing interfaces that aim to render different kinds of shapes. Also, the expressiveness of lines can replicate physical wire frames or iconic shapes to physically convey digital information to users. In addition, the inherent affordances of lines as a common material could provide a variety of tangible opportunities for users to seamlessly interact with complex digital environments. Finally, the customizability of lines in terms of length and configuration could expand the scalability and adaptability of shape-changing interfaces.

Our approach offers a unique perspective, illustrating how the use of lines could expand the interaction design space and increase the applicability of shape-changing interfaces in our daily lives. Here, we outline existing research directions for line-shaped interfaces and discuss enabling technologies across different fields. We also attempt to advance future research by comparing potential implementations and presenting an interaction design space for actuated-line interfaces, encouraging researchers and designers to explore the implementation, interaction design, and potential applications of line-based shape-changing interfaces.

Line-Shaped Interfaces

Researchers across various fields have proposed systems for physical shape-changing lines.

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Exploiting Lines

The *line* is a form that is primitive yet versatile. It can transform into curves, surfaces, and solid shapes. Furthermore, it is a familiar form that we encounter in everyday life as string, tape, or wires, providing various tangible interactions—including knotting, wrapping, tying, and connecting. Lines are also used to represent abstract information, from their use in ancient drawings to their current use to compose digital geometrical models through wireframes. The form of the line is also characterized by its ability to be separated and recombined; string or tape can be cut and rearranged to create various shapes and configurations.

HCI: Actuated-Line Interfaces

In the field of HCI, researchers have presented actuated-line-shaped interfaces for various applications. Several interfaces have been proposed to physically display and manipulate 3D curves for computer-aided design (CAD). SATIN is a haptic system that can render smooth curves of digital data by bending a flexible spline with motors (see Figure 1a).[7] AR-Jig is a handheld device comprising an array of actuated pins that can render digital curves (see Figure 1b).[8] Haptic Snake is another handheld device that uses a snake-robot mechanism to represent shapes of digital models in a space.[9] Actuated lines have also been transformed into a faucet to convey water usage (see Figure 1c)[10] and embedded into a mobile device to communicate emotion (see Figure 1d).[11]

Soft and light actuation techniques have also been presented to enable comfortable tangible interaction and mobile applications. Pneumatics were introduced to develop curling transformations (Figure 1e).[12] Shape memory alloys have been used for life-like motions.[11] These different techniques are discussed later in the article.

Shape-Changing Lines in Other Fields

Although its presence has been small in HCI, serpentine robots[13] have long been an area of active research (Figure 2a).[14] These robots often use a linear series of one-degree-of-freedom (DOF) actuators to create motion or gaits similar to that of snakes. Soft robotics techniques, such as pneumatic composites,[15,16] have also been explored to achieve high DOF transformations with fewer actuators (Figure 2b and 2c).

With the goal of developing programmable matter, other researchers have explored the abilities of snake robots and shape-changing materials to create different shapes, similarly to how proteins can fold into complex patterns. Ara Knaian and his colleagues proposed the concept of "milli-biology" to explore hardware composed of chained actuators and algorithms to create arbitrary shape from a single line (Figure 2d).[17] Skylar Tibbits presents the idea of 4D printing in his research, including transforming lines using 3D printed multimaterial lines (see Figure 2e).[18] Because the primary goal of these research efforts is to develop technology that can create various shapes, there are several limitations for real-time interaction, such as the transformation speed and ability to sense user interaction.

LineFORM and ChainFORM

Building on previous work, we explored an interaction design space with line-based shape-changing interfaces using prototype hardware based on serpentine robotics; we call this work LineFORM and ChainFORM.

In the LineFORM project, we aimed to seed a new direction of research for line-based shape-changing interfaces with two types of hardware of different scales (Figure 3a).[19] Although both types of hardware were composed with linearly connected motors, we hid the motors with black textiles to convey the concept of a line that can transform continuously. We used two different-scaled prototypes to present a wide breadth of possible applications.

The ChainFORM project further advances LineFORM with an advanced hardware design—specifically, with modular and rich I/O functionalities (Figure 3b).[20] These functionalities were enabled by custom-designed flexible PCB. The PCB was wrapped around commercial servo motors to create modules that provide the functionalities. The modular construction, which is the prime function of ChainFORM, lets users customize device configuration. The other functionality includes visual feedback with LED arrays, touch sensing with six capacitive sensors, deformation sensing with internal potentiometer, and shape actuation with the servo motors. With this updated hardware design, we expanded the interaction design space of LineFORM with regards to customization.

