ObjectSkin: Augmenting Everyday Objects with Hydroprinted Touch Sensors and Displays

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Augmenting everyday objects with interactive input and output surfaces is a long-standing topic in ubiquitous computing and HCI research. Existing approaches, however, fail to leverage the objects' full potential, particularly in highly curved organic geometries and in diverse visuo-haptic surface properties. We contribute ObjectSkin, a fabrication technique for adding conformal interactive surfaces to rigid and flexible everyday objects. It enables multi-touch sensing and display output that seamlessly integrates with highly curved and irregular geometries. The approach is based on a novel water-transfer process for interactive surfaces. It leverages off-the-shelf hobbyist equipment to fabricate thin, conformal, and translucent electronic circuits that preserve the surface characteristics of everyday objects. It offers two methods, for rapid low-fidelity and versatile high-fidelity prototyping, and is applicable to a wide variety of materials. Results from a series of technical experiments provide insights into the supported object geometries, compatible object materials, and robustness. Seven example cases demonstrate how ObjectSkin makes it possible to leverage geometries, surface properties, and unconventional objects for prototyping novel interactions for ubiquitous computing.

CCS Concepts: • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools*;

Additional Key Words and Phrases: Fabrication, printed electronics, sensors, displays, touch input, prototyping, interactive objects

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1 INTRODUCTION

A major goal in ubiquitous computing is to blend interfaces with existing objects and surfaces in our environment. This will allow computing to ultimately become one of the technologies that "weave themselves into the fabric of everyday life until they are indistinguishable from it." [33]

While existing technologies allow to augment everyday objects with sensors and output, they are limited in important aspects to leverage the full potential of existing objects for interaction. One is the wide variety of organic geometries of everyday objects that are designed for ergonomic use and have been perfected over many centuries. Recent work supports only a limited subset of geometries to be augmented. While simple developable geometries can be covered by a flexible sensor or display sheet [9, 20, 21, 27], more complex geometries remain

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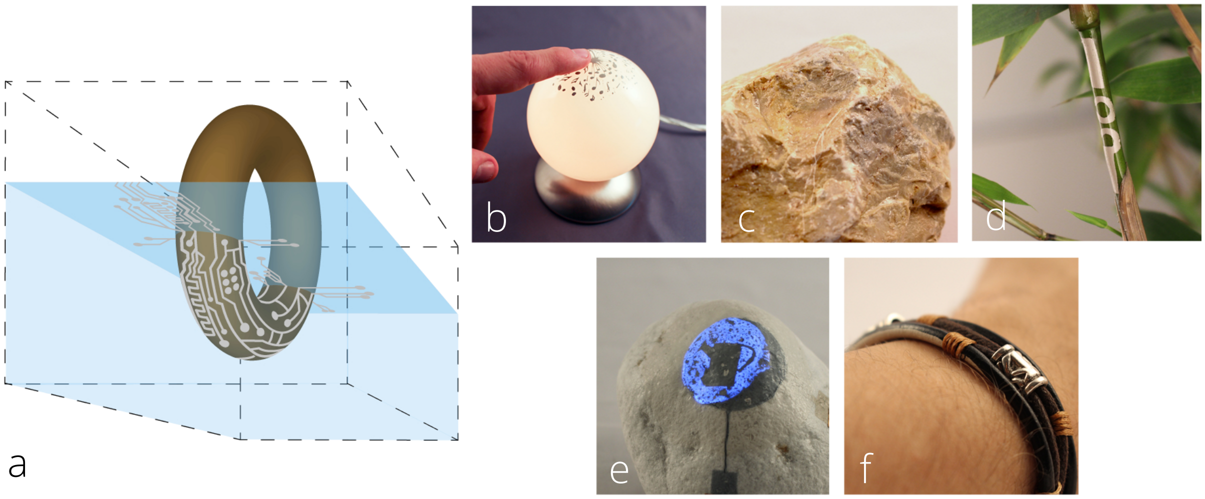

Fig. 1. ObjectSkin is a fabrication technology for adding interactive surfaces to everyday objects (a). It is used to realize custom sensors and displays that seamlessly conform to highly curved geometries (b) and the detailed surface structure (c) of a wide variety of everyday objects, including live plants (d), garden stones (e), and aesthetic wearables (f).

out of reach. A second aspect is the diversity of object materials with distinct visual and tactile features, which not only contribute to the aesthetics of everyday objects, but also serve as cues for interaction. Existing technologies are limited in their supported materials, e.g. a few 3D-printable polymers [4, 28, 35], or do not preserve the visuo-tactile properties of an object's surface [18, 34, 39].

These constraints have so far limited the possibilities for prototyping interaction on ubiquitous everyday objects. They especially limited the exploration of objects that are made of natural materials, such as leveraging the tactile cues of wood grain on carved objects, the natural patterns in plants and flowers, or the variety of different surfaces made from stone. Regarding geometries, they have also hindered research to go beyond the outer, easy-to-augment, surfaces, such as a watch strap [21], the outside of a coffee mug [9], or the head of a toy figure [4, 28, 35]. In contrast, everyday objects offer many more facets, including the inside of holes in rings or lattice structures, many small or thin parts in filigree jewelry, or highly-curved surfaces in tools, toys, and accessories. Thus far, these remain unsupported.

In this paper, we present ObjectSkin: a fabrication technique for adding very slim interactive surfaces to rigid and flexible everyday objects. ObjectSkin is the first technique to add conformal touch sensors and displays to highly curved and irregular geometries of everyday objects, e.g. a spherical lamp shade, a plant's stem, or fine-detailed jewelry. It uses hobbyist equipment available in HCI labs or maker spaces and enables thin, conformal, and translucent electronics on a wide range of materials, largely preserving the object's visual and tactile surface structure. This allows sensors and displays to seamlessly blend with the object's surface.

We contribute the fabrication technique, which is based on a water-transfer process of printed stretchable functional inks. We present the fabrication process in detail, including approaches for rapid low-fidelity and versatile high-fidelity prototyping.

We investigate what materials and geometries are supported by this technique, compare them with related work, and validate the results through a series of technical experiments. Their results confirm the method's ability to conform to highly curved geometries, to support a wide variety of materials, and to be long-lasting and robust against deformation on flexible geometries. We further illustrate the method's capabilities for prototyping interactive surfaces by showing how to realize non-invasive multi-touch sensing and display output on highly curved and rough surfaces.

We demonstrate how the fabrication method can enable new interactions on real-world objects, by leveraging newly supported organic geometries and the object's surface structure. To this end, we present seven diverse everyday objects that we augmented using our approach. A wooden ring and honeycomb pendant illustrate the use of the object's geometry, including holes, for geometry-guided touch gestures. A rough rock's surface structure serves as tactile feedback for eyes-free touch interaction. A collection of unconventional objects is enhanced with interaction capabilities, e.g., a live plant featuring a growing touch sensor.

In summary, the main contributions of this paper are:

- A new fabrication technique for thin and conformal interactive surfaces that seamlessly blend with an object's surface. It supports novel geometries and many materials.
- Non-invasive, i.e. on the object's surface, multi-touch sensing and display output on highly curved and rough surfaces
- Exploration of novel interactions for HCI, which leverage surface structure, object holes, and unconventional objects for interaction
- Evaluation of the approach, including the supported geometries, compatible materials, and robustness on flexible objects

The remainder of this article is structured as follows. We will first provide an overview of related work. We will then introduce the ObjectSkin approach and present the steps of the fabrication technique. Next we will investigate a variety of object materials and object geometries, which are commonly used in physical prototyping, and empirically assess their compatibility with the fabrication technique. We will then introduce how to use ObjectSkin to augment real-world objects with conformal sensors for touch and multi-touch input as well as with light-emitting displays. This enables novel interactions for HCI that will be presented. Finally, we will conclude with a discussion of limitations and directions for future work.

2 RELATED WORK

2.1 Sensing and displays on everyday objects

Work in HCI has demonstrated many techniques to sense interaction and provide visual feedback on everyday objects. A common approach to capture touch and provide high-resolution visual feedback uses computer vision and external projectors [2, 10, 11, 30, 36]. These approaches enable ad-hoc interaction on objects without applying sensors to their surface, but require external hardware, are limited in accuracy, and suffer from occlusion issues.

Other approaches detect touch input using acoustic [22] or capacitive sensing [26] on the object itself. These approaches can be seamlessly integrated in the object, but limit touch recognition to specific learned poses and locations. Electrick [39] proposes a different approach based on electric field tomography, which allows inference of the touch location on the object. It requires the object's surface to conduct electricity, e.g. through applying a layer of conductive coating. Our approach applies patterned electrodes, rather than one electrode covering the entire object. These enable custom shaped displays, match the object's geometry, and facilitate preserving the object's appearance by restricting the overlay to required regions.

