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

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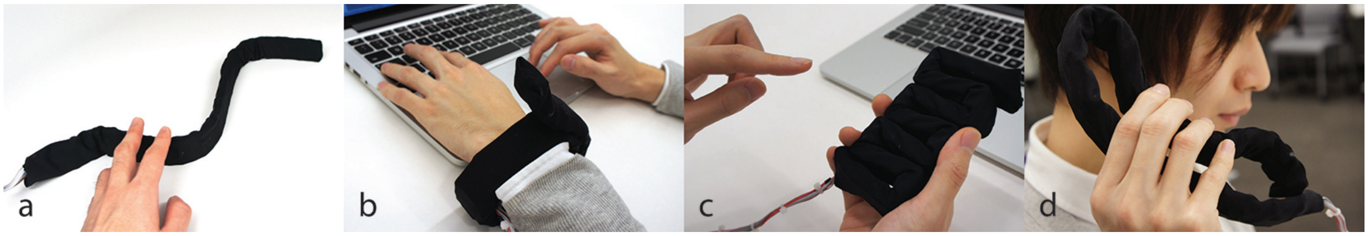

Figure 1. The LineFORM actuated curve interface can transform between shapes for mobile interaction: a) curve, b) wristband, c) surface, d) phone.

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-

UIST '15, November 08-11, 2015, Charlotte, NC, USA.
ACM 978-1-4503-3779-3/15/11.
http://dx.doi.org/10.1145/2807442.2807452

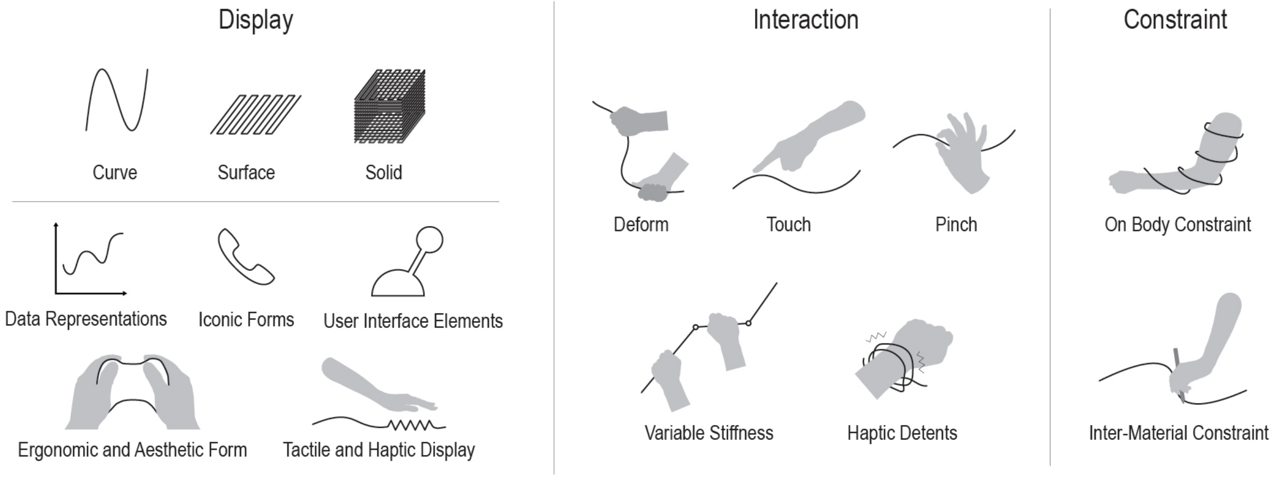

Figure 2. Design Space of Actuated Curve Interfaces.

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.

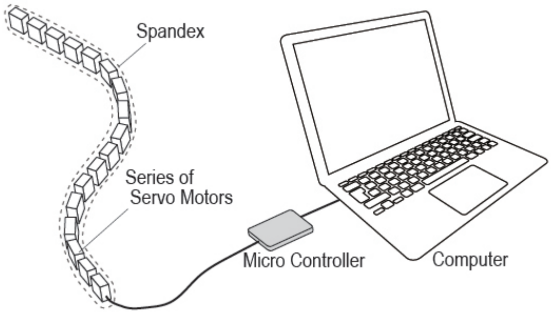

Figure 4. System Diagram of LineFORM.

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).

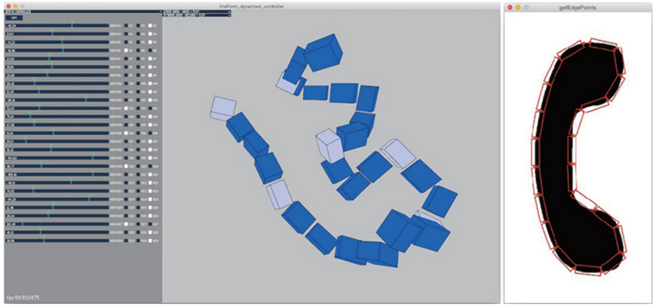

Figure 5. Software for Controlling Shapes (Left:GUI, Right:creating shape data from icon).

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.

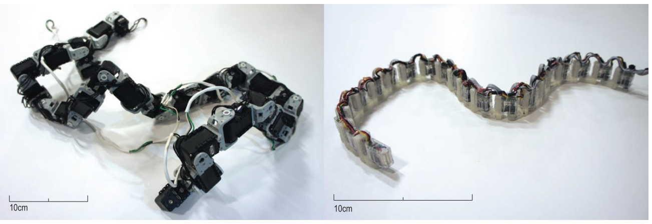

Figure 6. Two LineFORM prototypes. Without their skin, the underlying servo motors are visible (Left:Large, Right: Small).

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.

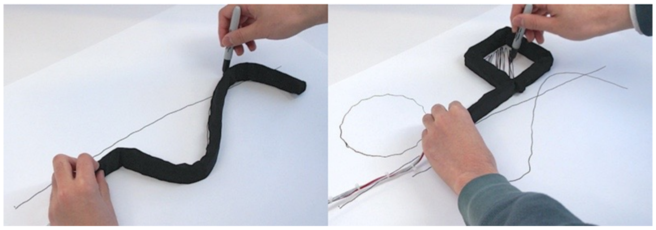

Figure 10. LineFORM can be used as a smart ruler with different shapes.

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.

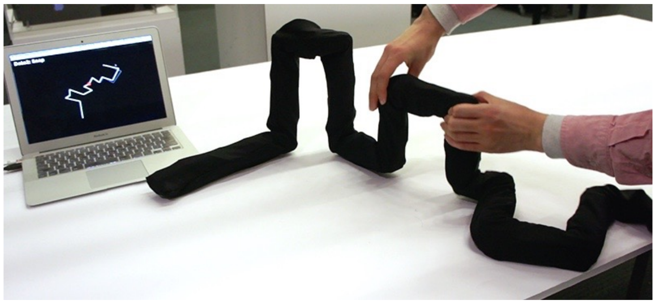

Figure 11. Users can manipulate CAD models with LineFORM. Here the curve is computationally limited to form right angles.

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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