Sensing Through Structure: Designing Soft Silicone Sensors

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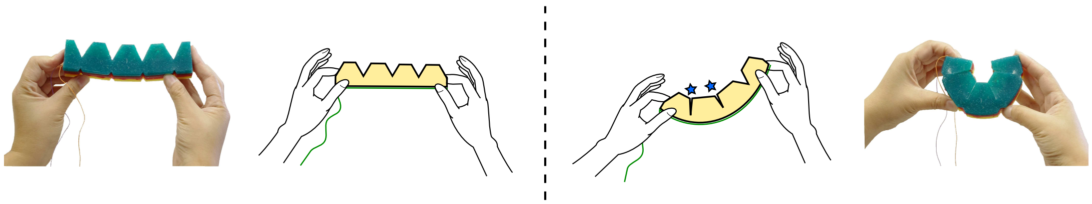

Figure 1. Sensing structures, such as our bend structure, above, physically remap a continuous deformation into a set of discrete displacements.

ABSTRACT

We present a method for designing and constructing rugged and soft multi-point sensors. Interactions applied to a soft material are reduced to structural units of deformation. These structures can then be embedded and instrumented anywhere inside a soft sensor. This simplification lets us design complex, durable sensors in easily manufacturable ways. In particular, we present a construction method of layering electronics between silicone pours to easily create sensors for arbitrary combinations of these deformations. We present several prototype sensors and discuss applications including toys, games, and therapy.

Author Keywords

Bend, sensors, games, controllers

ACM Classification Keywords

H5.2 Information interfaces and presentation: User Interfaces—*Input devices and strategies*

General Terms

Design, Human Factors, Measurement

INTRODUCTION

Objects in the physical world are being linked to the cyber world with increasing frequency, whether the objects manifest as input devices to computers, game controllers, or computer-augmented toys. As these computing devices become more prevalent and more personal, users are expecting them to have both a softer look and a softer feel. Boxy desktop computers now sit alongside soft Chumbys [3] and soon, flexible displays; hard actuated toys share aisle space with robotic plush animals; body-worn computing devices are moving from bulky calculator wrist watches to a range of soft e-textile materials; user input devices are pushing the bounds with attempts at soft input, from digital clay [19] to reactive fur [7]. Consequently there is a growing need for new design techniques that allow easy and natural integration of sensing into these emerging categories of soft computing devices.

Our approach to sensor design, "sensing through structure", exploits the deformability of the materials that are used to design these soft, flexible computing objects. We consider the character of the deformations induced by the user manipulating an object made of a flexible material such as silicone, and distill simple atomic structures that undergo consistent and easily measurable topological changes when such deformations are performed. Figure 1 illustrates one such atomic structure, used for capturing bend. We can calculate the approximate curvature of an object by using a set of simple binary switches embedded in the valleys of the structure: when the user bends the object, the valleys are closed and the switches are triggered. We can easily embed such structures into a wide variety of objects.

Sensing through structure is a simple, scalable approach to designing and integrating sensors into soft objects. A sensor can be easily designed to match its application: various basic structural units can be selected in any combination, captured with either digital or analogue sensors, and constructed with shapes customized to respond to specific ranges of motion.

Sensors built using this approach have a nice physicality. One can see – and feel – the structural units deforming, and

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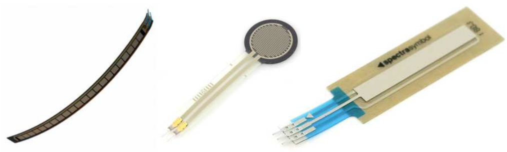

Figure 2. Common commercially available sensors – bend, pressure, and position. (images copyright Spectra Symbol and Interlink Electronics)

readily understand the inherent affordances and limitations of the sensor. The sensing structures can be designed to be clearly visible in the object where they are integrated, so the user can directly see the kinds of manipulation afforded by the object. Furthermore, the sensor's look and tactile feel can be controlled by selecting from a range of soft, pliable materials, and easily manufactured using methods we will describe in the paper.