2.2 Printed electronics in HCI

More closely related to our approach are techniques that add patterned electrodes, e.g. cut from copper tape [27] or printed [9, 15], to the object for sensing. Printed electronics have been used in HCI to realize custom touch sensors [9, 15, 20, 21] and displays for interactive surfaces [20, 21]. These can be applied to simple curved geometries, e.g. a watch strap [21], a folded lamp shade [20], or a coffee mug [9]. They support a variety of materials, but are limited to developable surfaces. This means that they are restricted to surface geometries that can be made from a flat sheet by folding, bending, cutting, and/or gluing, without use of stretching.

Non-developable object geometries are generally supported by approaches based on 3D printing. Integration of capacitive touch sensors and of light pipes to forward visual output has been demonstrated [4, 28, 35]. However, the geometries have so far been restricted to non-developable surfaces that are easy to augment, such as the head or belly of a toy figure [4, 28, 35]. In contrast, we aim to support more demanding geometries, which for instance include holes or many small or thin parts. This makes it hard to internally route printed wires or light pipes, as proposed in these approaches. In addition, we aim to enhance real-world objects of many different materials, whereas 3D printing is restricted to a small set of mostly polymeric materials.

Other approaches have presented stretchable printed electronics, e.g. made from silicone [31, 34]. These can be wrapped around non-developable geometries, but add a thick (>200μm) layer which does not preserve the visuo-tactile surface structure. Thinner approaches have been proposed to be used on the skin, based on temporary tattoo film or water-soluble PVA sheets [13, 17, 19, 32]. However, these approaches require a temporary transfer layer for application that is not elastic. This makes it impossible to apply the layer onto strongly curved non-developable surfaces (such as a sphere) and other demanding geometries, such as rough surfaces or holes.

In contrast, our approach uses an elastic film to overcome these limitations, as we discuss in more detail in Section 5. As a further contributing factor, our approach transfers liquid ink which is sintered afterwards on the object. We observed that this improves the ink's ability to stretch and to conform to complex geometries, compared to transferring already sintered traces as done in [17, 32].

2.3 Material science and printing technology

Printing conductors on varied materials and non-developable geometries is an ongoing research topic in material science. Promising results have been presented that leverage sophisticated machinery, processes, and inks, including omnidirectional inkjet printing using a robot arm [37], soft blanket gravure printing [12], and a special 3D printer for conformal antennas [1].

Recent work by Saada et al. [24] uses a water-transfer approach for pre-sintered conductive traces. This inhibits the traces from stretching during the water transfer. In contrast, our approach transfers liquid inks, which are sintered after the transfer. This allows the traces to stretch considerably when transferred onto the object, which is a requirement to support highly curved non-developable geometries. We discuss this in detail in Section 5. Our work further adds essential elements for rapid prototyping of input and output. These include true multi-layer electronics incl. VIAs through printed dielectric layers, conformal electroluminescent displays for visual output, and support for a larger variety of object materials. Lastly, the approach presented in [24] requires high-end lab equipment, similar to [1, 12, 37], as present in a specialized materials lab (Dimatix inkjet printer, specially produced PVA films, and sintering by hydrochloric fumes), while our approach works with hobbyist equipment.

3 FABRICATION TECHNIQUE

We contribute ObjectSkin, a fabrication technique to add surface-conformal input and output capabilities to 3D objects. It is the first technique to transfer printed electronic circuits for sensing and conformal displays onto 3D objects using a water-transfer approach. This allows for enhancing a wide range of geometries and materials that previously could not be augmented with conformal electronics, using simple off-the-shelf equipment and supplies.

3.1 Challenges

The development of ObjectSkin was driven by four main fabrication challenges, which are key to augmenting existing 3D objects with interactive surfaces:

(1) Very **thin**, **conformal**, ideally **transparent** electronics, to only minimally alter the visuo-tactile properties of the object surface
(2) Support of **non-developable** object surfaces
(3) Compatible with a **variety of functional inks** for sensors and displays
(4) **Non-invasive** approach, to be applicable to many materials and existing objects

To account for the varying demands of early and later phases of the design process, we present two approaches: one approach is tailored for the rapid fabrication of interactive low-fidelity prototypes, while a second approach is more versatile and yields higher quality results for fabricating high-fidelity prototypes. We start by introducing the main principle and will then detail the individual steps of the fabrication method.

3.2 Background

Our fabrication technique takes inspiration from hydrographic printing [16]. Hydrographic printing is a specialized process used to cover three-dimensional surfaces with visual patterns. It is commonly used for car parts, such as wheels, interior panels, or side mirror casings, but also for other complex geometries, including rifles, helmets, or game controllers. Its main benefit over other printing techniques, such as tampon printing, is that it is compatible with strongly curved and irregular geometries.

In hydrographic printing, a pattern is printed onto a water-soluble film (typically PVA) with color pigment-based ink. The film is then placed into a water basin, where it starts to dissolve into a viscous liquid, letting the ink pigments of the printed pattern float on the water surface. When an object is dipped through the ink and the film into the water, the printed pattern wraps around and closely conforms to the object. During this process, the film and ink stretch along the object's surface, allowing the ink pattern to cover the inside of holes and other difficult-to-reach areas.

In contrast to printing color images, printed electronics leverage the capabilities of a variety of functional inks, including conductors, dielectric materials, and electroluminescent inks. These functional inks differ from color pigment inks in multiple aspects, including their material composition, viscosity, and particle size. Moreover, they typically require bonding into a continuous functional layer, to ensure end-to-end conductivity or insulation. Patterns that are discontinuous cause a loss of functionality. In contrast, printed visual patterns do not need to be continuous; half-toning, for instance, makes use of this very property by printing small unconnected dots to vary the perceived color intensity.

Since hydrographic printing relies on stretching the ink on the water surface, a large amount of stretch (as resulting from conforming to curved surfaces) will simply result in low color intensity. For functional inks, however, this potentially results in loss of functionality, a major challenge which has not been addressed by related work [24]. To addresses this challenge, we propose a novel fabrication approach based on transferring liquid functional ink and provide an evaluation of the supported geometries, as we discuss in Section 5.

3.3 The ObjectSkin Fabrication Method

Fabricating an interactive object with ObjectSkin consists of four steps: digital design, print, water transfer, and post-processing. We will now describe each step and illustrate the process using an example: how to augment a wooden ring with a set of conformal touch sensors, to create a new wearable input device.

3.3.1 Digital design. The designer first creates a digital design, which defines the sizing, placement, and interconnect of the desired sensor or display components. Figure 2a shows an example circuit layout, created in a

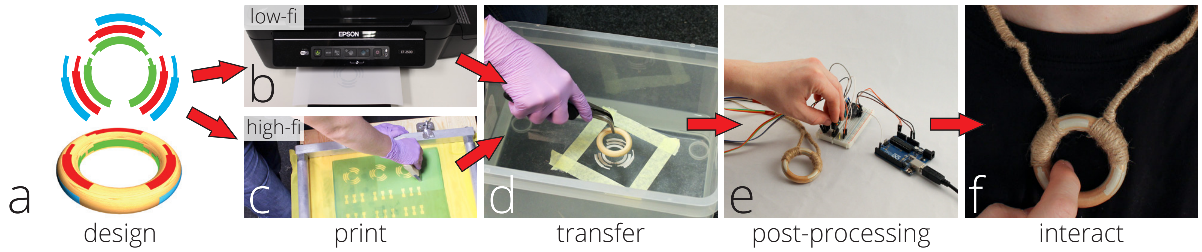

Fig. 2. ObjectSkin fabrication process. The digital design (a, color indicates mapping) is printed using the low-fidelity inkjet-based (b) or high-fidelity screen printing (c) approach onto a PVA transfer film. The object is dipped through the printed ink and dissolved transfer film, allowing the ink to conform to the object (d). After post-processing and connecting to a microcontroller (e), the prototype is ready for interaction (f).

vector graphics application, and the corresponding 3D rendering. Both have been color-coded to illustrate the mapping. The layout features 9 electrodes: 3 on the front (red), 3 wrapping to the outside (blue), and 3 wrapping to the inside (green) of the ring. We have manually created all designs for this paper in Adobe Illustrator.

The design is now ready to be printed onto a water-soluble transfer film (PVA[1]), either using the more rapid low-fidelity printing method or the more versatile high-fidelity method.

