Tactlets: Adding Tactile Feedback to 3D Objects Using Custom Printed Controls

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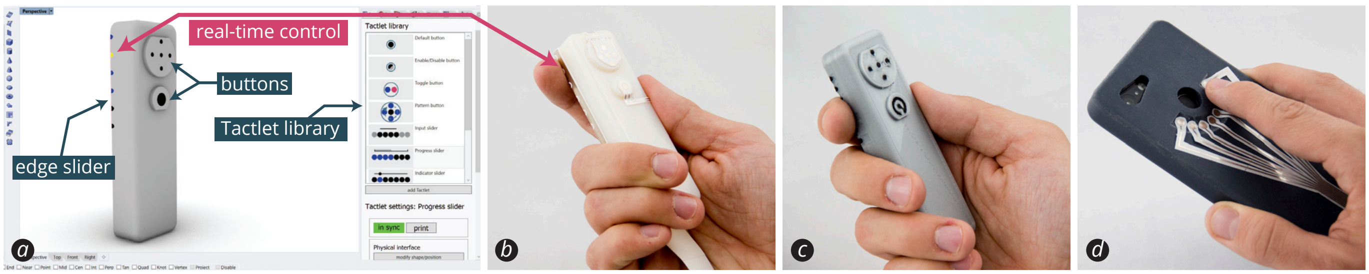

Figure 1. Tactlets is a novel approach enabling digital design and rapid printing of custom, high-resolution controls for tactile output with integrated touch sensing on interactive objects. (a) A design tool allows a designer to add Tactlet controls from a library and customize them for 3D object geometries. The designer can then fabricate a functional prototype using conductive inkjet printing (b) or 3D printing (c), and explore the interactive behavior of the Tactlet control. (d) This approach allows for rapid design iterations to prototype tactile input and output on a variety of objects.

ABSTRACT
Rapid prototyping of haptic output on 3D objects promises to enable a more widespread use of the tactile channel for ubiquitous, tangible, and wearable computing. Existing prototyping approaches, however, have limited tactile output capabilities, require advanced skills for design and fabrication, or are incompatible with curved object geometries. In this paper, we present a novel digital fabrication approach for printing custom, high-resolution controls for electro-tactile output with integrated touch sensing on interactive objects. It supports curved geometries of everyday objects. We contribute a design tool for modeling, testing, and refining tactile input and output at a high level of abstraction, based on parameterized electro-tactile controls. We further contribute an inventory of 10 parametric Tactlet controls that integrate sensing of user input with real-time electro-tactile feedback. We present two approaches for printing Tactlets on 3D objects, using conductive inkjet printing or FDM 3D printing. Empirical results from a psychophysical study and findings from two practical application cases confirm the functionality and practical feasibility of the Tactlets approach.

Author Keywords
Haptics; tactile output; rapid prototyping; fabrication.

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CCS Concepts
•Human-centered computing → Human computer interaction (HCI); Haptic devices; Interactive systems and tools; Interface design prototyping;

INTRODUCTION
As computing increasingly blends with the physical world, a growing number of computer interfaces get embedded inside physical objects. Examples are myriad and range from ubiquitous computing devices and tangible interfaces to wearable accessories and body-based devices. In this context, rapid prototyping of interactive 3D objects has become an indispensable method for quickly exploring and iterating new designs that offer custom geometry and custom interactive functionality.

Digital fabrication has been proposed as a new method for rapid prototyping of interactive devices [10, 25, 34, 32, 44]. By printing the custom device, rather than manually assembling it from conventional electronic components, the fabrication process can be considerably simplified and sped up. At the same time, as printable electronics commonly are very thin and deformable, more demanding geometries and advanced I/O capabilities can be realized. Prior work has demonstrated approaches based on printed electronics to equip custom-shaped 3D objects with various types of printed sensors for capturing user input [11, 34, 44, 45, 54] and printable output components, including light-emitting displays [35, 54] and actuators for shape-change [7, 57].

However, tactile output was so far left unaddressed. Fabricating custom interactive objects that include computer-controlled tactile output still relies on manually assembling conventional components [15, 36]. Moreover, the rather large form factors of typical motors and mechanical actuators tend to be incompatible with demanding object geometries.

In this paper, we introduce a novel digital fabrication approach for printing custom, high-resolution controls for tactile input and output on 3D objects. We call these controls *Tactlets*.

A Tactlet comprises a custom-printed arrangement of taxels (tactile pixels) that each sense touch input and deliver electro-tactile output. This makes Tactlets highly customizable and allows them to integrate with a wide variety of object geometries while augmenting them with virtual tactile feedback. One example is a touch slider that allows the user to set a continuous value via touch input and tactually renders virtual tick marks as well as the slider's current position.

Tactlets are designed digitally using a design tool and then printed. The design tool, a plug-in for the widely used 3D-modeling software Rhino3D, enables the user to easily augment a 3D-object model with desired tactile input and output capabilities at a high level of abstraction. The user can place and scale Tactlets on the 3D object and adjust high-level parameters. The design tool then automatically parameterizes the Tactlet accordingly and generates the low-level printable design. Once the object has been printed, the design tool offers a novel *real-time design mode*. In this mode, the tool offers live control of the object's tactile sensing and feedback. This allows for real-time exploration and refinement of design choices, such as dynamically adjusting parameters of Tactlets during hands-on interaction with the interactive object.

Our second main contribution is an inventory of 10 parametric Tactlet controls. Our inventory comprises several types of buttons and contributes several types of sliders, for tactile input, tactile output, tick marks, dynamic ranges, etc. Each template encapsulates a model of a Tactlet's interactive behavior, i.e. mapping between sensed user input and real-time tactile feedback, and a parametric model to generate its print design. In addition, it exposes high-level properties to the designer (e.g. enabled/disabled state, selected value, or output resolution).