In the next section, we describe related work. We then discuss the concept of sensing through structure, and sketch example structures. We detail the construction of several of our sensors and present applications. We conclude the paper with a discussion of future work.

RELATED WORK

While sensing through structure focuses on the topological properties of materials, sensors for most common motions – position, twist, bend, stretch, and pressure – rely on monitoring changes in the electrical properties of materials. For example, common bend, stretch, and pressure sensors are often built with a piezoresistive material; changing the length or cross-sectional area changes the resistance of the material. The off-the-shelf sensors shown in Figure 2 are built using this method. Another technique for sensing is electro-optical sensing. For example, Zimmerman [28] created an optical flex sensor that senses bending by measuring the amount of light able to pass through a flexible light guide. He placed a light source and photodiode on opposite sides of the light guide; when the guide was bent, the amount of light reaching the photodiode decreased. This technology was used in early data gloves. Measurand's ShapeTape [14] makes use of the same concept, building in multiple fiber optic sensors to measure bend and twist continuously along its length.

While these sensors work well with traditional hard devices and objects, embedding them in soft and malleable objects presents a number of difficulties. Most of today's sensors are either rigidly encapsulated in metal or hard plastic, or built on a thin plastic backing. These latter flexible sensors can bend and twist, but not shear and stretch. Hence they do not conform well to soft materials such as human skin, textiles, and foam. For example, if the bend sensor is placed at a human joint, e.g. in a data glove, it will shift and slide, interfering with natural motion. These sensors are also somewhat fragile and cannot be creased, which limits their applications and reliability. Most importantly, embedding hard sensors into soft objects alters the tactile, malleable properties of these objects, which is their key distinguishing characteristic from traditional hard devices. Our work introduces sensing solutions using a foam or silicone base, which avoids these problems.

The e-textile community has built flexible analogues of some of these sensors, using the same principles [2]. Sturdy fabric is used instead of a plastic base, and resistive foam or thread is used as the piezoresistive conductor; bend, pressure, and stretch sensors have been built this way [16]. For example, Shimojo et al. [21] created a pressure sensor grid from resistive foam and characterized its hysteresis. Our work provides a flexible and principled way to incorporate these materials.

An alternative approach to augmenting soft objects with sensing is to use external tracking, e.g. vision [6], magnetic sensing [5], or RFID [18]. Previous work has imbued silicone with structure to aid in tracking. GelForce [24] embedded markers in silicone to track its deformation using a camera-based system. Cameras also track silicone in ForceTile [12] using ID tags and PhotoelasticTouch [20] using polarization of light. While tracking generally requires less modification of the object being deformed (in particular, the object can be unpowered), it limits use of the object to specific locations. In the sensing through structure approach, all sensing is localized to the device itself, thus making it compact and portable.

Ideas of exploiting structural properties in sensor design can be found in the work of Mannsfeld et al. [13] and Papakostas [15]. In the former, the authors built an extremely sensitive pressure sensor by molding an elastomer with microstructural pyramidal holes in its surface; these holes squashed when pressed, changing capacitance. In the latter, Papakostas created a two-dimensional array of force-sensing elements on a polyester substrate with a spiral pattern cut around each element, restricting movement of the sensing elements to the perpendicular plane.

Unlike previous approaches, sensing through structure does not separate the *object* that the user deforms and the *sensors* used to measure it. Instead of adding sensing to pre-existing objects, we start by designing objects with their sensing capability in mind. In a broad sense, our approach can be described as "form equals function" [23][4], where the physical input, interactions, and device embodiment are designed in tandem, in harmony with its material construction. We present the details of this approach in the rest of the paper.

SENSING THROUGH STRUCTURE

Sensing through structure uses the physical changes in the topology of a deforming material to suggest structures for simple multi-location sensing. These atomic sensing structures make up a sensing vocabulary, to be used as building blocks when a sensor is designed.

