Capricate: A Fabrication Pipeline to Design and 3D Print Capacitive Touch Sensors for Interactive Objects

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ABSTRACT

3D printing is widely used to physically prototype the look and feel of 3D objects. Interaction possibilities of these prototypes, however, are often limited to mechanical parts or post-assembled electronics. In this paper, we present *Capricate*, a fabrication pipeline that enables users to easily design and 3D print highly customized objects that feature embedded capacitive multi-touch sensing. The object is printed in a single pass using a commodity multi-material 3D printer. To enable touch input on a wide variety of 3D printable surfaces, we contribute two techniques for designing and printing embedded sensors of custom shape. The fabrication pipeline is technically validated by a series of experiments and practically validated by a set of example applications. They demonstrate the wide applicability of Capricate for interactive objects.

Author Keywords

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

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation

INTRODUCTION

The emergence of additive manufacturing technologies enables users to rapidly fabricate custom-designed 3D objects. However, the interaction possibilities embedded in these objects are in many cases limited to mechanical functions. As a consequence, these objects are in a sense *passive* [18]. One common approach to prototype *interactive* 3D objects is to post-assemble electronic components and circuits. While practical and widely used, the pre-designed form factors of such sensors severely constrain the shape of the object and make it very challenging to realize complex 3D surfaces.

To provide more design flexibility, an emerging stream of research investigates how to embed customized interactive elements directly within the fabricated object [23, 19, 18, 6, 22]. However, while capacitive sensing is the main technique used in commercial devices for capturing touch, this was not accessible to users who seeked to fabricate 3D prints with embedded capacitive sensing. 3D printed capacitive touch sensing is not only challenging because it requires 3D printing of embedded conductors and electrodes; it is also challenging because existing designs for flat 2D touch sensors do not transfer well to complex 3D geometries.

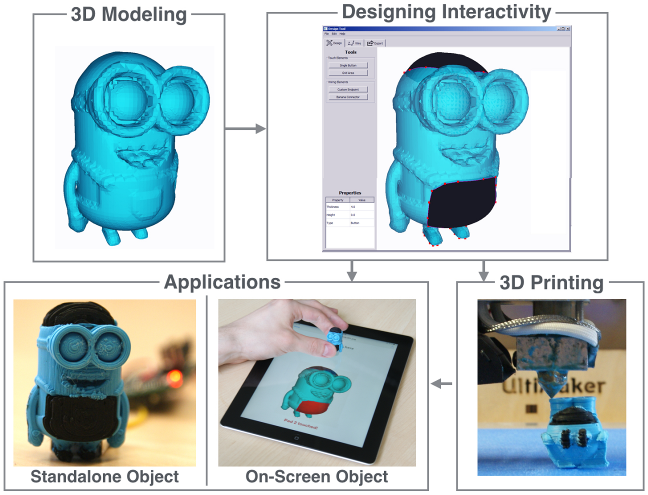

Figure 1: The Capricate Fabrication Pipeline (black parts are touch-sensitive).

In this paper, we contribute Capricate, the first fabrication pipeline for rapid design and 3D printing of interactive objects with embedded capacitive multi-touch sensors (see Fig. 1). 3D objects can be designed in a standard 3D modeling environment. Touch-sensitive areas are then added using our integrated design tool. The interactive object is then fabricated in a single print pass using a commodity multi-material 3D printer. This enables capacitive touch interaction on a wide range of 3D objects using either standard capacitive touch sensing controllers (e.g., an Arduino) or capacitive multi-touch surfaces (e.g., a tablet).

We further contribute two touch sensing techniques that support the creation of touch buttons and grids, all with custom 3D shape, size, and orientation on flat, ruled (i.e., surfaces produced by bending and twisting a flat plane) and doubly curved surfaces (i.e., surfaces curved in two directions).

We report on our experiences for multi-material 3D printing with carbon-based conductive materials and derive practical guidelines. Results from technical experiments and our first

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practical experiences show that Capricate is a viable approach to fabricate touch-sensitive interactive objects.

RELATED WORK

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 [17] or acoustic [14] sensors, or embedding cameras [18] or accelerometers [6]. These approaches involve manual assembly steps. Also, they require objects to be hollow and the cavities must be accessible from the outside.

