Line-based Shape Changing Interfaces: Implementation, Interaction Design and Potential Applications

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Abstract:	test

Line-based Shape Changing Interfaces; Implementation, Interaction Design and Potential Applications

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Introduction

The "Line" is a form that is primitive yet versatile. The line can transform into curves, surfaces and solid shapes. As a familiar form we encounter in everyday life as string, tape or wires, the line provides various tangible interactions, including knotting, wrapping, tying, and connecting. Lines are also used to represent abstract information, from their use in ancient drawings, to now, when they are used to compose digital geometrical models through wireframe. 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.

In the field of Human Computer Interaction (HCI), shape changing interfaces gained prominence in recent years. These interfaces transform their physical shape to display information in three dimensions and to 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 that are composed of a variety of forms and geometry[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 its versatility in various contexts and its adaptability in terms of physical form, the "line" would expand the interaction landscape for shape changing interfaces through multiple aspects. For example, the potential transformation capability of line would contribute to the possible shapes that can be created from a single shape changing interface. The expressiveness of lines can replicate physical wire frames or iconic shapes to convey digital information to users physically. Also, the inherent affordance of lines as a common material form would provide a variety of tangible interactions for users to seamlessly and intuitively interact with a complex digital environment. The customizability of lines to cut and reconfigure would expand the scalability and adaptability of shape changing interface as well. We believe versatility of line would make an impactful contribution to the research of shape changing interfaces.

In this article, we begin by outlining existing directions of line-shaped interface research for active interfaces, together with enabling technologies across different fields. The authors' research on actuated curve interface prototypes named LineFORM and ChainFORM are introduced as well. We then comparatively provide and discuss potential implementations to aid future research on actuated line interfaces. We present an interaction design space for actuated line interfaces that we defined through our exploration. Lastly, we discuss potential application areas and future work. This article intends to encourage future researchers and designers to explore the space of line-based shape-changing interfaces from a comprehensive point of view including implementation, interaction design, and potential applications.

Related Work

Researchers across various fields have been proposed systems for physical shape changing lines (Figure 1).

HCI: Actuated Line Interfaces

In the field of HCI, researchers have presented actuated line-shaped interface for various applications. A number of 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 [7] (Figure 1a). AR-Jig is a handheld device composed with array of actuated pins that can render digital curves [8] (Figure 1b). Haptic Snake is another handheld device utiizing snake robot-based method to represent shapes of digital models in a space [9]. Actuated lines have been used to convey information such as water usage as a faucet [10] or have been embedded into a mobile device to communicate emotion [11] (Figure 1c, d).

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

Shape-changing Line in Other Fields

Although there has been less research in HCI, Serpentine Robots [13] have long been an area of active research[14] (Figure 1f). These robots often use a linear series of one 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 a high degree of freedom transformations with fewer actuators (Figure 1g, h).

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. The MIT Center for Bits and Atoms proposed the concept of Milli-biology to explore hardware composed with chained actuators and software to create arbitrary shape from a single line [17] (figure 1i). Tibbits et al. presents an idea of 4D printing through his research including transforming lines using 3D printed multi-materials lines[18] (figure 1j).

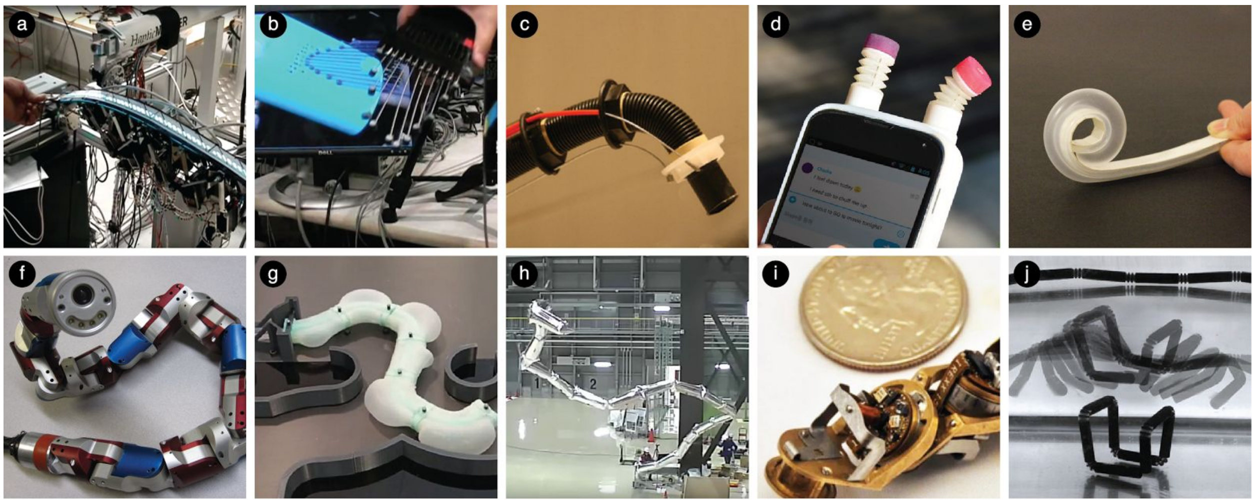


Figure 1. Actuated line-based interface in HCI and actuation technologies developed in other fields. (a: SATIN, b: AR-Jig, c: The Thrifty Faucet, d: Wrigglo, e: PneUI, f: Modular Snake Robot by CMU Biorobotics Lab, g: Soft Robotic Arm by MIT CSAIL, h: Giacometti Arm with Balloon Body by Tokyo Institute of Technology, i: Milli-Motein, j: 4D Printing.

LineFORM & ChainFORM

Building upon 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. Implementation and interaction design contribution of these projects are briefly introduced below.

In the LineFORM project, we aimed to open up a new direction of research on line-based shape-changing interface with two types of hardware of different scales [19] (Figure 2a). While both of the hardware were composed with linearly connected motors, we hid the motors with black textile to convey the concept of a “Line“ that can transform continuously. We presented an interaction design space using shape-changing lines, which we divide into categories of; Display, Interaction, and Constraints. We used two prototypes of different scales to present a wide breadth of possible applications. Our intention was to trigger future research to explore wide space of actuated line interface for HCI.

The ChainFORM project further advances LineFORM with an advanced hardware design, specifically with modular and rich I/O functionality (Figure 2b) [20]. This functionality was enabled by custom designed flexible PCB. The PCB was wrapped around commercial servo motors to create modules that provide these functionalities. The modular construction, which is the prime function of ChainFORM, enables users to customize the configuration of the device just like crafting materials. 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 mainly with the customization aspect.

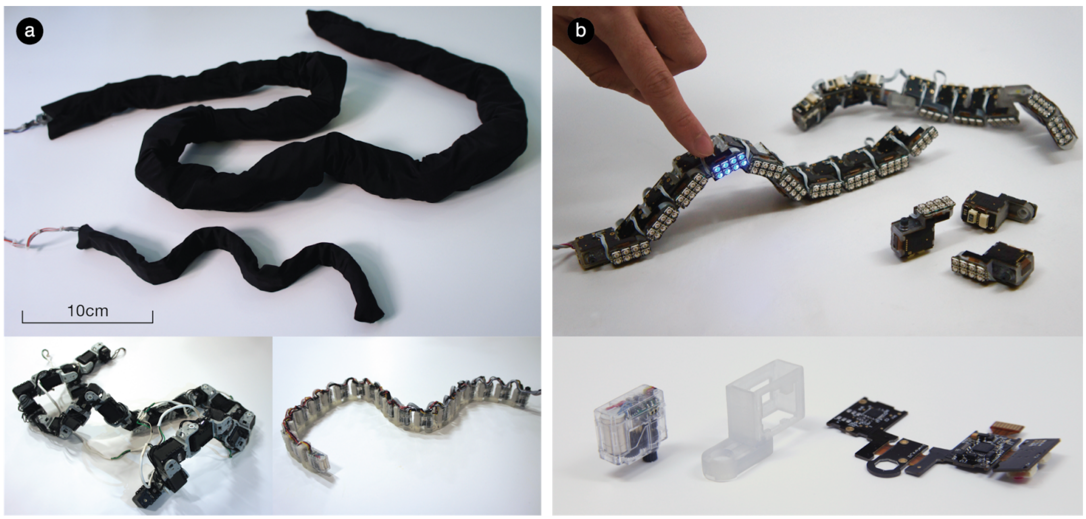


Figure 2. Prototypes of LineFORM and ChainFORM (a: large and small LineFORM hardware, b: ChainFORM, modular hardware with rich I/O functionality.)

Implementation Considerations

Here, we present an overview of potential implementations for realizing shape-changing line interfaces. Figure 3 shows the illustration and comparison of each method with different parameters. Each parameter is scaled from 1 to 5 (greater is better) by the authors' rating for state-of-the-art technologies. The aim of this comparison is to briefly categorize and summarize each method so that future researchers and designers can refer on it for developing specific shape-changing applications.

Series of Motors is frequently used in serpentine robotics research. This method entails chaining motors together into a line. Presently, commercial servo motors enable designers to implement actuated line interfaces with accurate and complex shape control. These aspects strongly supports the display functionality of the interfaces to 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 this method can create. However, we realized 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.

Two alternate methods we considered use electric motors for speed and force, but keep them separate from the shape-changing line itself through cables. These methods do not pose a limitation on the interface's length as they do not significantly fight their own weight and inertia during actuation.The first additional method is the **Cable-driven Pin Array**, which was presented in AR-Jig [8]. This method renders a dynamic physical line using an array of linearly actuated points. This method is 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. The shape-changing line cannot be grabbed by the user in this method.
The second method using wire is **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.

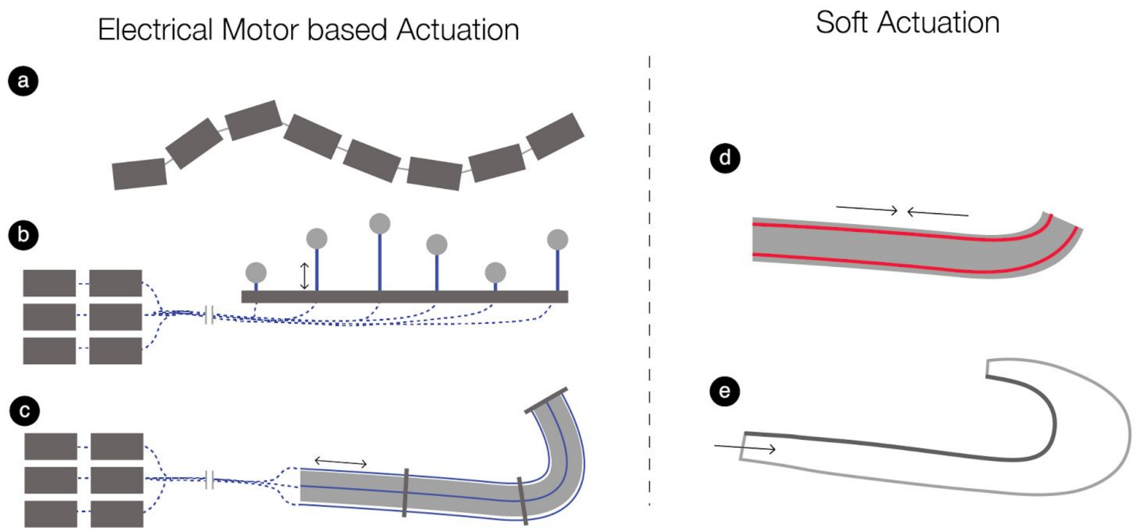
While systems that utilize electric motors face mechanical and physical constraints such as weight and rigidity, there are techniques that utilize flexible actuation systems to overcome these limitations.

