Flexibles: Deformation-Aware 3D-Printed Tangibles for Capacitive Touchscreens

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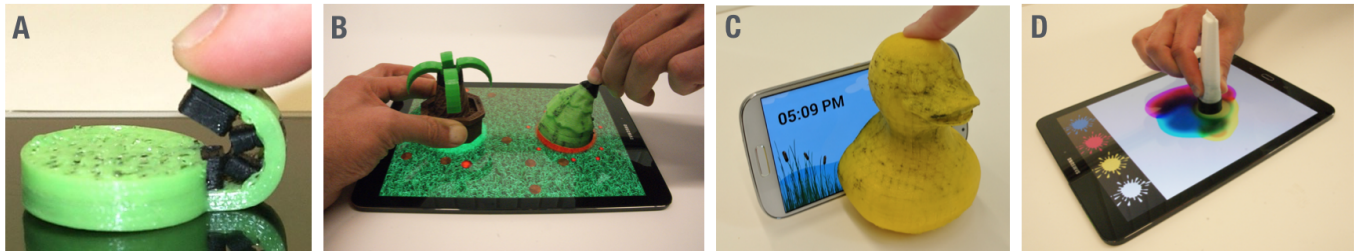jochen.huber
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Figure 1. Flexibles are 3D-printed deformation-aware tangibles that operate on capacitive touchscreens. By exploiting capacitive effects, new mechanisms enable the touchscreen to sense continuous bend (A & B), pressure (C), and squeeze input (D) at custom locations on the 3D object.

ABSTRACT

We introduce *Flexibles*: 3D-printed flexible tangibles that are deformation-aware and operate on capacitive touchscreens. Flexibles add expressive deformation input to interaction with on-screen tangibles. Based on different types of deformation mapping, we contribute a set of 3D-printable mechanisms that capture pressing, squeezing, and bending input with multiple levels of intensities. They can be integrated into 3D printed objects with custom geometries and on different locations. A Flexible is printed in a single pass on a consumer-level 3D printer without requiring further assembly. Through a series of interactive prototypes, example applications and a technical evaluation, we show the technical feasibility and the wide applicability of Flexibles.

Author Keywords

3D printing; digital fabrication; rapid prototyping; printed electronics; capacitive sensing; input; deformation; touch

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces – Input devices and strategies.

INTRODUCTION

Today's capacitive touch interaction on smartphones, tablets, and tabletops is often criticized as lacking haptic experience. To mitigate this, researchers propose interactive tangible objects that, when placed on a screen, enable physical control of on-screen contents [34, 18].

A large body of research focuses on enhancing tangible interaction on capacitive touchscreens. It has been shown that the capacitive touch sensor itself can be used to identify the location and orientation of a tangible object [34, 21, 7, 52]. Moreover touch input on an object's surface [7, 40, 20] or the configuration of mechanical controls with moving parts [7] can be detected. These approaches work with passive objects, which do not contain any electronics and therefore can be produced at low cost.

Moving beyond interaction with rigid objects, deformations are explored as a promising new input modality. Deformation is a very common and intuitive interaction in everyday life, such as bending a handle, squeezing a tube, or folding a sheet of paper. Prior approaches capture deformation input using camera-based touch tracking [12, 9], but require a stationary tracking solution in contrast to the now more commonplace and mobile capacitive touchscreens. Recent approaches utilize resistive [44, 49, 36, 1], capacitive [28], or pneumatic [50] sensing, but require an active object with embedded or tethered electronics and a power supply. This makes them less attractive for use as tangible objects on today's capacitive touchscreens.

We contribute to this stream of research by adding *deformation-awareness* to passive objects on capacitive touchscreens. *Flexibles* are 3D-printed tangible objects that recognize the deformations pressing, squeezing, and bending for tangible inter-

action on capacitive touch sensing hardware. They consist of deformable parts and embedded conductive sensing structures. Both are laid out in specific geometries to capture deformations and forward them to the capacitive touch sensor via capacitive coupling [34]. A Flexible can be fabricated in custom geometries using an off-the-shelf dual-extrusion 3D printer in a single print pass. It does neither require any embedded electronics nor any further assembly steps.

We introduce two principles for sensing deformations on capacitive touch sensors. On this basis, we present a set of mechanisms for capturing various forms of pressing, squeezing, and bending input. We also demonstrate how multiple mechanisms can be combined in an object. Results of technical evaluation studies show that changes in capacitance readings can be mapped to deformations of varying intensities.

With this new approach for sensing deformations of tangible objects, we contribute to the vision of interactive devices that are printed at once rather than being assembled [56]. Flexibles can be used to enrich interactions via physical manipulation of digital content, for instance, to provide faster, more fine-grained, or eyes-free input control on capacitive touchscreens. Also, they enable engaging interactions with customized 3D-printed tangible objects that are controlled by a smartphone without any additional power supply. We demonstrate these benefits with three interactive example applications.

The main contributions of this paper are:

- Two principles of mapping deformations in 3D-printed objects using commodity capacitive touch sensing hardware.

- 3D-printable mechanisms to capacitively detect multiple levels of pressing, squeezing, and bending input on passive 3D objects. Mechanisms can be combined in an object.

- Results from technical experiments investigating the accuracy of deformation sensing and example applications validating the practical feasibility of the approach.

RELATED WORK
This paper is situated in the areas of tangibles on interactive surfaces, deformation sensing, and fabrication of interactive 3D objects.

Tangibles On Interactive Surfaces
A body of research has investigated how optical approaches can be used to detect tangible objects on a touchscreen [2, 55]. More recent work is investigating how to detect tangibles using the now commonplace capacitive touchscreens. Many works apply variations of capacitance tags [34]. By embedding conductive material or by adding electronics to the tangible object, the capacitive touch sensor can detect presence and location of tangible objects [57, 52, 51], combinations of multiple objects [7], or forward touch on the object onto the touchscreen [7, 19, 20]. Other approaches utilize magnetic hall sensor grids to identify objects [25] and detect their posture above a screen [24].

While these approaches propose promising ways of interacting on capacitive touchscreens, they are restricted to rigid, non-deformable objects, and require additional hardware that needs to be assembled manually.

Deformation Sensing
Prior works also explore deformations as a powerful and engaging input modality. Deformation sensing can be achieved by embedding sensors into objects [27, 47, 53, 49, 30, 48] or using optical sensing [12, 9, 46, 45, 33, 54]. Other approaches employ resistive [44, 10, 1], capacitive [28], or piezoelectric [35, 36] sensing.