Moreover, we present two approaches for fabricating Tactlets on 3D objects through printing: rapid prototyping of thin ($270\mu m$) electro-tactile overlays using conductive inkjet printing, or 3D printing of objects with embedded electro-tactile taxels using a standard multi-material 3D printer and conductive filament. We realize individual taxels as two or more printed electrodes that generate localized electro-tactile output and capture user input with a resistive touch-sensing scheme.

Last, we validate the functionality and practical feasibility of the Tactlets approach. We present results from a psychophysical experiment that confirm the functionality of electro-tactile output and touch sensing on curved object geometries. We further present two use cases. An interactive phone case and a presenter with tactile feedback were iteratively designed and implemented using Tactlets. We present the iterative design process and results and discuss lessons learned.

Together, our digital design process, parametric Tactlet controls, and printing methods enable a new approach for realizing interactive objects with tactile feedback. As a first step, we demonstrate this approach using electro-tactile interfaces. However, the concepts generalize to other printed tactile technologies, including the high-level design, real-time design capabilities, and Tactlet controls. We hope our contributions will enable a large community of interaction designers, makers, and researchers to explore a next generation of embedded interfaces with rich tactile feedback.

RELATED WORK

Augmenting physical objects with input and output capabilities is an essential component of ubiquitous computing. Commonly used input modalities include touch [3, 9, 44, 45, 54], deformation [34, 46], and expressive gestures [42]. There are also numerous works investigating how to technically realize output modalities such as visual [25, 32, 34, 54] and auditory output [25, 32]. In this paper, we focus on tactile output.

Dynamic tactile feedback on interactive objects

Embedding haptic or tactile feedback in objects has been widely used to increase the user experience and interaction capabilities of mobile and physical computing devices [27]. For example, haptic feedback is utilized to offer physical feedback for visual controls [12, 30, 38, 58, 59, 61] and icons [2, 26], for rendering virtual textures and geometric features [1, 24, 40] and to implement shape-changing displays [7, 57].

The most commonly used method to augment physical objects with haptic or tactile feedback is to embed actuators inside the objects. For instance, shape-changing displays make use of embedded mechanical [7, 15], pneumatic [51] or magnetic [28] actuators, or the object itself is built from shape-changing materials [57]. Similarly, tactile interfaces have been realized by embedding actuators in the device [12, 30, 38, 59, 61]. This approach often suffers from low-resolution output. To increase the fidelity of tactile output and to support greater design flexibility, another stream of research investigates fabricating new tactile output devices, offering highly integrated actuators [2], deformability [36], or other tactile modalities such as thermal or electrical feedback [37, 49]. However, adapting these technologies to the geometry of a specific physical object commonly needs significant alterations and often leads to changes in object properties such as shape, flexibility, etc. Also, once fabricated, any additional refinement of the design requires significant time and effort.

To address these challenges, minimally invasive technologies for tactile augmentation of real objects have been investigated, for instance electro-vibration based on electro-static friction [1, 24]. One of the main limitations of electro-vibration is that a user can only feel the sensation while the finger is moving. Another minimally invasive approach is to use electro-tactile displays. These provide tactile sensations comparable to mechanical vibrations by directly stimulating nerve stems in the skin using controlled electric current impulses ($50-200\mu s$ pulses of $1-10mA$) [19, 60]. While limited in the dynamic range of intensities, they can be used to generate tactile feedback on objects independent of whether the finger is moving or stationary [18, 23]. Furthermore, recent research shows that electro-tactile interfaces can be easily fabricated using printing [21] and can be realized as thin and flexible interfaces [56].

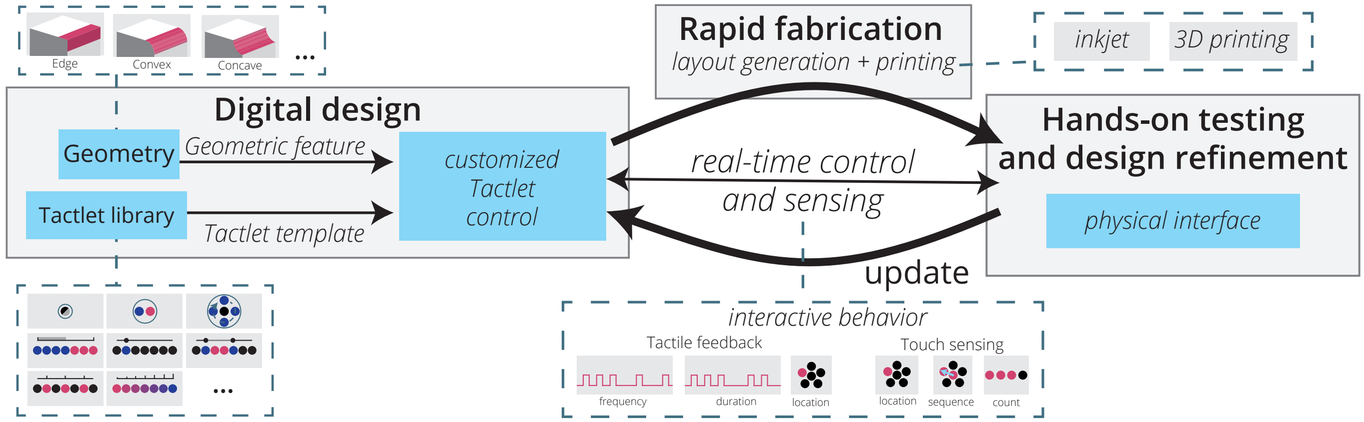

Figure 2. Conceptual overview of the design and fabrication process.

However, neither a systematic approach to identify the possible tactile renderings on physical objects nor a method to easily augment physical objects with electro-tactile interfaces has been studied. Therefore, in this paper, we investigate the design space, fabrication methods, and stimulation approaches to augment physical objects with electro-tactile stimulation. Furthermore, we propose to combine tactile stimulation and touch sensing to create interactive controls and show how to 3D print electro-tactile interfaces.