Heat Reactive Materials such as nitinol shape memory alloys can actuate small physical lines, as shown in Wrigglo [11]. As in the Cable-driven Tendon method, heat reactive wire is attached along flexible linear materials. Because this material can actuate by itself with heating, the system is lightweight and consumes less power than conventional motors. Major challenges of this system, are weak force, slow actuation speed and shape fidelity.

Pneumatics make use of 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]. While 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 small numbers 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.

There are many technical challenges such as maximum length, bulkiness, power consumption, and robustness which require technical breakthroughs in motors, batteries and other mechanical engineering technologies to overcome. Some of the latest promising inventions include micro motors, fishing line artificial muscles [21], and robot arms filled with helium gas

[16].



Method	Example Projects	Shape Complexity	Shape Accuracy	Force & Speed	Weight	Softness	Maximum Length	Mobility
(a) Series of Motors	LineFORM, ChainFORM, Haptic Snake	5	5	5	1	1	3	3
(b) Cable-driven Pin Array	AR-Jig	4	5	4	2	2	4	2
(c) Cable-driven Tendon	The Thrifty Faucet	2	3	3	3	4	3	2
(d) Heat Reactive Material	Wrigglo, Hairlytop Interface	2	2	1	5	4	2	5
(e) Pneumatics	PneUI, aeroMorph	3	3	4	5	5	4	2

Figure 3. Illustration and comparison of potential implementation methods.

Interaction Design Space

Here we describe the interaction design space of actuated line interfaces (Figure 4). The actuated lines can create expressive forms to display information, provide rich affordances for tangible interaction, constrain user's motion, and enable customization of length and configuration adjustments.

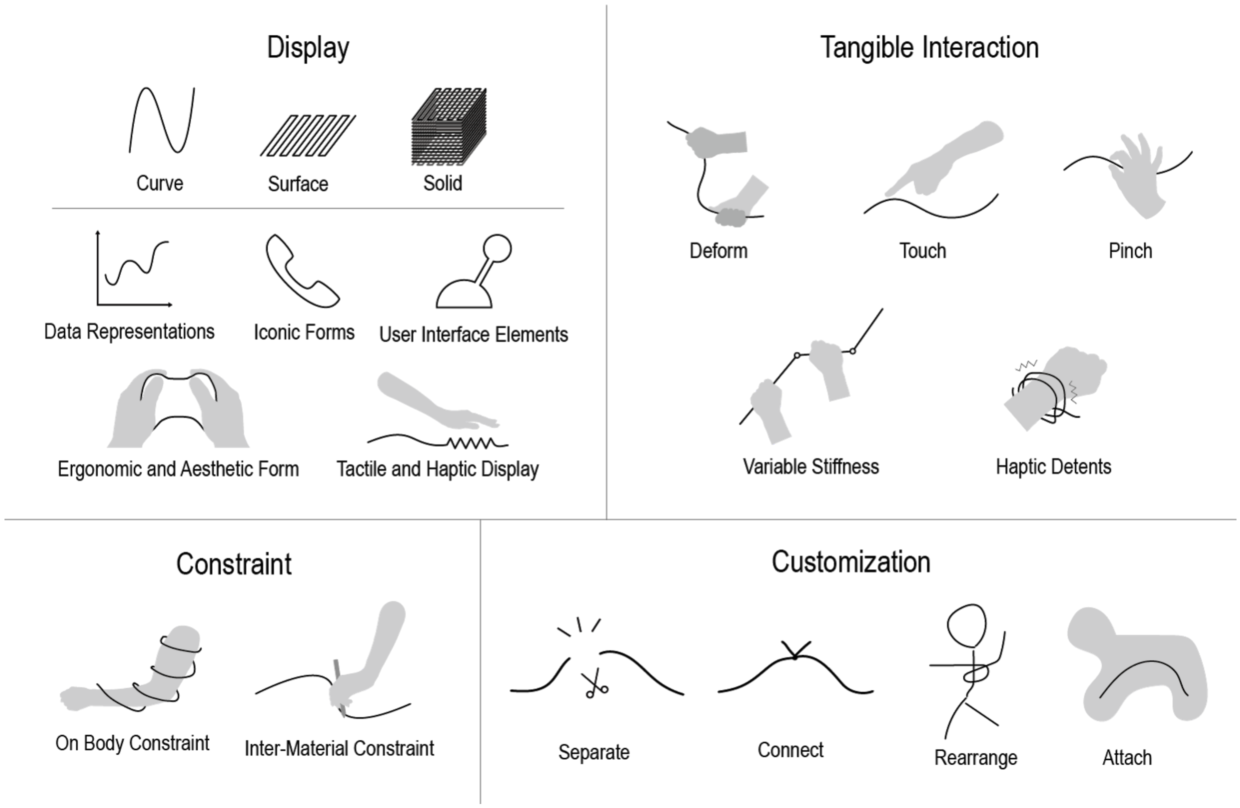


Figure 4. Interaction design space of actuated line interface for display, tangible interaction, constraint and customization.

Display

Lines can represent information through their physical expressiveness. Vector-based graphics have been a standard way to represent 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 primitive possibilities of actuated curve interfaces follow:

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 through a number of techniques: by creating tight serpentine curves or by their functional abilities to be folded, knitted, or woven similarly to textiles. These surfaces can be touched and manipulated and afford different interactions than curves. They are denser than curves and thus potentially afford greater portability.

Solids - We can also use the interface to create solid forms with 3D physical geometry by using space filling techniques. These techniques require a larger number of actuators, and only function with lines that can transform in 3D.

We can represent both static shapes and dynamic continuous motion with the interface based on the three types of shapes described above.

Utilizing Display

Using these different primitives we can display a variety of types of information and forms.

Data Representations - Data from underlying models can be physically rendered as a curve or section of a 3D model, a fit curve from statistical analysis, or a line chart. Many methods for physical data visualization can be applied in this context, though new ones need to be explored.

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 function of computational devices. Unlike graphical icons, these physical vector icons can physically function as well; in case of the phone icon, it can cover the mouth and ear of a user.

User Interface Elements - Actuated curve 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, physical affordances for different grasps, or that have certain aesthetic qualities. For example, a mobile actuated curve interface could change from game controller, enabled by touch sensors, to a wrist watch.

Tactile and Haptic Display - The changes in the shape of the actuated curve interface can apply force to the users hands or body for haptic feedback. For example, an actuated curve interface wrapped around the wrist can constrict to provide the user with a notification.

Reconfigurable Pixels - When pixels are aligned along the line, it can form a screen as a whole according to the shape of the interface. Utilizing the transformation capability, the display can reconfigure into various kinds of 2D and 3D shapes which can expand the concept of flexible displays.

Tangible Interaction

Physical lines have a number of inherent affordances and we interact with curved shaped objects (string, cord, wire) in daily life. By combining existing interactions with actuated line interfaces, we are able to 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 the digital model which the curve renders.

Touch - Actuated line interfaces allow the user to have 1D touch input along the form of line. It 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 the user as they interact with it.

Variable Stiffness - By dynamically changing the stiffness of the entire line or individual sections, the interface can allow users to deform only specific parts of the line. This can allow mechanisms similar to hinges to be rendered, where large sections of the display remain stiff but are free to rotate around specific areas.

Haptic Detents - Actuated curve interfaces can also provide haptic feedback to users by changing its own shape as it is being interacted with, for example simulating haptic detents as the user bends a section. Similarly, the device can create a physical snap-to-grid by only allowing, for example, only right angle manipulations.

Constraint

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 user's motion or action. These actuated curves can apply force to move or restrict movement of objects and users, and can act as a guide to users.

On-Body Constraints - Actuated curve interfaces can constrain the kinetic motion of the body by changing its shape and stiffness while in contact or worn by a user. The form factor of line enables it to wrap around the user's body like a bandage. This can allow users additional movement but restrict access to other movement, which can play a key role in kinetic learning, physical training and rehabilitation.

Inter-material Constraint - Actuated curves may 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 it, similarly to a ruler. The lines can also create closed curves to define a range for objects to be moved within.

Customization

As various line-based materials are used for craft and prototyping, length, arrangement and configuration of actuated curves are also capable of customization.

Separate - The length of lines can be shortened by separating the line similarly 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 - Also, the user can add length to the actuated curve by connecting multiple lines as we extend the length of strings by knotting 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. Together with its length customizing capability, lines are capable of constructing various forms by rearranging through deforming and branching. Actuation makes the rearranged construction animate to express motion.

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

Potential Applications

Leveraging the interaction design space, a variety of potential application can be achieved. We present the applications which were demonstrated using our prototypes (Figure 5).

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, a shape changing mobile device that can fit within our hands is possible. 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 (Figure 5a). As a transforming display, visual information can be represented on various shapes that fits to the contents being shown. Figure 5b shows some examples; circle shape for compass, square shape for text visualizer, and wrapping around body for fashion. By taking the advantage of customization capability; two users combine their devices to create larger screen for multi-user contents (Figure 5c).

As 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 more intuitively manipulate 3D models (Figure 5d). Active feedback can be utilized for loading data and assisting the modeling process by mirroring or snapping functions.

Weaving into Physical Environments

Utilizing its shape, line-based shape-changing interfaces can be integrated as linear objects in our daily life (Figure 5e). As a cable, it can transform according to connected devices (in case of the lamp, the line renders a lamp stand and lever). As a ruler, it can assist users to draw curves and shapes.

Similar to bandages, shape-changing line can be wrapped to a user's limbs for body augmentation (Figure 5f). The shape of line can adapt to various parts and sizes of bodies, and provide constraints to support rehabilitation or kinetic learning with sensing and actuation capability. Customizable functionality also contribute to this application by enabling users adjust the length of line, split it into smaller parts and attach to bodies.

Also inspired by linear craft materials such as tape, wire and string, we imagine shape-changing lines to be utilized to prototype interactive and animated crafts (Figure 5g). Strong customization capability shown in ChainFORM could let designers, artists or even children to create animated objects. Lines can be attached to passive materials such as paper or toys to make them move. Without any engineering or prototyping skills, users can use their hands to design motion of the craft. We believe the line-based interface with integrated functionality would lower the barrier for prototyping interactive physical applications.

Figure 5. Potential applications on actuated line-based interfaces (a: mobile device, b: display, c:modular display, d: CAD modeling tool, e: ruler and cable, f: body augmentation, g: prototyping tool)

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 possibility. In terms of the interaction design space, we feel that inter-material interaction has interesting directions, as we use line-shaped objects on a daily basis to manipulate other physical objects: to bundle, connect, or hang.

As 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 a necessity to evaluate and compare interaction with actuated line interfaces with other forms for shape-changing interfaces.

While current technologies and implemented prototypes are still immature, we imagine the future of actuated line-based interface as thin strings. Figure 6 shows some of our initial drawing and video prototype when coming up with the idea of shape-changing line. We foresee these visions to be realized with technical breakthroughs as discussed in the implementation.