While many of these approaches capture deformations in high fidelity, they are either incompatible with commonplace capacitive touchscreens, or require built-in, tethered, or stationary hardware.

Probably most closely related to our approach is work by Slyper et al. [44] and more recently Bächer et al. [1]. Slyper et al. embed wires inside manually fabricated soft silicone objects of varied geometry to resistively or magnetically sense versatile interactions, including bending, twisting, pressing, and stretching. Moreover, Bächer et al. contribute a computational approach to design and reconstruct complex deformations in 3D-printed objects by using resistive sensing. For both, objects have to be equipped with wires, need to be actively powered and read out using a dedicated microcontroller to which the object needs to be permanently tethered. In contrast, our untethered and passive approach uses capacitive coupling with a multi-touch sensor, therefore demanding a different set of requirements.

Fabricating Interactive 3D Objects
Embedding or attaching components to non-interactive objects through *post-assembly* is one approach to add interactive capabilities to 3D objects. This can be accomplished by attaching capacitive [37] or acoustic [29] sensors, or embedding cameras [38] or accelerometers [14]. Even though these approaches require only a few components, they imply additional effort or work only with objects that are hollow and can be opened after printing.

Recently, an emerging stream of research investigates how to embed *customized interactive elements* in 3D-printed objects. This includes adding interactive input and output functionalities in 3D-printed objects through light pipes [56, 5], by filling internal pipes with media post-print [39], or via pipes that transmit sound [22]. It has also been shown how to embed interactive structures that can be deformed on-demand [11]. Other approaches print interactive objects by means of conductive spray [17] or conductive plastic [23, 40, 41, 6, 20]. 3D printing is also explored for fine-grained design of deformation behavior of non-interactive flexible objects [32, 43, 31, 4] or to fabricate soft interactive objects [15]. Vazquez et al. contribute 3D-printed pneumatic controls that can capture deformation, but require air-tightly attached hardware [50].

Adding to this body of research, Flexibles are 3D-printed in a single pass without any additional assembly and operate on commodity capacitive touch sensing hardware.
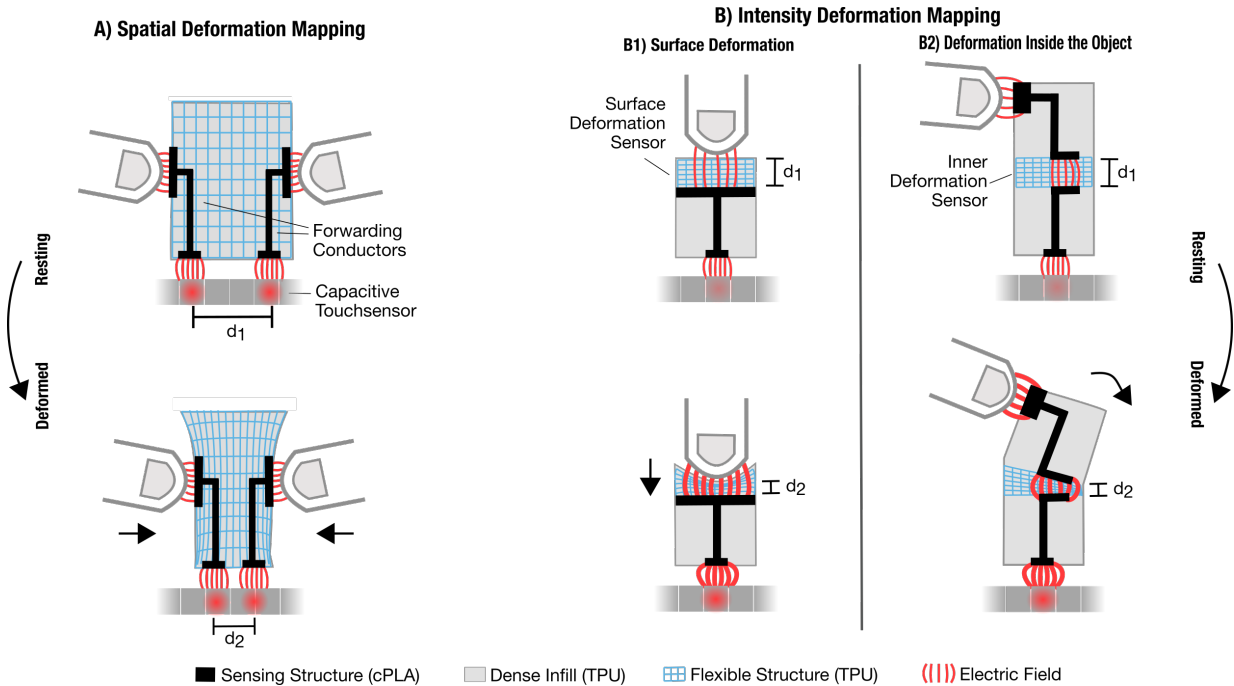
A) Spatial Deformation Mapping

B) Intensity Deformation Mapping

B1) Surface Deformation

B2) Deformation Inside the Object

Forwarding Conductors

Capacitive Touchsensor

d_1

d_2

Surface Deformation Sensor

Inner Deformation Sensor

d_1

d_2

Resting

Deformed

■ Sensing Structure (cPLA) ☐ Dense Infill (TPU) ⊞ Flexible Structure (TPU) (|||) Electric Field

Figure 2. Detecting deformations of a Flexible on a capacitive touchscreen via spatial (A) or intensity (B) deformation mapping.

FLEXIBLES

This section introduces the sensing principle that underlies Flexibles and presents the overall fabrication approach.

Basic Principle

Most commodity multi-touch controllers perform a variant of mutual capacitance sensing [58]: A voltage is consecutively applied to unconnected rows and columns of a conductive grid, creating a uniform electric field at each intersection of the grid. When a conductor, such as a finger, gets close, it alters the electric field at the corresponding grid location. This can be measured as a change in capacitance.

Based on this general scheme, Rekimoto [34] proposed capacitive tags as a means to detect tangible objects on capacitive touchscreens. The tangible object contains a conductor that reaches from the location where it is touched to the location where it is placed on the capacitive touchscreen. When the user touches the object, the conductor capacitively couples the finger to the touch sensor. This results in a detectable change in capacitance used to detect the presence and location of the object. Informally speaking, the touch on the object is "forwarded" to the on-screen location. We thus call such a conductor a *forwarding conductor*, or in short, *forwarder*. This approach extends upon this principle by employing one or multiple forwarders along with specific 3D-printed geometries in order to detect deformations with capacitive touchscreens.