Figure 3 gives some example structures. Diagrams *A* and *B* show bend structure configurations; *A*'s contacts trigger when bent a certain amount; *B*'s trigger as soon as they are bent. Diagram *C* contains contacts on both sides, which trigger in pairs when it is twisted, but only singly when it is bent,

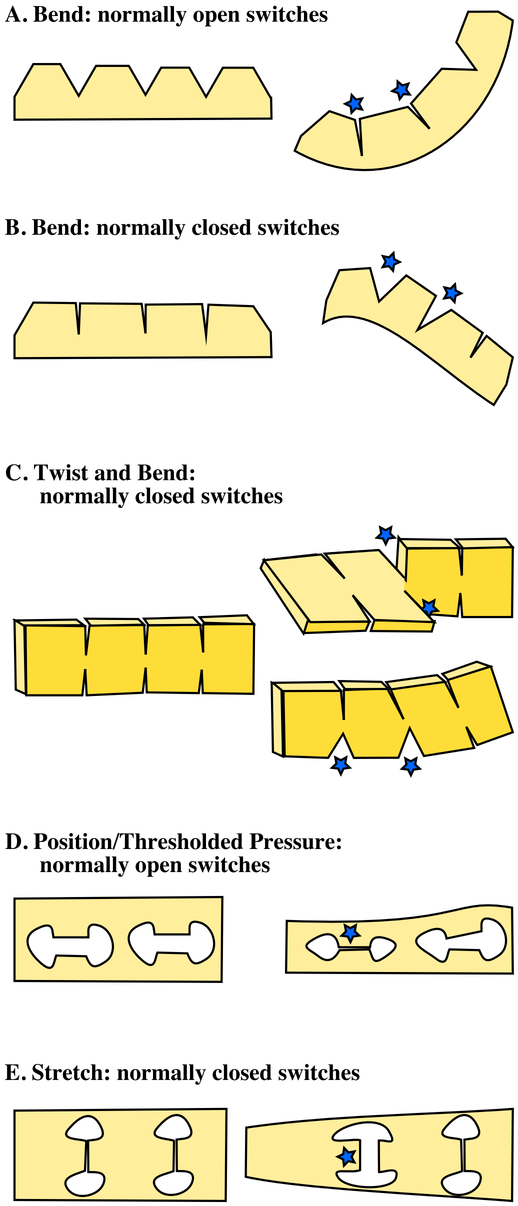

Figure 3. Examples of sensing through structure. The structure is in its default configuration in the left column. Stars are shown on the right where switch contacts are toggled when the structure is manipulated.

thus allowing us to measure both twist and bend with a single structure. Diagram *D* contains a structure for sensing pressure. As the material is compressed, the two sides of the switch meet; the width and shape of the switch allows the activation pressure to be customized. In diagram *E*, the switch is rotated to measure stretch. When the left side of the material is stretched, the left switch triggers as its contacts are pulled apart.

Other structures or combinations are possible. For example, the bend structure in *A* or B may be mirrored to measure two-directional bend, or combined with position or stretch structures.

Our approach simplifies the problem of complex multidimensional sensing, transforming it to the easier and cheaper problem of sensing a set of one-dimensional displacements. The nature of the sensors used for measuring the displacement is not essential; we can choose from a range of sensors, from simple contact switches to analogue capacitive proximity sensors, depending on the application.

The physical structure, also, is customizable to a range of applications. For example, the angle of the valleys in the bend structure should be chosen to measure an amount of bend appropriate to the particular application. Small and large angles could be alternated to trigger at two angles of bend. The shape of the cut in the pressure and stretch units should be altered to fit the dynamics of the base material; for example, we found that a double-convex cut worked best for silicone.

Finally, our structures are designed to naturally guide the user by providing clear physical affordances and constraints so that he can see and feel what can be done with the sensor.

DESIGNING SENSORS THROUGH STRUCTURE

In the following two sections, we describe the design of a bend sensor and a stretch/pressure sensor. To illustrate the generality of our approach, we build the bend sensor with bases of both silicone and foam, using fabric binary contact switches. We use a resistor network to minimize wiring. The stretch/pressure sensor we build out of silicone using analogue magnetic distance sensors whose values are transmitted over an I2C bus.