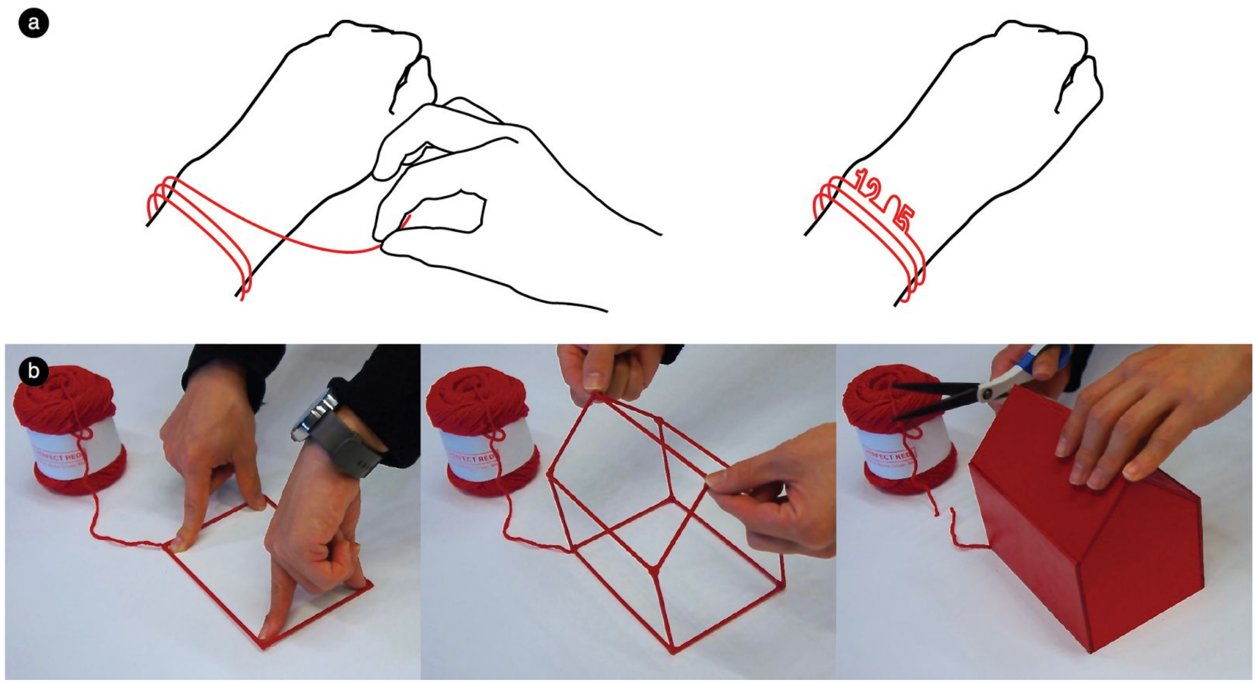


Figure 6. Initial Ideation of LineFORM (a: a thin line wrapped around a wrist and transforming to display information, b: a roll of shape-changing line used for 3D modeling by leveraging the physical affordance of strings.)

Conclusion

Through our study on shape-changing line, we envision the future where 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, empower our physical activity, and stimulate our creativity. We hope the potential direction of the actuated line interface discussed in this paper including implementation, interaction design and applications contribute to expand the future of shape-changing interface research.

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-Summary of difference from previous publications-

Part of the contents in this article was presented in ACM UIST 2015 & 2016. In this journal submission, we comprehensively describe the concept of line-based interface with additional description on previous work together with implementation consideration, expanded interaction design space, newly categorized potential application scenario and future vision. The aim of this article is to provide the overview of line-based interface for interaction design and implementation for share the future research space

-Previous Publication-

[1] Nakagaki, Ken, Sean Follmer, and Hiroshi Ishii. "LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint." Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology. ACM, 2015.

[2] Nakagaki, Ken, et al. "ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces." Proceedings of the 29th Annual Symposium on User Interface Software and Technology. ACM, 2016.

LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint

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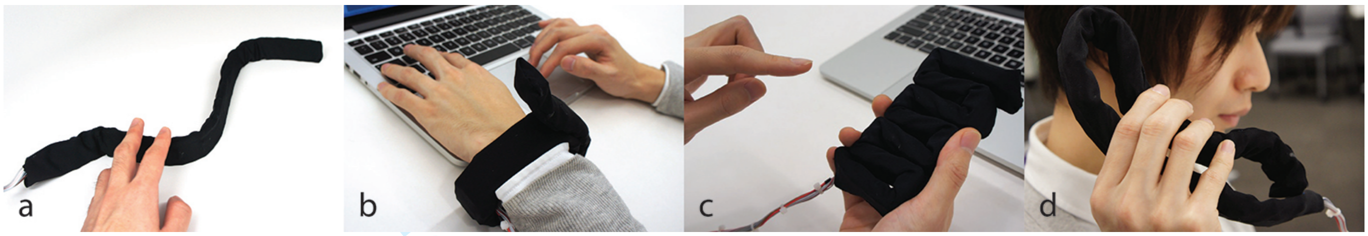

Figure 1. The LineFORM actuated curve interface can transform between shapes for mobile interaction: a) curve, b) wristband, c) surface, d) phone.

ABSTRACT
In this paper we explore the design space of actuated curve interfaces, a novel class of shape changing-interfaces. Physical curves have several interesting characteristics from the perspective of interaction design: they have a variety of inherent affordances; they can easily represent abstract data; and they can act as constraints, boundaries, or borderlines. By utilizing such aspects of lines and curves, together with the added capability of shape-change, new possibilities for display, interaction, and body constraint are possible. In order to investigate these possibilities we have implemented two actuated curve interfaces at different scales. LineFORM, our implementation, inspired by serpentine robotics, is comprised of a series chain of 1DOF servo motors with integrated sensors for direct manipulation. To motivate this work we present applications such as shape changing cords, mobiles, body constraints, and data manipulation tools.

Author Keywords
Shape-Changing Interfaces; Tangible User Interfaces; Curves.

ACM Classification Keywords
H.5.2. User Interfaces: Input Devices and Strategies, Haptic I/O.

INTRODUCTION
When interacting in our daily lives we use a variety of different tools and implements, and the line or curve is a common form that we encounter, be it as strings, cables, or wires. Strings can be tied to secure things or tied around your wrist as a reminder, cables are used to transmit data or electricity, and many artists use wire to make sculptures that express complex characters or motion through simple, abstract form. On screens, vector and line drawings can highlight and abstract information, and come to life through animation. How can we combine the physical affordances of ropes, strings or wire with the dynamism of the animated graphical curves? What if these ropes and cables could move themselves? What if a rope could tie itself? There are rich possibilities for interaction through curve based interfaces [8, 19, 20], however we believe they must also be tightly coupled with shape output to allow for richer interaction.

Researchers have recently explored the use of shape change to convey information and to provide dynamic affordances for interaction. However these explorations have mainly focused on shape changing surfaces [18, 7], volumes [6], and actuated tabletop robots [1]. The rich affordances of curves, as well as the simplicity to abstract information, is missing from these interfaces. The use of shape-changing curves or chains has not been explored in detail in HCI, but it is fundamental in biology and robotics. Protein folds into functional three-dimensional structures from a random coil. Researchers in robotics have been inspired by protein folding and have proposed theories and built prototypes of a chain-based robotic systems which can reconfigure into any shape [11]. In addition, bio-inspired serpentine robots have the ability to locomote in a variety of environments, moving through narrow passages or climbing poles [17, 21]. Our goal is to apply these same mechanisms to novel interfaces.

We believe that actuated curve interfaces provide many advantages for display, interaction, and constraint, and this paper presents a first investigation into these techniques. To explore these possibilities we introduce the LineFORM system, which is comprised of a number of 1 DOF rotational servo actuators in series that is based on methods often seen in the serpentine robotics field. We have developed two ver-

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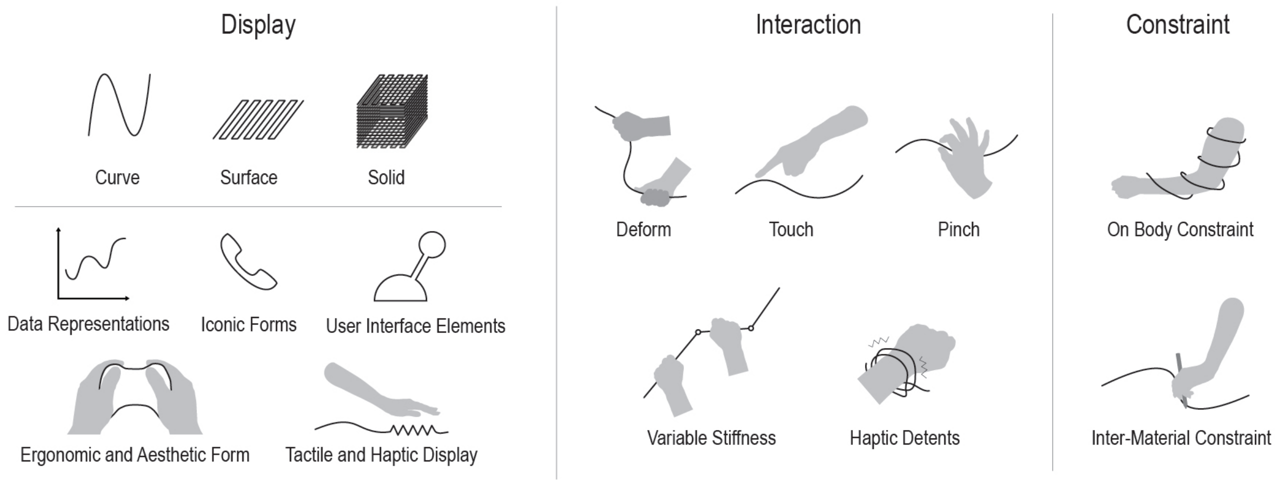

Figure 2. Design Space of Actuated Curve Interfaces.

sions of LineFORM, a large scale 3D version and a smaller, higher resolution 2D version. LineFORM can physically *display* expressive 2D and 3D shapes, both for information representation and for dynamic affordances. Users can *interact* with LineFORM through direct deformation and touch and it can provide haptic feedback through variable stiffness joints to enable such interactions as physical snap to grid. Finally, LineFORM can act as a *constraint* for the user's motion or the motion of other objects to guide user actions. In this paper, we explore the design space of actuated curve interfaces, clarify several methods of interaction, describe two prototype implementations at different resolutions and scales, and demonstrate motivating applications in a variety of domains.

RELATED WORK

HCI researchers have explored a variety of passive curve based input devices that leverage the rich physical affordances of curves. Direct manipulation of 3D curves and splines can be easily and expressively controlled by bending and shaping a flexible curve with embedded sensors[8]. The affordances of ropes have been explored and utilized in the entertainment and gaming domain, allowing for exertion based interaction [25]. Other researchers have explored utilizing the cords attached to our devices as input devices for control of music by pinching and sliding along a headphone cable [20] or to turn off a light by knotting a power cable [19].

Researchers in the field of shape-changing interfaces have investigated how to move beyond physical input, such as those demonstrated in the curve based input devices, to more active interfaces which use physical shape and form as an output medium [16]. Many different topologies for shape-changing interfaces have been explored ranging from actuated points [12], surfaces [7, 18], solids [6] and modular robots[15]. One area that has been less explored is actuated curve interfaces, which are not highlighted in great detail in review papers [16].

However, there have been some initial investigations of actuated curves in HCI. A number of actuated interfaces have been created to physically display and manipulate 3D curves for Computer Aided Design [3, 2], though these have been grounded or require large cables. Actuated curves have been used to convey information such as water usage [22] or have been embedded into a mobile device to communicate emotion [14]. Different techniques have been used for actuation from bi-stable geometries [10] to pneumatic composites [26].

Although there has been less research in HCI, Continuum or Serpentine Robots [17, 21], also known as Snake Robots, have long been an area of active research [24]. These Serpentine robots often use a linear series of One Degree of Freedom actuators to create motion similar to that of snakes and tentacles. Different actuation techniques have been explored in this context, and soft robotics techniques such as pneumatic composites [23, 13] and jamming [4] have been used to achieve a high degree of freedom manipulation with fewer actuators. Towards the goal of programmable matter, other researchers have explored the abilities of this class of robots to create different shapes, similarly to how proteins can fold into complex patterns [11].