3.3.2 Low-fidelity printing. For rapid low-fidelity prototyping, fabrication speed is the key factor. The quickest way to achieve custom printed electronics is typically using inkjet technology [15, 24]. However, available approaches are limited to specially coated paper [15], which is not compatible with water transfer, or require specialized printers [24], not commonly available in HCI labs.

We thus investigated the possibility to rapidly inkjet-print conductors on PVA film using standard desktop inkjet printers. Based on the available off-the-shelf inks, we selected a conductive polymer (heat-curable PEDOT:PSS ink, Heraeus CLEVIOS P JET 700 N). PEDOT:PSS has the advantage of being translucent, which allows the object's visual appearance to be preserved. While PEDOT:PSS in a similar formulation has been used to print conductors onto PET film using a desktop inkjet printer [29], we had to examine its suitability for hydroprinted interactive surfaces. To this end, we tested the ink's compatibility with the PVA film and water-transfer process using a consumer-grade inkjet printer (Epson ET-2500).

Our results show that in addition to the fast printing speed (less than a minute in our example) and high printing resolution (5.760 x 1.440 dpi), the approach produces very thin ($\sim 2\mu m$) and translucent conductive layers. These are well-suited for low-fidelity prototyping of touch sensing, despite the quite low conductivity of printed traces. By printing two layers of ink, we achieved an approximate sheet resistance of $900k\Omega/\square$. This is not unexpected, however, since inkjet printing of conductors on many materials using consumer-grade hardware is still an ongoing research topic in material science. For robust touch sensing, designers should ensure that the size of electrodes exceeds $15x15mm^2$.

3.3.3 High-fidelity printing. In contrast to low-fidelity prototyping, high-fidelity prototyping focuses on quality over fabrication speed. For prototyping interactive surfaces with printed electronics, this translates to higher spatial sensor resolution, enabled by smaller minimum feature sizes thanks to conductors with a higher conductivity, and additional interface elements, e.g. multi-layered touch sensors and displays enabled by a larger variety of functional inks supported by this approach.

[1]We used "DP PrintXer" film purchased from http://hydrographics-shop.com

Our high-fidelity printing method is based on screen printing of functional inks, which offers a wide variety of compatible inks and requires simple hobbyist screen printing equipment [21]. In contrast to classical screen printing of circuits, however, our fabrication method exhibits different demands, as the printed pattern must be water-transferrable. We therefore investigated the following functional inks, to realize multi-layer electronics, displays, and transparent conductors.

- A highly conductive silver ink that can be used for printing conductive structures of small feature size: Gwent, C2131014D3, $0.1\Omega/\square$, $25\mu m$ layer height
- A translucent polymeric PEDOT-based conductor with lower conductivity: Gwent, C2100629D1, $500 - 700k\Omega/\square$, typically 0.5-1.5μm layer height [23]
- A dielectric ink that can be used for printing insulating or dielectric layers: Gwent, D2070209P6, $10\mu m$ layer height
- An electroluminescent ink that can be used for printing light-emitting displays: Gwent, C2061027P15, $30\mu m$ layer height

The results of our experiments show that these inks, printed on hobbyist screen printing equipment, are compatible with the water-transfer step. They further show that this approach is capable of printing conductors with much lower resistance compared to the low-fidelity approach (approx. $0.25\Omega/\square$, see Section 4.1). These capabilities enable printing of small feature sizes, e.g. traces of 1mm width, multi-layer touch sensors, and EL displays, as we discuss in detail in Section 6 (Sensors & Displays) below.

For our example, a negative mask containing the design is created; then one layer of conductive silver ink is screen-printed onto the PVA film (see Figure 2c).

3.3.4 Water transfer. To transfer the ink onto the object, the approach employs a water-transfer process. The PVA film is placed (ink side up) onto a basin filled with warm water (27-30$°C$). Within 60-80 sec. the film dissolves into a viscous liquid. To further dissolve the film and facilitate ink adhesion to the object, an activator[2] is sprayed onto the film. The object, in our example the wooden ring, is then dipped through the film into the water (see Figure 2d). This allows the film to wrap around the object.

During dipping, the object needs to be aligned with the pattern on the water surface. To ease replication of the technique and to support rapid prototyping, our approach employs a manual alignment and dipping process. We tested the practical feasibility using a range of different patterns and everyday objects. Our results show that manual alignment is precise enough for many prototyping applications. We could achieve an alignment error below 1mm for smaller objects and objects with holes, such as the honeycomb pendant (see Figure 9c). Larger and bulkier objects make it more difficult to precisely align the design, as they tend to offer less fine-grained visual cues that help with the alignment. Our results show that this level of precision is still sufficient for many applications. For instance, the multi-touch stone has a misalignment of $< 5mm$ and is fully functional (see Figure 8b). However, for more precise alignment and increased quality, additional measures can be taken, e.g. by improving visibility through a mirror of the basin's floor, by simple rods for mechanical guidance, or by fully automated approaches, as proposed in [40].

Next, to attain its functional properties, the ink needs to be heat-cured. We could successfully cure all inks with a heat gun after they had been water-transferred. We cured silver, dielectric, and phosphor inks for 3 minutes, screen-printed PEDOT for 5 minutes and inkjet-printed PEDOT for 3 minutes. Our results also show that drying the film before curing for about 5 minutes with a fan improves surface conformity. While these experiments show that the water transfer is possible, the effect of the water-transfer step on the conductivity of transferred patterns remains unclear. We investigated this question in a technical experiment:

[2]We used MST-Design Dippdivator (4-Methyl-2-pentanone) from https://www.amazon.de/dp/B004HU87JA

Fig. 3. Materials. Top left: sample covered with transparent PVA transfer film, bottom right: after washing the PVA transfer film off.

Method: We applied two traces of silver ink (5 x 10 *mm*) onto polished marble. One trace was directly screen printed onto the marble object, while the other was realized using our high-fidelity water-transfer approach. Both traces were cured under the same conditions. We took 10 resistance measurements for each trace (over its diagonal) using a multimeter (Fluke 8846A).

Results: Both traces achieved comparable resistance, with measurements ranging between between 0.7Ω and 1Ω (screen-printed: mean 0.88 Ω, SD=0.09; water-transferred: mean 0.75 Ω, SD=0.18). This suggests that the water-transfer process does not have a negative effect on the ink's conductivity.

3.3.5 Post-processing & connecting. In hydrographic printing, the remaining PVA layer on top of the color ink is washed off and an additional clear coat is applied. For our fabrication technique, washing and leaving the PVA film on the object each have their respective advantages.

For rapid prototyping, the PVA film can remain on the object. This speeds up the fabrication process and protects the functional layer. As the PVA is very thin ($\sim 4\mu m$), conformal, and transparent, it has little effect on the resulting interactive surface.

For high-fidelity prototyping, the PVA layer is washed off. We found ~3 min washing to be sufficient, as we illustrate for various materials in Section 4.2. This allows layers that are transferred on top to connect to the underlying layer, e.g. for multi-layer electronics with VIAs. It also produces thinner and more conformal results.

In the last step, the printed circuit is connected to the controller hardware, e.g. a microcontroller and a battery. When keeping the PVA film, connectors are attached to the object before transferring the circuit. The printed circuit is then water-transferred directly onto these connectors. In our experience, this works well with connectors made of adhesive copper tape. For washed prototypes, a connector is connected directly on top of the printed layer.

In our example, we wash off the PVA film and connect wires using z-axis conductive adhesive tape[3]. The wires are then connected to an MPR121 chip and Arduino Uno for touch sensing (see Figure 2e). The ring is now ready to sense the user's interaction (see Figure 2f). In a final optional step, one can perform additional post-processing, for instance applying a clear coating to further protect the printed layers.