Recently, an emerging stream of research investigates how to embed *customized interactive elements* in 3D printed objects and how to design and print conductive traces [2, 12]. This includes redirecting in- or output channels through light pipes [23, 3] or unfilled pipes [19] in printed objects. Other approaches print interactivity by means of conductive threads [7] or conductive spray [8]. Adding to this body of research, we contribute a fabrication pipeline for capacitive touch sensors that supports flat, ruled, and also doubly curved surfaces.

Fabricating Custom Capacitive Sensors

Midas [20] contributes a digital design approach based on a vinyl cutter and conductive sheets. Other approaches [9, 13, 5] show how off-the-shelf inkjet printers can be used to realize thin and deformable capacitive touch sensors of custom shape that can be embedded into or wrapped around objects. While widely used and practical, they require additional assembly effort, are only applicable for flat and ruled surfaces, and not suited for doubly curved surfaces.

In addition, researchers propose different techniques that integrate electrical components directly into 3D printed objects by means of conductive wires [4], silicone [15], sprays [16], inks [1], or threads [7]. Lopes et al. suggest a hybrid approach that combines 3D printing with electronic components [11]. However, they do not discuss capacitive touch sensing. Research in material science demonstrates the feasibility of capacitive sensing with low-conductive 3D printed conductors [10, 21]. Their proof-of-concept prototypes use all-flat and manually designed touch electrodes for sensing of simple touch buttons (one point of contact). Capricate allows for realizing touch grids (multiple points of contact) on flat, ruled, and doubly curved surfaces.

DESIGNING WITH CAPRICATE

While the emergence of digital fabrication technologies allows users to rapidly *print* custom 3D objects, the *design* of touch electrodes is still a tedious task and often requires expert knowledge in CAD. This is partially due to the fact that custom-shaped areas on a 3D surface need to be selected, extruded, and fused manually with the original model. In addition, when designing complex touch grids, a multitude of touch electrodes need to be designed and wired by hand and possibly have to be mapped onto a doubly curved surface. Adding capacitive touch sensing to such surfaces is one of the main challenges addressed in Capricate.

To mitigate these difficulties, we propose a design tool as part of Capricate allowing users to intuitively (1) *design* custom-shaped touch sensors on complex 3D surfaces, (2) automatically *wire* these to pre-designed or custom-shaped endpoints, and (3) *generate* fabrication files to 3D print the object.

Designing A user can design custom-shaped touch sensors on any part of the 3D model by using a two-step interaction technique: (1) After selecting whether a touch button or grid should be created, she indicates the rough location and the approximate size of the sensor on the 3D surface (see Fig. 2a). The user is supported by a 3D visualization that closely follows the 3D surface as the mouse cursor hovers over a part of the object. This indicates where the sensor would be placed. The size of the selection can be adjusted using the mouse wheel. By clicking, the touch sensor is applied to the desired location. (2) Then, similar to adjusting free-form paths in 2D drawing applications, the user can fine-tune the shape and size of the initial selection by dragging existing edge points or by adding new edge points between two lines (see Fig. 2b). In case of a touch sensor grid, the user can freely define the number of electrodes it shall contain.

To offer a rich variety of interactions, Capricate supports two different touch sensing modes: (1) *Standalone* uses a standard capacitive touch controller. The object is wired to the controller via standard sockets (e.g., banana connectors) on the object. The embedded touch electrodes are automatically wired to those sockets. (2) *On-Screen* uses capacitive forwarding (similar to [24]) onto a smartphone or tablet screen