Implementation Considerations

Here, we present an overview of potential implementations for realizing shape-changing line interfaces for HCI

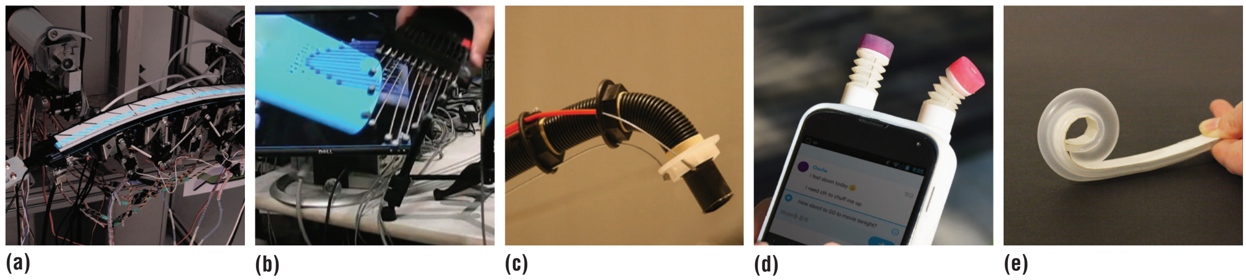

Figure 1. Actuated-line-based interface in HCI: (a) SATIN,[7] (b) AR-Jig,[8] (c) the Thrifty Faucet,[10] (d) Wrigglo,[11] and (e) PneUI.[12]

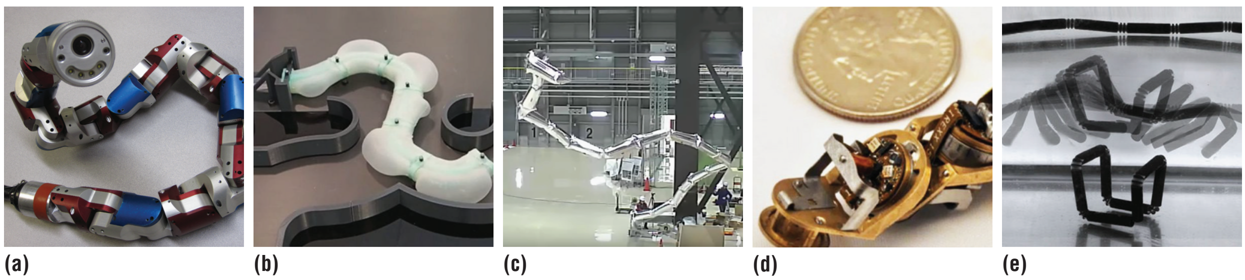

Figure 2. Actuation technologies developed in fields other than HCI: (a) the Modular Snake Robot,[14] (b) the Soft Robotic Arm,[15] (c) the Giacometti Arm with Balloon Body,[16] (d) Milli-Motein,[17] and (e) 4D printing.[18]

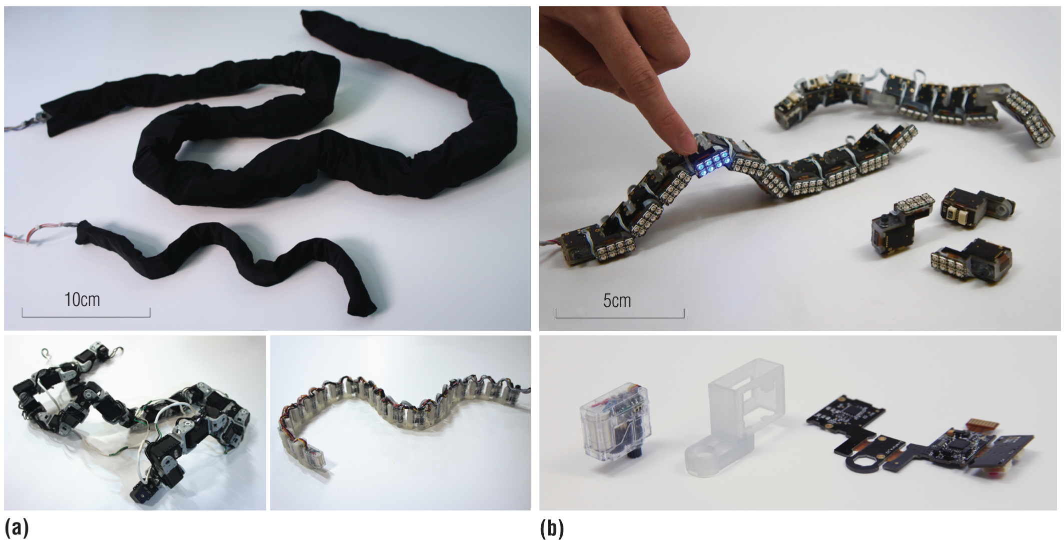

Figure 3. Prototypes of LineFORM and ChainFORM: (a) large and small LineFORM hardware with and without cover fabric, (b) the ChainFORM prototype and its modular hardware with rich I/O functionalities.

research. We compare five methods to help future researchers and designers better understand the various options for developing specific shape-changing applications (see Figure 4).

Motor-Based Actuation

Three of the five methods we compare rely on motor-based actuation, which has been a traditional approach in the field of robotics.