In contrast to the prior research, our work investigates the broader space of actuated curve interfaces with many degrees of freedom to allow for interaction and display of both 2D and 3D curves. Though our implementation is technically similar to that of serpentine robots, they have not yet been explored in the context of interaction, and our system requires different techniques to enable direct manipulation by, and sensing of the user. Our goal is to overview a broad set of interactions and applications for snake robotics in HCI, with less focus on our specific implementations and with the hope of inspiring further research in this area.

ACTUATED CURVE INTERFACES

Here we describe the design space and interaction potential of actuated curves for shape changing UIs (Figure 2). These actuated curves can create expressive forms to display information, provide rich affordances for interaction, and constrain a user's motion.

Display

Curves and lines can easily represent information and data by making use of the abstractness of their form. Vector-based graphics have been one of the standard ways to represent data. Also, curves have the capability to represent not only 2D or 3D curves, but also a single continuous curve can be bent and shaped to form surfaces and solid-based shapes. The unique display primitive possibilities of actuated curve interfaces follow:

Curves - 2D or 3D physical curves can be displayed by changing the orientations of individual sections of the actuated curve.

Surfaces - Actuated curves can also transform into surfaces through a number of techniques: by creating tight serpentine curves or by the capabilities inherent in lines to fold, knit, or weave just as textiles are made with yarn or string. These surfaces can be touched and manipulated and afford different interactions than curves. They are also more dense than a curve and thus potentially afford greater portability. Chains of actuators oriented with the same rotational axis can create only 2D planar surfaces, whereas chains of actuators with alternating orientations can create 3D surfaces.

Solids - We can also use the interface to create solid forms with 3D physical geometry by using a space filling technique [11]. This requires a larger number of actuators, and only functions with chains of actuators with alternating orientations.

We can represent both static shape and dynamic continuous motion with the interface based on the 3 types of shapes as above.

Utilizing Display

Using these different primitives we can display a variety of types of information and forms.

Data Representations - Data from underlying models can be physically rendered. This could be a curve or section of a 3D model, a fit curve from a statistical analysis, or a line chart. Many methods for physical data visualization can be applied in this context, though new ones need to be explored [9].

Iconic Forms - Physical Icons can be displayed, such as the shape of a phone when there is an incoming call, see Figure 1 d.

User Interface Elements - Actuated curve interfaces can be used to display interface elements, such as switches, or sliders that users can manipulate, see Figure 7.

Ergonomic and Aesthetic Form - Different forms can be physically rendered that provide ergonomic support, physical affordances for different grasps, or that have certain aesthetic qualities. For example, a mobile actuated curve interface could change from the shape of game controller, enabled by touch sensors, to a wrist watch for different applications or settings.

Tactile and Haptic Display - The changes in the shape of the actuated curve interface can apply forces to the users hands or body to provide haptic feedback. For example, an actuated curve interface wrapped around a wrist can constrict to provide the user with a notification.

Interaction

Physical curves have a number of inherent affordances and we interact with curved shaped objects (string, cord, wire) in daily life. We can pinch, pull, twist, knot etc. By combining such existing interaction to actuated curve interfaces, we are able to explore new interaction techniques. Because actuated curve interfaces are un-grounded, they can be picked up and manipulated from many angles.

Deformation - Actuated curve interfaces can be deformed like strings or wires. Changes to the shape of the curve can be reflected in the digital model which the curve renders.

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

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

Active Feedback

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

Variable Stiffness - By dynamically changing the stiffness of the entire curve or individual sections, the interface can allow users to deform only specific part of the line. This can allow mechanisms similar to hinges to be rendered, where large sections of the display remain stiff but are free to rotate around specific areas.

Haptic Detents - Actuated curve interfaces can also provide haptic feedback to users by changing its own shape as it is being interacted with, for example simulating haptic detents as the user bends a section. Or the device can only allow users to manipulate it so that it forms right angles, or physically constrain its deformation allowing for physical snap-to-grid.

Constraints

Curves and lines give us notions of "limitation, range, etc..." and often function as borders or bindings. Similarly, actuated curve interfaces can provide physical and dynamic constraint to limit a user's motion or action. These actuated curves can apply forces to move or restrict movement of objects and users, and can act as a guide to users.

On-Body Constraints - Actuated curve interfaces can constrain kinetic motion of the body by changing its shape and stiffness while in contact or worn by a user. This can push users to certain areas but restrict access to others.

Constraints for Multi-Material Interaction - Actuated curves can not only constrain users bodies directly, but also constrain users' motion through physical objects such as tools, similar to dynamic constraints proposed by Follmer et al. [6]. Physical lines can create a trajectory that guides users by moving physical tools along it, similarly to a ruler. The lines can also create closed curves to define a range for objects to be moved within it.

Configuration and Hardware

A variety of design factors of actuated curves define the set of display possibilities - such as the number, spacing, and size of actuators, the maximum angle of rotation, and the orientation and pattern of actuators. Different scales often translate to different amounts of required force and changes in resolution, enabling drastically different interactions and applications.

Different actuation techniques also change the abilities of the actuated curve interfaces. Servo motors are strong, but relatively large. Pneumatic actuators can create continuous motion but it is difficult to have many sections and requires compressed air. Shape Memory Alloys are light but relatively weak and hard to back drive.

LINEFORM

In order to explore the design space of actuated curve interfaces, we implemented two hardware prototypes comprised of servo motors in series, which we call LineFORM (Figure 3). Our intention was to explore different aspects of actuated curve interfaces by building different scale prototypes. The large prototype, which features high torque, deformation sensing, stiffness change and can render 3D structure, was used for applications such as 3D body constraints and Computer Aided Design. A second smaller and higher resolution LineFORM focuses on shape display in 2D for mobile and cord based interaction.

Figure 3. Two LineFORM prototypes which have different scales (A: Large, B: Small).

System Design

The overall design of the system is composed of three parts: a series of connected servo motors, an Arduino Mega microcontroller for motor control and sensing, and a Mac OS computer running custom applications written in processing that control LineFORM (Figure 4). By controlling the angle of each servo motor with a microcontroller, the interface can change its overall shape. The angle of each motor is defined by the software on the computer and sent to the microcontroller through serial communication. The stiffness of each joint can be computationally controlled by changing the torque applied by the motor. Additionally, a user's deformation of the LineFORM can be detected by extracting the value of the potentiometer in the servomotors. Touch data is detected by adding pressure sensors on a spandex skin over the device. The spandex skin also protects connectors and helps users view the LineFORM as a single device.

In our Processing software, we define a model which contains the angle and stiffness for each individual servo. Various means of fitting the required data to the model, from direct 1:1 mapping to a mass spring optimization. LineFORM's digital model is updated both from changes caused by the digital computation and simulation as well as interaction from the user at 60fps.

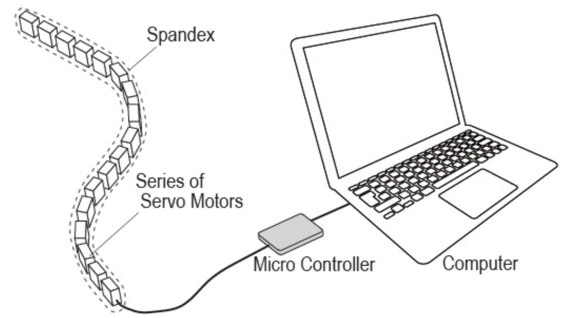

Figure 4. System Diagram of LineFORM.

Our higher level control for the overall shape and motion is based on fitting a curve to a shape. In the case of creating shape data from iconic data, we extract outline from binary image data as series of vectors, then calculate the angle for each servo motor according to length of each joint (Figure 5 Right). This is a slightly different, and more simple, task than the inverse kinematic control needed to move a serpentine robot towards a goal, as we do not care about the position of the end effector for most applications [21]. In addition, we can also load in previously recorded shape data from either deforming LineFORM directly by hand (only available with larger prototype) or by adjusting angles of servo one by one using GUI (Figure 5 Left).

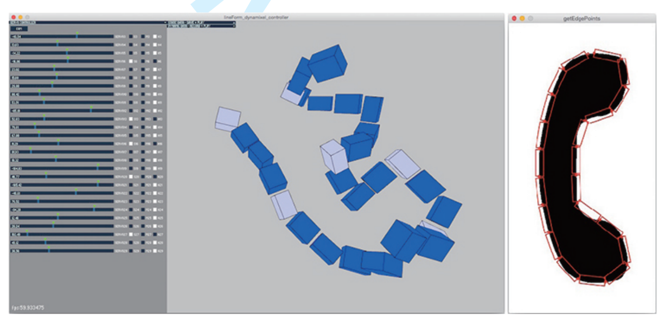

Figure 5. Software for Controlling Shapes (Left:GUI, Right:creating shape data from icon).

3D Prototype - The larger LineFORM prototype utilizes 28 Dynamixel AX-18A servo motors (torque of 18.3 kgcm and speed of 0.103 sec/60) (Figure 4 Left). The size of each motor is 32 x 50 x 40mm, and the length of each joint with the mounting bracket is 7cm. The total length is 186cm. The motors are connected with their axis of rotation alternately perpendicular to one another (X after Y) so that it can form 3D structures. This servo motor can change the torque as well as terms of the PID controller and detect the angle as default feature of product and all data is transmitted in sequence through a daisy chain scheme. Each servo rotates within range of 206 degrees. Also by default, as long as they are connected to power, these servos have a strong holding torque even if they are at rest because the DC motor included in each servo motor is powered to create a resistance force. Thus, we added a relay in each servo motor to disconnect the DC motor from the power supply so that it provides less friction when a user deforms it. We can also control the compliance of each joint by changing terms of the PID controller, changing its stiffness or elasticity.

2D Higher-Resolution Prototype - The smaller LineFORM prototype is comprised of 21 HS-5035HD Digital Ultra Nano Servos by Hitec (torque of 0.8 kgcm and speed of 0.10 sec/60) (Figure 4 Right). The size of each motor is 18.6 x 7.6 x 15.5mm, so that length of each joint is approx. 2.4cm together with the custom 3D printed bracket. The total length is 47cm. Motors are connected in single direction limiting it to 2D structures but increasing its resolution. This prototype does not support active torque control or detection of deformation input, though it would be easy to modify. Each servo rotates within range of 232 degrees.

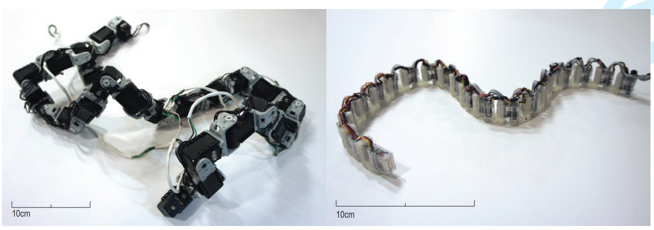

Figure 6. Two LineFORM prototypes. Without their skin, the underlying servo motors are visible (Left:Large, Right: Small).

APPLICATIONS

Shape-Changing Mobile Device

This application demonstrates the capability of LineFORM to transform into various form factors to create dynamic affordances and display simple notifications. By wrapping around a user's wrist, LineFORM can become a smart wristband. It can provide haptic feedback as active notification by constricting around the user's wrist. It can also display static notification, like a Flag, by shaping a tab on the end so that it gives the affordance of peeling off from the wrist (Figure 1 b). Once the user peels off the device from the wrist, it transforms into flat rectangular surface by folding itself into tight serpentine curves and then the user can give touch input (Figure 1 c). Lastly, when the user wants to make a call, it transforms into the vector icon of a telephone which lets the user both understand the mode and functionally allows her to easily grip and hold it up to her mouth and ear (Figure 1 d). We believe this is a meaningful research direction along with general purpose interaction techniques for small devices.