A Flexible is a 3D-printed material composite, which consists of two main functional structures (see Figure 2):

1. The *sensing structure* is embedded within the 3D-printed object and is used to recognize deformations by forwarding them onto the touchscreen. It is made of a conductive polymer.

2. The *flexible structure* is printed near the sensing structure to allow the 3D-printed object to deform at specific locations. It is made of a deformable dielectric elastomer.

Both structures can have a custom size and 3D shape. Multiple sensing and flexible structures can be embedded within a 3D-printed object. The remainder of the object is made of denser flexible material with higher solidity.

We propose two principles to detect object deformations with a capacitive touchscreen: *spatial deformation mapping*, considering the spatial location of forwarders on the touchscreen, and *intensity deformation mapping*, considering the intensity of the capacitance.

Spatial Deformation Mapping

In spatial mapping, a deformation of the object is sensed by capturing the location of forwarders on the touchscreen (see Figure 2A). The 3D object is made of a flexible structure that allows it to deform in one or multiple dimensions. At least two forwarders need to be embedded inside this flexible structure. When the object is deformed, they change their relative position on the sensor grid.

Using this technique, fine-grained deformations that are oriented parallel to the touchscreen's surface can be detected, thanks to the touchscreen's high spatial resolution. However, it is not directly applicable to out-of-plane deformations.

Intensity Deformation Mapping

The second approach, intensity deformation mapping, enhances the forwarder inside the object in a specific way, such that it modifies the intensity of the capacitance reading depending on deformation (see Figure 2B).

Surface Deformation

Deformations that occur at the surface of the object, where the user is touching it, can be captured with a structure that we call *surface deformation sensor* (illustrated in Figure 2B1): the forwarder is overlaid with a flexible structure that acts as a deformable dielectric. When a user applies force, the flexible structure is compressed and the finger gets closer to the conductor.

Following the plate capacitor model [3], a variation in distance d results in a change in capacitance, i.e. $C \propto A/d$ where A refers to the cross-sectional area of the capacitor's plates. Based on the assumption that a distance variation relates to the amount of force exerted onto the flexible structure, we are able to infer deformations from variations in capacitance that are captured by the touchscreen. As will be shown in the evaluation section below, this principle allows to detect multiple intensities for specific deformations using commodity capacitive touch sensing hardware.

Deformation Inside the Object

Many deformations do not primarily occur at the surface location where the user is touching the object. To capture deformation at interior locations within a volumetric object, we propose a structure that we call *inner deformation sensor* (illustrated in Figure 2B2). At the interior location where a deformation shall be captured, the forwarder is interrupted by a 3D-printed capacitor. The capacitor consists of two parallel plates. A flexible dielectric in-between the plates deforms when the object is deformed. This alters the distance or the angle between the plates of the capacitor and thereby modifies its capacitance, as well as the overall capacitance of the entire sensing structure.

Implementation

3D Design and Fabrication

Flexible and sensing structures are combined in mechanisms that allow to detect different types of deformations. Multiple of these mechanisms can be integrated into the digital model of the object. For our prototypes, we manually designed the geometry using Blender and OpenSCAD. In future implementations, this could be automatized by computationally generating both structures to fit a given 3D model (c.f. [40]). We have already started to automatize this process by creating reusable scripts in OpenSCAD which allow generating sensing structures depending on adjustable parameters (e.g. size and thickness of conductors).

We decided to implement Flexibles using commonly available 3D printers. This makes the approach accessible to a wide audience. We used a standard dual-extrusion FDM 3D printer (Ultimaker Original with dual extrusion kit), and commercially available printing materials.

The sensing structure consists of carbon-doped Proto-pasta Conductive PLA (cPLA) with a volume resistivity of $30 - 115\Omega cm$. We printed cPLA with a 0.8 mm thick nozzle at a temperature of 220 ° C. We used the cooling fan and retraction of 5 mm (speed 20 mm/s).

The flexible structure is printed with NinjaFlex TPU, a Polyurethane composition (material shore hardness 85A). We printed the flexible structure with a 0.4 mm thick nozzle at a temperature of 230 ° C with a retraction of 12 mm and the cooling fan turned off (speed 30 mm/s).

The flexible structure's infill and density are important factors when fabricating deformation-aware objects because the composite of air chambers and flexible material both affect the dielectric properties required for capacitive sensing and the object's deformability. Unfortunately, most infill patterns are primarily designed to maximize stability and minimize material usage. We tested common infill patterns and found that the 3D Honeycomb pattern is best suited because the inherent 3D structure of each honeycomb allows for equal deformations in each direction (see Figure 3). We experienced an infill density of 25%, i.e. deformability of up to 1/4 of the original length, to result in an adequate sensing performance. This optimizes the deformability and dielectric constant of the flexible structure, i.e. the material between the sensing structure and the user's finger.

Designers may want to reduce the density to increase the deformability. However, as shown by [26], a smaller infill density would reduce the overall dielectric constant of the flexible structure due to the dielectric constant of NinjaFlex TPU being twice as high compared to air. As a consequence, the sensitivity of the capacitive sensor would be reduced.

For infill densities up to 100%, the flexible material nearly exhibits the properties of a solid material. Designers may use this effect to adjust the object's haptic or avoid unintentional deformations. Moreover, multiple infill densities for varying parts of the object can be achieved by splitting the object's 3D model into multiple parts and assigning each a specific density.