Series of motors. Serpentine robotics research frequently uses a series of motors. This method entails chaining motors together in a line. Currently, commercial servo motors let designers

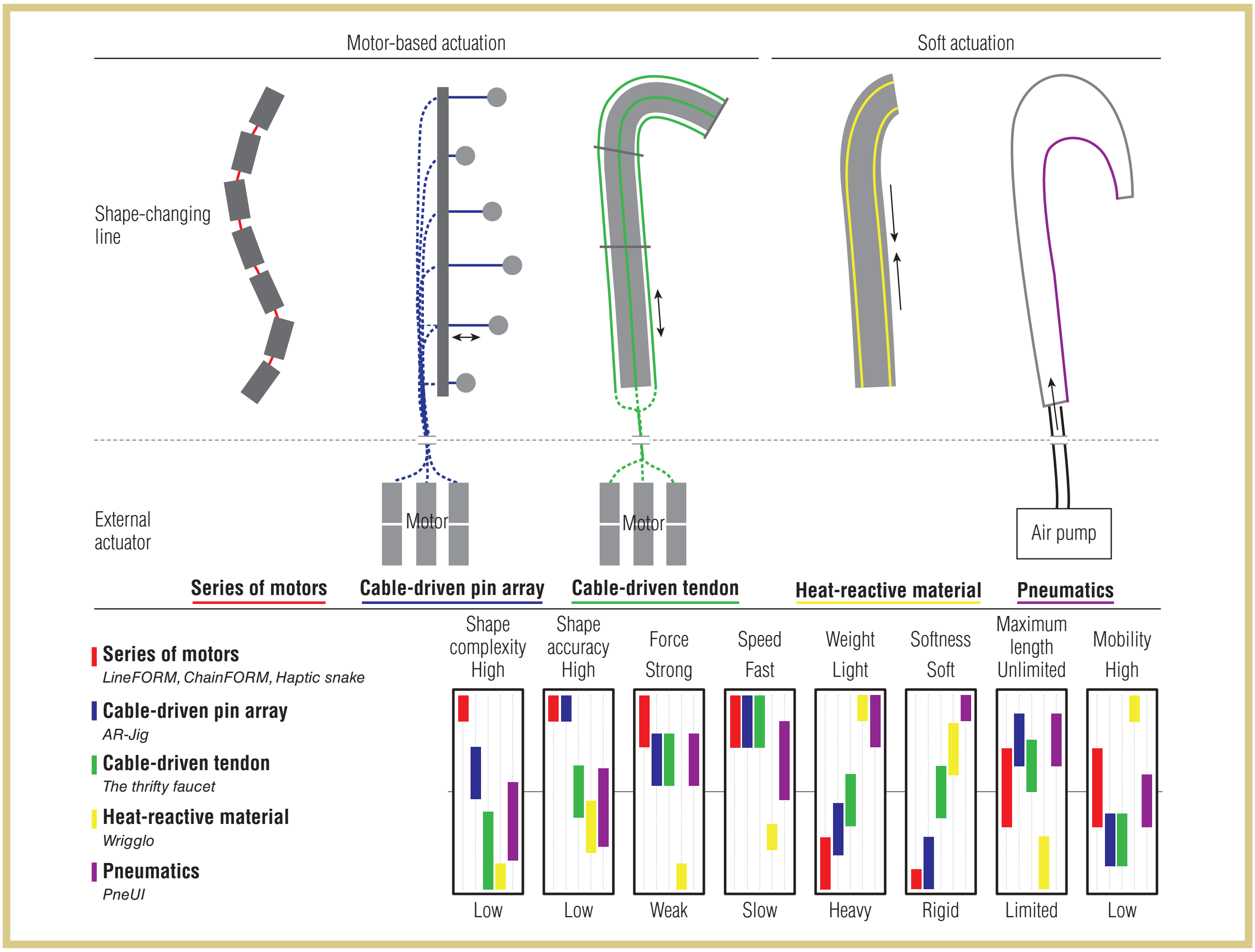

Figure 4. Illustration and comparison of potential implementation methods for shape-changing line interfaces. Each parameter (from shape complexity to mobility) is scaled between two extremes, with a relative range for each method (higher is better). We approximately scored these implementation methods for line-based interfaces as a suggested guide for future research.

implement actuated-line interfaces with accurate and complex shape control, thereby supporting interface display functionality such that it can represent various shapes. Unfortunately, the weight and rigidity of coupled motors can be uncomfortable for tangible and wearable interactions.

We chose this implementation method for LineFORM and ChainFORM because of the variety and complexity of 2D and 3D shapes it offers. However, we observed that the motors can break when lifting the weight of a whole line in 3D. This method is therefore limited to specific lengths to maintain robustness.

Cable-driven methods. Two alternative methods we considered use electric motors for speed and force but keep them separate from the shape-changing line itself through cables. In these methods, the potential interface's length is not limited by the actuators' weight compared to the series of motors method, as long as a number of cables can be routed within the shape-changing line.

The first additional method is the *cable-driven pin array*, which was presented in AR-Jig.[8] It renders a dynamic physical line using an array of linearly actuated points, and it's also relatively good for shape variety and accuracy—although it can only create 2D shapes on a plane. This method renders contours rather than interactive lines, so the user can't grab the shape-changing line.