Design tools and interactive fabrication

Our work is also inspired by a stream of research on design tools for fabricating custom 3D objects and by approaches that merge physical interaction into the digital fabrication process.

Design tools enable a high-level digital design process that abstracts from low-level fabrication parameters. Tools have been contributed for various application areas: designing objects with desired haptic properties [50], designing mechanisms [13], designing electronics circuits [39], or designing interactive 3D objects [25, 32, 34, 44, 43, 45]. While several approaches support designing custom touch sensors [25, 32, 34, 45], the design of tactile output has so far been limited to low resolution, e.g. through embedding a vibrating device [25] or through pneumatic actuation [44]. In contrast, our approach enables taxel-based tactile output at a density comparable to the electro-tactile acuity of the index finger tip (4mm center-to-center spacing) [20]. Moving beyond GUI-only design tools, related work has also proposed approaches for designing a digital model using physical, hands-on interaction. For instance, this has been shown to be a viable alternative to control the fabrication process [29, 55], to customize an object's shape [6, 48, 52, 53], or to define placement of interactive components [43]. To the best of our knowledge, we present the first approach to allow digitally designing and printing tactile input and output controls for interactive objects.

DESIGN AND FABRICATION PROCESS

An overview of the digital design and fabrication process of Tactlets is illustrated in Figure 2. We contribute a novel *high-level digital design* approach, based on standard 3D modeling and new parametric controls, that enables easy placement and customization of Tactlets on a 3D object. Once designed, a physical prototype can be quickly *realized through printing*. To further ease and speed up iterative prototyping, we contribute a *real-time design mode*. It enables hands-on testing and design refinement on the fabricated prototype, while instantly propagating design updates of the interative behavior, e.g. parameters of the electro-tactile stimulation, between the design tool and the fabricated prototype.

Digital design

The process starts with the digital design. The goal is to enable the designer to easily and rapidly define the tactile input and output capabilities for a desired 3D object. Inspired by the success of toolkits for Graphical User Interfaces (which abstract from pixel-level I/O to high-level user interface controls), our approach allows for designing at a high level of abstraction.

To this end, we contribute the Tactlets design tool (see Fig. 3), which allows the designer to select Tactlet templates from a library, place them on a 3D model, and customize them. The design tool is implemented in C# as a plugin for Rhino3D, a popular computer-aided design (CAD) application, using the RhinoCommon .NET SDK[1]. This enables the designer to use all of Rhino's standard 3D-modeling features and to import models. The design tool offers a library of Tactlet templates, including buttons and sliders (see section Tactlet Templates).

The designer first selects a desired Tactlet template. Then she places it at the desired location on the mesh of the 3D-object model. This is done either by selecting the Tactlet's center point and size, or by selecting its start and end point, or by defining a free-form curve on the mesh that the Tactlet shall be mapped to (see Fig. 3).

The tool then passes the selected geometry to the template, which based on its model automatically parameterizes the concrete taxel layout (i.e., size and placement of taxels). For instance, to create a slider Tactlet on an edge of the object, the slider template generates taxels along the edge's path in the 3D model. It sets the radius of taxels to the default value stored in its model and spaces taxels with the maximum possible density to yield the highest possible resolution of sensing and output. The design tool immediately visualizes the Tactlet

[1] https://developer.rhino3d.com/guides/rhinocommon/

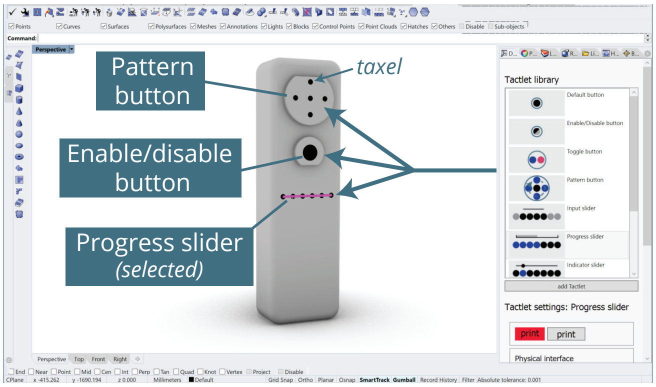

Figure 3. Digital design example: A prototype of a new tangible presenter device with tactile feedback is designed in the Tactlets design tool. It should let the user monitor the progress of a slide presentation and slide timing. The 3D model features two button-shaped protrusions. From the library of Tactlet templates, two Tactlet buttons, "next" and "previous", are placed on the two protrusions of the model. A slider is placed on the front of the device that will give tactile output about the slide progress.

design by rendering the individual taxels on the 3D model (see Fig. 3). The designer can then further customize the Tactlet by adapting its parameters (e.g. resolution of the slider) or by changing the shape or placement of the Tactlet (e.g. adapting the curve of a slider). The tool visualizes changes in real-time.

Rapid fabrication

To fabricate the interactive object, the design tool generates a printable low-level electrode layout of the electro-tactile interface. The generated design is then printed using one of two alternatives: For rapid fabrication within minutes, conductive inkjet printing [21, 22] can be used to print a thin, flexible electro-tactile overlay to be attached to the object. Alternatively, the interactive object can be 3D printed using a commodity FDM 3D printer and conductive filament, realizing the object with the embedded electro-tactile interface in a single pass. Both techniques enable a taxel density of 2mm diameter at 4mm center-to-center spacing.

After printing, the interface is connected to the Tactlets controller, a custom hardware unit that interfaces with the printed electrodes to control the electro-tactile stimulation and to sense touch input. The controller allows selection of the intensity/amplitude ($0-3mA$, in $15\mu A$ steps), the frequency ($1-200Hz$), and duration ($1ms$ steps) of the electro-tactile stimulus. The hardware supports stimulating one single taxel or multiple taxels at the same time through temporal multiplexing. It is extensible to support multiples of 8 taxels. Our configuration supports 16. For integrated sensing of user input, we employ a resistive sensing scheme using the same electrodes used for stimulation. Sensing is time-multiplexed with stimulation and runs at $25Hz$. Details on the implementation of the hardware controller are given below.