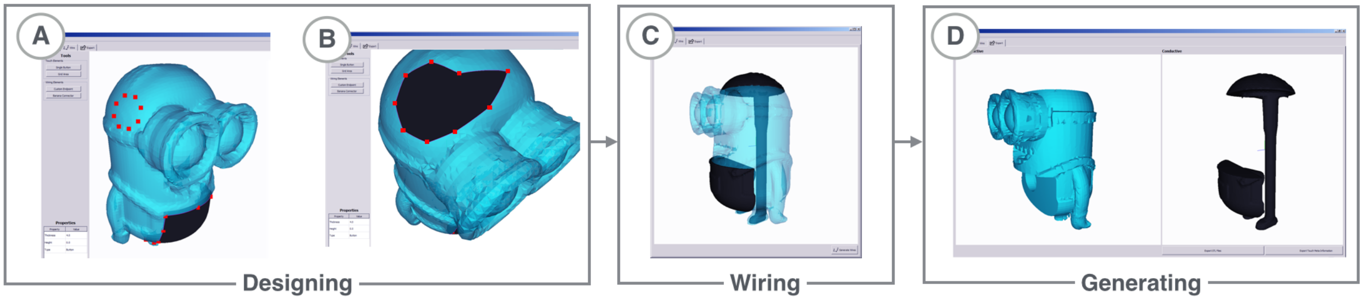


Figure 2: Designing with Capricate: A user (a) chooses a sensor type, selects an approximate location on the surface, and (b) fine-tunes the selection. The tool (c) automatically wires the sensors to endpoints, and (d) generates the files for 3D printing.

(see Fig. 1). For this, a user has to create custom endpoints (e.g., flat electrodes on the object's resting contact points).

Wiring Both modes support auto-routing of touch electrodes without the need for schematics (see Fig. 2c). We employ a dynamic routing approach based on A* (as in [19]). It operates on a graph consisting of a regularly-spaced 3D grid created inside the 3D model. Thus, each touch electrode is routed to its nearest endpoint.

Generating Fabrication files for multi-material printing are automatically created by partitioning the 3D model in conductive and non-conductive parts (see Fig. 2d). Code is generated to facilitate the mapping of a standalone or on-screen touch event to the respective 3D touch electrode.

TOUCH SENSING ON DOUBLY CURVED SURFACES

Capacitive touch sensing on flat and ruled surfaces (e.g., cylinders or cones) can be effectively implemented with standard rectangular lattices [9, 13, 5, 20]. However, rectangular lattices produce significant distortions when mapped on doubly curved surfaces, resulting in non-uniformly distributed touch points [3]. Although promising topologies for spherical surfaces have been proposed [3], touch sensing on arbitrary doubly curved surfaces remains a challenge.

Capricate addresses this challenge by contributing two techniques for touch sensing on custom-shaped areas of doubly curved surfaces. The first technique consists of *curved surface touch electrodes*, which closely follow the curvature (see Fig. 3a). To significantly speed up the fabrication process, the second technique utilizes *flat subsurface touch electrodes* and an automatic sensor calibration to account for the variance in overlying non-conductive material (see Fig. 3b).

Curved Surface Touch Electrodes

Using this technique, electrodes follow the exact geometry of an object's surface. To achieve reliable capacitive touch sensing with the same resolution within a touch sensitive area, touch electrodes need to be distributed evenly on the selected area. This is the main challenge that we address in two steps: First, touch points are *uniformly distributed* in the selected area using a graph optimization mechanism. Second, *touch electrodes are generated* directly on the object's surface, using a region growing approach.

Step 1: Uniform Touch Point Distribution

While rectangular and Fibonacci lattices can be used for flat, ruled and spherical surfaces [3], it is challenging to uniformly distribute touch points on custom-shaped areas of doubly curved surfaces (see Fig. 4). To address this, we propose an iterative graph optimization technique to create touch grids with n uniformly distributed touch points on a 3D surface: First, n vertices are randomly selected as touch points inside the selection. Second, a repulsion force f_e is evaluated iteratively for each vertex v and its adjacent vertices W by summing up all distance reciprocals: $f_e = \sum_{\vec{v} \neq \vec{w}_i} (|\vec{v} - \vec{W}_i| + c)^{-1}$. Each touch point is then moved to the adjacent vertex with lowest repulsion until all positions converge.

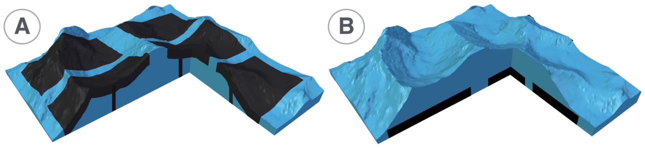


Figure 3: Cross-section of the Himalaya mountains model showing touch sensing with (a) curved electrodes on the surface, and (b) flat electrodes in the subsurface (black parts are touch-sensitive).