The second method using wire is the *cable-driven tendon*, which can be found in the implementation of the Thrifty Faucet.[10] In this method, multiple linearly actuated wires are attached along a flexible linear material and manipulated. The variety of shapes and possible length are limited in this method, but it maintains the shape of the line for display and tangible interaction.

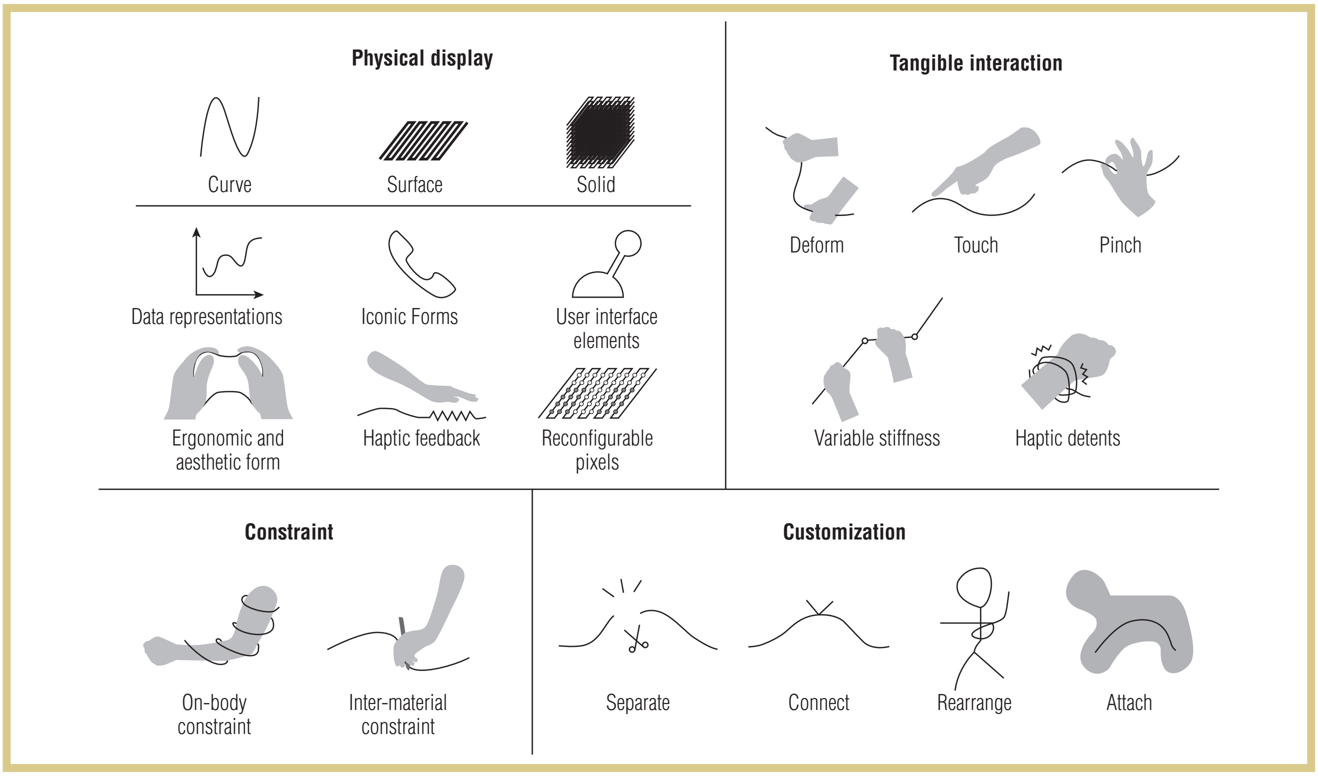

Figure 5. The interaction design space of actuated-line interface for physical displays, tangible interaction, two types of constraints, and customization.

Soft Actuation

Although systems that use electric motors face mechanical and physical constraints, such as weight and rigidity, certain techniques can exploit flexible actuation systems to overcome these limitations.

Heat-reactive materials. Heat-reactive materials, such as nitinol shape-memory alloys, can actuate small physical lines, as shown in Wrigglo (see Figure 1d).[11] As in the cable-driven tendon method, heat-reactive wire is attached along flexible linear materials. Because this material is physically actuated by heating, the system is lightweight and consumes less power than conventional motors. Major challenges of this system are its weak force, slow actuation speed, and shape fidelity.

Pneumatics. Pneumatics use pressurized air to actuate objects. HCI researchers have presented pneumatically actuated interfaces in the shape of lines whose transformation is pre-programmed with patterned air bags to create curling or bending shapes.[12] Although the airbags are lightweight and provide soft interaction, these systems require air pumps that are often bulky and heavy. Additionally, a significant portion of existing work uses a small number of airbags with limited transformation capabilities. It is a challenge for pneumatic techniques to create a wide variety of transformations while keeping the system simple and lightweight.