Real-time design mode: Hands-on testing and refinement

The design tool contributes a *real-time design mode* to support rapid hands-on testing and design refinements using the printed prototype. We consider this a critical feature, as tactile feedback cannot be adequately conveyed through a rendering in the design tool and instead needs to be physically experienced.

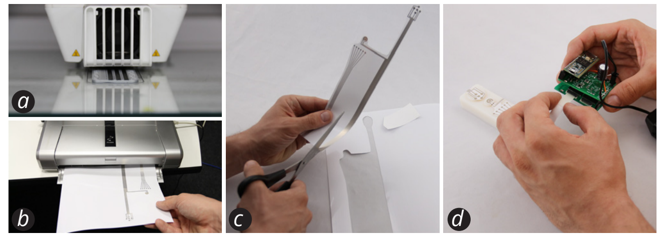

Figure 4. Rapid fabrication example: The designer prints the physical prototype on a 3D printer (a). Alternatively, she prints the interface on a conductive inkjet printer (b), cuts it out (c), and attaches it. Finally, the prototype is connected to the Tactlets controller (d). The entire fabrication (b-d) of the presenter prototype takes less than 5 minutes.

In this mode, the design tool and the fabricated prototype are connected and synchronized in real-time. To physically explore design options, the design tool offers live control of the prototype's interactive behavior. Conversely, by leveraging the sensing capabilities of Tactlets, the properties of a Tactlet can also be changed directly on the prototype itself and the digital design instantly updated.

To support rapid testing and refinement of a design, the design tool offers various options. It allows customizing the interactive behavior, moving a Tactlet on the object or modifying its size or shape, and adding or removing a Tactlet.

Explore and refine the interactive behavior

In the real-time design mode, Tactlets are interactive. The design tool processes captured input and renders tactile output according to the Tactlet's defined interactive behavior. A dedicated thread handles real-time processing of incoming touch data, sending actuation commands to the controller. The touch data are thresholded and touch-up and touch-down events distributed in an event-driven architecture. Tap events (i.e., lifting the finger within $< 30ms$ [31]) are detected based on timing of touch events and made available for listeners.

When the designer modifies properties of a Tactlet in the graphical design tool (e.g., enabled/disabled, selected position of a slider, etc.), the behavior of the physical prototype is updated accordingly in real-time. This allows the designer to physically experience the interactive behavior of a Tactlet and, if desired, refine the design. To ease debugging of a design, the design tool visualizes any user input sensed as well as all tactile stimuli provided on the physical object (see Fig. 5a). For rapid testing, the tool further offers a procedure to calibrate the user-dependent intensity of electro-tactile stimulation to a comfortable level.

Hands-on refinement

Modifying the behavior of the physical prototype through adjusting properties in the graphical user interface creates an indirection, requiring the designer to switch back and forth between the object and the graphical user interface. Since Tactlets feature input-sensing capabilities, the tool offers an alternative option: *hands-on refinement* to change properties of Tactlets directly on the physical object. To do so, the user selects a property to modify in the user interface and then physically sets it to the desired value.

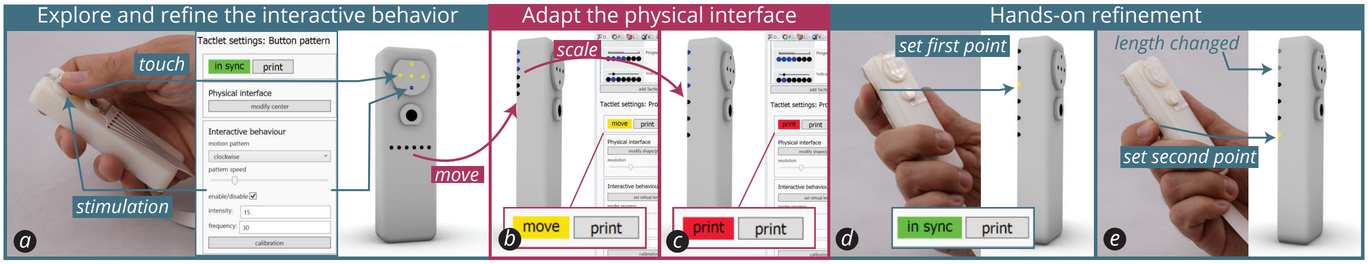

Figure 5. Real-time design mode example: (a) the designer explores the tactile output of the designed Tactlets. She can adjust and test different high-level parameters, e.g. the slider's progress value. Touch input is visualized on the 3D model in real-time. The designer moves the slider from the front (a) to an edge on the model's backside (b), as tactile guidance. (b) The tool indicates that the printed physical interface can be moved to the new location on the object and does not need to be re-printed. (c) The designer then increases the slider's length, a refinement which requires to re-print the interface. (d & e) After printing, the designer quickly adapts the length of the progress slider to be within comfortable reach of her finger. She first selects the start point directly on the object (d), followed by the end point (e). The length is updated immediately and visualized in the design tool (e).

Hands-on refinement can be used to change properties that define the tactile stimulus (e.g. frequency, temporal patterns, enabled/disabled state). While the designer is touching the taxel, the tool continuously sweeps through the valid range of values and renders the tactile stimuli accordingly. When the desired value is reached, the designer releases the touch, which sets the new value. In addition, it is possible to change properties defined by selecting a taxel location. For instance, the length of a tactile slider control can be dynamically shortened by defining a start and end taxel within the overall length of the slider (this results in outer taxels being disabled), as illustrated in Fig. 5d & e.