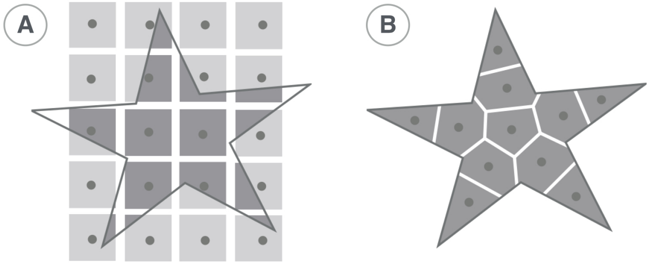


Figure 4: Comparing the distribution of touch points (gray circles) on a custom shape in 2D: (a) the standard touch grid layout, (b) our surface touch electrodes technique.

Step 2: Touch Electrode Generation

Using the uniformly distributed touch points, n electrodes are then generated using a Dijkstra-based region growing approach, which results in a Dirichlet tessellation of the object's surface. First, each vertex is assigned to the electrode with the smallest euclidean distance. Second, all faces whose vertices all belong to the same electrode are also assigned to it. All faces where vertices belong to different electrodes form a gap in-between and thus avoid accidental interconnections. Third, electrodes are extruded along the normal directions and can, optionally, be submerged under the surface. To maintain a 3D printable model, the object's 3D model needs to be adjusted. This is achieved by removing the volume occupied by the computed electrodes using boolean subtraction. Example objects with doubly-curved surfaces are depicted in Fig. 5.

Flat Subsurface Touch Electrodes

Instead of printing surface electrodes, a second touch sensing technique consists of printing flat touch electrodes, which sense touch through the overlying non-conductive material (see Fig. 3b). This can significantly speed up the fabrication process due to less switching between materials. Switching is time-consuming and with our printer takes approx. 40 s (as identified in the implementation section below). In contrast to the previous technique, which may span many printing layers, flat electrodes can be printed on just a few layers – although they may be slanted.

Capacitive sensing is capable of capturing touch through non-conductive materials. However, sensor readings are greatly affected by the *overlay thickness*, i.e. the distance between a finger and a touch electrode. As the overlay thickness might be different for each touch electrode, it is important to separately calibrate each one to be able to precisely classify touch.

Given the great differences in overlay thickness, using the same threshold for all electrodes would be unreliable.

To address this challenge, we present an auto calibration technique which calibrates each touch electrode independently. It does not require any manual interaction, as it makes use of the geometric information available in the 3D model. For each touch electrode, the average thickness t_{avg} of material that overlays it in normal direction can be calculated from the 3D model (for varying overlay thicknesses above one touch electrode, the average gives a good approximation even if a finger would approach it inclined). Moreover, a *material function* $f(t) = \Delta C = |C_{touch} - C_{noTouch}|$ exists, which needs to be empirically measured for an overlay material. It relates a change in capacitance ΔC to different overlay thicknesses t. By using an approximation, we are able to predict a specific capacitive change for each overlay thickness computed from the 3D model. Using ΔC the specific threshold thr for a touch electrode can be computed as a percentage of the capacitance change to expect. E.g., for 90% the threshold would be set to $thr = 0.9 \cdot \Delta C = 0.9 \cdot f(t_{avg})$. To improve precision, we weigh the ΔC's from an activated electrode and all neighboring electrodes by thickness to interpolate the x-y-position and then compute the z-position from the 3D model.

By using our results for commonly used PLA (as identified in the evaluation section below), a nonlinear least squares model and the capacitance formula $C = \epsilon_r \epsilon_0 A t^{-1}$, we can compute an approximation of the material function $f_{PLA}(t) = a \cdot t^b$ with $a = 0.80096$ (SD 0.04231) and $b = -0.64139$ (SD 0.0456) with a residual standard error of 0.0753 (*df* = 4).