New Directions

There are many technical challenges in each method, because the methods have a maximum length, are bulky, have high power consumption, and struggle with robustness. Overcoming these challenges will require technical breakthroughs in motors, batteries, and other mechanical engineering technologies. Some of the latest promising inventions include micro motors, fishing-line-based artificial muscles,[21] and robot arms filled with helium gas.[16]

Interaction Design Space

Figure 5 shows the breadth of the interaction design space for actuated-line interfaces. The actuated lines can create expressive forms to physically display information, provide rich affordances for tangible interaction, constrain the user's motion, and enable the customization of length and configuration adjustments.

Physical Display

Lines can represent information through their physical expressiveness. Vector-based graphics have been a standard way of representing data. Curves, in addition to representing 2D and 3D information, can be bent and shaped to form surfaces and solid-based shapes. The unique display possibilities of actuated curve interfaces include

- *curves*—2D or 3D physical curves can be displayed by changing the orientations of individual sections of a line;
- *surfaces*—actuated curves can transform into surfaces by creating tight serpentine curves or exploiting their ability to be folded, knitted, or woven (similar to textiles), and these surfaces can be touched and manipulated, afford different interactions from curves, and are denser than curves and thus could afford greater portability; and
- *solids*—the interface can also be used to create solid forms with 3D physical geometry using space-filling techniques, which require many actuators and only function with lines that can transform into 3D.

We can represent both static shapes and dynamic continuous motion with an interface based on curves, surfaces, or solids. Furthermore, we can use these different options to display a variety of information forms and types.

Data representations. Data from underlying models can be physically rendered as a curve or as a section of a 3D model, as a fit curve from statistical analysis, or as a line chart, because lines are commonly used to represent abstract data.

Iconic forms. Physical icons can be displayed, such as the shape of a phone when there is an incoming call for mobile devices. Various iconic shapes that we are familiar with in GUIs can be used to represent functions of computational devices. Unlike graphical icons, these physical vector icons can physically function as well—in the case of the phone icon, it could cover the user's mouth and ear.

User interface elements. Actuated-line interfaces can be used to display interface elements, such as switches or sliders that users can manipulate. Similar to the concept of dynamic affordances,[4] the actuated line can afford various interactions from users according to functions of digital data.

Ergonomic and aesthetic form. Different forms can be physically rendered that provide ergonomic support or physical affordances for different grasps, or that have certain aesthetic qualities. For example, a mobile actuated curve interface could change from a game controller, enabled by touch sensors, to a wristwatch.

Haptic feedback. The changes in the shape of the actuated curve interface can apply kinetic force or tactile textures to the user's hands or body for haptic feedback. For example, an actuated curve interface wrapped around the wrist can constrict to provide user notifications.

Reconfigurable pixels. When pixels are aligned along the line, the line can form a screen according to the shape of the interface. Using the transformation capability, the display can reconfigure into various kinds of 2D and 3D shapes, expanding the concept of flexible displays.

Tangible Interaction

Physical lines have a variety of inherent affordances, and we interact with curved objects (string, cord, wire) in daily life. By combining existing interactions with actuated-line interfaces, we can explore new interaction techniques. The actuated line interfaces can be picked up and manipulated from many angles.

Deformation. Using our hands, actuated-line interfaces can be deformed like strings or wires. Changes to the shape of the curve can be reflected in a digital model rendered by the curve.

Touch. Actuated-line interfaces let users have 1D touch input along the form of the line. The interfaces can have 2D or 3D touch input by transforming into surface or solid forms. Touch can be used to select functions or areas of a curve to be manipulated.

Pinch. With its thin shaped form, line-shaped interfaces provide the affordance of pinching. Pinching provides another interaction modality that is especially useful while holding the device, making touch information more meaningful.

Active feedback. Beyond input alone, actuated curves can use their shape output to provide active physical feedback to users as they interact with the interface.

Variable stiffness. By dynamically changing the stiffness of the entire line or individual sections, the interface lets users deform only specific parts of the line, rendering mechanisms similar to hinges, where large sections of the display remain stiff but are free to rotate around specific areas.

Haptic detents. An actuated curve interface can also provide haptic feedback to users by changing its own shape during interaction—for example, simulating haptic detents as the user bends a section. Similarly, the interface can create a physical snap-to-grid by allowing only right-angle manipulations, for example.

Constraints

Curves and lines provide notions of "limitation" or "range" and often function as boundaries. Similarly, actuated curve interfaces can provide physical and dynamic constraints to limit a user's motion or action. These actuated curves can apply force to move or restrict the movement of objects and users and can act as a guide to users.

On-body constraints. An actuated curve interface can constrain the kinetic motion of the body by changing its shape and stiffness while in contact with or worn by a user. The line's form factor lets it wrap around the user's body like a bandage, offering users