Adapting the physical design

Moving, scaling, or deleting a Tactlet is enabled through direct manipulation in the design tool's 3D view. The Tactlet directly adapts its taxel layout to the new 3D-object geometry. The tool then automatically determines whether the change can be realized by keeping the current printed prototype. A Tactlet can be deleted or downscaled by disabling all or some of its taxels, respectively, while keeping the prototype. Some cases of moving can be dealt with by simply physically moving the printed overlay to a different location on the object (in case conductive inkjet printing was used for fabrication). If so, the tool provides visual indications that guide the designer to perform this step. In all other cases, the tool indicates that printing a new version of the physical interface is required.

LIBRARY OF TACTLET TEMPLATES

In this section, we present an inventory of 10 Tactlet templates. They allow the designer to realize interactive objects with a variety of tactile behavior, including various types of buttons and slider elements.

Each template is implemented as a C# class that encapsulates the taxel layout generation and the interactive behavior. A template defines high-level properties that can be set in the design tool or at run-time (e.g., enabled/disabled). In addition, it defines events (e.g., button clicked) with corresponding listeners. The interactive behavior is implemented by taking touch and tap events as input and then correspondingly stimulating individual taxels.

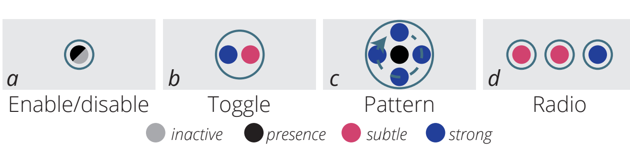

Figure 6. Templates for button Tactlets

Basic Building Block: Electro-tactile Taxel

A taxel is the basic building block of Tactlet templates. A taxel senses touch contact via resistive sensing. In addition, each taxel allows for electro-tactile output of varying duration (ms) and frequency (Hz). For most Tactlets two levels of distinguishable frequency are sufficient. We use default frequencies of 10Hz for *subtle* and 150 Hz for *strong* output (reflected as color of taxels in Fig. 6 and 8). We opted against using stimuli of different amplitude, as the perception of amplitude is very user-dependent, and instead calibrate the intensity to a level that the user perceives as comfortable. By default, upon touch contact, a taxel provides a *presence feedback*: a subtle pulsating output (150/50*ms* on/off). This feedback allows the user to discover the presence of a taxel, and therefore the Tactlet, during eyes-free interaction.

Taxels are circular to ensure a uniform current distribution [17]. Their size is scalable, ranging from 1-3mm radius. Several taxels can be arranged to enable spatial elements (such as a linear slider) and high-resolution tactile output, i.e. a density comparable with the highest tactile acuity for electro-tactile stimulation at 4mm center-to-center spacing [20].

Tactile Buttons

The most basic control is a **tactile button**. It consists of a single taxel, parameterized by its *location* (X,Y, Z) and *radius* (mm). By default, a button provides presence feedback while it is being touched. Tapping a button triggers a selection event (sent to all registered listeners). The designer can change this to a double-tap, if desired.

Disabling presence feedback allows creation of an **enable/disable button** that when disabled can no longer be discovered using taction (Fig. 6a & 7a). It offers the additional boolean parameter *enabled*. This feature can be used to temporarily hide functions that are currently unavailable.

Graphical user interfaces offer several types of buttons that provide additional states, e.g., a toggle button or checkbox.

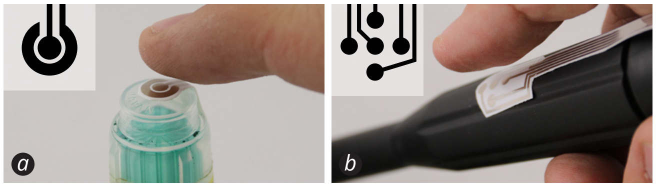

Figure 7. Two printed button Tactlets placed on curved geometries: (a) enable/disable button and (b) pattern button.

We realize a **tactile toggle button** that when tapped toggles between two states and triggers an event. It is composed of two taxels (Fig. 6b). For either *toggle state*, one of the taxels provides continuous strong output, while the other provides continuous subtle output. Both taxels are spaced with a 5 mm distance, to ensure that both taxels can be simultaneously felt when the finger pad touches the button.

Tactile radio buttons allow selection of one from a set of choices. They are realized by grouping multiple buttons, of which only one can be *selected*. Selection is reflected as continuous strong output (Fig. 6d). The designer is free to define a custom arrangement of buttons belonging to one radio group. For instance, she may place each button on a distinct geometric feature to allow for eyes-free exploration.

Adding more taxels allows for buttons that offer more versatile patterns of tactile feedback. We illustrate this with a **tactile pattern button** (Fig. 6c & 7b). It comprises one center taxel and 4 additional taxels arranged in a concentric circle of 3 mm radius. It offers circular tactile output by stimulating taxels in one circular *direction* (clockwise or counter-clockwise) as a sequence of strong pulses at *pattern speed* (Hz). This pattern can be used to convey additional states, e.g., indicating direction (forward or backward) in a video or slide presentation.

Tactile Sliders

Extending the size of a Tactlet beyond the size of a finger pad enables Tactlets that can be actively explored using finger movement. A basic example consists of a series of taxels arranged along a path (e.g. line, curve, circle) on the object's surface. We refer to them as a *tactile slider*. The placement of a slider is parameterized by setting the property *path* (NURBS). Of note, a slider can be placed on a distinct geometric feature, such as following an edge, ridge, groove, or going across a curved surface. This enhances eyes-free discoverability and offers tactile guidance of the user's finger when sliding. An additional property is output *resolution* defining the number of taxels along the path. Taxels are spaced at least 4mm apart to be distinguishable.

By default, all taxels of a slider provide presence feedback upon touch for discoverability. Disabling selected taxels, however, allows dynamically adapting a slider's length. For this purpose, the properties *start taxel* and *end taxel* can be set to define the bounds of the active area of the slider (Fig. 8a). For instance, this can be a useful property to adapt the length of a slider on a handheld object such that it is within finger reach for a given user's hand size (see Fig. 5d & e).