Multi-Location Bend Sensor

We built the bend sensor from the normally open bend structure in Figure 3A. We tested bases of both silicone and foam. The silicone is colorful and has a fun feel that demands to be touched and squished, and would work well in sensors that are handled directly by the user. The foam we used has easier overall compression, and thus is appropriate for applications such as stuffed-animal innards. We now describe the construction and wiring.

Construction

The silicone bend sensor was constructed from a stretchy silicone, Smooth-On Dragon Skin, with a hardness of Shore 10 and elongation break at 1000%. Stranded 32-gauge wire was connected to a copper polyester conductive fabric for the contact switches.

We laser-cut the mold layers from 4.6mm cast acrylic sheets. Figure 4 shows the molding process, with trace layers sandwiched between insulating layers.

In Step 1, the mold is set up for the outside insulating layer and the first trace layer. Trace layers create zigzag tunnels in which to place the wiring. In Step 2, these layers are poured.

In Step 3, the trace mold is removed and replaced with wiring and contact switches. We coil the wire before placing it in the tunnels so that it pushes against the tunnel walls. This friction lock anchors the wires and resistors while more

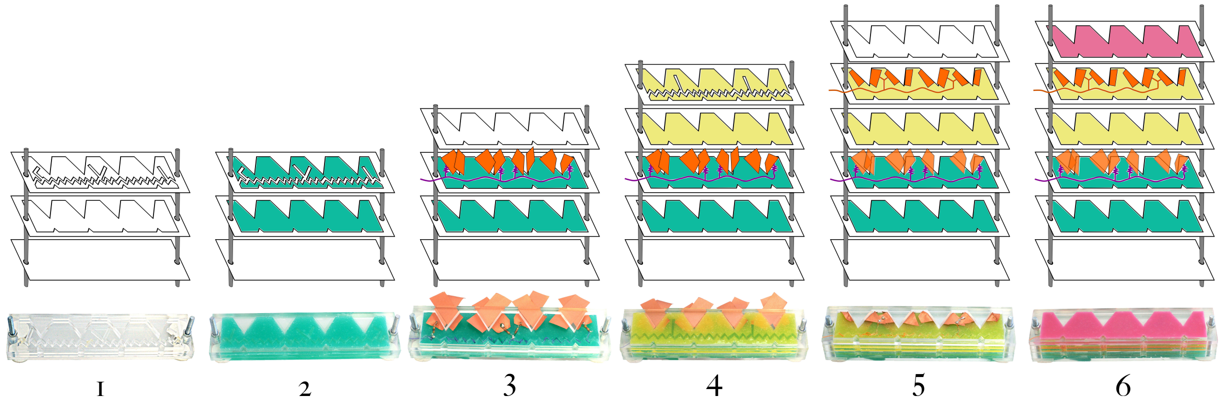

Figure 4. The silicone bend sensor was built with successive silicone pours from back to front, with alternating insulating layers and and trace layers. Wiring is shown with purple and orange lines; contact switches made from conductive fabric are orange polygons.

silicone is being poured on top, stopping the wires from floating. The traces also guide the wires into a zigzag pattern, giving them slack for bending. Wires in an early prototype without this feature promptly snapped at the solder joints.

In Step 4, an insulating layer and the second trace layer are poured. In Step 5, the contact switches are threaded through the mold and folded over on top. The unconnected half are connected to the signal tracing being laid.

Step 6 creates a top insulating layer which also anchors the contact switches in place. Opposite ends of the switches are thus embedded between layers of silicone, using the self-stick property of silicone to anchor them firmly without glues or mounting hardware. The conductive fabric we chose does not shred and is tarnish resistant, so this construction creates rugged switches that cannot peel off. Figure 5 shows the result.

An important strain-relief feature in our design are the small valleys across from the switch-containing valleys; these move the center of rotation away from the bottom of the sensor and towards the middle, in line with the wire. These valleys make the silicone easier to bend at these points, and reduce the amount the wire has to stretch when the sensor is bent backwards. Additionally, all solder joints are moved away from the centers of rotation.