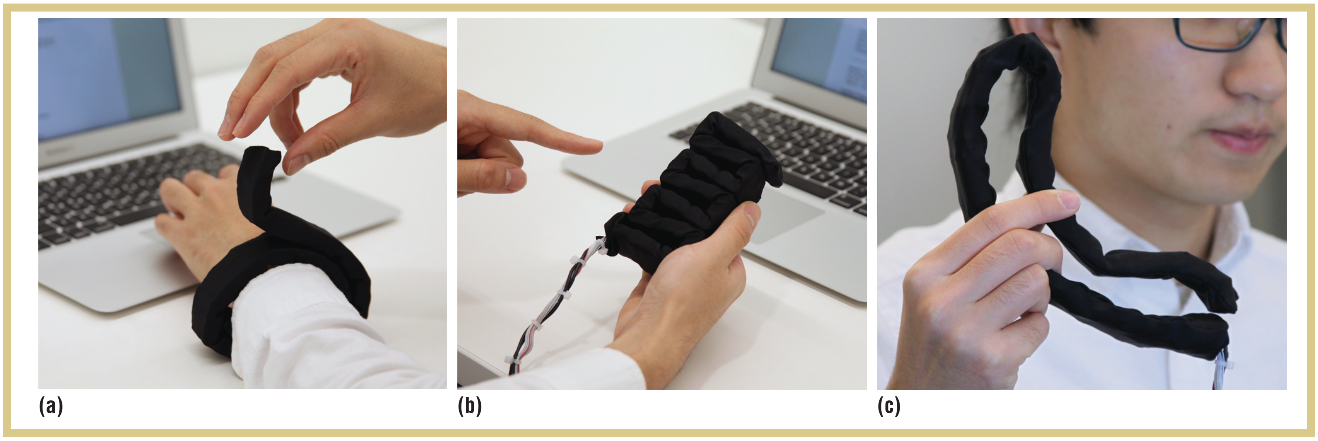

Figure 6. A shape-changing mobile device that can transform from a (a) wristband for active notification to a (b) surface for touch interaction, to a (c) phone with iconic and functional shape.

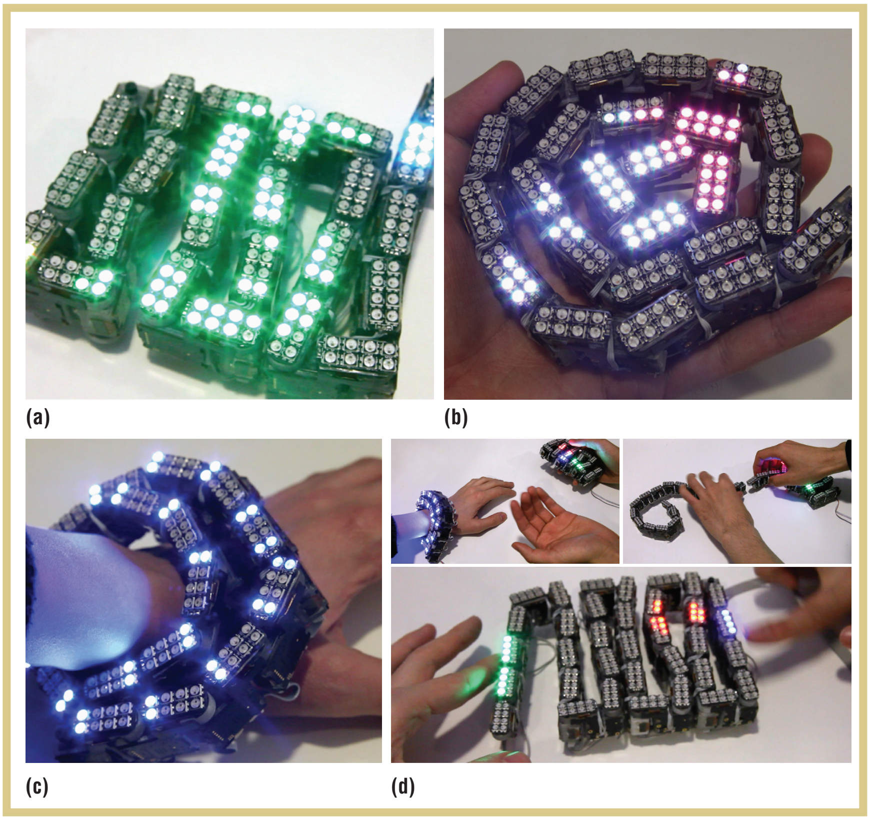

Figure 7. Examples of a reconfigurable display, including a (a) square, (b) circle, (d) body wrap, and (d) modular display.

some additional movement but restricting other movements, which can play a key role in kinetic learning, physical training, and rehabilitation.

Intermaterial constraint. Actuated curves can not only constrain users' bodies directly but also constrain a user's motion through physical objects such as tools.[4] Physical lines can create a trajectory that guides users by moving physical tools along the line, similarly to a ruler. The lines can also create closed curves to define a range within which objects can be moved.

Customization

Because various line-based materials are used to shorten, lengthen, prototype, arrange, and configure actuated curves, customization is possible.

Separate. The length of lines can be shortened by separating the line, similar to cutting strings. Users can remove a specific length of actuated curves in the same way tape from a roll of material would be cut.

Connect. The user can lengthen the actuated curve by connecting multiple lines, just as we extend the length of strings by tying them together. During the prototyping process, when users realize the length of actuated curve is insufficient, they can add length through additional actuated curves.

Rearrange. Construction of actuated curves can be rearranged to create complex shapes and configurations. In addition to offering customized lengths, lines can construct various forms by rearranging themselves through deformation and branching. Actuation makes the rearranged construction animated to express motion.

