FlexiBend: Enabling Interactivity of Multi-Part, Deformable Fabrications Using Single Shape-Sensing Strip

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ABSTRACT
This paper presents *FlexiBend*, an easily installable shape-sensing strip that enables interactivity of multi-part, deformable fabrications. The flexible sensor strip is composed of a dense linear array of strain gauges, therefore it has shape sensing capability. After installation, FlexiBend can simultaneously sense user inputs in different parts of a fabrication or even capture the geometry of a deformable fabrication.

Author Keywords
Shape-sensing strip, fabrication, multi-part, deformable.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION
New 3D fabrication tools, e.g., 3D printers, have simplified the design and fabrication of physical objects. In addition to fabricating simple forms, fabricating materials into multiple movable parts, such as by adding controllable widgets on a fabrication, can provide additional functionality. Further incorporating pliable materials further increases fabrication flexibility. Given the increasing versatility of personal fabrications, designers have begun exploring the possibility of adding interactivity to these fabrications.

Various techniques have been proposed to enable interactivity of multi-part, deformable fabrications by distributing optical [10, 13] or mechanical [11, 12] sensors into the parts. Slyper *et al.* used distributed resistive sensors in silicone-made physical models to sense deformations [10]. Willis *et al.* embedded optoelectronic components in optic prints to detect user interactions [13]. Sugiura *et al.* also embedded multiple wireless FuwaFuwa modules, each of which consisted of a pair of IR-LEDs and photosensors, into soft objects to sense its deformation through the reflected light measurements [11]. Vanderloock *et al.* embedded electrodes in soft objects stuffed with conductive fillings to sense deformation by measuring the difference in resistance between electrodes [12]. However, properly installing numerous sensors in physical models increases complexity for makers.

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Figure 1. (a) FlexiBend is an easily installable shape-sensing strip that enables interactivity of (b) multi-part, (c) deformable fabrications.

Previous research has also proposed the use of time domain reflectometry techniques [14], a single acoustic sensor [2, 8], a swept-frequency generator-receiver pair [4, 6, 9], or a camera [7] to provide interactivity of fabrications and to allow makers to enable the sensing mechanisms with ease. Wimmer and Baudisch [14] used time domain reflectometry techniques to enable touch interactions on deformable surfaces. Lamello [8] used an acoustic sensor to detect user interactions on specific-designed tangible comb-like sound-making structures. Acoustruments [2] also proposed a system of passive, physical sound-transmission mechanisms for enabling an acoustic sensor to recognize user interactions. Acoustic- [4] or capacitive-based [6] swept-frequency sensing methods are also useful for sensing user interactions with everyday objects or specific-designed 3D printed objects [9]. However, these methods cannot capture high-dimensional inputs such as the geometry of a deformable physical model or multiple moving parts at the same time. Sauron [7] attached a single camera to a 3D printed prototype to observe the interior portions of input components to determine the user interactions. However, the model often required specific structure designs to bypass the line-of-sight problem.

FLEXIBEND: THIN, FLEXIBLE SHAPE-SENSING STRIP
This work presents *FlexiBend* (Figure 1), an easily installable shape-sensing strip that enables multiple degree-of-freedom

(DOF) interactivity to fabrications. FlexiBend uses a dense linear array of strain gauges to achieve shape sensing capability. After installing a FlexiBend into a multi-part or deformable object, the FlexiBend can simultaneously sense the user inputs on its parts or deformed geometry. This novel sensor facilitates makers to enable interactivity of multi-part or deformable fabrications with ease.

Exploring Usable Shape Sensors

This research first attempted to develop thin, flexible shape-sensing strips that can be embedded in fabrications. Commercial resistive-based (e.g., Flex and Bend-Mini) and fiber-optics-based (e.g., ShapeTape [1]) devices are available for shape sensing. Researchers have also developed piezoelectric bend sensors such as FlexSense [5]. However, these solutions are either too large to embed in a 3D printed object or do not have sufficient resolution to sense fine-grain interactions at the required level of detail. Hence, the proposed solution is to use conventional sensor units but with customized shapes.