In a basic case, such a series of taxels allows for tactile rendering of a *one-dimensional* variable: A **tactile progress slider**

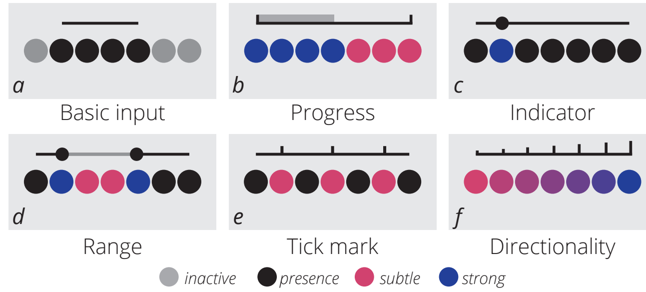

Figure 8. Templates for Slider Tactlets.

provides continuous strong output on a percentage of taxels that corresponds to the current *value* ([0..1]), whereas the remaining taxels provide continuous subtle output (Fig. 8b). Thus the current state can be explored with one finger.

For input, a **tactile input slider** lets the user set a *value* by tapping on a location on the slider (Fig. 8a). Tactile exploration (remaining $> 30ms$ at a taxel) provides presence feedback.

Inspired by traditional mechanical sliders or sliders in GUIs, we realized an advanced control that combines selection with tactile feedback of the selected value. A **tactile indicator slider** renders a tactile indicator, like a "knob", at the position on the slider representing the currently selected *value* ([0..1]), illustrated in Fig. 8c). The tactile indicator is rendered as strong pulsating output (150/50 ms on/off). It can be selected by tapping, which changes the pulsation to a continuous output while the user is dragging the indicator to the desired position. Once the finger is lifted, the new value is set and the indicator again rendered as pulsation. A **range slider** extends this Tactlet by adding a second virtual indicator, allowing selection of a *range* ([0..X,X..1]) of values (Fig. 8d). The selected range between indicators is rendered as continuous subtle output.

In addition to active virtual elements, e.g. indicators that can be dragged, sliders can also incorporate passive virtual elements. Adding a subtle continuous output at selected taxels allows adding **virtual tick marks** (Fig. 8e). These support rapid tactile discovery of key positions on the slider. Tick marks are defined as *positions* ($\{x \in [0..1]\}$).

For tactile discovery and guidance, it may be desirable to provide feedback on the directionality of a slider, i.e. in which direction the input *value* is increasing or decreasing. A **directionality slider** provides such tactile feedback using continuous output on all taxels, with varied frequencies (Fig. 8f). The taxel corresponding to the lowest value is set to subtle (10 Hz), while the taxel corresponding to the highest value is set to strong (150 Hz) output. The remaining taxels are assigned a linearly increasing frequency from subtle to strong. For instance, a linear input slider has taxels with increasing frequency from one end to the other, while a slider for audio balance could feature a low frequency in the center and increasing frequency towards both ends of the slider.

PRINTING OF TACTLETS

To physically realize Tactlets, we contribute an approach for printing electro-tactile feedback alongside touch sensing on

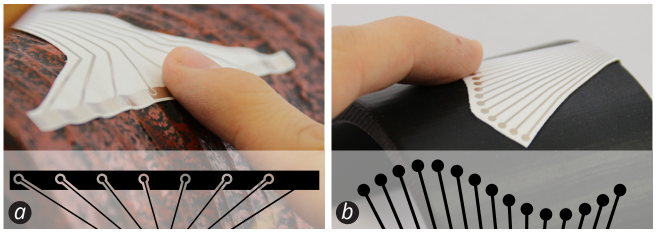

Figure 9. Two printed slider Tactlets with (a) lower and (b) higher taxel resolution placed on curved geometries.

3D objects. It comprises a method for automatically generating a low-level printable layout from the high-level design specified in the design tool. Furthermore, we present two fabrication approaches for printing the physical interface: using conductive inkjet printing or 3D printing.

Generating the Printable Layout

Our algorithm for generating a printable layout leverages the fact that a Tactlet is modular and parametric, consisting of a specific arrangement of taxels. Therefore, the basic approach is to map each taxel to one printed electrode (of equal radius). This electrode acts as an anode for electro-tactile stimulation and as one of the electrodes for resistive sensing of touch input. Stimulation and sensing require the user to simultaneously touch another electrode for ground. The algorithm first checks whether there is an electrode of another taxel in close proximity (distance $\leq 4mm$). In this case, this electrode can temporarily act as the ground while the present taxel is stimulated or sensed. We call this principle *mutual ground* (Fig. 10a). If no other electrode is neighboring, the tool adds a *dedicated* grounding electrode. This electrode is extended as a ground for multiple isolated taxels (Fig. 10b).

For conductive inkjet printing, a 2D-vector layout is generated. Each electrode is generated as a circle of the taxel's radius. The electrode locations are mapped such that they preserve the surface distance between taxels across the 3D mesh. To help the user attaching the printed overlay on the correct location on the 3D object, markers for visual alignment are generated. The resulting layout is exported as a vector graphic for printing.

To generate a printable layout for 3D printing, a 3D model is generated that is partitioned into conductive parts (electrodes, traces) and non-conductive parts (the actual 3D object). Each electrode is generated by calculating the intersection between a sphere at the taxel's center and the taxel's radius with the 3D model. Two 3D-printable STL files are created by subtracting the conductive parts from the model (boolean difference).

In our current implementation, traces to connect the electrodes are routed manually. Future versions could integrate established auto-routing approaches, e.g. as used in [34, 45].