Shape-Changing Cord

This application demonstrates how the shape-changing interface can be integrated with a line-shaped everyday object, cord. One example is a cord which transforms according to modules connected. For instance, when it is connected to a lamp module, it changes the shape to stand/shade for lamp and forms an input lever to enable the user to control the brightness (Figure 7). Another example is a representation of data/energy flow for data cables (Figure 8) or prototyping cables of electronics so that the user can understand the invisible flow in the cable.

Figure 7. LineFORM used as a shape-changing cord which transforms into a lamp. A user can control its brightness through a rendered lever.

Figure 8. A shape-changing cord represents data flow through physical motion.

Body Constraints

This application demonstrates how whole body motion can be constrained by wrapping the actuated curve interface around limbs or joints like bandages so that it acts as an exoskeleton. Within this mode, it can constrain each of the user's arm joints dynamically by changing the stiffness, and it can also record motion and replay back on your body (Figure 9). This example enables users to learn kinesthetic motion such as sports and dances as an external motor memory or to provide physical feedforward and guidance for gestural interaction [5].

Figure 9. LineFORM wrapped around an arm to constrain body motion.

Smart Ruler

LineFORM can be used as a shape-changing ruler to support user drafting and drawing by providing a curve to draw lines along it or a boundary to define a region to fill within it, see Figure 10. It can change from a straight line, to a sinusoidal curve, and a variety of other shapes. Constraints can be dynamically changed according to tools, environments and actions; pen, paper, and the process of drawing.

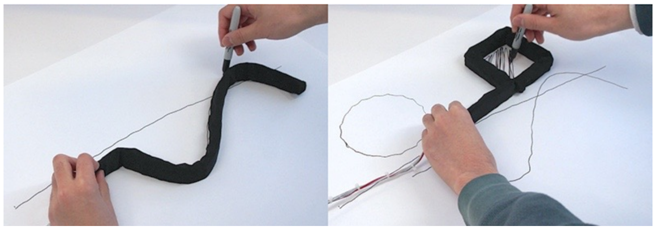

Figure 10. LineFORM can be used as a smart ruler with different shapes.

Computer Aided Design

LineFORM can be used to physically render and manipulate bezier or NURBs curves in 3D. Users can freely modify the model through direct deformation of its shape, or in another mode the curve remains stiff until a user pinches individual joints to loosen their stiffness. Direct manipulation and shape output can be combined to create various interaction techniques such as rendering hinges (change the stiffness on specific segments to enable users to partially deform), mirroring (detect deformation on one side to make symmetrical deformation on the other side), and snapping to grid (the line automatically snap to certain angles after users manipulate it roughly), see Figure 11.

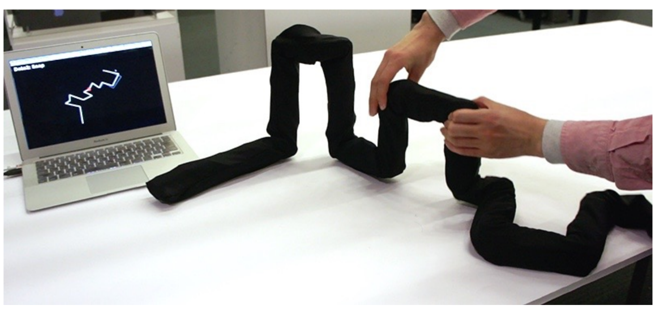

Figure 11. Users can manipulate CAD models with LineFORM. Here the curve is computationally limited to form right angles.

LIMITATIONS AND FUTURE WORK

Though we have not done any formal evaluations, LineFORM has been demonstrated to over 100 visitors to our lab during a demo day and we have collected their initial feedback and observed some limitations in our own use. One initial observation is that the larger LineFORM can startle users when it quickly changes form. In contrast to other grounded shape-changing interfaces such as shape displays, actuated curve displays can have a much greater change in scale, transforming from very small areas to much larger ones. As such, new techniques for feedback, feedfoward and compliance are needed. We also hope to evaluate interaction with actuated curve interfaces and compare with other form factors for shape-changing interfaces.

There are a number of technical limitations of our current LineFORM prototypes as well as limitations of actuated curve interfaces in general. One technical limitation of our current system is its limited resolution. In our current system design, resolution depends on the size of the motors used, which increases costs and power consumption that can be an issue for specific applications such as mobile devices. To represents smoother lines, other actuation technologies which have organic shape transformation can be considered (pneumatic, SMA, etc.). When replicating 3D shapes, there are obvious technical implications of torque and weight trade offs. Our system requires efficient servo motors or other actuation techniques to be developed to allow it to create more complex 3D forms. Another approach would be to submerge actuated curve interfaces in a fluid and make them neutrally buoyant - this would limit the contexts for interaction, but might allow a larger range of 3D shapes to be created. As for control algorithms, we plan to develop further system for automatic-wrapping around a body required in the wristband and body constraint applications. Predicting the collision between servomotors according to the input shape data, and optimising the final shape is also needed.

Though actuated curve interfaces can create solid forms, it is difficult to replicate wireframes or mesh data. Also the length of the interface might always be a limitation of how complex and large the shapes are that it can replicate. To address these limitations, it might be possible to extend and connect different sections of actuated curve interfaces, similar to modular snake robots [24].

Although we have implemented the prototypes to be able to control the angle and stiffeness of each joint within the display, future work could enable control of other physical parameters such as length, stretchiness, or thickness. This could improve its capabilities for transformation and expressiveness. Adding visual feedback on the periphery of lines to change their appearance, either by means of projecting mapping or by attaching small flexible displays, could allow for a whole new set of interactions, and is ultimately where we believe the most interesting applications lie.

We mainly discussed the direct interactions between humans and the actuated curve interface, however we feel that inter-material interaction (interacting with physical objects) has interesting directions from the perspective of interaction design, because we daily use line-shaped objects to manipulate other physical objects; to bundle, connect, or hang. In addition it might be useful to combine actuated curve interfaces with other shape output interfaces such as tangible tabletop robots [1].

CONCLUSION

In this paper we explored a new category of shape-changing interfaces which are based on linear series of actuators. These actuated curve interfaces have potential applications in a wide variety of domains, as demonstrated in the paper. We envisage LineFORM-style devices coupled with flexible displays as next generation mobile devices, which can display complex information, provide affordances on demand for different tasks, and constrain user interaction. We have shown that a relatively small number of actuators can be used to achieve an expressive display, and these systems may be easier to prototype than other form factors of high resolution shape display. Our hope is that this work will motivate others to further explore the space of actuated curve interfaces, from novel actuators to new interaction techniques.

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ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces

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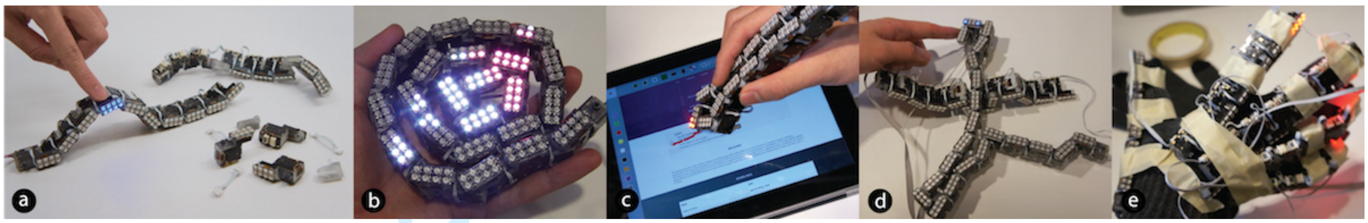

Figure 1. Device and application examples of the ChainFORM hardware system. (a: ChainFORM hardware configurations and modules, b: reconfigurable display, c: shape changing stylus, d: animated character, e: haptic glove.)

ABSTRACT

This paper presents ChainFORM: a linear, modular, actuated hardware system as a novel type of shape changing interface. Using rich sensing and actuation capability, this modular hardware system allows users to construct and customize a wide range of interactive applications. Inspired by modular and serpentine robotics, our prototype comprises identical modules that connect in a chain. Modules are equipped with rich input and output capability: touch detection on multiple surfaces, angular detection, visual output, and motor actuation. Each module includes a servo motor wrapped with a flexible circuit board with an embedded microcontroller.

Leveraging the modular functionality, we introduce novel interaction capability with shape changing interfaces, such as rearranging the shape/configuration and attaching to passive objects and bodies. To demonstrate the capability and interaction design space of ChainFORM, we implemented a variety of applications for both computer interfaces and hands-on prototyping tools.

Author Keywords

Actuated Curve Interfaces; Shape Changing Interfaces; Modular Robotics

ACM Classification Keywords

H.5.2. User Interfaces: Input Devices and Strategies, Haptic I/O.

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INTRODUCTION

As shape changing interfaces being an emerging field in HCI, a lot of actuation techniques have been introduced to provide physical shapes to represent digital data and to embody spatial interactions [9, 4]. Researchers are continually seeking techniques that have a variety of transformational capabilities in different geometries and scales [14, 24]. To extend the sensing and display capability of such shape changing interfaces, extra sensors or cameras and projectors have been installed for detecting human input and displaying information on the active surfaces. However, this strategy poses a challenge for scaling the system, which presents a problem, especially for mobile applications. To push the boundaries of shape-changing interface research, another approach calls for self-contained systems that integrate sensing, actuation and display across different scales, geometries, and transformations.

We present ChainFORM: a modular integrated hardware system that has a chained, linear form factor (Figure 1). The hardware comprises identical actuated modules connected in series, which allows the user to customize the length and the configuration of devices they construct. The form-factor of line and the modularity expands the possibility of transformation for both shapes and scales. In addition, each module integrates sensing, actuation, and display, enabling a wide array of applications and interactions to be developed with a uniform, easily scalable hardware infrastructure. Our approach is a step toward a general platform for custom shape-changing interfaces. Building on the idea and implementation of modular and serpentine robotics[17, 33, 35, 34, 30], we intend to extend their knowledge and technique to enrich interactions with shape-changing interfaces.

In this paper, we describe the technical implementation of our prototype and present a wide range of applications to demonstrate the modularity and rich input and output capability of our hardware design. We conducted technical evaluations and discuss the capabilities and limitations of our current prototype, with points for future improvement.

The contributions of the paper are as follows:

1. We developed a modular shape changing interface system which has a linear configuration. The module connect together to form an arbitrary linear shape using mechanical joints and electrical communication architecture.
2. We designed each module of the hardware system to have self-contained sensing, actuation and display system together for rich interaction capability.
3. We performed technical evaluations of the system.
4. We implemented a variety of application scenarios for shape changing computer interfaces and actuated prototyping tools.

RELATED WORK

Modular and Serpentine Robots

Many modular robotic systems and concepts have been proposed in the robotics field [17, 33, 35]. Our design is similar to that of modular snake robots which use identical modules based on motors with linear communication architecture [34, 30]. Although the focus of such systems is mainly on locomotion, we focus on how the hardware can interact with users to represent information and detect human input. Most robotics systems use modular systems because of robustness and maintenance-ease purposes, in contrast we take this capability for users to customize their own interfaces in different scales and configurations.