A strain gauge, which is a thin bend sensor typically used to monitor deformation in rigid structures, is apparently an ideal candidate. Deformation changes the electrical resistance of a strain gauge. This resistance change, which is usually measured with a Wheatstone bridge, can be used as an indicator of deformation. A dense array of multiple strain gauges can provide a thin, flexible and high-resolution shape sensor.

Understanding Strain Gauges

An experiment is performed to determine how deformation actually affects the resistance reading. We made six short flexible strips, each of which contains one strain gauge sensor. This study first fabricated six short flexible strips, each of which contained one strain gauge sensor. Each strip was fit to a set of plastic molds, which described semicircles of different radiuses (Figure 2a). Bending the strain gauge sensor into semicircles of different radiuses is the same as bending the sensor to a specific angle. Nine bending angles (-30 to 30 degrees) were tested.

The experimental results (Figure 2b) show that the sensor readings are linearly related to the bend angles indicated by the strain gauges. The variance among strain gauges also indicates that calibration is required before use. Based on these experimental results, a shape-sensing strip was fabricated using an array of strain gauges.

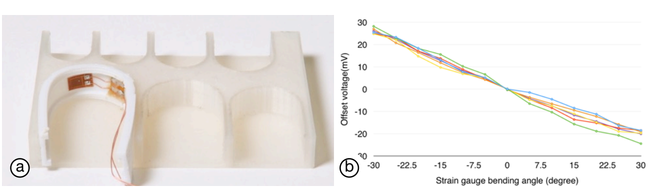

Figure 2. Experimental comparison of deformation and resistance in strain gauges. (a) Apparatus. (b) Results.

IMPLEMENTATION

Sensing Hardware

Figure 3a shows the hardware prototype. Sixteen strain gauges were mounted on a flexible base fabricated with a 3D-printer and pliable filament, NinjaFlex[1]. The base ensures structural integrity and uniform deformation of FlexiBend. Each strain gauge in the array detects the direction of the local bending, which increases or decreases its resistance. The resistances of all 16 strain gauges were collected by a main board consisting of a micro-controller (Atmel ATMEGA328P), a 16-bit analog-to-digital convertor (TI ADS1115), and two low-ohmic 8-channel multiplexers (NXP NX3L4051) at a consistent refresh rate of 45 fps. Figure 3b is a schematic diagram of the overall hardware architecture.

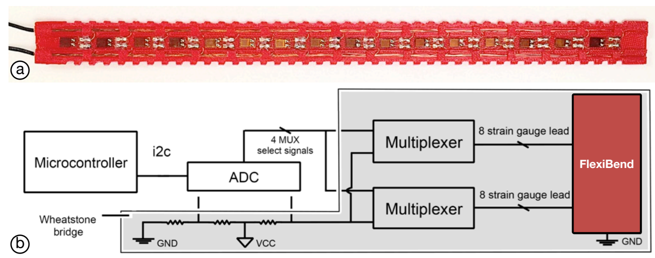

Figure 3. (a) FlexiBend prototype. (b) Hardware architecture.

Signal Processing and Calibration

A strain gauge describes an arc segment in the length of the strain gauge. Therefore, 16 discrete arc segments are uniformly distributed across the FlexiBand. Figure 4 shows the process used to convert isolated arc segments to a flexible curve representing shape. The first arc segment was replaced with four uniformly distributed points. At the end point, we travelled along another arc segment in the length of a known gap between strain gauges in the strip. The radius of the gap segment was calculated as the linear interpolation of the adjacent strain gauge segments. The next strain gauge segment was then replaced with four points. The process was repeated until the last strain gauge segment was reached. After the process, 64 (16x4) points are used as pivots to guide a spline curve. For calibration, the entire strip was fit to five cylindrical objects of different radiuses. Therefore, all strain gauges could be calibrated simultaneously.