Capacitive Sensing

Capacitance raw data was obtained from a regular smartphone (Samsung Galaxy S4) and tablet (Samsung Galaxy Tab S2) equipped with a standard touch controller (Synaptics S5000B). By rooting the Android phone and activating Synaptics debug mode, we obtained the capacitive values from the sensor as an 8-bit raw image with a resolution of 28x16 at 9 FPS. Up to 30 FPS are possible (c.f. [13]).
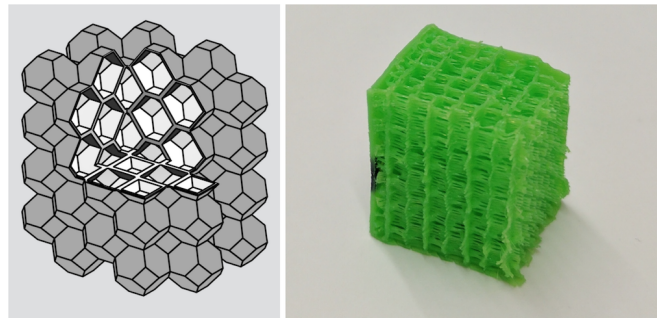

Figure 3. Illustration of the 3D Honeycomb infill pattern as a rendering (left) and as a 3D-printed flexible TPU cube (right).
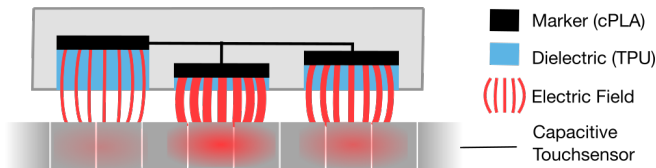
Figure 4. Flexibles are identified and localized by varying the thickness of a dielectric between a marker and the touchsensor, resulting in a measurable difference in capacitance.

Identifying and Localizing Flexibles
Flexibles are identified and localized on the touchscreen via unique rotation-variant point patterns (c.f. [7, 21, 51]). These patterns are made of conductive material and are directly 3D-printed into the object's contact area. We improve over prior work by increasing the number of states that a single capacitive point can encode, leveraging the opportunities of 3D printing combined with capacitance measurements. By varying the amount of dielectric material that is printed between a capacitive point and the touchscreen, the intensity of the capacitance can be controlled (see Figure 4).

In our experiments, we could reliably distinguish three different states of a point. To differentiate Flexibles, we then consider the relative strength of all points in the pattern to each other. Once an object is recognized, the respective capacitive values inside the contact area (known from the 3D model) are used to recognize deformations. We have implemented a library that can be used by Android apps on a device that provides access to raw capacitances. It sends events when a Flexible was detected, its position or orientation changed, or a deformation was detected.

Calibration
A Flexible needs to be manually calibrated once before use. To that end, the user places the object onto the touchscreen and holds it without deforming it. The system records a series of capacitance values and stores the mean as the value for minimal deformation. Then, the user deforms the object as much as possible. The system again records a series of values and stores the mean as the maximal deformation. Using these values, the minimum and maximum of an empirically-derived mapping function are adjusted to take variations in printing quality and human capacitance into account. We detail on such mapping functions in the evaluation section below.

DEFORMATION-AWARE MECHANISMS
Based on spatial and intensity deformation mapping, deformation-aware mechanisms can be created that detect various types of deformations. We cover pressing, squeezing, and bending deformations. For each type of deformation, we first present a basic mechanism that capacitively senses the basic deformation with varying intensity. Second, we extend the basic mechanisms to also capture the on-object location where the force was applied or the direction of the deformation.

Pressure Deformations
Pressure input on the surface of the object can be captured using intensity deformation mapping with a surface deformation sensor, as introduced above and illustrated in Figure 2B1.

Press
To detect pressing, a surface deformation sensor is placed inside the object. Its flexible structure allows the user's finger to press into the object (see Figure 5A and B).

The main challenge is to find a suitable geometry for the sensor's conductor and to preserve deformability of the flexible structure at the same time. We explored different types of geometries and found that the best strategy consists of designing the conductor in a 3D geometry that mimics the outer shape of the 3D object at the location where it is to be pressed. Similar to the original design of a plate capacitor, this geometry maximizes the cross-sectional area between the user's finger and the conductor and also ensures a constant thickness of the dielectric flexible structure.

The designer defines this geometry by selecting an area of interest around an arbitrary location on the object's surface in the 3D CAD model. The selected area is downscaled by the required thickness of the flexible structure and translated in the normal direction to lie under the object's surface. The volume between the object's surface and the conductor is then filled with the flexible structure.

For our prototypes shown in Figure 5A and B, both surface deformation sensors (cross-sectional size of 10x10 mm²) are placed inside the object with 4 mm of flexible structure overlaid. Moreover, both are connected to the underside of the object using a forwarder with a size of 5x5 mm² at the contact face, such that the touchscreen can capture the capacitance.

The connection does not have to be straight. A slightly modified conductor routing allows for forwarding press input to an arbitrary location on the touchscreen. For instance, this makes it possible to capture press input that occurs besides the touchscreen (e.g. Figure 5B) or on objects with overhangs.

Localized Press
The mechanism for pressure input can be extended to not only capture a single pressure value but also to estimate the 1D or 2D location where the press occurs on the object's surface. To that end, the surface deformation sensor is spatially replicated into multiple distinct sensors, which each connects to different
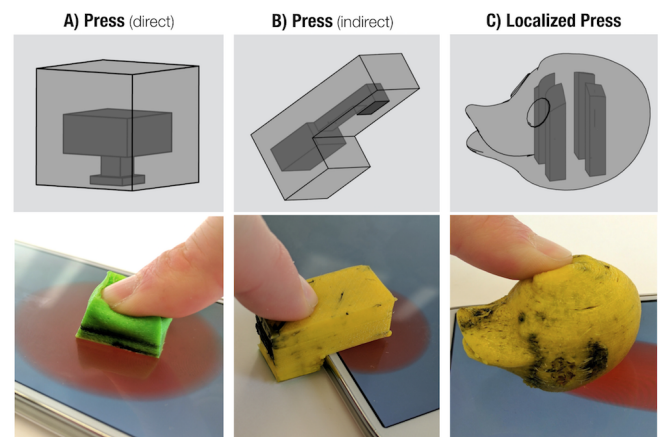

Figure 5. The pressure mechanisms illustrated as a rendering (top) and deformed by a user (bottom).

areas on the touchscreen. Hence, their capacitance values can be read out separately. This allows for simultaneously measuring pressure input on various distinct locations on the object. By using bilinear interpolation between all values, the location of the press on the surface can be estimated.

One of our prototypes is shown in Figure 5C. Here, a duck's head is equipped with four distinct surface deformation sensors. They are laid out in a 2x2 grid of 18x18 mm² (4x4 mm² per sensor) with 7 mm of flexible overlay. By using bilinear interpolation, we experienced that 3x3 locations can be robustly identified with this 2x2 grid.