The foam bend sensor was made out of a base of soft foam with a firmness of 5 psi and 25% deflection. Conductive fabric tape with conductive adhesive backing was placed along the valleys to create contact switches; conductive thread was attached to the underside of the tape and then wired through

Figure 5. A completed silicone bend sensor.

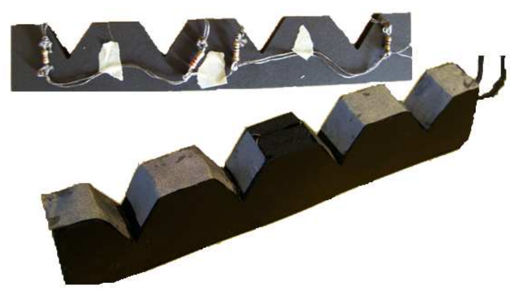

Figure 6. ***Top*, the foam sensor was built from back to front; shown is the ground plane wiring being laid on the first layer. *Bottom*, the completed sensor.**

the sensor. We isolated the ground layer and the signal layer between slices of foam. The sensor is shown in Figure 6.

Electronics

The challenge in sensor construction with many points of contact is to minimize the wiring as much as possible. The naive approach (Figure 7A), connecting each switch to a single microcontroller input, does not scale. We solved the problem by using a binary-weighted resistor Digital-to-Analogue Converter (DAC) technique (Figure 7B). With this technique, only two wires come out of the sensor body. Binary-weighted DACs and a similar idea, R-2R ladders, have been around since at least the 1920s in communication systems [17]. They can be found in toys and midi keyboards.

Every switch is connected to its own resistor and acts as a single bit; the DAC combines the bits into a single analogue resistance. Each resistor is a power of two larger than the previous, and thus all combinations can be differentiated by a microcontroller reading this analogue value. We used resistor values of 470 ohms, 1K, 2.2K, and 4.7K.

Using the circuit described above, we can track the state of the switches using the following algorithm. Let the indicator variables $S_i \in \{0, 1\}$ represent the state of the N switches. Using the formula for sum of resistances in parallel, the re-

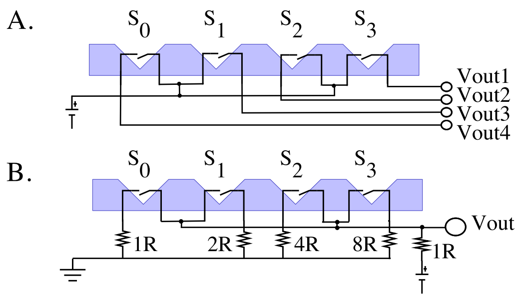

Figure 7. Two methods for wiring switches.

sistance of the sensor, R_{total}, takes the following form:

$$\frac{1}{R_{total}} = \frac{S_0}{2^0 R} + \frac{S_1}{2^1 R} + \frac{S_2}{2^2 R} + \frac{S_3}{2^3 R} + \ldots = \sum_{i=0}^{N-1} \frac{S_i}{2^i R}$$

Then the following loop would continuously sample $(S_0, S_1, \ldots, S_{N-1})$, the configuration of the sensor:

$R_{remaining} \leftarrow \frac{1}{R_{total}}$
for $i = 0$ to $N - 1$ **do**
  if $R_{remaining} \geq \frac{1}{2^i R}$ **then**
    $S_i \leftarrow 1$
    $R_{remaining} = R_{remaining} - \frac{1}{2^i R}$
  else
    $S_i \leftarrow 0$
  end if
end for

This method, however, is subject to error; small variations in resistance could result in the "$\geq$" incorrectly evaluating false, and a completely wrong answer being returned. In practice we found it safer to precalculate the 16 resistance values expected from all different combinations of switches, store these as integer values in the microcontroller's memory, and in real time find the closest.

Analogue Stretch/Pressure Sensor

The concept of sensing through structure encourages any sensing mechanism to be used to measure the deformation in a structural unit. Up until now we have been using only binary contact switches, appreciating the elegance of using a resistor DAC for the wiring. It is possible, however, to use analogue sensors. We built a prototype stretch/pressure sensor which uses magnetic distance sensors to monitor the width of four oval holes along its body.