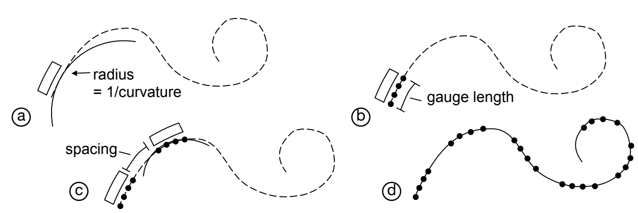

Figure 4. Procedure of converting 16 curvature points reported by the strain gauges into a smooth curve using spline interpolation.

Evaluation

To evaluate the actual shape-reconstruction performance of the prototype, the ground truth (the actual shape of the FlexiBend) was captured by using a calibrated IR camera and a diffuse-illumination (DI) tracking platform [3] (Figure 5a). After the camera image was obtained (Figure 5b), a threshold was set for extracting its shape (Figure 5c). Then, a thinning algorithm was used to obtain the spine of the FlexiBend.

[1] http://www.ninjaflex3d.com/

Based on the known parameters, e.g., the length and density of the strain-gauge array, the strain gauge positions are obtained from the spine, as shown in Figure 5d.

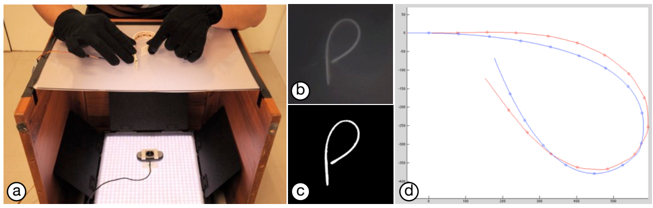

Figure 5. (a) Experimental setup for ground-truth capturing. (b) Captured image. (c) Extracted shape. (d) Extracted spine (blue) and the reconstructed shape (red).

The shape reconstruction results were compared with the ground truth by aligning the results with ground truth according to the position of the first strain gauge. The Euclidean distances of the pair of sensors between the ground truth and the reconstructed shape were then calculated, and the distances were averaged to obtain $\bar{d}_0$. The construction results were rotated 1 degree according to the first sensor, and another average distance $\bar{d}_1$ was calculated, and so forth. After all integer angles θ between π and $-\pi$ were tested, the error distance is deemed as the smallest one of all $\bar{d}_\theta$ collected. Seventeen shapes were tested, including the shapes with one, two or three bipolar turns.

Results: The mean error of a joint's X/Y position was 7.15mm (SD=3.62mm). The average cumulative end point inaccuracy was 18.81mm (SD=6.47mm). These performance tests results were used to evaluate the efficacy of the hardware prototype and shape reconstruction method.

WIDGET DESIGNS FOR MULTI-PART FABRICATIONS

This section introduces several widget designs (Figure 6) that makers could apply in their mult-part fabrications and designs. Each widget is designed as a cavity with an entry and an exit to allow allows a constrained physical part to move inside. In the cavity of a widget, the FlexiBend is loosely mounted. (Figure 7) shows how the landmarks, which are located in both the entry and the end of the cavity, fix the position and length of the FlexiBend by locking the gear-shape pattern on its edge. The design of this locking mechanism enables the FlexiBend to be segmented into isolated parts to serve multiple widgets simultaneously.

Switches and Buttons

Figure 6a shows how a switch widget can be designed as a lever with a pivot at its center. When a user presses the lifted part of a switch down, the part bends the FlexiBend into another shape, and the shape change is deemed as the state change of the switch.

Figure 6c shows that, by adding a spring structure under the lever of a switch, the switch can function as button. Pressing the button down compresses the spring as well. When the button is released, the expanding spring recovers the state of FlexiBend. Adding a small tine to the button can provide additional auditory and haptic feedback for users [8].

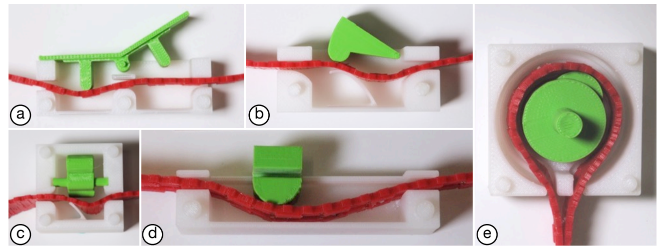

Figure 6. Example widget designs. (a) Switch. (b) Button on the side. (c) Button on the top. (d) Slider. (e) Knob.