4 OBJECT MATERIALS

Everyday objects are made of many different materials with diverse visual and tactile properties. These are important cues for an object's look and feel. Despite its apparent relevance for prototyping, adding conformal input and output to a wide range of object materials is largely unexplored. While printed electronics on flat

[3] We used 3M™ Z-Axis Conductive Tape 9703

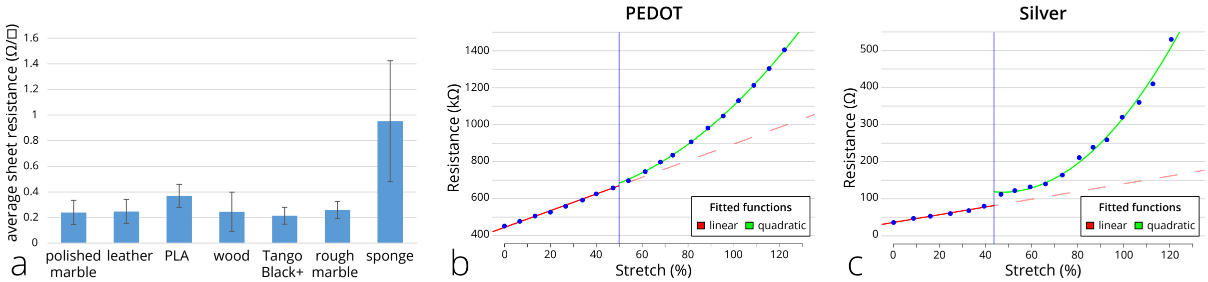

Fig. 4. Evaluation results: a) Sheet resistance on different materials using the high-fidelity approach. b) and c) Change in resistance by stretching for PEDOT and silver ink respectively. Trends are indicated by a fitted linear model (red) for data points below the blue line and quadratic fit (green) for points above. The dashed red line illustrates the continuation of the linear model.

surfaces have been shown to support a variety of substrates [21], conformal electronics for 3D geometries have only been demonstrated on skin for on-body interaction [13, 17, 19, 32] and conductive traces transferred onto 3D-printed plastic and glass [24].

In this section, we show how ObjectSkin contributes towards filling this gap. To this end, we evaluate the approach regarding three main questions relevant for prototyping ubiquitous interactive surfaces:

- Which materials, typically used for prototyping, can be augmented?
- How do these materials affect the achievable functional quality, i.e. conductivity?
- How robust and durable are the results, especially against typical deformation of flexible materials, e.g. bending and stretching?

To answer these questions, we carefully selected a set of sample materials and tested two important criteria: conductivity and ink adhesion. For flexible materials, we further evaluated mechanical robustness. Since an exhaustive evaluation of all material properties is beyond the scope of this work, we selected materials that are frequently used for prototyping, but also included edge cases with potentially challenging material properties. We further ensured that the selected materials would vary regarding the following properties: class (e.g. ceramics, polymers, naturals, and composites [6]), water-absorbing vs. water-repelling (since our technique relies on water transfer), surface roughness (for conformity), and flexibility. According to these characteristics, we selected rigid plastic (PLA), flexible plastic (Stratasys TangoBlack+), polished marble, rough marble, pine wood, leather, and organic sponge, as illustrated in Figure 3.

4.1 Conductivity

The conductivity of hydroprinted conductors is the primary indicator of material compatibility. It also indicates the achievable quality, as higher conductivity allows for smaller electrode sizes and more precise sensing.

Method: We tested the conductivity in terms of approximated sheet resistance, similar to [15]. We screen-printed and transferred 6 silver samples of 20mm length and varying width (0.8, 0.9, 1.0, 1.2, 1.6, 2.6 mm) onto a sample of each material and cured them under the same conditions. We then measured the resistance R of each sample, calculated the sheet resistance R_s according to the formula $R_s = R\frac{width}{length}$, and averaged the results for each material. We use this approximation since special sheet resistance probes for smooth sheets of material cannot be applied to the rough surfaces we tested.

Results: The results are illustrated in Figure 4. The resistances range between $0.15\Omega/\square$ and $0.64\Omega/\square$, excluding the sponge which exhibits higher resistance ($0.36\Omega/\square$ to $1.45\Omega/\square$). These results show that the approach achieves good results on a wide range of materials, comparable to conductive inkjet ($0.2\Omega/\square$ [15]) and traditional screen-printing (ink's reference sheet resistance: $0.1\Omega/\square$ at $25\mu m$). This even holds true for rough, soft, and flexible materials. Not surprisingly, our challenging edge case, the sponge, showed a higher resistance and high variability. Nevertheless, these are still in an acceptable range for prototyping many types of ubiquitous interactive surfaces.

4.2 Ink adhesion

We further tested for ink adhesion, as an additional indicator of material compatibility. Ink adhesion is important for the printed sensors and displays to retain their designed shape on the object.

Method: We tested ink adhesion using a pattern of silver ink ($10x10mm$) that was screen-printed and transferred onto a sample of each material. We cured all samples under the same conditions. The samples were then washed thoroughly under flowing water while rubbing (~3 minutes) to remove the PVA film. This serves as a conservative estimate for ink adhesion, because rubbing is not necessarily required for removing the PVA film if the film is washed for a longer duration (~8 minutes). We visually inspected all samples before and after washing and documented the results in photographs. We further verified that all samples remained conductive after washing.

Results: Figure 3 shows the resulting images. Our results show good adhesion for all materials before washing. After washing and rubbing, the results are still surprisingly good, with the exception of our edge case (sponge). Our results indicate no visible difference in adhesion in relation to the material's flexibility (e.g. marble vs. leather) or roughness (e.g. rough vs. polished marble).

4.3 Robustness

We evaluated the mechanical robustness of our approach regarding stretch and repeated bending of flexible geometries. This test provides further insight into material compatibility, since flexible materials are bent and occasionally stretched during use. We further evaluated the long-term conductivity of the printed traces.

4.3.1 Stretching.

Method: We printed and transferred traces of screen-printed silver and PEDOT on two samples of elastic thermoplastic elastomer (NinjaFlex filament printed on FDM printer). The conductive traces were designed using a horseshoe pattern (15 x 10 mm, 3 windings), which initial testing revealed to be necessary for robustness against stretch. We stretched the samples up to 120% and measured their resistance in $1mm$ ($\sim 7\%$) intervals.

Results: We found the resistance to increase approximately linearly until 39% stretch for silver (resistance increased 2.2x, 36 Ω to 80 Ω) and 54% for PEDOT (resistance increased 1.5x, 451 kΩ to 697 kΩ). Both samples remained conductive beyond these points, but their resistance increased non-linearly. We fit linear and quadratic models to the respective ranges of the data, as illustrated in Figure 4b and c, to visualize these trends. Adjusted R-squared for the linear models for silver and PEDOT is 99.45% and 97.97% respectively. The Residual Standard Error for the quadratic fit is 12.32Ω and $2.755k\Omega$ respectively.

These results suggest that sensors printed on flexible materials are robust to occasional moderate stretching ($< 10\%$). Even for greater stretching the functionality can be retained; however, the corresponding increase in resistance may reduce the sensing quality.

4.3.2 Bending.

Method: We evaluated the robustness to repeated bending using a narrow (2 x 20 mm) and a wide (5 x 10 mm) silver trace transferred to two pieces of the same leather using our approach. As a conservative estimate for robustness, we bent each piece 10, 30, and 50 times around a cylinder smaller than a finger (4 mm radius). We measured the resistance in the initial condition, directly after each trial, and after 1, 5, and 60 minutes.

Results: The narrow trace remained conductive after being bent 10 times, but broke during the second trial with 30 repetitions. The wide trace remained conductive through all 80 repetitions. Its initial resistance (1.4Ω) increased up to 30Ω during the last trial. We observed a slow recovery down to 10Ω after 60 minutes, similar to the behavior of nanoparticle-based strain gauges[25].

These results indicate that the printed sensors are sufficiently robust to be used in interactive prototypes based on flexible materials. Since such an interaction is typically less demanding than our conservative estimate, even narrow traces can be used. For demanding cases, wider traces increase the robustness.

4.3.3 Long-term conductivity.

Method: We transferred and cured 5 samples (5 x 40 *mm*) each of screen-printed silver and PEDOT onto a 3D-printed material (Stratasys VeroWhite+). We then measured the resistance of the samples over the course of 6 months.

Results: For both samples, we measured a change in resistance of less than 1% (silver: 0.45Ω, PEDOT: 43.3kΩ). These results indicate that there is no temporal degradation of the conductors printed with our approach within a reasonable time-span for use of a prototype.

4.4 Discussion

Our evaluation regarding material compatibility and robustness shows that ObjectSkin supports diverse materials for prototyping. On our selection of materials, the approach achieves conductivity similar to approaches used for prototyping interactive surfaces on flat sheets [15, 20, 21]. Similarly, the ink adheres well to the materials, with or without washing. For flexible materials, our results indicate sufficient robustness against common deformation. Thus, the tested materials provide a basic inventory for many prototyping applications. The results further indicate that the approach is likely to be compatible with a larger variety of materials that exhibit similar properties. However, edge cases with different properties, as demonstrated with the sponge, can also produce results that are still acceptable for prototyping. This is in line with anecdotal evidence we gained when we successfully used the approach on additional materials, including glass, a live plant, different types of wood, and other 3D-printed materials, including elastic TPU (NinjaTek NinjaFlex), rigid ABS (FormFutura EasyFIll ABS), and clear PolyJet material (Stratasys VeroClear). However, we also identified a few samples of less compatible materials. These include silicone and latex, due to insufficient ink adhesion, and textiles, where coarse woven structures and a high demand of stretchability remain difficult challenges.