Robot Prototyping System

There are commercial products available for users to construct robots with customizable joints, blocks and brackets [5, 19]. Dynamixel servomotor system enables users to link the servomotor modules together with a dedicated bracket system [7]. They have daisy chain communication architecture where every motor can be controlled by a shared communication bus. ChainFORM has a similar communication system, but our hardware system can detect tangible interactions and display visual feedback with LEDs specialized for developing an interactive system. Also, our module is relatively small and light weight that users can construct hand held sized interfaces and easily attach to other materials. Furthermore, Dynamixel system requires manual address assignment for each module, in contrast our system automatically assigns the address to each module, which allows for quicker prototyping.

Modular Interfaces

In the field of HCI, modular hardware systems have been explored both for sensing and actuation to enable users to customize their own interfaces. As for input systems, Jacobson et al. presented a modular sensing device for CAD tools that can be customized to adapt to various character models to tangibly design postures and motions [15]. SensorTape has the form factor of tape that user can cut and arrange the length and shape of the sensor array using flexible circuit boards with a chained communication system design [6]. Another work demonstrates block-like interface, that automatically detected changes in shape. [32]. Phigets[11] and LittleBits[2] are toolkit which enable users to create interactive objects with various input and output modules.

Various concepts and methods of shape changing interfaces have been presented recently in the field of HCI to render physical shape of digital data and provide dynamic affordance for physical interactions [4, 24, 9]. Because the scalability of these systems is often limited to the size of the hardware designs, there have been some modular systems proposed to create custom actuated interfaces. Topobo and Bosu are toolkits for designers and kids to create kinetic crafts and motion with tangible interactions[23, 22]. ShapeClip is a prototyping tool that is composed of linear actuated modules for constructing customized shape displays [13].

Line-based Interfaces

Within the HCI field, there have also been proposed various types of tangible interfaces which have form factor of lines. ShapeTape was introduced as a passive 3D modeling tool that leveraging the flexibility and affordance of a spline[12]. FlexiBend is a tape-like input interface that can be attached to deformable materials for fabricating multi-input interfaces [3]. Katsumoto et al. presented a bi-stable geometries for a controller composed with chained mechanical hinges and proposed applications that provide different digital functions according to shapes [16].

As a novel form of shape changing interfaces, LineFORM introduced the concept of actuated curve interface leveraging the dynamic transformation capability and tangible interaction of lines [20]. Although their implementation was not able for users to change the length of the hardware, in our system, in addition to modular design, we intend to enrich the concept and interaction for an actuated curved interface with rich sensing capabilities and display technologies.

CHAINFORM

Function and Interaction Overview

ChainFORM is a modular hardware system which is composed of identical modules. Each module has rich sensing and actuation capability (Figure 2).

The module can detect tangible interactions by users. Specifically, the angular deformation and the way users touch the modules can be detected. The ChainFORM module can provide several outputs. One is motor actuation, it can change the angle of the joint and also torque can be controlled to lock the joint or loose so that user can deform by their hands and also feel different stiffness as tactile feedback. The color of the surface of each module can be displayed with LEDs to provide visual feedback.

The core feature of ChainFORM is its modularity. This feature enables users to customize the length and configuration of the chained hardware. We were strongly inspired by linear craft materials such as strings, wires or tapes that can be cut to separate and knotted to connect, and our hardware design enables the user to customize the interface similar to these

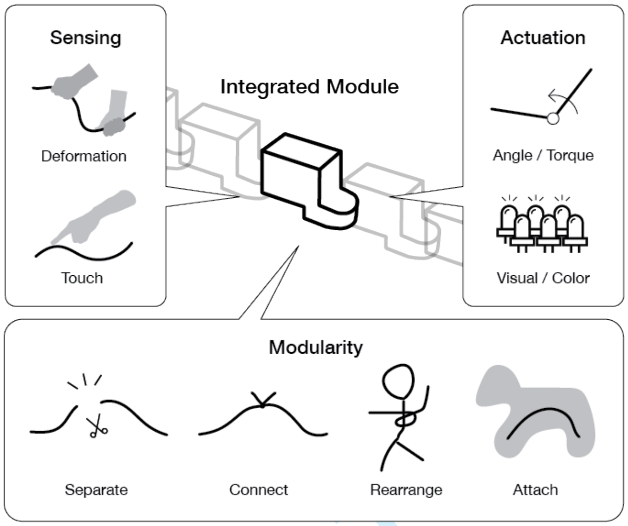

Figure 2. The integrated module with three functionalities; Sensing, Actuation and Modularity.

materials. Leveraging the capability, users can rearrange the configuration of the device to create desired shape and transformation. Because of its relatively small size, it can also be attached to passive objects or bodies to detect input and actuate accordingly.

System Design

The overall system is composed of a chain of integrated modules, a master board and a software on a computer. The master module contains a Teensy 3.2 with an ARM Cortex-M4 (MK20DX256VLH7, Freescale). The master coordinates the communications between the modules and shuttles data to the computer over USB. The software was developed using Processing on OSX computer.

Module Design

The module of our system is composed of three components as shown in Figure 3; a circuit board, a 3D printed bracket and a servo motor. The motor is placed inside the 3D printed bracket and the bracket provides a mechanical connection for joining to another module. Some parts of the circuit board are designed to have flexible hinges (Figure 4a), so that it can be wrapped around the 3D printed bracket which incorporates the motor. Using the joint of this 3D printed bracket, only 2D planar transformation can be created. Therefore we also developed a joint that translate this configuration into 3D to expand the transformation capability (Figure 5). For the servo motor, we used HS-5035HD (Hitec) which is the smallest servo motor we could find on the market.

The circuit board contains ATmega328p (Atmel) microcontroller, which is the “brain” of the module. MTCH6102 (Microchip) was used to perform capacitive sensing. A small solid-state relay, G3VM-21UR11 (OMRON) was used to turn on/off the torque of servo motor. An array of 8 Neopixels Mini (Adafruit) was used for the LED display covering a single surface of a module. The circuit board is designed to integrate six capacitive sensing surfaces, as shown in Figure 4B,

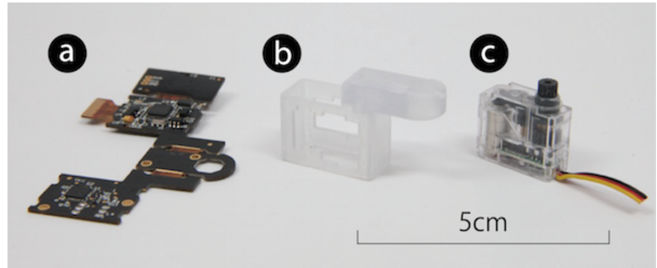

Figure 3. The components of each module (a: circuit board with flexible hinges, b: 3D printed bracket, c: HS-5035HD Servo Motor.

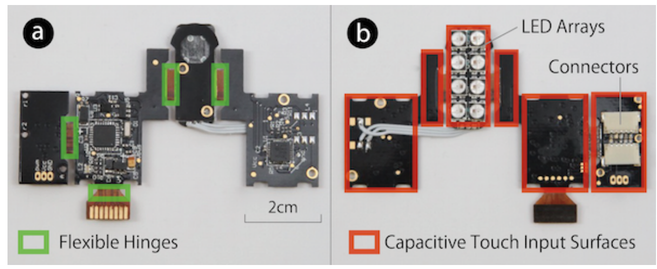

Figure 4. Design of the circuit board (A: inner side, B: external side).

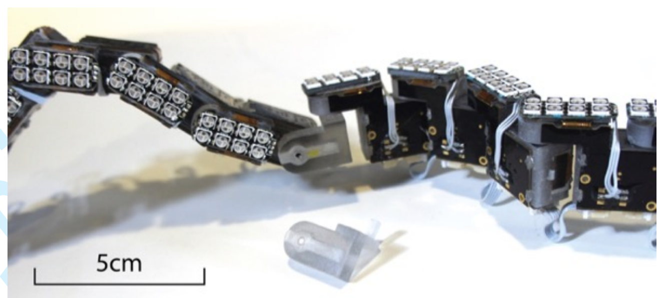

Figure 5. A joint that translates the motion into 3D configuration.

so that every surface of the module is capable of touch sensing.

Figure 6 shows the system configuration of each module. We modified each servo motor to read the input of internal potentiometer values and to control the connection of the wire to the motor so that the motor axis can either be flexible for manual control or actuated(stiff) for transforming and locking shape (Figure 6). Two connectors are used to attach the modules in series using a 5-wire cable for communication and power.

Chained Communication Architecture

We wanted the users to have an ability to quickly add and disconnect modules, without the need to reprogram the network. To do so we developed a communication architecture that automatically determines how many modules there are and how they are connected. Furthermore, we wanted to have real-time I/O, even with a large number of modules. There are no ready-made communications protocols that do so. We created a custom network based on the I2C protocol and inspired by the SensorTape Project [6]. We believe that the developed

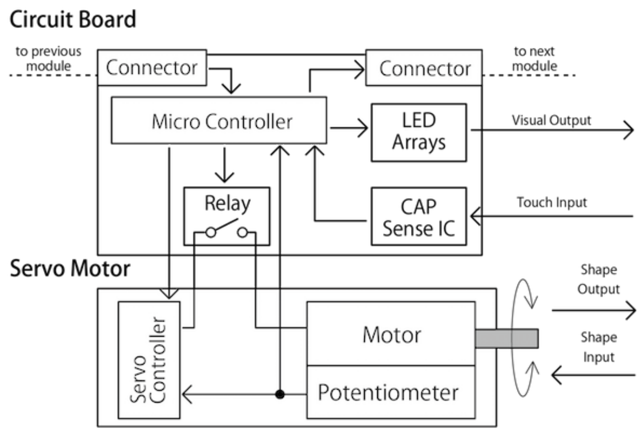

Figure 6. System configuration of each module.

network architecture can be applied to other types of modular systems, therefore we explain it in detail.

The network has two parts; the serial peer-to-peer connections between the modules and the global Inter-Integrated Circuit (I2C) bus. The peer-to-peer network only ran once after start-up. It was used to assign a unique address to each module based on how far they are from the master. Peer-to-peer scheme functions similarly to a shift register. The master sends a "0" to the first module, which assigns its address to "0". The first module sends a "1" to the next module. This cascade repeats until the last module is reached. At the end, each module has a unique address and is individually addressable by the I2C bus.

During normal operation, the I2C master polls the modules sequentially, and immediately sends the data to the PC over 12 Mbit/sec USB connection. After polling all the modules, the master checks if there is any data from the PC (e.g, motor or LED commands). If data is available, it is instantly transmitted to the addressed module. Then, the polling resumes.

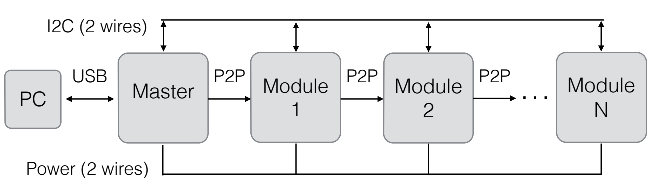

Figure 7. Network architecture of ChainFORM. All the modules and the master share the same power, ground and I2C bus. Also, each module is connected to it's neighbor for peer-to-peer communications. In total, there are 5 connections between all the modules.

Software Control

Our Processing-based software is designed to communicate with the chained hardware system through Teensy. Every input data including potentiometer and touch sensing data are received every frame and output data can be sent once every frame (60 Hz framerate). Our GUI system enables users to control angles and torque of each motor and visualize raw input data. Visualization can be switched between 2D and 3D. We developed some mid-level software application for specific function and interactions described below.