Conductive inkjet printing

The tactile interface can be printed using a commodity inkjet printer (Canon Pixma IP 100) filled with silver-nanoparticle ink (Mitsubishi NBSIJ-MU01) [22]. We use coated paper (Mitsubishi NB-RC-3GR120). Once printed, one or multiple interfaces can be easily attached as an overlay onto a 3D-printed or real-world object using double-sided tape (Tesa universal). This is the preferred method for rapid low-fidelity prototyping, as the interface can be printed, attached, moved or re-printed within minutes. We found the interfaces to be robust to repeated use during prototyping over multiple days.

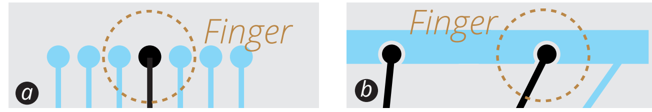

Figure 10. Approaches for realizing the low-level electrode layout for a taxel: (a) temporarily using a neighboring electrode as a taxel's ground electrode or (b) generating a dedicated, additional ground electrode.

Conductive 3D printing

For high-fidelity prototyping, interactive objects can be 3D printed with the tactile interface integrated in a single pass. We use a commodity dual-material FDM 3D printer (Ultimaker S5) with off-the-shelf PLA (Ultimaker) for the model and conductive PLA (cPLA, Protopasta conductive filament) for the embedded electrodes (see Fig. 4a). We 3D printed multiple prototypes (including those shown in Fig. 1c and 13c) that were fully functional and successfully tested by the authors. 3D printing allows for a wider range of supported geometries and interfaces that better integrate with real tactile cues. Although cPLA printed structures have low electrical conductivity, the highest resistance we observed in our 3D-printed models (cross section $6mm^2$, length $90mm$), ranges in the 10s of $k\Omega$. This is an order of magnitude less than average skin resistance (100s of $k\Omega$ [56]) and below the maximum supported resistance of our hardware ($320k\Omega$ for 1.25mA/400V). Therefore, cPLA conductivity does not affect the performance of the tactile stimulation. 3D printing is, however, slower than inkjet printing and requires printing the entire object. To our knowledge, this is the first 3D-printed electro-tactile interface presented in the literature.

Hardware Controller

The implementation of the hardware controller for electro-tactile output is based on the schematic presented in [56]. It comprises a voltage-to-current converter (0-$3mA$), two output multiplexers (Supertex HV513) with 16 parallel output channels, and a Teensy 3.2 microcontroller, which connects to the design tool via serial port (Bluetooth or USB). Stimulation uses a controlled current with a variable voltage up to $400V$. It requires calibration per user. Dynamic changes in contact resistance (e.g. through moisture) are automatically compensated.

We added resistive touch sensing by leveraging the fact that to receive electro-tactile stimuli at a taxel a user must touch at least two electrodes. The controller sends a low probing current to each electrode ($82.5\mu A$, $200\mu s$), at an intensity well below the absolute threshold of electro-tactile perception [56]. We measure the voltage between the active electrode and ground (all other electrodes) using the ADC input of Teensy and a voltage divider circuit. Since the pulses are current controlled, touched electrodes result in a lower voltage than non-touched electrodes (i.e. open circuit). A threshold to detect touch is set in the design tool (default: $7.4V \approx 90k\Omega$). Sensing one electrode takes 2.5 ms, during which actuation for 2ms is interleaved with sensing for 0.5ms. Electrodes are scanned sequentially, resulting in a sensing frame rate of $25Hz$ for 16 electrodes.

The hardware features two standard FPC connectors (pitch 1mm, 8pins) to connect the printed interfaces. For 3D-printed objects, the 3D-printed wires are connected to copper wires soldered to a FPC breakout board (Adafruit 1325), which is connected to the controller using a standard FPC cable. Inkjet-printed sheets are directly clipped into the FPC connector.

EVALUATION

To validate the functionality and practical end-to-end feasibility of our proposed method, we conducted a psyhcophysical evaluation and realized two application cases using the Tactlets approach. Each application case comprised the design and implementation of an interactive object and involved several design iterations. We present the results and discuss insights and lessons learned.

Empirical Evaluation of Sensing and Tactile Feedback

While prior work has demonstrated the functionality of printed electrodes for electro-tactile stimulation [21, 56], these were limited to planar geometries or interfaces that wrap around the finger. In pilot experiments, we found that other geometries, e.g. including convex curvature, can pose problems to deliver stimulation and to sense touch. While the soft finger conforms to a certain extent to the geometry, depending on the curvature and inter-electrode spacing, the finger may fail to make contact with two neighboring electrodes, the requirement for electro-tactile stimulation (cf. Fig. 11b). To confirm the functionality of our printed interfaces, we thus conducted a psychophysical study with users, which tested the absolute threshold of sensation at taxels on geometries of various curvature and at various finger positions.

Pilot study

In a pilot we identified suitable geometries and a suitable taxel spacing for the experiment. As a baseline reference, we used a *planar* geometry. We then identified challenging yet realistic cases of curved surfaces: a *convex curvature* of 13mm diameter (used as smallest curvature in [41]) and a *concave curvature* of 19mm diameter (index finger width of adult western males [14]). For electrodes aligned orthogonally to an edge, we noticed that it is not possible to touch multiple electrodes simultaneously, even at a small taxel spacing (2mm), unless the angle of the edge is quite large ($> 120°$). Sharp edges with smaller angles are supported, however, if the electrodes are oriented along the edge, e.g. for a slider (Fig. 5d). We thus included this condition ($60°$ *edge*) as a realistic sharpest feature to augment with tactile output (see Fig. 11a).

We further explored a suitable taxel spacing. We found 3mm center-to-center spacing to be the maximum distance so that people with small fingers could still make contact with two adjacent taxels on convex curved surfaces (see Fig.11b).

Method

Our hypothesis was that participants could consistently perceive electro-tactile stimulation on all four geometries (planar, concave, convex, edge) at two points on the finger (centered under finger pad and offset by 3mm), at a light contact force (0.1–0.7N $\approx$ force during tactile exploration).