5 OBJECT GEOMETRIES

In this section, we discuss object geometries, a second crucial aspect for prototyping interactive surfaces on diverse everyday objects. We present ObjectSkin's capabilities to support highly curved and irregular geometries and discuss its contributions towards prototyping on *developable* and *non-developable* (also called *doubly-curved*) geometries.

5.1 Non-developable surfaces

Adding conformal sensors and displays to non-developable surfaces offers many geometric challenges. These include surface structures of different roughness, holes and cavities, and varying degrees of curvature in two dimensions. To augment such geometries with a thin overlay requires the overlay to be elastic, i.e. to conform to non-developable curvature by stretching.

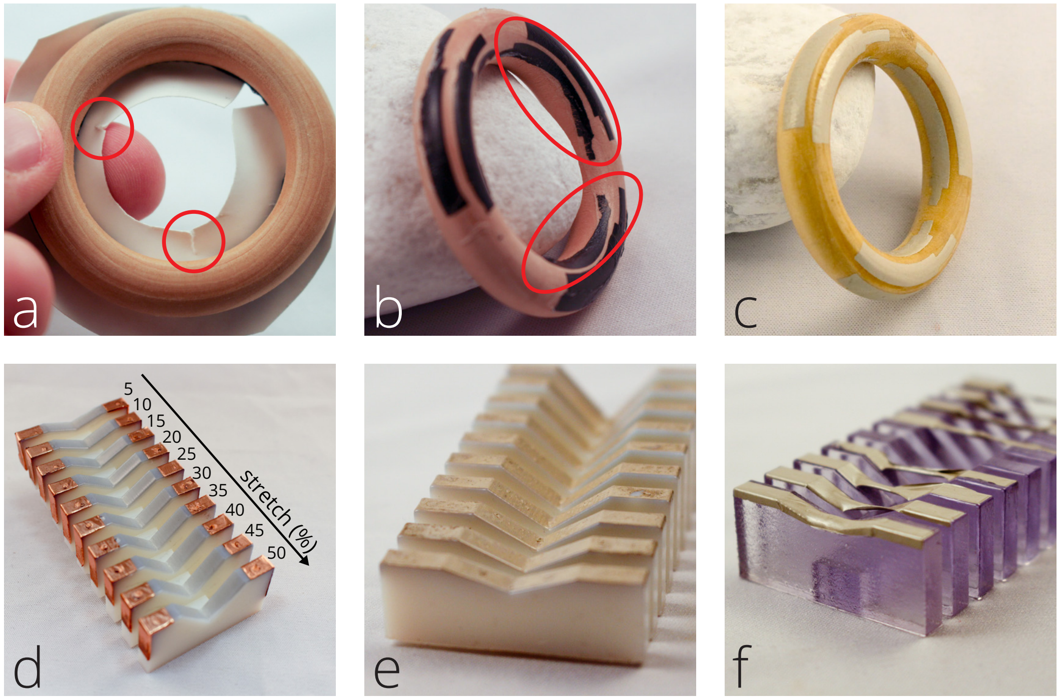

Fig. 5. Evaluation of supported geometries. a) A non-elastic transfer layer cannot wrap around a non-developable geometry. The layer tears where an elastic layer would expand (red circles). b) As a result, the pattern is distorted and cannot fully cover the torus' inside surface (red ellipses). c) Our approach produces the expected conformal result covering the inside surface to the full extent. d) 3D-printed geometry to evaluate different percentages of stretch during dipping. e) Silver ink stretches and conforms to the geometry using our approach. f) Traces sintered before transfer form bridges instead of stretching and conforming.

While this fundamental requirement excludes approaches that use conventional printed electronics [9, 20, 21] or other sheet material [5], related work on skin-worn electronics has presented solutions for conformal electronics on different body locations [13, 17, 19, 32]. They transfer an elastic electronics layer, which is able to conform to the skin's wrinkles. However, since they use a non-elastic transfer layer, i.e. tattoo paper backing [13, 19, 32] or a PVA sheet[17], to directly apply the electronics to the target surface, their method is limited to slightly doubly-curved geometries, e.g. the forearm. This problem becomes apparent when trying to apply a tattoo film or PVA film to strongly-curved non-developable geometries, e.g. a sphere or a torus. The non-elastic transfer layer cannot conform closely enough (see Figure 5a) and hence inevitably causes wrinkles and distortions (see Figure 5b).

ObjectSkin, in contrast, uses an *elastic* transfer layer. By dissolving the PVA layer on the water bed, it can stretch during the transfer process and therefore makes it possible to add sensors and displays to strongly-curved non-developable geometries (see Figure 5c). However, in addition to the elastic transfer layer, the electronics must also be elastic during transfer to conform to non-developable geometries. To this end, our approach sinters the inks *after* the water transfer, since sintering drastically reduces the elasticity of the material. To illustrate

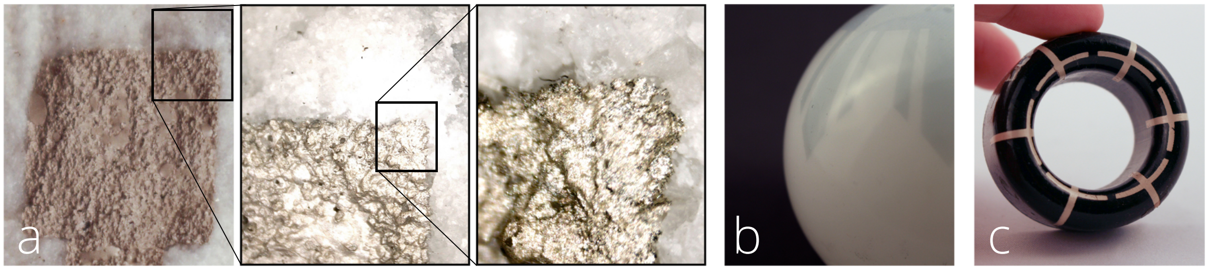

Fig. 6. Printed electronics transferred with the proposed approach conform closely to highly curved non-developable geometries. a) Silver conductor conforming to a rough stone surface (image of $1cm^2$ patch and magnification of selected area). b) Translucent PEDOT conductor conforms to white glass sphere without distortion. c) Silver traces wrapping into hollow cylinder geometry.

the importance of this step, we created a prototype with conductive traces that we had already sintered before water-transferring them, as proposed in [24]. The results are depicted in Figure 5f. It can be clearly observed that instead of stretching and conforming, the sintered traces form bridges over the concave area. In contrast, our method is able to closely conform to the geometry (Figure 5e).

In consequence, the supported non-developable geometries essentially depend on the ink's ability to stretch on the water surface during the water-transfer process. We therefore conducted an experiment to determine the maximum amount of stretch after which the conductive and dielectric layers can still gain their respective functionality (after sintering).

Method: We transferred 10 samples (5 x 40 *mm*) of each ink (screen-printed: silver, PEDOT, and dielectric ink; inkjet: PEDOT) onto a 3D-printed test geometry. The geometry was designed to stretch the midsections (10 *mm* long) of the 10 parallel strips from 5% to 50% in 5% increments (see Figure 5d). For the dielectric material, we covered the test geometry with conductive copper tape before and after printing and tested for conductivity between both copper layers. For the conductors, we measured the resistance of each sample.

Results: We found silver could be successfully stretched up to 30% (resistance increase 3.8x, 0.45Ω to 1.71Ω), screen-printed PEDOT up to 15% (resistance increase 1.6x, 43.3 kΩ to 77.8 kΩ), and inkjet-printed PEDOT up to 10% (resistance increase 3.2x, 230 $M\Omega$ to 741 $M\Omega$). The dielectric ink insulated both copper layers up to 30% stretch. These confirm the potential of functional patterns to conform to non-developable geometries. They also reveal that the high-fidelity approach is better suited for strongly-curved geometries.

This makes it now possible to augment unusual and novel geometric features with interactive surfaces, as we illustrate with three examples:

- The approach enables thin sensors that closely conform to rough surface structures and retain their tactile properties. Figure 6a illustrates how closely the transferred traces conform to the surface structure.
- It allows covering strongly curved surfaces without creating bumps or wrinkles. We demonstrate this with the smooth conformal results of a translucent conductor transferred onto a sphere, depicted in Figure 6b.
- Sensors and displays can be smoothly wrapped into and through holes, while closely conforming to the surface. Figure 6c shows an example of a hollow cylinder with a doubly-curved top surface. The electrodes conform along both curvatures and wrap onto the inside surfaces of the hole.