Squeeze Deformations
Next, we investigate how to capture squeezing. In contrast to pressing, squeezing is characterized by a *bilateral* compression from two sides pointing inside the object. Like for sensing of pressure, surface deformation sensors can be employed to capture squeezing.

Squeeze
Similar to pressure input, our tests revealed that the most suitable geometry for a squeeze-aware surface deformation sensor is mimicking the object's outer shape.

One of our prototypes is shown in Figure 6A. Here, an object is equipped with a surface deformation sensor (cross-sectional size of 10x10 mm²) with 7 mm of overlying flexible structure to both sides of the object's surface. The sensor is connected to the underside of the object using a forwarder with a size of 3x3 mm² at the contact face.

Localized Squeeze
Besides the amount of squeezing, the location of the fingers on the object's surface can be of interest (e.g. distinguishing a squeeze from left-to-right or front-to-rear). Similar to the localized pressure mechanism, the surface deformation sensor can be spatially replicated into multiple sensors, each facing a different direction. The rough squeeze input location is then identified from the pair of opposite sensors that have the highest value. By using interpolation between adjacent sensors, the resolution can be improved further.
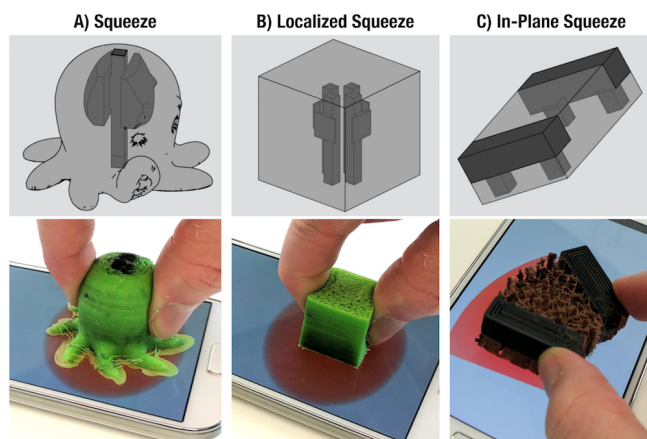
This mechanism is illustrated in Figure 6B. Here, a cube is equipped with four distinct surface deformation sensors (cross-sectional size of 10 x 10 mm²), aligned in 90° angles. Each sensor's forwarder connects to the touchscreen with a contact size of 3x3 mm². The sensors are placed at 7 mm distance from the respective faces of the cube.

In-Plane Squeeze
Utilizing spatial deformation mapping, the following mechanism is able to infer squeeze deformations in the touchscreen's plane. For this mechanism, four forwarders are placed at the outer edges on the underside of the object. Pairs of two forwarders are connected with the object's upper surface, to ensure capacitive coupling between the user's finger and the touchscreen. The remainder of the object consists of a flexible structure, which allows squeezing the object.

When the object is deformed, the on-screen locations of the forwarders at the object's bottom change. If a threshold for all four forwarders is exceeded, their respective distances on the screen are used to approximate a contour of the object, allowing to compute the intensity of the squeeze deformation. This mechanism utilizes the higher spatial resolution of the touchscreen to sense more fine-grained squeezing. However, it is limited to squeeze deformations that are performed in parallel to the touchscreen.

A prototype is illustrated in Figure 6C. Here, a cuboid is equipped with four forwarders (contact size of 5x5 mm²). Each two are connected to each other by a conductor of size 30 x 10 mm² and separated by 30 mm of flexible structure in between.

Bend Deformation
Bend deformations inside an object can be detected using intensity deformation mapping, as illustrated by Figure 2B.

Binary Bend
We present a binary bend mechanism that uses intensity deformation mapping to detect whether it is bent or not (see Figure 7A). It consists of one forwarder at the object's contact face and a series of inner deformation sensors at its deformable tail (see Figure 7A). The user can grab the object at the outer
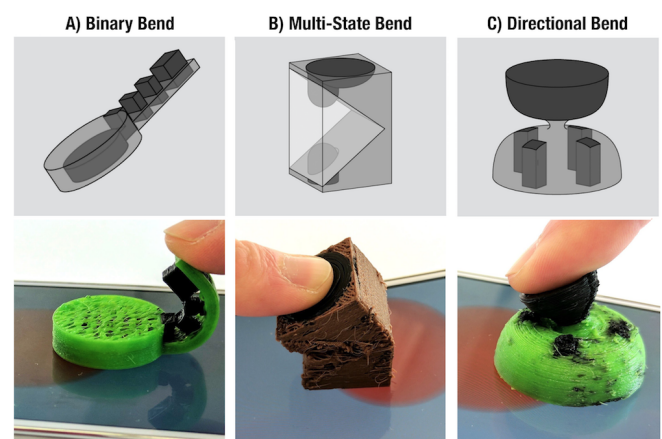

Figure 6. The squeeze mechanisms shown as a rendering (top) and deformed by a user (bottom).

Figure 7. The bend input mechanisms shown as a rendering (top) and deformed by a user (bottom).

end of its tail and deform the bendable structure. Multiple separate forwarders laid out at regular intervals on the bendable structure act as inner deformation sensors: they form a capacitive bridge that is closed as soon as the object is strongly bent. Bending utilizes inner deformation sensors because a bend cannot be directly inferred from the distance of a user's finger to a conductor.

One of our prototypes, shown in Figure 7A, utilizes a circular forwarder on the touchscreen (diameter of 12 mm). The forwarder connects to two inner deformation sensors (each with a size of 4x2 mm²), which end with a conductor for coupling with the user's finger (size of 4x5 mm²). We employ air as the dielectric material in-between the inner deformation sensors (separated by 3 mm), which makes it easier to print. The capacitance significantly changes when all conductors are physically connected. Thus, this mechanism is well suited to detect binary bends but does not allow to infer a bending angle. In addition to bending, the mechanism may also be used to capture folding, since it can be printed in slim geometries.

Multi-State Bend

Increasing in complexity, the multi-state bend mechanism detects multiple bending states in a fixed direction, which is pre-defined by the designer. It utilizes an inner deformation sensor that consists of multiple parts: The upper half of the sensor connects via a forwarder to the user's finger and the lower half of the sensor connects via a forwarder to the touchscreen. By bending, the user reduces the distance between the upper and the lower forwarder. Hence, a capacitance change is induced on the screen. As will be shown in the evaluation section below, this mechanism is able to distinguish between four bending states.