IMPLEMENTATION

Multi-material 3D printing with carbon-based materials implies practical challenges that stem from using multiple materials in a single print pass. To successfully 3D print objects with integrated conductive parts, we propose several practical guidelines. These are applicable for any FDM-based 3D printer and are implemented by injecting custom G-Code into existing slicing routines. Furthermore, we describe the apparatus underlying Capricate.

Practical Guidelines for Multi-Material 3D Printing

To prevent residuals at the time of switching materials, retract the previously used material by 1 mm. While the print head moves more than 1 cm without extruding, lift the z axis by 1 mm and lower it before continuing extrusion.

Since carbon particles reduces the viscosity of the ABS material, the likelihood that the nozzle gets clogged is considerably increased. We experienced that clogging can occur as soon as the extruder has been inactive about a few minutes, often resulting in print fails. *To prevent clogging* cool down the previously used extruder to the non-flowing state (to 150°C for conductive and 100°C for non-conductive material). Then, extrude the next material on a garbage stack located at the printing origin (10 mm for conductive and 6 mm for non-conductive). We found that this prevents the nozzle from clogging independent of the time the extruder remained unused. This modification takes 40 seconds per material switch and costs less than 1 cent of material.

To prevent disconnection in traces, use a trace diameter that is a multiple of the nozzle diameter (with our nozzle diameter at least 4 x 0.8 mm). Therefore, the maximum density of wires is in our implementation 4 wires per cm^2 (with 3 mm wire spacing). This also defines the maximum density of touch electrodes.

Apparatus

Capricate requires a multi-material 3D printer and a conductive material. We used an Ultimaker Original 3D printer with Dual Extrusion Kit (ca. $1500) and a commercially available conductive ABS material (cABS) with 5-8% carbon by Torwell Technologies (ca. $50 per kg), which has an average resistivity of 8Ω * mm. We identified an optimal extrusion temperature of 230°C (nozzle diameter 0.8 mm) with the cooling fan turned off.

Our controller board consists of an Arduino Micro (tethered to a PC) and a MPR121 capacitive sensor (12 sensing pins at a framerate of 29 Hz). We connected the sensing pins and the printed object with crocodile clips or banana connectors. Capricate uses either WebSockets or direct touch input to send touch events to an application.

EXAMPLE APPLICATIONS

To show the practical applicability of Capricate, we developed example applications in three contexts: rapid prototyping of physical input, wearable computing, and tangible UIs.

Rapid Prototyping of Physical Input Devices

We printed several physical input devices (see Fig. 5a). One of them was a *hemispherical input device* with which users may navigate in a hierarchy by rotating fingers around the hemisphere and select an item by pressing the touch area on top. Also, mechanical structures can be printed to sense *physical manipulations*. The pushbutton includes a spring mechanism such that pushing of the button is capacitively sensed using a touch electrode connected to the controller and a forwarding electrode without any connection. The design principle of the physical slider consists of a series of rectangular-shaped touch electrodes that are linearly arranged and a conductive sliding knob. Both designs can distinguish between touching and physically manipulating. Moreover, we designed an on-screen *directional pad*. Untethered touch electrodes are printed on its four ends. These forward a touch onto a capacitive surface when pressed by a user.

Wearable Computing Devices

With Capricate users can rapidly design and 3D print *highly individualized* wearables (e.g., an interactive ring or wristband) or accessories for existing wearable devices (e.g., a touch sensitive frame for Google Glass with more touch sensing possibilities). As proof of concept, we printed a bracelet that features an embedded doubly curved slider and an interactive glasses frame that can recognize touch-gestures on its front and left side (see Fig. 5b).