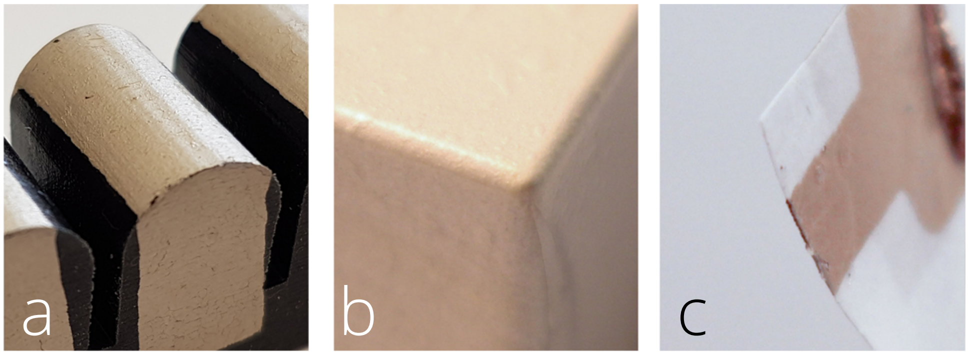

Fig. 7. ObjectSkin facilitates augmentation of developable geometries. a) A touch sensor conforms to the round edge of a half-cylinder shape. A sheet-based sensor would have to be cut along the edge to conform without wrinkles. b) Transferring a sensor onto a cube's corner results in a smooth continuous layer. A sheet-based sensor would have to be cut along one edge and thus be discontinuous. c) A conductive trace conforms to a very thin edge ($\sim 0.1mm$) by wrapping onto both sides of a piece of paper (one side and the edge is pictured).

5.2 Developable surfaces

ObjectSkin also supports developable geometries, which can be augmented by existing fabrication approaches [9, 20]. The approach improves upon prior work by adding support for developable geometries that so far had required cutting and gluing. We present three examples that illustrate the advantages of our fabrication method:

- A closed cylinder made from a sheet of paper requires cutting and gluing. Thus, a sensor or display across its curved edge would have to be cut as well, which is not possible in many cases. ObjectSkin allows printed electronics to be wrapped across the edge without cutting or gluing (Figure 7a).
- A sensor applied over the corner of a cube illustrates the same advantage: One edge would require cutting and gluing when folded from a sheet-based sensor. In contrast, our approach forms a smooth continuous layer by wrapping and stretching (Figure 7b).
- Our approach enables traces across sharp edges. We successfully transferred traces to angles as sharp as the edge of a $\sim 0.1mm$ thin piece of paper (Figure 7c). The traces remain conductive while an angle this sharp would break a trace folded from a sheet sensor.

6 SENSORS AND DISPLAYS

In this section, we present how input sensing and display output can be realized, leveraging the fabrication capabilities of ObjectSkin.

6.1 Touch sensing

Touch is a common modality for interaction, which has been used extensively in related work [9, 20, 21, 27, 39]. Capacitive loading mode sensing, which is supported by prototyping platforms such as the Arduino[4], makes it possible to rapidly and easily create touch sensors that require only one simple electrode [3]. With ObjectSkin, we enable such electrodes on highly curved geometries.

Both the low-fidelity and the high-fidelity approach can be used. The low-fidelity approach offers a thin translucent conductor, which enables electrodes to be placed over distinct visual features of everyday objects. We

[4]https://www.arduino.cc/

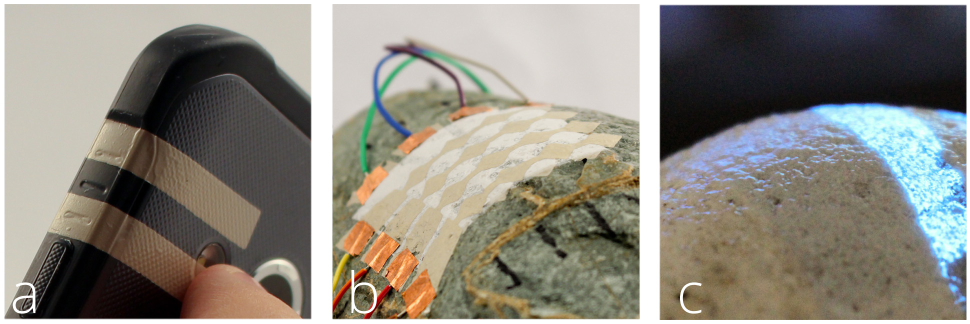

Fig. 8. Conformal sensors & displays: touch extension on smart phone (a), multi-touch matrix on rock (b), and electroluminescent display on stone (c).

have successfully implemented touch sensors (10*mm* radius, see Figure 1b) based on loading mode capacitive touch sensing, using the CapSense library [3] for Arduino or a dedicated touch sensor chip (Freescale Semiconductor MPR121).

The high-fidelity approach supports a more conductive translucent conductor (PEDOT) and a highly conductive opaque conductor (silver). This supports smaller electrodes and longer conductive traces. Our results show that the MPR121 chip could detect touch reliably for conductive traces as thin as 3 mm (PEDOT) and 1 mm (silver).

In addition to dedicated sensing hardware, ObjectSkin makes it possible to leverage existing touch sensors in everyday objects, such as those found in lamps or smart phones. To this end, a conductive trace connects to and extends an existing touch surface. This principle has been presented for sticker sheets [14]. Our approach extends beyond prior work in enabling such traces to closely conform to the object's geometry, allowing for a seamless integration even on highly curved and irregular object geometries (Figure 8a and Video Figure).

6.2 Multi-touch sensing

While a single conductive layer with individual electrodes is sufficient to sense touch at a few locations, this technology does not scale to higher-resolution multi-touch sensing. Thus, commercial multi-touch sensors use multi-layer matrix electrode layouts. However, these have not been supported on highly curved geometries so far.

To enable multi-layer electronics on highly curved object geometries, we had to address three challenges:

- Transferring multiple layers of different functional inks, which retain their functionality
- A means to insulate adjacent conductive layers (also on highly curved geometries)
- An approach to connect the controller to the printed multi-layer circuit

We address the first challenge by transferring and curing each layer one after another, aligning them on top of each other on the object. Transferring all layers at once would require curing them in advance, thus removing their ability to stretch during dipping. In consequence, the display would conform less to the surface, as we discuss in Section 5.1. For quick prototyping, the PVA film can be left on each layer. To achieve thinner and more conformal multi-layer structures, the PVA film is washed off after curing.

To insulate adjacent conductive layers, a layer of dielectric ink is added between them. As this layer is digitally designed and printed, the designer can flexibly define locations that should be insulating. VIAs (conductive connections between two adjacent layers) can be created by modifying the design of the dielectic layer to feature holes at location where conductivity between layers is desired. At those locations, the PVA film must be washed off because otherwise it would act as an insulator.

The main concern for highly curved geometries is that the insulation could break down and cause a short circuit, because of the inherent stretch those geometries generate. Therefore we investigated whether the dielectric layer remains functional when stretched up to 30%, which is the maximum stretch factor we identified in Section 5.1 above.

For connecting the controller to multiple layers, we present three possible approaches. The fastest approach is to modify the design such that it features exposed conductive pads for each individual layer. It must be ensured that those pads are not covered by subsequently transferred layers. Wires can then be attached to those pads after all layers have been water-transferred. As a second approach, each layer can be connected before the next layer is water-transferred on top of it. The most elegant approach consists of using VIAs to route all connecting traces to one layer for connection to the controller.

To verify the feasibility of this approach, we realized a capacitive row-column scanning multi-touch sensor on a particularly demanding object: the non-developable and rough surface of a stone (Figure 8b). It consists of a 4 x 4 diamond pattern matrix [8] (4 x 4*cm*). The sensor comprises three functional layers overall: two layers of conductive electrodes (silver) that are separated by one dielectric layer. The printed sensor was controlled using an MPR121 chip. The sensor is fully functional and highly conformal to the fine details of the stone's surface (see Figure 8b and Video Figure).

6.3 Display output

In addition to sensing, ObjectSkin also supports the fabrication of active light-emitting displays. Our approach is based on screen-printing of thin-film electroluminescent (TFEL) displays [21].