Attach. Actuated lines can be attached to other materials, similar to wires used during the structuring of sculptures. Combined with other materials, users can customize not only the motion of the line but also the movement of various materials.

Potential Applications

Researchers can leverage the interaction design space to develop a variety of applications. We present some potential applications using our own prototypes.

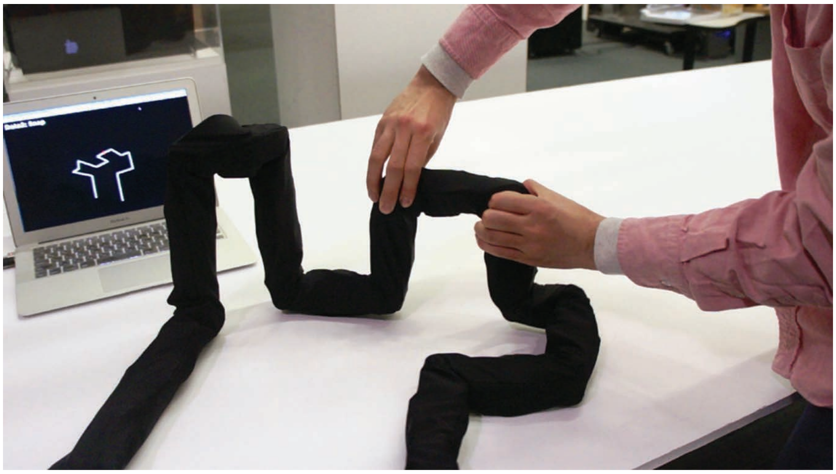

Figure 8. A line-based tangible computer-aided design (CAD) interface, which lets users manipulate 3D models.

(a) (b)

Figure 9. Integrating line-based interfaces into physical environments: (a) a transforming cable and (b) ruler.

Dynamic and Adaptive Computer Interfaces

As a dynamic and adaptive computer interface, a single shape-changing line can support a variety of interactions with digital environments and data. For example, using relatively compact hardware, we can create a shape-changing mobile device that can fit within our hands. Such a mobile device could transform from a wristband for active notification to a surface shape for touchpad-based interaction, and even to an iconic phone shape when calling someone (see Figure 6).

As a reconfigurable display, visual information can be represented on various shapes that fit to the contents being shown. Flexible displays are usually based on a planar form, but the form of line has richer shape-rendering capabilities as a transforming display. Figure 7 shows some examples—a square for text visualization (Figure 7a), a circle for a compass (Figure 7b), and a body wrap for fashion (Figure 7c). Also, by exploiting the potential for customization, two users can combine their devices to create a larger screen for multiuser contents (Figure 7d).

Finally, because lines are frequently used to represent geometrical data in computer graphics such as wire-frame, mesh, and Bézier curves, shape-changing lines could also be used for CAD interfaces that let users tangibly manipulate 3D models (see Figure 8). Active feedback can be utilized for loading data and assisting the modeling process by mirroring or snapping functions. Familiar tangible interaction with line-based material can be used such as pinch, bend, or stretch.

Weaving into Physical Environments

Utilizing its shape, line-based shape-changing interfaces can be integrated as linear objects in our daily life (see Figure 9). As a cable, it can transform according to connected devices (in the case of the lamp, the line renders a lamp stand and lever). As a ruler, it can assist users to draw complex curves and shapes by constraining the motion of a pen.

Similar to bandages, shape-changing lines can be wrapped around a user's limbs for body augmentation (see Figure 10). The strong adaptability of a line can quickly conform to various body parts and sizes and provide constraints to support

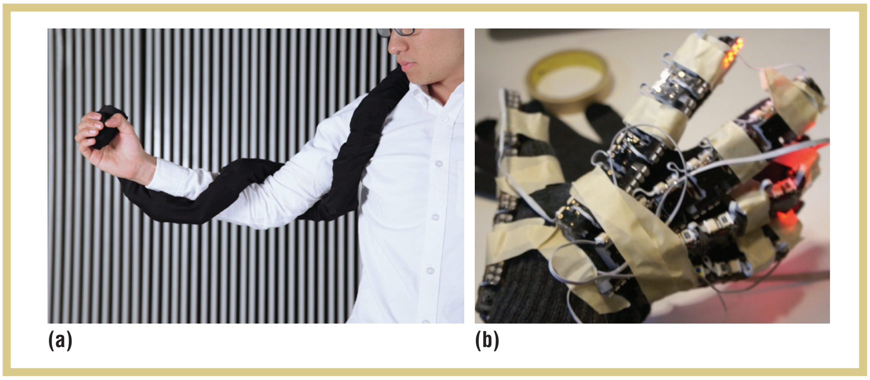

Figure 10. An adaptive and customizable body augmentation tool for (a) arms and (b) hands.