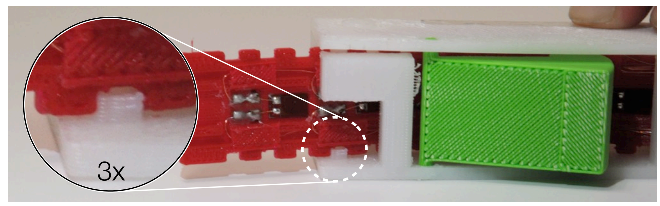

Figure 7. Locking mechanism. The landmarks lock the gear-shape pattern on the edges of the FlexiBend, segmenting a single FlexiBend into isolated parts.

Sliders and Knobs

Figure 6d shows the design for the slider widget. When a user moves the slider along the track, the handle deforms the FlexiBend, and the position of slider can be captured by measuring the position of deformation. Similarly, Figure 6e shows the design for the knob widget. Deformation is measured at the angle of the knob.

Figure 8 shows the sensor readings of a FlexiBend, which is embedded in a slider widget. The sensor readings between the forth strain gauges in the array (SG4) and the eleventh strain gauge in the array (SG11) shows that FlexiBend senses the position of deformation as the position of the slider changes. Therefore, it can detect the position of the slider. However, the bent does not effect SG11, the sensor located outside the widgets. The sensor reading of SG11 remains static when the slider moves, which indicates that the locking mechanism (Figure 7) works effectively.

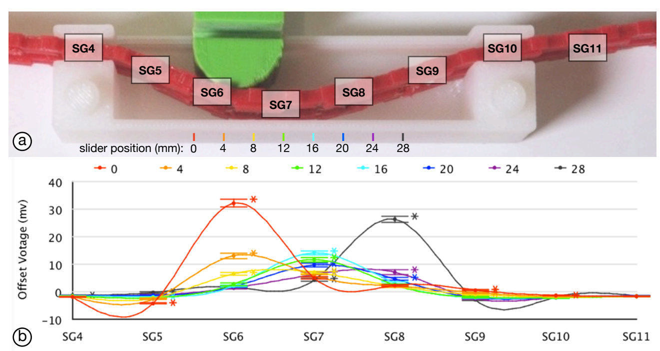

Figure 8. Sensor values versus the positions of a slider. (a) Example of eight positions at 4mm intervals in the slider. (b) The sensor values with * mark of each position are distinguishable with $>95\%$ accuracy.

Numbers of slider positions

A formal measurement is conducted to determine the number of slider positions that the system can be reliably distinguishable. The data collection procedures were as follows. First, move the slider to the start position. Then, move the slider

1mm away from the start position each time. For each position, 100 samples of the eight strain gauges' sensing data (i.e. SG4 - SG11) were captured. The measurement is repeated 10 times. Thus, 30 positions x 100 samples x 10 repeats = 30000 data were measured.

Data analysis. For each position, we calculate each sensor's mean value and the covered area of its two standard deviation (SD) of the 1000 samples. A position is deemed reliably distinguishable from another position if any one of the eight sensors has non-overlapping 95% ($\pm$2SD) confidence interval. Otherwise, they cannot be reliably distinguished.

Results. The experimental results show that all positions at 4mm intervals in the 30mm slider are distinguishable with $> 95\%$ accuracy. That is, the 30mm slider can recognize at most 8 positions reliably.

Example Applications

Two examples are shown to demonstrate how to apply the widget designs into multi-part fabrications.

The *Toy Pistol* (Figure 9) consists of a button and a slider, as the internal structure shown in Figure 1b. In a first-person-shooting (FPS) game, a slider is used to select the weapon from the menu, and the trigger is pulled to confirm. The user presses the trigger to shoot. When the bullets run out, the user reloads the bullets by pushing and pulling the slider.