Construction

For the silicone stretch/pressure sensor, we wired an SS49E magnetic hall sensor to each of the four ovals, and placed small rare earth magnets on the other sides. The setup with zigzag traces is shown on the right of Figure 8. Silicone was then poured over both the electronics and the magnets, encasing them completely.

The ovals allowed about 15mm of travel, a range trackable by the magnetic sensors. The sensor could thus monitor both stretch and pull, shown in Figure 9.

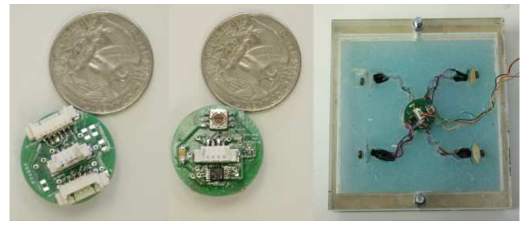

Figure 8. *Left,* top and bottom views of our I2C-bus PCB. *Right,* a snapshot of the molding process with the PCB placed on the bottom layer of the analogue stretch/pressure sensor.

Electronics

To minimize wiring, we switched to a bus-based system. We designed a PCB, shown in Figure 8, which takes four analogue inputs and transmits them on an I2C bus using a TI ADS1015 chip. The boards are designed to be chained together. The four bus wires connect to the top of the chip (left image) and come out the bottom (center image). An I2C address selector switch is located on the bottom of the board. Any analogue sensors can be connected to the connectors on the top of the board.

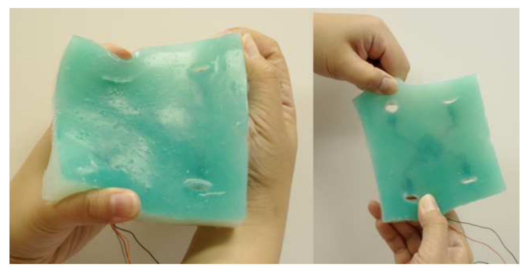

Figure 9. With analogue magnetic distance sensors, both stretch and pressure can be tracked.

APPLICATIONS

We evaluated the sensing through structure approach by building a computer game, two toys, and an interactive cellphone case. We present these designs, and discuss the potential applications of our approach in other areas.

Games

Sensing through structure can be used to design inexpensive interfaces to video games, in instances where they have the right tactile feel. Similar to the game BopIt! [9], one could combine a multitude of structures to create a highly customized user interface.

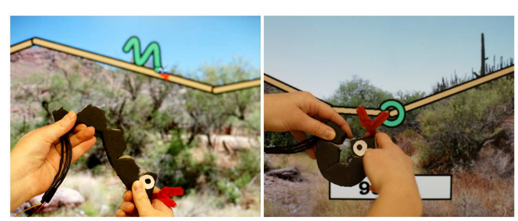

Figure 10. The bend sensor as snake controller.

As an example, we created a game based on the American folklore legend of the hoop snake. This snake would place its tongue in its mouth so it was shaped like a wagon wheel, then roll down hills chasing after its victims. In the game, moving the snake by undulating the snake sensor in an s-curve shows off our sensor's ability to recognize complex gestures using only binary sensing. The speed of undulation controls the speed of the snake onscreen. Folding the snake sensor into a hoop to roll the snake down hills demonstrates using our bend sensor as a configuration sensor. Figure 10 shows our game in action. We tried our game with both the foam and silicone bend sensor as the snake. An informal user study showed that the bend sensor was easily understood as a controller, and very entertaining.

Toys

An increasing connection is being made between toys and computers. A good example of this trend is the popular Webkinz [25], which shows how a commercial success can be created using even a nebulous connection between real and virtual toys. Research projects such as Huggable [22] and Swamped! [11], and commercial animatronics such as the Pleo [10], show how sensors can make a toy more interactive and compelling.