Color Mapping Function for LEDs - Mainly for reconfigurable display applications, we developed a function that the color of each LED can be defined through default sketch function on Processing. As the software receives potentiometer values, it can estimate the whole shape of the device and location of each LED. Using this function on the software, users only need to write codes on visualization such as shapes, texts or loaded images which are default functions for Processing. Then, according to the visual sketch and location of each LED, the software automatically allocates a color for each LED 8. In our implementation, we built this application only for 2D transformation, but we believe this can be applied for 3D transformation with extra joints and 3D sketching functions.

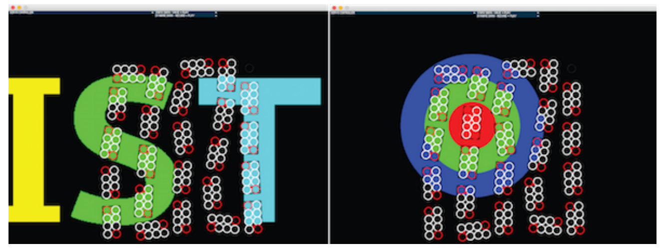

Figure 8. Software on Processing to allocate LED color according to the visual sketch on screen (left: texts, right: shapes).

Record and Replay with Hands - We developed a function for shape and motion design. For chain-based hardware design, it is complicated to generate target shape and motion by coding because users need to define an angle for each module to get the whole shape. We developed manual record and replay function to overcome this problem. Similar to Topobo [23], the shape and motion can be recorded based on the potentiometer values and replayed back anytime. Non-programmers can easily design motion without programming, and programmers can develop interaction system to replay these shapes and motions according to specific input data from sensors.

APPLICATIONS

Here, we present applications that demonstrate the capability of proposed system. We mainly proposed two categories of applications. The first category is computer interfaces that can adapt to user's needs and digital functions with transforming and modular capability. This category includes three applications; adaptive input interface, shape changing modular display, and shape changing stylus. The second category is prototyping tools that leverage the customizability of our hardware system to make creation process of actuated interactive system easier. We propose two application under this category; animated craft and body augmentation tool.

Computer Interfaces

Adaptive Input Interface

This application presents input interfaces which can transform into various form factor that can adapt to a different function on computers and provide dynamic physical affordances[9] to users. Specifically, this system could be used to applications which require various input. For example, for

CAD software, the chained interface can let users manipulate vector data tangibly as a line and form a touch surface as a color picker(Figure 9a, b). The modularity of the system enables users to have multiple controls on demand such as rotation sensors or sliders for CAD as shown in 9c.

By turning off the motor torque on specific joints, it can produce mechanical hinge input interface. Figure9d, e shows examples of a gun controller that can detect when the trigger is depressed, and 2 DoF joystick that is be constructed using joints for 3D transformation. This input could be used for gaming applications that require different controller for different modes. This sensing interface can be combined with motor actuation to provide haptic feedback to users.

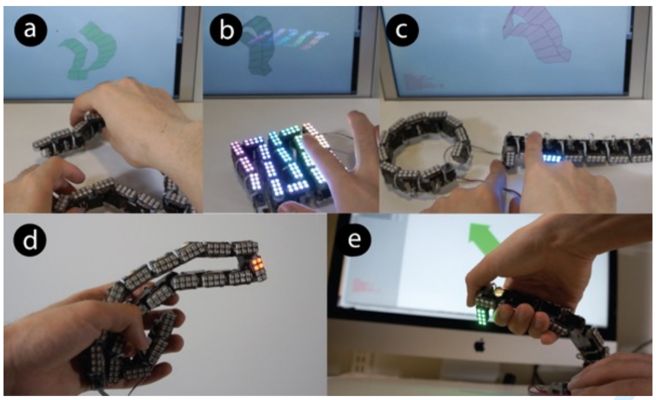

Figure 9. Examples of dynamic and modular input interfaces (a: tangible curve manipulation, b: touch surface for color picker, c: rotary sensor and slider for rotation and scaling created from single line, d: gun controller with mechanical toggle input, e: 2 DoF joystick interface.)

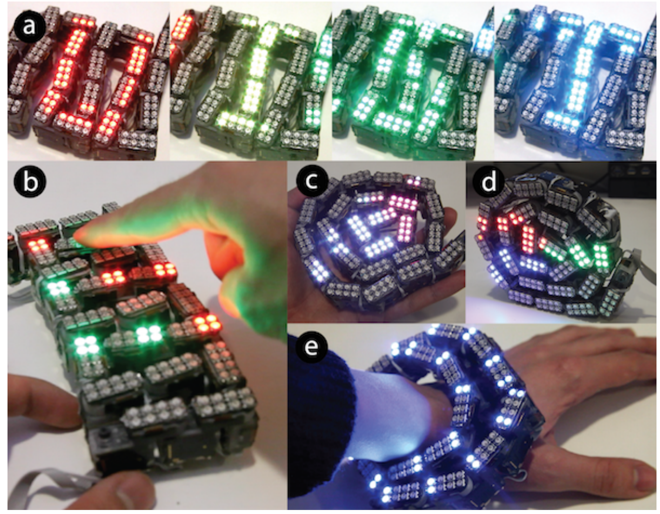

Figure 10. Examples of reconfigurable displays (a: square for showing texts "U, I, S, T", b: rectangle for pass code, c: circle for compass, d:circle for analog clock, e: wrapping around a wrist as fashionable wearable device)

Shape Changing Modular Display

Utilizing the LED arrays on each module, ChainFORM can construct displays in various shapes. Although a lot of systems for shape changing flexible displays have been proposed, they mostly consist of rectangular surfaces that can create slight curves [10, 26]. In contrast, our chained hardware system has more dynamic transformation capability to create shapes either in 2D or 3D. Using our display technology, we can imagine a future smartphone that can change shape from rectangular shapes to present texts or pass cord lock information, to circle shapes for navigating users as a compass (Figure 10a,b,c). Similar to smart watches that can change the visual skin, our system can inform time in various shapes and appearance according to users' preferences (Figure 10d). Utilizing the form factor of a line, this display can wrap around objects to change any surface into displays. Especially when attaching on our body, it can be wearable displays for fashions (Figure 10e).

The modular functionality of ChainFORM enables users to customize the size of the display as well. Figure 11 shows the example scenario utilizing the modularity. When multiple users have personal mobile displays composed with ChainFORM(a), they can combine their displays(b) to create a large display that can provide multi-user contents such as movies or gaming(c). Conversely, a large screen can be split into small personal displays for multiple users. Comparing to other modular display systems [1, 18, 25], our system can physically actuate and it is scalable from few centimeter small unit to large displays together with rich tangible sensing capability. Our approach of display with a chain of LED arrays has more freedom and capability of transformation than other modular display techniques.

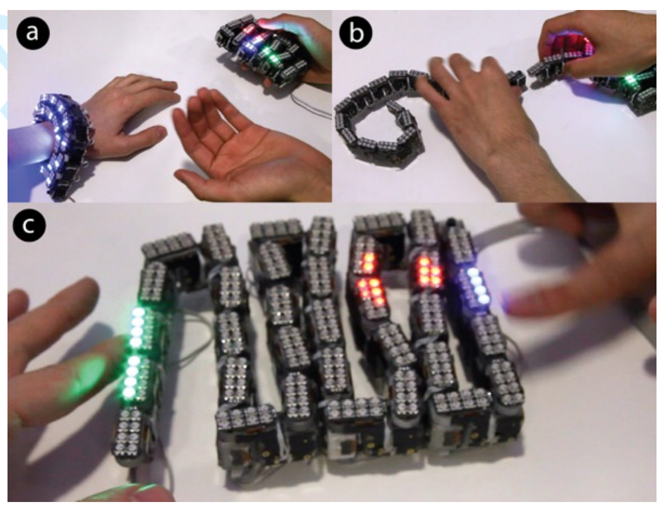

Figure 11. User scenario with modular display for multi-user interaction (a: two separate ChainFORM displays for personal use, b: combining two displays, c: connected into a single chain, the device reconfigure to one large display for multi-user applications, in this case, the Pong game.)

Shape Changing Stylus

The relatively small size of the modular system allows building of transforming hand-held tools. Using our prototype, we developed a stylus device which transforms according to the function in digital CAD software. Similar to the multi-touch pen system presented in [28], the CAD function can be defined by the way users hold the grip utilizing the multiple touch sensing surfaces (Figure 12a). Our proposed stylus interface transforms the physical shape of tool tip instantly once users change gripping. The tip becomes pen for thin stroke, brush for wide stroke and magnifying lens for zooming (Figure 12b, c, d). LED can help users visualize what kind of color they are picking now.

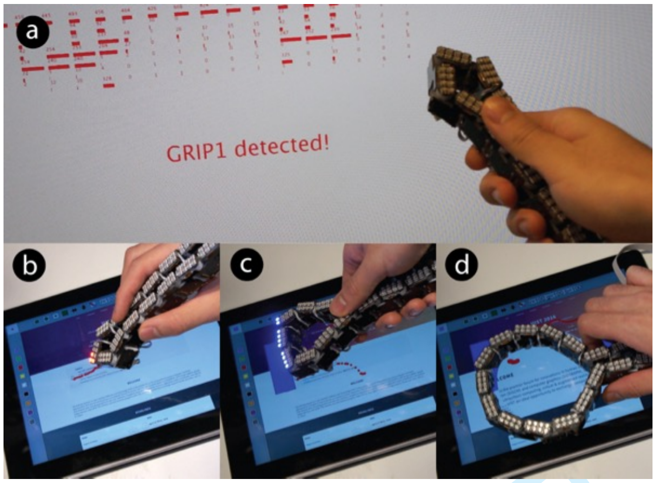

Figure 12. Stylus interface that can transform according to the grip (a: detecting grip with multiple touch sensing feedback, b: pen mode for thin stroke, c: brush mode for wide stroke, d: magnifying glass for zooming).

Prototyping Tool for Actuation and Interaction

Animated Craft

As a prototyping toolkit, modularity and rich interactivity of the ChainFORM system allow crafting animated objects. Children can learn to build an active mechanical structure through prototyping. Artists may quickly prototype storytelling medium. Just like using traditional linear craft material such as wires or tapes, the user can deform, cut, connect and attach to other materials to construct their own shapes and motions. For example, as Figure 13a shows, the user can make a stick figure character that reacts to touch by changing his facial expression with LEDs and by moving his body.

Users can attach the hardware with customized length and configuration to paper crafts or hand puppets as an actuated skeleton to create expressive motion (Figure 13 b, d). The user can use LEDs for additive expressions, such as facial emotion as Figure 13c shows. Comparing to previous works of attachable actuators for animated crafts [21, 29], our hardware design has capabilities for a wider variety of motion, sensing tangible interactions, and visual representation. It is enabled by a high density of actuators, sensors, and LEDs. Moreover, the actuation enables materials not only for expression but also for actual kinetic locomotion. Figure 13e shows an example of turning a plain box into a walking robot, using ChainFORM as legs.

To design the motion of the chain, users can either write a code on Processing or, to make it more accessible to non-programmers, tangibly program the motion using record and replay function, similar to Topobo[23]. Not only dynamic motion but also passive stiffness can be defined by users to generate joints and hinges just like character rigging in Computer Graphics.