Figure 9. (a) In the FPS game, a user browses the available weapons using the slider on the top of a toy pistol, (b) shots by pressing the trigger, and (c) reloads the bullets by pushing or pulling the slider.

The *Radio Tuner* (Figure 10) consists of a button and a knob. A user activates the tuner by double-clicking the button and then previews the channel in different frequencies by rotating the knob. When the desired channel is found, the user locks the frequency by clicking the button and unlocks the frequency by clicking the button again.

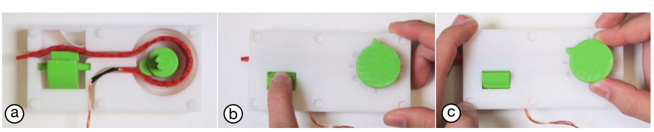

Figure 10. (a) Radio Tuner. (b) A user activates the tuner by double-clicking the button, (c) previews the channel in a range of frequencies by rotating the knob.

TRACKING THE GEOMETRY OF DEFORMABLES

Since FlexiBend is a shape-sensing strip, it can track the geometry of a deformable fabricated from pliable materials. By preserving a guide in the physical model, a user can easily embed a sensor into the deformable fabrication as its spine. After the installation, deforming the model also affects the shape of the spine. Therefore, the system can use the reconstructed shape of the spine to track the geometry of deformable fabrications.

Figure 11 demonstrates a deformable seahorse puppet with a FlexiBend embedded in its spine (Figure 1c). In a puppetry storytelling application, a user makes the seahorse look humble and shy by bending its body and nodding his head or makes him looks confident and proud by bending his head up. The emotion of the seahorse is also displayed through the facial expression shown in the screen.

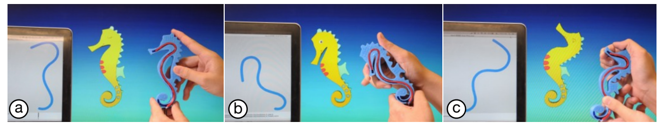

Figure 11. (a) Puppetry storytelling. (b) The user makes the seahorse nod its head to look humble and shy, and (c) makes the seahorse bend his head up to look confident and proud.

DISCUSSION

Sensing 3D Operations

The current implementation effectively detects shapes in 2D. Adding an inertial measurement unit (IMU) to a FlexiBend also allows the use of spatial gestures such as tilting or shaking. FlexiBend can also sense 3D gestures on deformable fabrications such as twisting, stretching, and bending the spiral model shown in Figure 12. However, it cannot reconstruct the actual 3D shape of the spiral model.

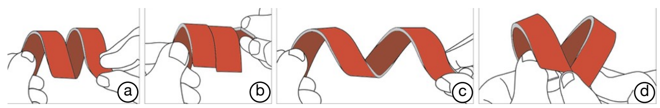

Figure 12. (a) Forming a FlexiBend into a spiral shape to enable 3D operations, such as (b) twisting, (c) stretching, and (d) bending.

Customizing a FlexiBend

Makers can customize a FlexiBend in different density, length, thickness as needed. Increasing the density by deploying a strain-gauge array in higher density or in multiple layers allows for more subtle user operations. Increasing the length by using several multiplexers in parallel enables simultaneous detection of more widgets. Decreasing the thickness by fabricating the FlexiBend using flexible printed circuits (FPC) not only increases flexibility, but also increases durability because of the reduced structural deficiencies. To illustrate the potential of FPC fabrication, this study fabricated a simple prototype in which a 1x6 array of strain gauge sensors was implemented with adhesive copper and paper. The paper-thin FlexiBend effectively resolves a shape consisting of two bipolar turns (Figure 13).

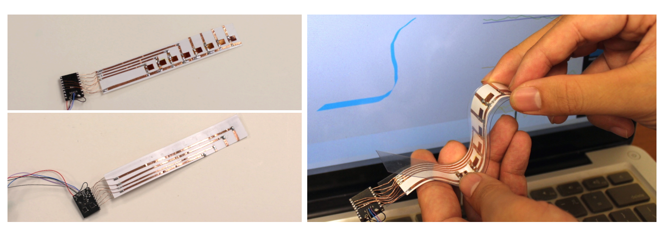

Figure 13. Paper-thin FlexiBend made of a 1x6 array of strain-gauge array, which is implemented with adhesive copper and paper.