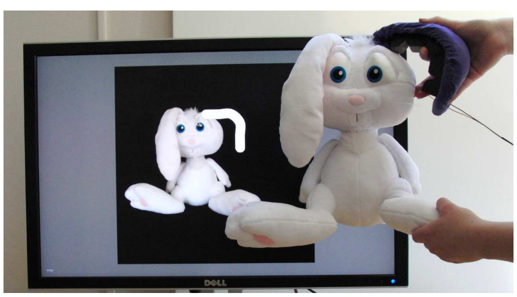

Figure 11. A bend-sensor rabbit earmuff.

Instrumenting dolls and stuffed animals with sensing skeletons is expensive and introduces hard elements into a soft toy. Our sensing structures, however, fit perfectly sewn into fabric doll clothes, and achieve a good price / performance point. A proof of concept is shown in Figure 11. The rabbit's earmuff contains our bend sensor, allowing the rabbit's virtual double to mimic ear poses.

We also designed a custom toy, which we call "Cat Stretch". The cat-shaped toy has embedded in it four of the normally closed stretch structures from Figure 3E, two along its body and one each along its ear and tail.

In contrast to the bend sensor, the cat stretch sensor was built from the inside out. Trace layers were poured around a central insulating layer and small slits made through the layers with a sharp knife. The contact switches were threaded through the slits and wiring laid around this core layer, as shown in Figure 12. As each outer insulating layer was poured, the cuts were continued with a sharp knife. Figure 13 shows the result. When the cat is stretched, the two sides of a given contact switch part, sending a unique resistance to the microcontroller.

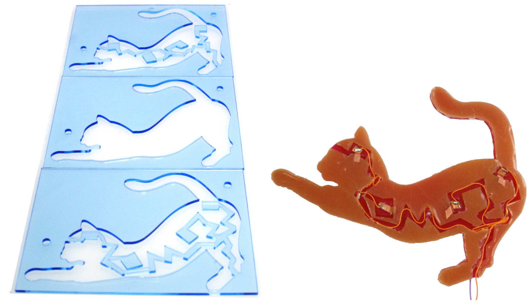

Figure 12. Middle mold layers and central core of the cat stretch sensor.

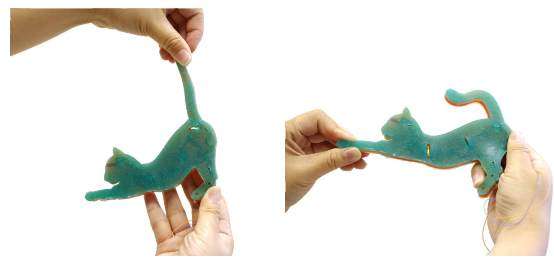

Figure 13. Cat Stretch: The cat has stretch switches around its body.

Our cat-shaped stretch sensor is a toy simple and cheap enough to be a giveaway, and could be used as a stress toy, or for computer-mediated play. Sensing through structure works well with Cat Stretch: instrumenting the silicone to get complete knowledge of the forces on it would be a difficult problem, but here a few switches are enough to roughly encode the state of the system given the affordances of cat stretching.

These two example toys, both using binary switches, are also well suited to the interactions between toys and children. Children often push toys to the extremes of their (joint) limits; cheap binary sensing is thus appropriate. Also, our sensors provide more control by having tactile, built-in limits, thus eliminating frustration from ambiguity in sensor use.

Personal Electronics Accessories

To demonstrate the "form equals function" approach of sensing through structure, we designed an iPhone® case whose physical affordances embody the intended interactions with the cellphone.

The interactive cellphone case was built out of silicone in the shape of a guinea pig, using the same methods and materials as the previous sensors. To interface with the phone, we took apart a pair of iPhone® earphones with remote, soldering wires directly to the contact pads of the remote's three buttons. These wires were then connected to the switches inside the case.

In the guinea pig case, a bend structure is located in each of the two sets of fur. The fur along the length of the phone demands to be stroked downward, as shown in Figure 14; doing so lowers the cellphone's volume. In contrast, stroking the upward-facing fur raises the phone's volume. A pressure

Figure 14. A user turning down the volume with the cellphone guinea pig case. The diagram of a mold slice shows the routing to the three switches.

structure is located in the guinea pig's button nose; pushing it controls play/pause.