Printed Tangible User Interfaces (TUIs)

TUI designers may use Capricate to create tangible controls that represent a specific form and also have interactive behavior. For example, we fabricated an interactive model of the

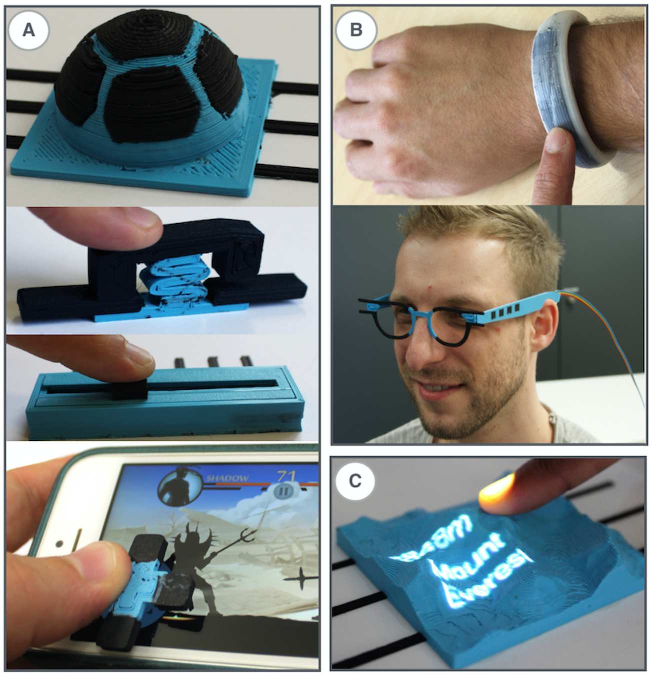


Figure 5: A series of example objects for (a) physical input prototyping, (b) wearable computing, and (c) printed TUIs.

Himalaya mountains with 6 embedded touch electrodes to facilitate the exploration of related information (see Fig. 5c). Names and heights of Himalaya mountains are top-projected when the user is touching on the respective location on the object. This application can be extended to distinguish touch on toy characters (see Fig. 1), separate letters, number, icons, or braille, thus allowing for haptic alphanumeric or iconic mapping to digital information.

TECHNICAL EVALUATION

To show the viability of Capricate, we evaluated the performance of 3D printed touch sensors with respect to their conductivity and dimension. Moreover, we examined the effect of PLA overlays for different thicknesses.

Conductivity

As the conductivity of the material influences the performance of capacitive sensing, we evaluated the resistivity ρ of a conductor printed with cABS, which depends on several factors: the fill density, the printing pattern, and the direction of electrical flow. As our objective was maximal conductivity, we used only 100% fill density. We identified significant differences in resistivity ($t(12) = 5.927, p < .001$, 14 samples at $100x12x1mm$) depending on whether the printing pattern consists of horizontal traces that are aligned ($\rho_{avg} = 4.382$ $\Omega * mm$, SD 1.285) or perpendicular ($\rho_{avg} = 8.171\ \Omega * mm$, SD 0.658) to the direction of electrical flow. In vertical direction, the average resistivity was $\rho_{avg} = 9.976\ \Omega * mm$ (SD 1.729). The measurements show that the resistivity highly depends on the direction of electrical flow. Thus, we recommend to print conductive traces alongside the direction of electrical flow and adapt slicing algorithms accordingly.

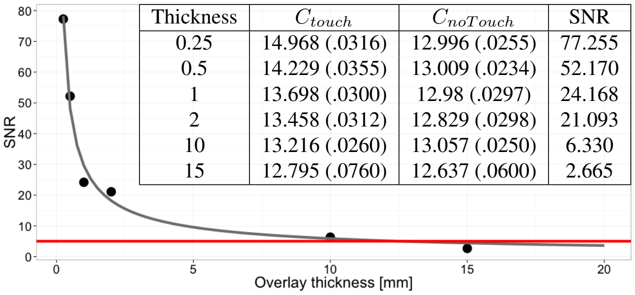
Dimension of Touch Electrodes

To examine the performance of capacitive sensing with cABS, we analyzed different touch electrode dimensions with varying resistances of the connecting traces. We measured the changes in capacitance (i.e., touched or not touched by a finger) for varying electrode sizes (ø = 5, 10, 15, 20 mm) and increasing resistors (with resistances of 20 to 120 $k\Omega$, 10 $k\Omega$ intervals). We found that for all sizes, the wire resistance should not exceed 30 $k\Omega$. Otherwise, the signal-to-noise ratio (SNR) drops below 5:1, jeopardizing robust touch sensing.