CONCLUSION AND FUTURE WORK

This work developed FlexiBend, a shape-sensing strip designed specifically for ease of use. Several fabrication scenarios were also presented. Makers can use this novel sensor to fabricate multiple-part, interactive, deformable physical objects through a combination of mechanical designs, and easily install the sensor inside. Due to the ease of installation, makers also can reuse the FlexiBend in different physical models, which makes it an useful tool for iterative prototyping.

Future work will consider unsolved complexities in designing 3D models that are compatible with FlexiBend, such as routing a FlexiBend to the different widgets of a fabrication. Future work will also develop modularized software tools to support the physical design.

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REFERENCES

1. Balakrishnan, R., Fitzmaurice, G., Kurtenbach, G., and Singh, K. Exploring interactive curve and surface manipulation using a bend and twist sensitive input strip. In *Proc. ACM I3D '99* (1999), 111–118.
2. Laput, G., Brockmeyer, E., Hudson, S., and Harrison, C. Acoustruments: Passive, acoustically-driven, interactive controls for handheld devices. In *Proc. ACM CHI '15* (2015), 2161–2170.
3. Matsushita, N., and Rekimoto, J. Holowall: Designing a finger, hand, body, and object sensitive wall. In *Proc. ACM UIST '97* (1997), 209–210.
4. Ono, M., Shizuki, B., and Tanaka, J. Touch & activate: Adding interactivity to existing objects using active acoustic sensing. In *Proc. ACM UIST '13* (2013), 31–40.
5. Rendl, C., Kim, D., Fanello, S., Parzer, P., Rhemann, C., Taylor, J., Zirkl, M., Scheipl, G., Rothländer, T., Haller, M., and Izadi, S. Flexsense: A transparent self-sensing deformable surface. In *Proc. ACM UIST '14* (2014), 129–138.
6. Sato, M., Poupyrev, I., and Harrison, C. Touche: Enhancing touch interaction on humans, screens, liquids, and everyday objects. In *Proc. ACM CHI '12* (2012), 483–492.
7. Savage, V., Chang, C., and Hartmann, B. Sauron: Embedded single-camera sensing of printed physical user interfaces. In *Proc. ACM UIST '13* (2013), 447–456.
8. Savage, V., Head, A., Hartmann, B., Goldman, D. B., Mysore, G., and Li, W. Lamello: Passive acoustic sensing for tangible input components. In *Proc. ACM CHI '15* (2015), 1277–1280.
9. Savage, V., Schmidt, R., Grossman, T., Fitzmaurice, G., and Hartmann, B. A series of tubes: Adding interactivity to 3d prints using internal pipes. In *Proc. ACM UIST '14* (2014), 3–12.
10. Slyper, R., Poupyrev, I., and Hodgins, J. Sensing through structure: Designing soft silicone sensors. In *Proc. ACM TEI '11* (2011), 213–220.
11. Sugiura, Y., Kakehi, G., Withana, A., Lee, C., Sakamoto, D., Sugimoto, M., Inami, M., and Igarashi, T. Detecting shape deformation of soft objects using directional photoreflectivity measurement. In *Proc. ACM UIST '11* (2011), 509–516.
12. Vanderloock, K., Vanden Abeele, V., Suykens, J. A., and Geurts, L. The skweezee system: Enabling the design and the programming of squeeze interactions. In *Proc. ACM UIST '13* (2013), 521–530.
13. Willis, K., Brockmeyer, E., Hudson, S., and Poupyrev, I. Printed optics: 3d printing of embedded optical elements for interactive devices. In *Proc. ACM UIST '12* (2012), 589–598.
14. Wimmer, R., and Baudisch, P. Modular and deformable touch-sensitive surfaces based on time domain reflectometry. In *Proc. ACM UIST '11* (2011), 517–526.