One of our prototypes is shown in Figure 7B. It utilizes a circular upper forwarder (diameter of 17 mm) combined with a circular lower forwarder (diameter of 5 mm) separated by 7 mm of flexible structure in between.

Directional Bend

Two-dimensional bending of a flexible object becomes possible if two volumetric parts are connected to each other by a thinner structure. For instance, the head of a figurine is connected to its torso by a thinner neck, allowing the head to be bent around two axes (see Figure 7C). We focus on this type of bending in the following.

To that end, the multi-state bend mechanism is spatially replicated to cover a broader range of 2D directions, similar to a 2D ball joint: The upper half of the mechanism consists of a forwarder and a thin connecting dielectric structure, printed with high density to strengthen the connection. At the same time, the lower half forms multiple distinct forwarders arranged in a circular way that connect to the touchscreen. Together with the upper forwarder, they form inner deformation sensors. When the object is bent in one direction, the upper forwarder gets closer to one or two of the lower forwarders, while it gets more distant from the remaining forwarders. This results in capacitance changes that can be measured by the touchscreen. Using this technique, a bending direction between 0° and 360°

can be estimated by interpolating between the capacitance of adjacent lower forwarders.

Figure 7C illustrates one of our prototypes. It utilizes a circular upper forwarder (diameter of 24 mm) mounted on a thin dielectric structure (diameter of 3 mm). The lower half consists of four distinct forwarders (contact size of 5 x 5 mm²) connecting independently to the touchscreen. We successfully tested the mechanism for up to eight forwarders placed at the lower half of the object.

Touch Contact Input

Of note is, that all these mechanisms are also suited to sense touch contact, i.e when the user's finger is touching the forwarder with minimal force. This results in a measurable increase of capacitance, which can be clearly differentiated from no touch contact, but which is considerably weaker than when a deformation occurs.

Combining Mechanisms

Despite deformation-aware mechanisms by themselves offer rich expressivity, they can also be combined inside of one object in parallel, resulting in various configurations that provide even greater possibilities. To that end, their forwarders are laid out such that they lead to distinct locations at the underside of the object. Hence, their values can be read out independently and simultaneously by the touchscreen.

A sufficient spacing between conductors is required. In our tests, a spacing of 5 mm between forwarders was satisfactory to ensure independent sensing performance. As an example, Figure 9 illustrates two mechanisms in a single object routed onto the contact area to simultaneously sense press and squeeze input.

EXAMPLE APPLICATIONS

To demonstrate the practical feasibility and the potential of our approach, we developed three interactive example applications.

Angry Trees

The first example is a tangible game, inspired by Angry Birds (see Figure 8). Users can play against each other by using two Flexibles: a palm tree and a Christmas tree. By bending and then releasing a tree, virtual fruits (either coconuts or Christmas balls) are thrown at the opponent. The on-screen
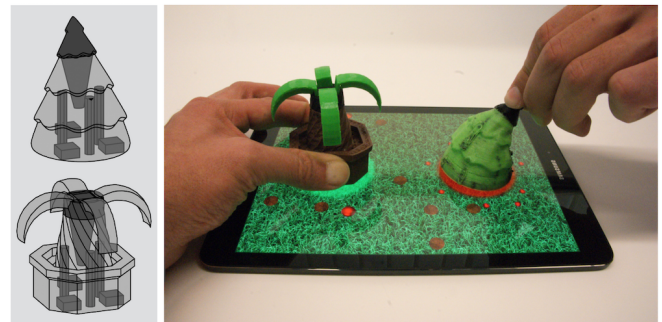

Figure 8. Interactive board game: two angry trees throw their fruits at each other.
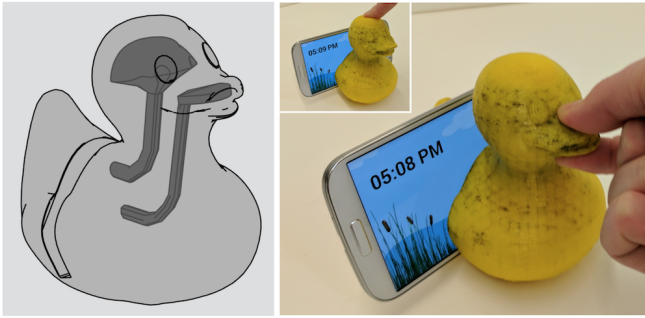
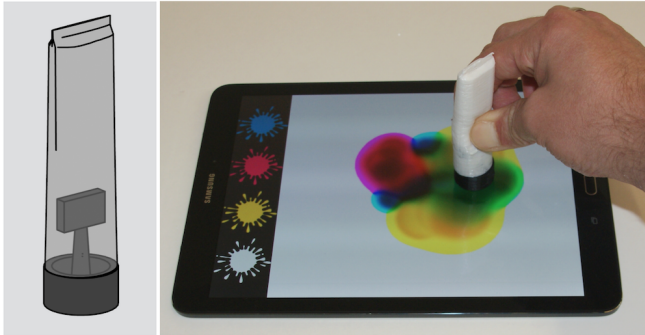**Figure 9. The alarm clock reacts to a squeeze or press (top left).**

Figure 10. Mixing colors by squeezing them out of a deformable tube.

trajectory of the fruits takes into account the current position and rotation of the tree on the screen. Using a simple physics simulation, the amount of bending defines how far the fruits are thrown on the screen. By squeezing a tree, all fruits are thrown. If a tree has no fruits left, they can be picked up again by squeezing.

Alarm Duck

To demonstrate the use of Flexibles for interactive devices, we implemented a docking station, shaped like a rubber duck, that operates as an alarm clock (see Figure 9). It enhances a smartphone with deformation-aware controls. The system launches an alarm clock application when a user docks the smartphone at the back of the duck. The user sets the alarm time by squeezing the duck's beak until the desired wake-up time is displayed on the smartphone. By squeezing more firmly, the time on the display changes more quickly.

At night, the user can press on the top of the duck for easy-to-reach functionality. A slight press shows the time left to sleep on the smartphone's display. A harder press lets the system read the time aloud. When the alarm goes off, the smartphone plays a chirping sound. The user can squeeze the beak to turn on snoozing. The length of the snoozing time depends on how firmly the user squeezes.