Our approach consists of transferring and curing four functional layers: a layer for the bottom electrode (silver), a dielectric layer, a layer of electroluminescent ink (blue phosphor, Gwent C2061027P15), and a translucent top electrode (PEDOT). As each of the slim layers is transferred and cured one after another, each conforms closely to doubly-curved and rough surfaces before curing. We thereby improve on prior work that applied TFEL displays to developable geometries [21], wrapped thicker silicone overlays [34], or applied a complete cured stack [32].

To demonstrate the technical feasibility, we have realized a TFEL display segment that conforms to a rough stone's surface, as illustrated in Figure 8c.

7 NOVEL INTERACTIONS FOR HCI

ObjectSkin is an enabling technology for input and output on a wide variety of everyday objects. In this section, we present an exploration of novel interaction possibilities that our method enables. They are based on new geometries, the object's surface structure, and use of unconventional objects.

7.1 Geometry-guided touch gestures

Everyday objects offer a vast variety of complex geometries, e.g. in toys, tools, or filigree jewelry. Prior HCI research has mostly focused on a subset of geometries, consisting of easier-to-augment object surfaces, e.g. the head or belly of a toy figure [4, 28, 35], the outside of a mug [9], or the top of a folded lamp shade [20].

ObjectSkin allows us to approach everyday objects from a new perspective: imagining interaction on all their surfaces, including those that are more difficult to augment, e.g. with holes or many small or thin parts. We demonstrate how this enables novel interaction possibilities, by exploring touch gestures on two example objects: a wooden torus ring and a filigree honeycomb-style pendant.

7.1.1 Torus ring. From many available objects with holes, we selected a wooden ring, which we imagine could be worn on a necklace, for its aesthetics and appealing shape (see Figure 9a).

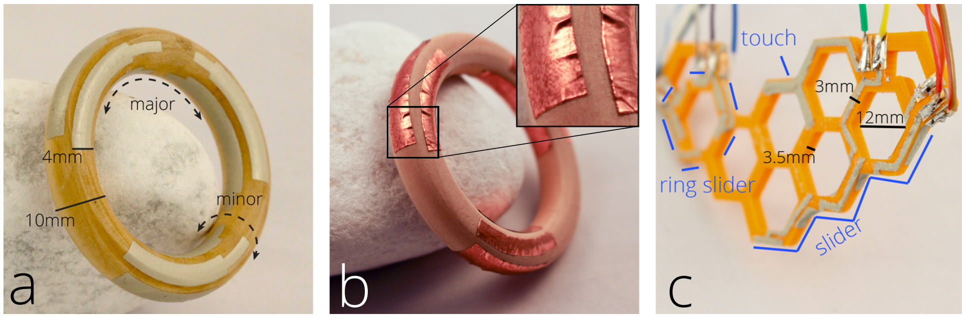

Fig. 9. Prototyping geometry-guided touch gestures. A wooden ring (a) is augmented with 9 conformal electrodes to support circular gestures following its major and minor radii. In contrast, adhesive copper tape causes wrinkles due to the non-developable geometry and edges due to its thickness (b). A honeycomb pendant (c) illustrates three geometry-guided touch interactions.

In an initial expert group brainstorming session, we explored the geometry's affordances. Our results show that the continuous curved surface allows users to perform a set of different touch gestures and fluently combine them:

- sliding with one or multiple fingers along the ring's major radius (on its inside, outer side, front, or back)
- sliding inwards or outwards in the perpendicular direction (along the ring's minor radius), at various locations on the ring, either by touching with one finger or by pinching with two fingers

We transferred these findings into the design of a novel interaction device: a music player control embedded in the ring, which is worn on a necklace. The device supports 3 circular sliding gestures in both directions along its major radius. These are mapped to continuous seeking inside a song, changing tracks, and changing the album. In addition, the device features 6 inward- or outward-rotating gestures to adjust the volume, turn the device on or off, and switch between equalizer presets.

Based on this design, we created a prototype using our high-fidelity approach. We completed the prototype using the MPR121 chip, which reliably detects touch input on all electrodes. Gestures are classified with a simple rule-based classifier, based on the sequence of touch locations.

To investigate the benefits of ObjectSkin, we compared our prototype to two baseline alternatives: manual application of adhesive copper tape (similar to [27]) and a temporary tattoo-based approach (as presented in [32]). Aligning the different electrodes with adhesive copper tape was challenging and we quickly noticed that the copper tape did not conform well enough. The resulting surface was not smooth, which disturbed the gestures' execution and made them feel less fluid. This was mainly due to edges that result from the tape's thickness and due to small wrinkles that result from wrapping non-stretchable copper tape onto the non-developable geometry (Figure 9b). The tattoo paper resulted in a much thinner layer that did not produce noticeable edges. However, due to the paper backing of the tattoo paper, it was not possible to wrap the electrodes onto the torus' geometry without distortion, especially onto the inside of the hole (Figure 5a and b). In contrast, our approach results in a smooth surface and successfully conforms to the non-developable geometry (Figure 9a).

7.1.2 Honeycomb pendant. As a second example for advanced geometry, we selected a honeycomb-style pendant. It features a filigree geometry with thin structures and many small faces on all sides (See Figure 9c). Expert group brainstorming revealed four main types of touch gestures:

- Discrete circular motion along the six sides inside a honeycomb cell

- Touching either side of a cell similar to a six-way joystick
- Sliding along the top or bottom edge of the pendant, spanning multiple honeycomb cells
- Using the connection point between three adjacent honeycomb cells as a discrete touch point

Considering the wearable form factor of the pendant, we envision it being used for quick gesture-based interaction in various mobile scenarios, including interpersonal communication, navigation, and smart home applications. We designed an example device that implements the four touch gestures and illustrate their use in different use cases.

In a smart home environment, we leverage the honeycomb cell structure to conveniently control the ambient light. To this end, the six inside faces of a cell are mapped to six positions on a color wheel, allowing the user to fluently browse through the color spectrum in an eyes-free manner. We found the leftmost, rightmost, and bottom cell most convenient to access. Accordingly, we augmented the leftmost cell with six electrodes, one on each inside face (see Figure 9c), to capture the circular movement. In addition, we designed a slider to allow changing the light's brightness. It is located on the structure's bottom edge for convenient access. It features four touch electrodes to increase or decrease the brightness with a sliding gesture. To illustrate the use of honeycomb intersections for touch, we added a discrete touch button at an intersection point in the top center to quickly turn the light on or off.

As the pendant would be worn throughout the day, its controls support different application scenarios. For mobile navigation, for instance, the touch button could quickly open a map showing the user's current position for orientation. Once the map is displayed, e.g. in a head-mounted display, it could be zoomed in or out using the slider control. However, the sensor designs themselves are versatile to support different interaction for versatile scenarios. The electrodes of the circular slider, for example, also detect discrete touch contact on each of the six sides of a honeycomb cell. One might leverage this, for instance, for interpersonal communication, allowing six distinct actions to be performed for each contact assigned to an individual cell.

In total, our design uses 11 very small (6 x 2 *mm*) electrodes to implement the described controls (see Figure 9c). Adding this large number of electrodes to the filigree structure makes it very demanding to route conductive traces on the object that connect electrodes with the controller. In order to route connecting traces for all 11 electrodes to two endpoints (top left, top right), the traces need to be applied across edges, e.g. to use the front, outer, and inner sides of the hexagon pattern for routing.

It would be very time-consuming and prone to misalignment if one had to manually add those traces to the filigree geometry, as required in established approaches using copper tape or temporary tattoo paper. For such geometries, ObjectSkin offers the advantage of wrapping all traces automatically during dipping. This allowed us to use more complex routing. We fabricated the final prototype using our high-fidelity approach with silver ink, as illustrated in Figure 9c. For sensing, we connected an MPR121 chip, which reliably detected touch input on all electrodes.

7.2 Surface structure for eyes-free touch interaction

Besides their individual geometries, everyday objects vary in the tactile cues their surfaces provide. This tactile feedback is central to how a user perceives a surface.

ObjectSkin enables sensors that closely conform to an object's surface structure, as illustrated in Figure 6a, allowing its tactile feedback to be preserved. We demonstrate the benefits of this capability by adding touch sensors onto surface structures with distinct tactile cues, allowing for eyes-free touch interaction.