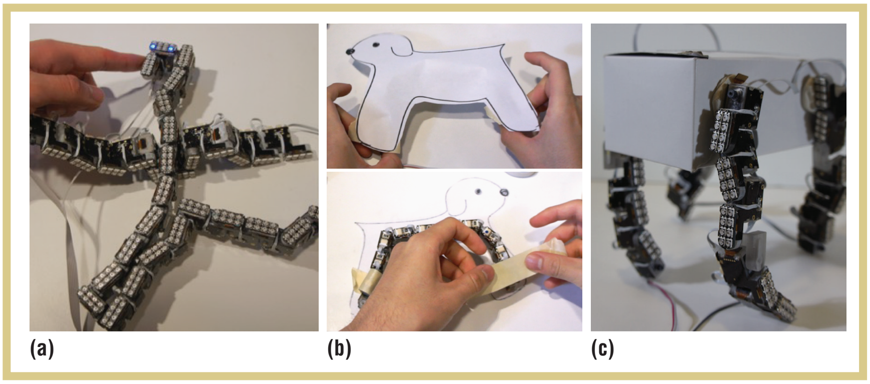

Figure 11. A prototyping tool for interactive animated craft: (a) constructing shapes with the interface, (b) attaching to paper as dynamic physical skeleton, and (c) adding legs to objects for locomotion design.

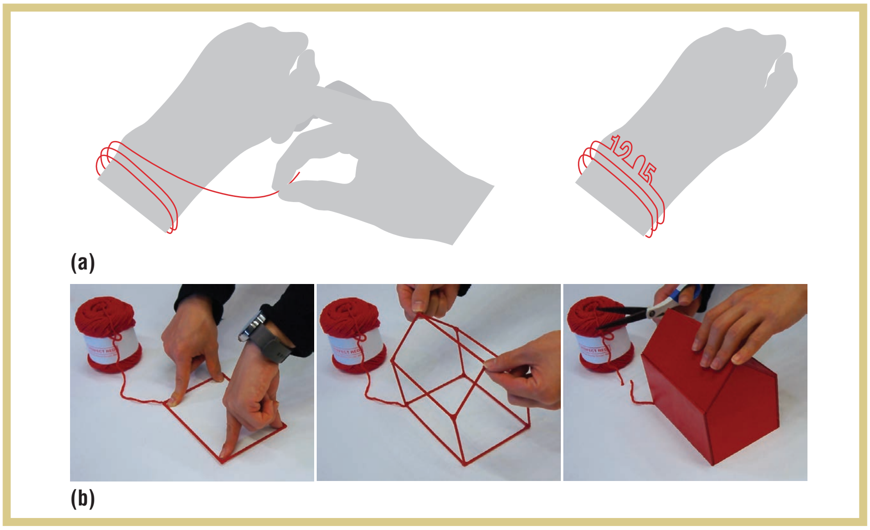

Figure 12. The initial ideation behind LineFORM reflects our future vision for research: (a) a thin line wrapped around a wrist as a wearable interface that can transform to display information, and (b) a roll of shape-changing line used for 3D modeling by leveraging the physical affordance of strings.

rehabilitation or kinetic learning with sensing and actuation capability. Customizable functionality also contributes to this application by enabling users to adjust the line length, splitting it into smaller parts and attaching it to bodies.

Also inspired by linear craft materials such as tape, wire, and string, we imagine using shape-changing lines to prototype interactive and animated crafts (see Figure 11). ChainFORM's strong customization capability could let designers, artists, or children create animated objects. Lines could be attached to passive materials, such as paper or toys, to make them move. Without any engineering or prototyping skills, users could use their hands to design various motions. Line-based interfaces with integrated functionality could thus lower the barrier for prototyping interactive physical applications.

Future Research Directions

Although current interfaces are mostly able to control angles, future work could enable control of other physical parameters, such as length, stretchiness, and thickness. These abilities would expand the physical display and tangible interaction design possibilities. In terms of the interaction design space, actuated-line interfaces for intermaterial interaction have interesting directions, as we use line-shaped objects on a daily basis to manipulate (bundle, connect, or hang) other physical objects.

When we demonstrated LineFORM with large audiences, we observed that the larger LineFORM can startle users when quickly transforming. In contrast to other grounded shape-changing interfaces, shape-changing line interfaces can have a much greater change in scale, transforming from small areas to much larger ones. As such, new techniques for feedback, feedforward and compliance are needed. Additionally, we find it a necessity to evaluate and compare interaction with actuated-line interfaces with other forms for shape-changing interfaces.

Although current technologies and implemented prototypes are still immature, we envision the future of actuated-line-based interfaces as thin strings. Figure 12 shows some of our initial drawings and prototype when coming up with the idea of shape-changing lines.

We envision a future in which computational capabilities are weaved into the physical spaces of everyday life, not only as computers but also in furniture, clothes, or other physical tools. Such material-like interfaces will support seamless interactions with the digital world, empowering our physical activity and stimulating our creativity. We hope the potential directions of the actuated-line interface we've discussed here will help advance future research into shape-changing interfaces.

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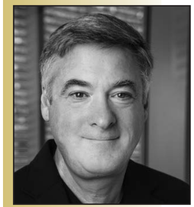

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