Squeezy Tube

In this example, a squeezable tube is used together with a touchscreen (see Figure 10). In analogy to a physical pipette, users can select elementary colors by placing the tube onto a color on the display and then squeeze the tube. The color can

then be dispensed by placing the tube on another screen location and squeezing it. Depending on the amount of squeezing, more or less color is dispensed, which allows for mixing of colors. This opens up a broad range of tangible applications in education (c.f. [42]), for instance to more directly combine different amounts of virtual fluids.

EVALUATION

We conducted technical experiments to evaluate the accuracy of the press, squeeze, and multi-state bend input mechanisms with users.

Accuracy of Pressure Input

First, we tested the press mechanism with the object shown in Figure 5B. To compare the actual force with which the object is being pressed to capacitance, we mounted a force sensing resistor (FSR) inside the object, in-between the flexible dielectric and the conductor of the surface deformation sensor. As the object is being pressed, force is exerted onto both the FSR and the press mechanism. We logged analog-to-digital (ADC) readings from the FSR and raw ADC readings from the capacitive touchscreen controller simultaneously by wiring them to the same computer. Five participants had the task to each press onto the object with a continuously increasing normal force, from no force to pressing firmly. This generated 500 data points. By conducting the study with users instead of a mechanical apparatus, we account for the inter-individual differences in users' capacitive responses.

As shown in Figure 11, the press mechanism is capable of sensing multiple intensities of pressure. For very small forces (<30), the capacitance increases without considerable effect on the measured force. This is the phase when the finger slightly touches the object with an increasing contact surface. This is followed by a quite linear mapping between capacitance measurements and applied force. For large forces (>300), the flexible structure reaches its limits in elasticity and the mapping is non-linear. This behavior can be modeled with a nonlinear least squares model based on a sigmoid. With this, we can compute a mapping function from capacitance to
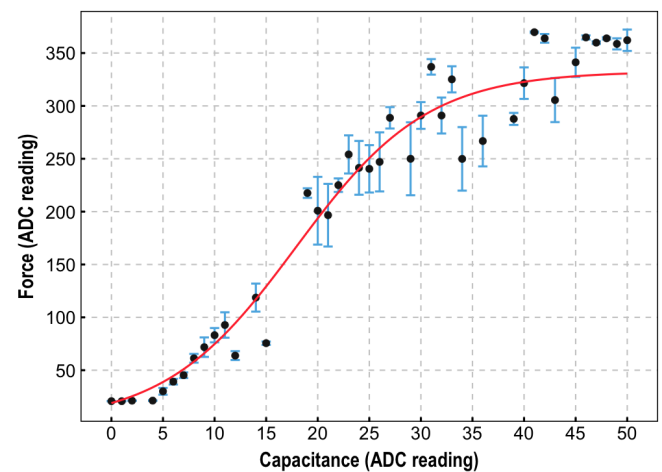

Figure 11. Mean forces (with standard deviations) for measured capacitances for press input. The mapping function is shown in red.
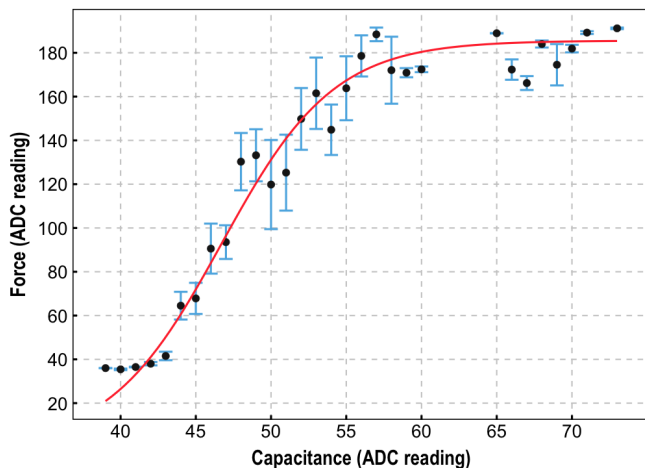
Figure 12. Mean forces (with standard deviations) for measured capacitances for squeeze input. The mapping function is shown in red.

Figure 13. Mean capacitances (with standard deviations) for four pre-defined bend states.

force $f(C) = a/(1 + exp(-b*(C-c)))$ with a = 332.73 (SD 5.92), b = 0.16 (SD 0.007), and c = 17.89 (SD 0.50) with a residual standard error of 43.8.

An object's response may differ due to variations in the printing process or individual properties of the user. As discussed, this needs to be compensated by adjusting the minimum and maximum of the mapping function via calibration. The mapping function is specific to the mechanism's geometry.

Accuracy of Squeeze Input

We next tested the accuracy of the squeeze mechanism. Similar to the task above, we collected 500 samples with five study participants who had to squeeze an object with varying force.

Figure 12 illustrates, that this mechanism is able to measure multiple intensities of squeezing. We can fit a nonlinear least squares model based on a sigmoid. With this, we can compute an approximation of the function $f(C) = a/(1 + exp(-b*(C-c)))$ with a = 185.56 (SD 4.38), b = 0.27 (SD 0.02), and c = 46.71 (SD 0.32) with a residual standard error of 42.1. Similar to the results for pressure input, the gradient is smaller for small ($<$40) and bigger forces ($>$160).

Accuracy of Bend Input

For the multi-state bend mechanism (see Figure 7B), we recorded raw capacitive ADC readings for four pre-defined bend states: rest state (with no force applied), slight bend, strong bend, maximal bend (with maximal force applied). Participants had to deform the object to match a given bend state. In each trail, an image was displayed on a computer screen that showed a photograph of the object in the target state. For each condition, capacitance data was recorded. In total, we collected 1200 samples (for 5 users).

Across all samples, the mean values were 3.77 (SD 2.1) for rest state, 6.51 (SD 2.23) for slight bend, 10.37 (SD 2.55) for strong bends, and 22.81 (SD 5.5) for maximal bends (see Figure 13). The results show, that at least four different bend states can be reliably distinguished across different users.
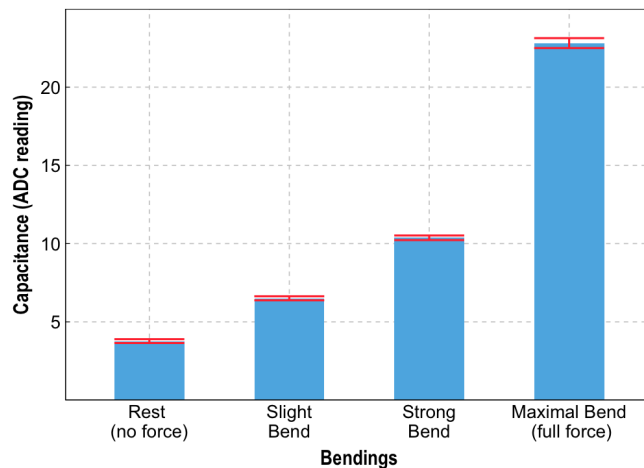
DISCUSSION AND LIMITATIONS

This paper presents first results on how to leverage capacitive coupling between a touchscreen and a 3D-printed object to sense specific pre-defined deformations. However, Flexibles have limitations that must be considered during design, fabrication, and sensing.