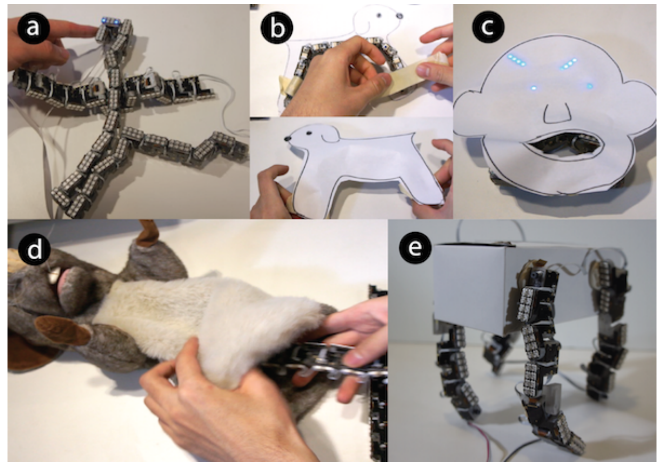

Figure 13. Examples of animated craft (a: interactive stick man, b: attaching to paper craft and recording motion by hand, c: facial expression represented with transformation and LEDs, d: installing in hand puppet, e: attaching to a plain box as a leg for locomotion).

Body Augmentation Tool

Leveraging the customizing and attaching capability, the ChainFORM system enables users to construct customized body augmentation devices, as our bodies have different size and shapes. Figure 14a shows an example of attaching to gloves to augment our fingers, that can be used either for a haptic glove in VR contents or for rehabilitation tool to help grasping objects for elders. Figure 14b shows attaching a long piece of ChainFORM to the back of an ordinary shirt as an external smart spine that can sense posture and correct by actuating. Our modular system would make personal fabrication and prototyping of body augmentation tool easy and accessible for users.

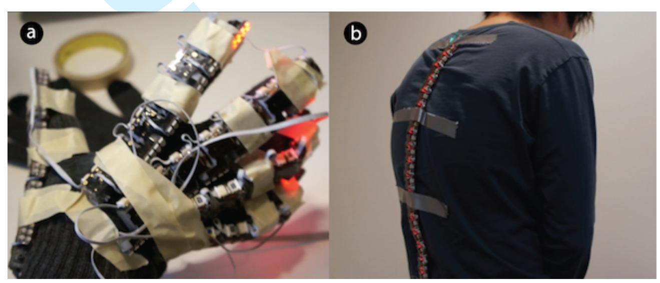

Figure 14. Examples of body augmentation using ChainFORM (a: haptic glove, b: external smart spine for posture correction.)

EVALUATION

Technical Evaluation

Speed: To have seamless interactions, it is important to have high update rate, even if there are many ChainFORM modules. The download data rate from the computer to the modules is 170 kbits/sec. The upload data rate from the modules to the computer is also 170 kbits/sec. Download and upload rates share the same I2C bus, running at 400kHz. Theoretically, the data rate can be up to 400 kbits/sec. Due to overhead, we only utilized 43% of maximum capacity of the bus, even with much timing optimization.

The I2C bus is the bottleneck of the current speed, as bus capacitance makes higher speeds unreliable. A different signaling method, such as CAN (Controlled Area Network) bus with differential pair can have bandwidth as high as 2Mbit/sec [8].

The download and upload rate is independent of the number of modules, and is shared between modules. For example, one module will have download data rate of 170 kbits/sec but with 10 modules, each one will be allocated 17 kbits/sec. The raw USB data rate from the master to the PC was 12 MBit/sec. The actual data rate depends on the computer's USB driver. Windows 7 driver could not deal well with frequent small packets. MAC OSX (10.9.4) USB driver worked more effectively.

In practice, the raw data rate translates to about 2ms of latency for each module. The latency is shown in Figure 15. Ideally, modules would be updated at a frame rate of 30Hz, which is especially important for animations on LED displays. The data shows that up to 17 modules can be updated in one frame.

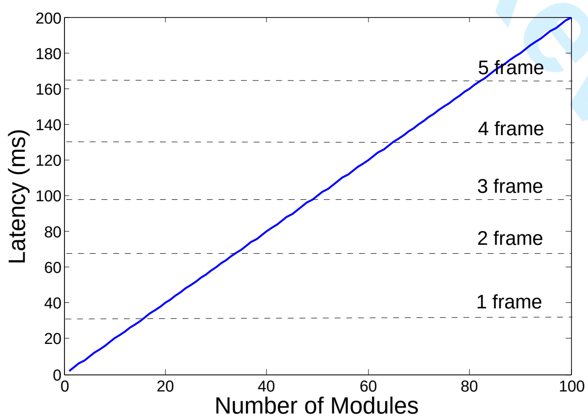

Figure 15. Latency with different number of modulus. The latency is also shown in terms of frame rate (at 30Hz). For example, updating 50 modules will take 3 frames.

Force: The force of the system relies on the servomotor we use for each module. The servomotor used for ChainFORM has a torque of 0.8kg.cm. As for haptic joystick or gloves, this torque can be perceived by users when the force is applied to a finger according to Walmsley et al[31]. Accordingly, the torque can also be perceived with the back of user as the external spine application, while it is not enough to directly 'move' their back to correct posture. In our prototyping process of locomotive craft application shown in Figure 13e, we observed that the system can hold and move the weight of box up to 350g.

Power Consumption: The power consumption is important as it influences how many modules can be connected together. The average power consumption of each module is 83.0 mA, when the LED shield and motors are on. The maximum peak current is 125 mA. When the motor and LED shield are off the power consumption decreases to 13.3 mA. The motors consume the most energy: 51.5 mA.

Maximum Length: An important consideration is how many modules can be theoretically connected together. There are three main considerations: communications reliability, power delivery, and address space.

First, the address space is limited to 7 bits or 127 modules. The address space is defined programmatically, so it's not a fundamental limitation.

Second, the power delivery. Each module needs to have enough power to power its parts. With high currents, the resistance of the power wires can create a large voltage drop at modules that are further away from the power supply. Each module needs at least 3.6 V to function and the maximum supply voltage is 9 V. The resistance of 3 cm 28 AWG cables that connect the modules together is 0.0062 Ohm. The maximum resistance of each connector is 0.040 Ohm. The peak current consumption of each module is 125 mA. We calculated the voltage drop with a different number of connected modules, as shown in Figure 16. We found that the maximum number of nodes that can be powered is 32. The main source of resistance are connectors between modules, as each module contains two of them. Without the connectors, up to 112 modules can be powered. It is likely there are more resistance sources, such as the power supply cable, and the PCB traces. A larger number of nodes can be connected if using thicker wires with less resistance and using a different type of connectors. Also, the modules can be powered by two power supplies from two sides of the chain, as we had to do when powering 35 modules.

Third, high-speed I2C bus is very susceptible to parasitic capacitance, that increases with the number of modules. By measuring the RC-constant, we calculate that the base parasitic capacitance is 83 pF and each node adds 3.3 pF of capacitance. This leads us to believe that up to 96 modules can be safely supported until reaching the maximum of 400 pF, as specified in I2S standard [27]. This limitation of I2C can be avoided by using different signaling method, such as differential signaling or by using wireless communications between modules.

The above analysis indicates that the power delivery limits the number of modules to 32. Largely, it is caused by the resistance of the connectors between the modules.

DISCUSSION AND FUTURE WORK

Technical Limitation and Improvements

Various technical aspects of the implementation can be improved. The resolution of LED arrays is one obvious spec that can be improved that our current system requires large screen to show only single alphabet as shown in Figure 10a. The resolution can be improved by using a small pixelated display instead of discrete LEDs. Also, there was only single surface of LED arrays, but having LEDs on every surface of the module would expand the display capability especially in 3D configurations. Adding pixelated displays or more displays will require faster communication speeds and more memory

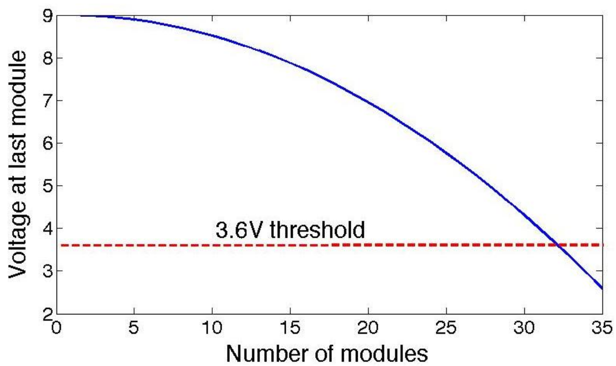

Figure 16. Simulation of voltage drop at the last module, with different number of modules connected. The module can not function if voltage is below 3.6V. The estimated maximum number of modules is 32

to maintain real-time interactions. In the future, we plan to use a differential communication scheme to increase the raw data rate to 2 Mbit/sec, which will allow higher resolution displays.

Improving the Joint for Easy Manual Assembly

The mechanical connection between each module can be designed to include electrical connection as well so that it is easier for users to assemble the device, similar to littleBits [2]. We could design a joint that can be connected in multiple configurations without additional joint, and the configuration could be recognized by sensors or electrical connections automatically. Because our system requires restarting the software when the configuration of the module is changed, we plan to introduce hot plug communication system which can recognize the updated configuration in real time.

Applying the Architecture to Other Motors and Actuators

Although the size is relatively small to be attached to different materials and objects, the torque is weak for some applications. Utilizing the general design of our implementation technique which uses circuit board design that turns ordinary servo motors into daisy chained controlled system, we could develop a board which can adapt to various servo motors so that users or designers can choose the motors according to their size and torque for appropriate applications which require scalable and modular system. We even foresee that the chained architecture system could be applied to other actuation techniques such as pneumatics for lighter and softer purposes, such as actuating clothing.

Adding Modules for Further Interaction and Configuration

We also consider one next step of ChainFORM to have other types of modules which provide different sensing and actuation functions. For example, accelerometers, cameras, speakers, mics, or pulse sensing modules could be added for various applications such as input interfaces, mobile devices, and wearables. In addition, we are interested in building a branch modules which can split the module into two or more branches of a chain. Advanced communication architecture is required for such implementation, as they will need to detect the branching.

Self Assembly Functions

While our system design requires manual assembly for changing the length and configuration, implementing self-assembling function may expand the display and interaction possibility as well. This will allow multiple ChainFORMs to autonomously connect together. Minimizing the size of the module can be a challenge because this function requires adding extra actuators which can clutch other modules as previous reconfigurable robotics system do [35, 17, 33]. Also, it is challenging to develop the algorithms and sensors required for autonomous assembly.

Conducting Workshops for User Study

Regarding the strong customizability and prototyping aspect of ChainFORM, we are very interested in conducting workshop-based user studies. We plan to observe the usage of ChainFORM and how it would stimulate the creativity of children, designers, and artists. Towards this user study, improvement of the software is required especially for a non-programmer to prototype interactions easily. Also, this would require making the modules easy to manufacture at larger scale.

Further Applications for Explorative Learning

We would like to explore further applications which demonstrate the novel interaction of ChainFORM, leveraging the customization capability. One domain is learning tools. This kind of application lets users customize length or shape of the device that represents abstract information, then observe behavior through their transformation to learn algorithms or underlying abstract ideas. For example, architecture simulation for learning physics and structure : A user can construct a different structure of buildings or bridges to see how they behave when an external/virtual force (e.g. earthquake) is provided through motion and visual feedback. The physical exploration aspect could be applied to learning molecular structure or protein folding as well.

CONCLUSION

In summary, we introduced chained modular hardware system that can transform, display visual information, and detect tangible interactions. We presented the broad set of applications that shows the potential interaction capability of the hardware. We believe that the modularity and integrated sensing, actuation and display capabilities of ChainFORM will enrich our interaction for computer interfaces and prototyping tools.

In addition, we envision a future that the ChainFORM system becomes an accessible roll of material just like tapes or strings, so that user can easily cut and connect the material to create customized interfaces, tools, wearables or even furniture that can sense our intention, transform to adapt to our hands and bodies, and inform us through display.

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