We implemented a prototype based on a rock that features areas of different roughness (see Figure 10a). We identified two adjacent areas that exhibit different roughness and distinct tactile feedback. We then designed and transferred two electrodes (15*mm* diameter, spaced 5*mm* apart) onto the rock using our low-fidelity approach. We used the MPR121 chip for capacitive touch sensing. The prototype demonstrates that the sensor electrodes

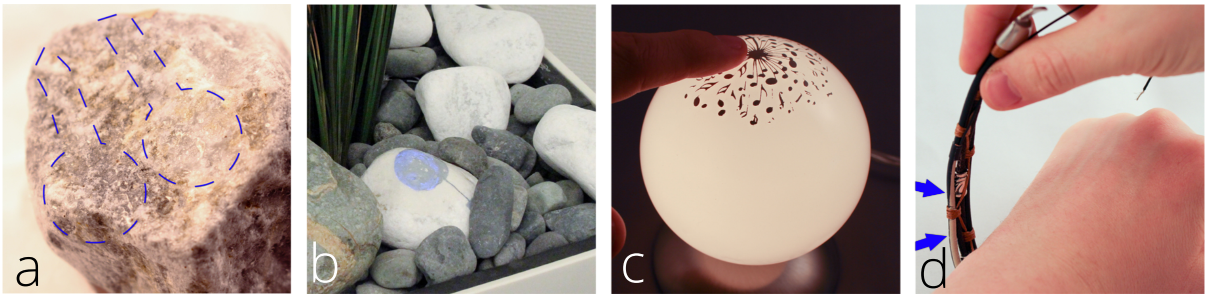

Fig. 10. Augmented everyday objects for novel interactions. A rock is augmented with two translucent electrodes (marked with dashed lines), leveraging two areas of distinct roughness for eyes-free interaction (a). Prototyping interaction on unconventional everyday objects: a garden stone (b), a glass lampshade (c), and a leather bracelet (d, electrodes at arrows).

conform closely to the surface structure and preserve the tactile feedback, providing sufficient tactile cues for the user to distinguish the two touch elements without visual feedback.

7.3 Interaction on unconventional objects

ObjectSkin is capable of augmenting a wide variety of everyday objects. We present four application examples of how unconventional objects can be augmented and used for interaction.

Growing touch sensor on live plant. We augmented a live bamboo plant with a touch sensor. As bamboo grows fast, the sensor is designed to stretch and grow with it. Therefore the touch electrode (9 x 15 *mm*) is laid out in a stretchable horseshoe pattern (Figure 1d, Video Figure). Touch contact is captured using the MPR121 chip.

Interactive glass lampshade. We turned a conventional lamp into a customized interactive piece of furniture. We applied artwork, depicting a "music flower", in silver ink onto the lamp's spherical glass shade. The artwork acts as a touch sensor to turn on and change the brightness (4 levels) of the lamp, but also blocks part of the light for a unique artistic effect (Figure 10c, Video Figure).

Leather bracelet for activity tracking. A sensor measuring the electro-dermal activity (EDA) was applied to the inside of a leather bracelet. It allows the wearer to measure the EDA in a subtle manner, for example to gather data on the stress level. Two electrodes are applied to one thin band of leather, making use of our approach's ability to conform to delicate details (Figure 10d).

Garden stone as peripheral display. We augmented a garden stone with an electroluminescent display to act as a subtle reminder for watering the plants. The stone fits into a natural stone arrangement surrounding a plant. Based on readings from a connected moisture sensor, it displays an unobtrusive visual notification for the user when the soil gets too dry (Figure 10b, Video Figure).

8 DISCUSSION

We have demonstrated that ObjectSkin supports input and output modalities on a wide variety of materials and non-developable geometries. It offers novel capabilities for prototyping interaction on everyday objects, making it an enabling technology for makers and HCI researchers.

8.1 Scalability

We have printed on transfer film up to A3 size and used a water basin with a slightly larger opening and 30 cm depth. Since multiple layers can be connected, ObjectSkin can exceed these dimensions as long as the part to augment can be submerged in the basin. We have demonstrated this by printing on a large bamboo plant for which we only submerged individual stems into a small basin.

The maximum number of sensor and output components is defined by the capabilities of the controlling hardware. The MPR121 touch sensing chip is limited to 12 electrodes but multiple chips can be used in parallel via an I2C connection. As electronics are getting smaller, thinner, more flexible, and increasingly powerful, we believe that in the future interactive objects can be realized in a fully self-contained way by including microcontrollers and batteries on the surface.

The resolution of sensors and displays is limited depending on the printing method. For low fidelity, fingertip-sized ($\sim 15x15mm^2$) touch sensors can be realized. However, since the inkjet printer provides a much higher spatial resolution (5.760 x 1.440 dpi), ink with better conductivity could allow for smaller sizes. For high-fidelity prototyping, we were able to print traces as thin as $300\mu m$ and realize touch electrodes as small $2mmx6mm$.

8.2 Quality

Our results regarding geometries show that the conductivity of a transferred pattern depends on the amount of stretch it underwent during the water transfer. This implies that the uneven structure of highly textured surfaces, e.g. rough wood or stone, can result in a locally inhomogeneous conductivity. For touch sensors, we could not observe an effect of this inhomogeneity on a variety of highly textured surfaces. For display output, however, it affects the luminance, which can be observed as darker spots (see Figure 8c). While the resulting displays are still well-suited for prototyping purposes, this effect needs to be considered when prototyping on highly textured surfaces.

8.3 Ease of fabrication

We could verify that two days of experience are sufficient for non-experts to learn the screen-printing process, as reported in [21]. The water transfer does not add significantly to the overall difficulty. We found that about 10 trials were enough to achieve less than 5 *mm* misalignment and avoid artifacts, such as air bubbles. A steady hand improves both printing and the transfer. The transfer does not require any special equipment, except for the materials used and a water container. Printing, transferring, and post-treatment of a single functional layer takes between 20 and 40 minutes.

8.4 Advanced fabrication options

To make our fabrication technique reproducible, we relied on standard inks and equipment. It remains to be investigated how the process can be further improved with optimized ink formulations. UV curing could allow for curing on more materials. In hydrographic printing, pre-processing, e.g. priming or smoothing, is used to facilitate ink adhesion. Post-print finishing, e.g. sprayed clear coating, helps to better protect the ink but also offers artistic options. While these steps are potentially beneficial to further enhance the quality and robustness of ObjectSkins, we purposefully omitted them in favor of preserving the materials' visuo-tactile properties.

8.5 Advanced sensing

ObjectSkin brings printed electronics to highly-curved non-developable surfaces of 3D objects. Our results show that this enables them to sense interaction on the surface. Given related work that employs sensors on the outside of an object to infer what is happening inside, e.g. by electrical impedance tomography [38] or pressure sensors [7], we believe our fabrication technique bears the potential to also sense phenomena inside the object.

8.6 Design

We have demonstrated that manual design is feasible for complex components, e.g. multi-layer displays, and doubly-curved geometries. To further ease the design, we envision the user being supported by a 3D design environment with abstraction algorithms, which allow the user to design the sensors and output directly on the 3D model. In particular, calculation of the distortion caused by stretching of the ink, as proposed by [40], can be helpful for complex geometries and non-expert or novice users. However, our results show that for many rapid prototyping applications slight distortion can be accounted for or even neglected in manual design. Nevertheless, our quantitative findings, including maximum stretch, conductivity based on materials, and limits on electrode dimensions, form the basis for a formal model required in a computational design tool for ObjectSkin.

8.7 Safety

For our fabrication process, we recommend using standard protection measures, e.g. rubber gloves and goggles, and following the guidelines on health and safety that are supplied with the materials' safety data sheets.

9 CONCLUSION

This paper contributes ObjectSkin, a fabrication technique for adding slim, conformal, and translucent interactive surfaces to rigid and flexible everyday objects. It comprises two variants, for low-fidelity and for high-fidelity prototyping, based on water transfer of printed electronics. We describe in detail how the technique can be replicated with hobbyist equipment available in HCI labs or maker spaces.

ObjectSkin supports a wide variety of materials and enables augmenting highly curved and rough non-developable surfaces. We present experimental evidence on material compatibility, highlighting the approach's applicability in many prototyping applications. We further illustrate the novel geometric possibilities ObjectSkin enables compared to related work and substantiate our results with experiments on the geometric limitations.

To show the approach's capabilities for interactive surfaces, we present the fabrication of conformal touch sensors and multi-layer electronics for multi-touch sensing and electroluminescent display output. Together with ObjectSkin's newly supported geometries, these capabilities enable prototyping of novel interactions on everyday objects. We demonstrate interactions that leverage the object's surface structure and geometry, in a series of prototyping examples. These include geometry-guided touch interaction, surface roughness for eyes-free interaction, and augmentation of unconventional objects.

Altogether, our contributions enable HCI researchers and makers to prototype interactive input and output surfaces on a large variety of everyday objects. This enriches the possibilities of investigating interaction on novel geometries and objects while preserving their visuo-tactile feedback.

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