Set of Deformations and Resolution

In general, a flexible object can be deformed in many complex ways. This paper explores a basic and widely used set of deformations. More complex deformations (e.g. twisting) or continuous, high-resolution deformation input are not covered. The main reason is that the electrical properties of today's flexible conductive printing materials are interference-prone (see appendix of [1]).

Despite these restrictions, we demonstrated that multiple intensity levels of pressing, squeezing and bending can be captured, alongside information about the location or direction of the deformation.

Material Fatigue and Latency

We found no evidence of material fatigue after repeatedly deforming the object (more than 500 times). This is in line with Ion et al. [16] who demonstrate that the same TPU material can be deformed 5000 times without noticeable degradation.

Also, the approach does not rely on deforming the conductive material; only non-conductive parts are deformed. This avoids latency known from flexible conductors, such as eTPU, whose resistance is dependent on both history and rate of deformations performed over time [1].

Scalability and Geometries

Scalability is an important issue, as the size of a Flexible and of the capacitive touchscreen may vary from small (e.g. smartphones) to very large (e.g. wall-sized displays). The mechanisms presented in this paper use sensing structures that are optimized for the size of a fingertip (16-20mm [8]). Hence the results apply only to deformations that are performed with fingers. Also, the approach requires a volumetric object inside

which conductors can be routed. Therefore, geometries with thin structures, high curvatures, or cavities remain challenging.

The minimal size of a mechanism is limited by the rather low resolution and the high nozzle diameter of today's commodity 3D printers. Using our print setup, the minimal cross-sectional size of the sensing structure's conductor is 3x3 mm². A second limit to miniaturizing mechanisms relates to the flexible structure. If shrunk, the sensing resolution will be reduced because the flexible structure is deformable to a lesser extent. For very thin objects (<4 mm), the sensors will not function properly because there is no space for compressing the flexible structure. Future printers and materials, which can be extruded with smaller nozzles, are likely to alleviate these restrictions.

Designers may increase the cross-sectional size of the sensing structure's conductor to enhance its sensitivity or to better match a larger body part for interaction (e.g. hands). However, the maximum size of a sensing structure is not only limited by the printer's print volume (for our setup 21 x 21 x 20 cm). It is also limited by the rather low conductivity of the conductive material and by environmental stray capacitance. We successfully tested lengths of a forwarder up to 15 cm without noticing an influence on sensing performance. We recommend that designers construct conductors only as large as necessary for their use case. It is also possible to increase the thickness of the flexible structure, to enable greater deformations. However, an increasing thickness of the flexible structure weakens the capacitive effect. Therefore, the size of the sensing structure should be increased accordingly. We found a thickness of 4 mm to 10 mm to be a good trade-off between the sensor's sensitivity and the deformability of the material.

Movement of Objects
When object movement is detected, the software maintains the last known deformation state. Hence, deformation sensing and object movement can only occur sequentially. As the spatial resolution of touch grids is limited, the forwarders of a Flexible are not always perfectly aligned with one intersection point of the grid. In that case, the capacitance splits up into different intersection points, which affects the sensor readings. Uninterrupted sensing could be implemented by using a specialized kernel with bilinear interpolation of readings from adjacent intersection points.

Flexibles printed with TPU at their lowermost layer exhibit a higher stiction and friction compared to PLA on touchscreen glass. Nevertheless, we observed that TPU objects were easily moved by our participants. Depending on the application, designers may want to increase or decrease the stiction or friction of a Flexible. This can be achieved by varying the ratio of PLA and TPU in the object's lowermost layer. In contrast to our print setup, this would require a 3D printer that can handle at least three materials (cPLA, TPU, and PLA).

Unintentional Input
Capacitive measurements could be affected by capacitive effects when the user is unintentionally touching another location. Likewise, capacitive cross-talk between adjacent conductors could influence the sensor readings. To minimize these effects, designers should consider the following aspects:

(1) The cross-sectional area of a surface deformation sensor should be much larger than of the remaining forwarders inside the object. (2) Any forwarder should be located rather in the center of the object than close to its outer sides unless the forwarder is designed to be touched by users for capacitive coupling. A forwarder should be as thin as possible and distant from other forwarders. The specific dimensions depend on the printer's resolution and the conductivity of the material. We experienced that adjacent forwarders should maintain a minimal distance of at least 5 mm. (3) The infill density at non-interactive locations should be increased to avoid accidental deformations.

Due to the rather low resolution of today's 3D printers, the larger cross-sectional area of wires is a reason for cross-talk between conductors that are routed in parallel. This is a noteworthy issue in objects with many spatially replicated forwarders or combined mechanisms, which require many forwarders. Future printers are likely to mitigate this issue due to increased resolution.

Commodity Touch Sensing Hardware
Despite using unmodified commodity touch sensing hardware, the approach uses a debug interface to capture raw capacitance data. Open access to such data would require a modified driver which could be supplied by OEMs.

CONCLUSION
This paper has presented 3D-printed flexible tangibles, called *Flexibles*, that add deformation-awareness to passive tangibles on standard capacitive touch sensing hardware. Flexibles enable many new possibilities for interaction with on-screen tangibles. We contributed two deformation mapping principles and a set of 3D-printable mechanisms that capture press, squeeze, and bend input. They can be integrated within custom geometries and on many custom locations on the tangible object. A Flexible itself is completely passive and 3D-printed in a single pass on a consumer-level 3D printer without further modifications.

With advances in 3D printing technology, we believe that deformation-aware tangible objects will become an important part of interaction with capacitive touchscreens. Based on the mechanisms presented in this paper, future work should investigate how to ease the fabrication process with automated design tools and how to apply auto-generation of deformation sensing mechanisms in order to support more complex geometries.

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