We experienced a minimum thickness of 0.2 mm for touch electrodes resulting in measurable capacitance change. The minimal touch electrode width and length are defined by the nozzle diameter (here 0.8 mm). For most minimal traces with size of a single nozzle diameter (0.8 mm, 0.2 mm layer height) we were able to reliably sense a capacitance change up to 10 cm. The touch electrodes may be printed on the outermost layer or alternatively embedded inside the surface, allowing fully disguised touch sensing under any colorized material. To hide touch electrodes, the overlay should have at least the height of one printing layer (here 0.2 mm).

Overlay Thickness

To implement and test the flat subsurface touch electrodes technique, we evaluated the effect of PLA overlays for different thicknesses onto sensing performance by measuring capacitance in a 2 seconds interval either with or without touching (for circular electrodes of fingertip size with ø = 15 mm). The results show that for cABS the maximum overlay thickness is 10 mm. Fig. 6 illustrates that the thickness greatly influences the sensing performance in terms of SNR. For 10 mm, the difference in capacitance are still robustly measurable with a SNR of 6.33 as shown by a t-test (t(3968.786) = 194.799, p < 0.001). For thicker overlays, the SNR falls below a minimal SNR of 5:1, which is generally considered as the lower bound for robust touch detection. Therefore, flat subsurface touch electrodes can be placed at most 10 mm underneath the outermost point on the surface; further the maximum height difference (along the surface normal of the touch electrodes) between any two points on the surface cannot exceed 10 mm. If these requirements cannot be met, the sensor should be implemented using the curved surface touch electrodes technique.



Thickness	C_{touch}	$C_{noTouch}$	SNR
0.25	14.968 (.0316)	12.996 (.0255)	77.255
0.5	14.229 (.0355)	13.009 (.0234)	52.170
1	13.698 (.0300)	12.98 (.0297)	24.168
2	13.458 (.0312)	12.829 (.0298)	21.093
10	13.216 (.0260)	13.057 (.0250)	6.330
15	12.795 (.0760)	12.637 (.0600)	2.665

Figure 6: Comparison of touch / no touch for varying overlay thicknesses of PLA. The red line marks a minimal SNR of 5.

LIMITATIONS

Capricate allows to 3D print touch sensors. However, there are currently several limitations.

Geometries

While applicable for many doubly-curved surfaces, geometries consisting of small structures (< 1 mm), high curvatures, or holes remain challenging. Future work should investigate touch sensing techniques on such geometries.

Resolution

First, the number and density of electrodes in our examples is rather low, particularly in touch grids. This is limited by the rather low resolution of the printer and the nozzle diameter. Future printers and materials, that can be extruded with smaller nozzles, are likely to alleviate this issue in the future. Second, touch electrodes are currently distributed uniformly across the surface. While adequate for most cases, this may be inefficient for steep geometries. Future work should investigate adaptive layouts (e.g., adapt to local surface curvature). Third, the number of input pins on the controller board is currently limited. This can be increased with a custom-designed board, by adding multiplexers or by using mutual capacitance controller boards. The latter also requires novel touch electrodes that should be investigated by future work.

Hovering

Due to the high resistivity of cABS, the detection of other capacitive sensing modalities besides touch is very challenging. While we could successfully detect hovering within small distances above the surface (<10 mm) of a fingertip sized electrode ($\o$ = 15mm), larger distances cannot be reliably captured. Future work should investigate additional input modalities that can be captured with capacitive sensing.

CONCLUSION

In this paper, we presented Capricate, a fabrication pipeline to design and print capacitive touch sensors embedded in 3D printed objects. It is based on a multi-material 3D printing approach and uses affordable off-the-shelve materials and 3D printers. Our design tool allows users to easily create custom-shaped touch sensors on 3D surfaces of objects. In addition, we contributed two capacitive touch sensing techniques on doubly curved surfaces by sensing directly on the surface or via flat subsurface electrodes. As to printing objects along with touch electrodes and traces, we presented a number of practical guidelines for multi-material 3D printing of carbon-based conductive materials. Several example applications showed Capricate's applicability. Our technical experiments validated our approach; beyond that, it can serve as a helpful blueprint for evaluating future materials. We plan to conduct user studies to test the effectiveness of Capricate.

ACKNOWLEDGMENTS

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