Other Uses

Many other areas exist where sensing through structure can be effectively used. For example, sensors designed with our approach could be useful in wearable computing. Stretch and pressure formulations could measure movement of the torso. Our bend sensor nestles into the curve of a finger, and would work well in a data glove.

Computer modeling presents another possible application. An analogue version of the bend sensor could work well for curve editing. Alternatively, a squishable touchscreen made out of the stretch / pressure sensor could be used for 3D surface modeling. Because our sensors are cheap and quick to home-manufacture, custom versions could be created for control of individual animation riggings.

Our sensors have also generated interest from an autism therapist. She was excited by their potential ability to collect child play data while being non-threateningly soft and colorful. Play is used for both assessment and intervention in autism [27], but is hard to analyze [1]. Recent work by Westeyn et al. [26] instrumented several plastic toys with sensors, but found the form factors of the toys too general to elicit specific actions. Our sensors' distinctive affordances could encourage a child into a particular action. The bend sensor could test pose mimicry; the stretch sensor, strength. We hope to explore work in this area in the near future.

DISCUSSION

People found our sensors to be engaging and liked their softness. The silicone bend sensor was particularly successful – the colors drew the eye, and everyone who picked it up spent a minute or two just bending it into different configurations, testing its limits and enjoying its tactile sensation.

In general, our game controllers, toys, and cellphone case were easily understandable. The snake controller proved amusing and its gestures masterable. The cat toy looked fun, but its interactions were not as easily grasped by people; designing the outer insulating layer to reveal more of the switch contacts would make its affordances more apparent. People enjoyed the natural motion of stroking the interactive cellphone case. At its current scale the case could be part of a speaker stand; with miniaturization and covered magnetic switches it could be a practical cellphone case.

The exposed contacts in our sensors beg the question of whether our sensors will remain rugged over time. The fabric contacts we used are tarnish resistant, and the silicone durable. Accumulated dirt on the contacts, however, would increase the resistance of the material, breaking the resistor DAC calculations. A calibration routine where the user closes (or opens) each switch individually would give the computer enough data to recalculate the resistances. If the sensor is being used in an application which expects certain configurations, changes in resistance could be tracked over time transparently to the user. As long as the contacts degrade somewhat uniformly, maintaining an order of magnitude difference in resistance, the sensor will continue to work. Alternatively, the contacts could be protected by encasing the sensor in an outer layer of foam or stretchy fabric, possibly filling the holes in the structural units with a piezoresistive foam.

CONCLUSION

We have presented sensing through structure, an approach that uses the topological, rather than electrical, properties of objects and materials to design and construct sensing solutions for measuring motion. The approach is general: arbitrary combinations of sensing units can be constructed using our silicone method, and either analogue or binary measurements can be made. We have used only soft materials and low-cost manufacturing methods, which can be replicated by anyone interested in creating custom sensing interfaces.

Our sensors enable interactions ranging from dynamic, time-based gestures, to static poses and configurations. We have shown both types of input in the hoop snake game, and static poses in the toy proofs of concept. Dynamic gestures can be more complex with multi-location sensing. Onscreen visualizations can tween between configurations, covering for the lack of more expensive continuous sensing. In the static case, the conformability of the sensor lets the user hold it in a pose with a comfortable amount of tension. The sensor can also be designed, and the contacts placed, to capture poses with maximum robustness and efficiency.

Our approach emphasizes building multi-location sensors with discrete inputs. This approach works well for toys and games, where the physicality of the device can be more important than its accuracy. In our work, as switch contacts are made, the sensor provides tactile feedback, making gesturing more efficient. A traditional bend sensor, for example, reveals little about its limits.

In the future we would like to explore new applications of our sensors. We are particularly excited about applying our results to child therapy, customizing our sensors to children's needs. We would also like to exploit a particular facet of sensing through structure in games and toys: its transparency. Gross [8] argues against the increasing trend of technology-enhanced children's toys being "black boxes" whose interior functioning is hidden from the user. Our sensors, when made with clear silicone, completely reveal their inner workings. With unambiguous use and understandable construction, they present a viable alternative to the current trend.

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