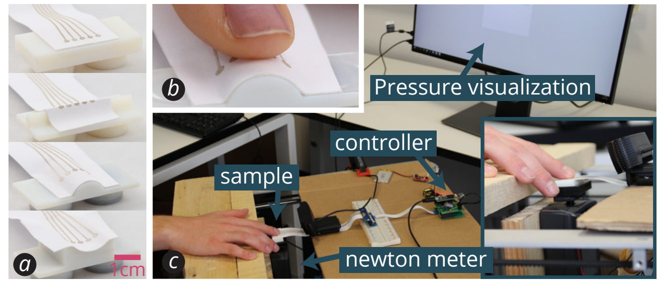

Figure 11. Study overview: (a) planar, convex and concave geometries used; (b) finger on convex curved geometry, and (c) study setup.

We recruited 15 participants (5 female, age 22 to 41) from our university campus. We 3D printed the four geometries and attached printed overlays, each with 5 electrodes in a straight line (3mm center-to-center, 2mm radius), shown in Fig. 11a. To enable direct comparison to related work, we screen printed the overlays. Our method is based on the classical method of limits [8, 16]. We used a random double-staircase method (to minimize errors of habituation and expectation [4]), with 20 steps per staircase. Staircase steps were presented with frequency 30Hz, carrier pulse $200\mu s$, and intensity steps of 0.1mA, as in prior work [56]. The starting intensity for the descending staircase was calibrated for each taxel by increasing the intensity to a comfortable level. Each step was presented for a maximum of 3 seconds followed by one second of rest. Participants pressed the space bar on a keyboard when they felt a stimulus. Contact force was measured using a digital force gauge and visualized on a computer screen. Participants were asked to keep the force in the target interval ($0.1 - 0.7N$) to avoid an effect of contact force.

We collected data on 4,800 trials (20 points per staircase x 2 staircases x 2 taxels x 4 geometries x 15 subjects). We further recorded voltage values reported by our sensing component for all electrodes and captured a close-up video of the finger placement on the sample to enable later in-depth inspection. Participants were asked to describe their perception and comfort of the stimulation after the experiment.

The data analysis revealed that the 20 staircase steps, which we had identified in a pilot study to be sufficient for convergence of staircases, were not sufficient to reach convergence in a total of 6 cases (5 participants). While in all those cases the participants did perceive the stimulation on both taxels, we could not determine a reliable estimate for the sensation threshold. Therefore, we excluded the data of these 5 participants.

Results

Figure 12 plots the absolute thresholds for all four geometries and all participants, averaged for both taxel locations. Thresholds range from $0.15mA$ to $0.73mA$ mA. The highest absolute threshold recorded (P08, convex geometry) is 4.32 standard deviations ($\sigma = 0.52$) below the maximum stimulation intensity of our controller ($3mA$). 14 participants reported pulsating or vibration-like sensations. If stimuli were strong, 8 participants described that they felt needle-like sensations.

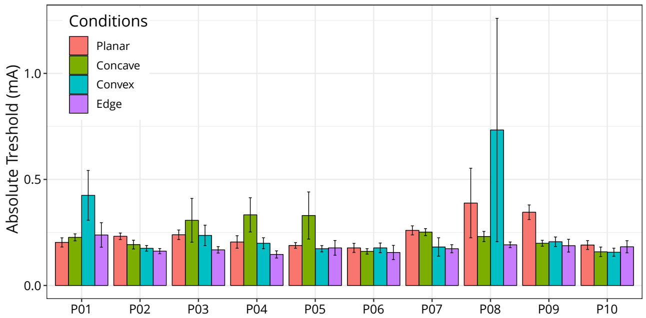

Figure 12. Study results: Absolute threshold of the stimulation intensity (mA) for each curvature condition for each subject.

To evaluate touch sensing, we calculated the average signal-to-noise ratio (SNR) for all users (across all taxels and all geometry conditions). It amounts to 51.4 ($SD = 22.1$). This indicates our sensing system works well above the expected SNR for a robust touch sensor (e.g. in capacitive sensors robust SNR is 15) [5].

These results confirm the technical feasibility of electro-tactile stimulation on planar, convex, concave and edge geometries and verify the maximum distance between electrodes (3mm) that works robustly for users.

Figure 13. Application case 1: Through several iterations different slider Tactlets are quickly prototyped on a smart phone case. (a) A long slider on a curved edge on the back of the case, (b) a short slider wrapped around the top left curvature, and (c) a curved concave slider on the back of a 3D-printed prototype. (d) All Tactlets are digitally designed in the design tool.

Application case 1: Phone case

Inspired by Haptic Edge Displays [15], we aimed to prototype and explore a similar tactile interface on the edge of a smartphone, while leveraging the benefits of our approach: a slimmer form factor, compatibility with curved geometries, and rapid design iterations.

We downloaded a 3D model of a phone case[2] for a Pixel 3 smartphone and printed it on an Objet Connex3 260 printer. We imported the model into our design tool.

We started our design by exploring a slider on the side of the case, similar to the one presented in [15]. However, we placed it on the curved edge on the back to use this geometry as a tactile guide for eyes-free interaction (see Fig. 13a). We implemented a simple application for scrolling through the pages of a PDF displayed on the smartphone and used it to iteratively test various configurations of the slider: A simple input slider allows scrolling through the PDF, while a slider with distinct tick marks indicates different sections in the opened document.

We wondered whether the same interaction would be possible on a shorter slider placed on the strongly curved surface around the top left corner of the case. We designed and fabricated the slider (see Fig. 13b and d) and tested the same application. We found the geometry to provide good tactile orientation; however, scrolling the document was more difficult and tick marks were limited to two due to the smaller size. The real-time design mode of the design tool allowed us to quickly test the use of this slider for a different, eyes-free, scenario. We placed the phone in a pocket and manually set different progress values; this confirmed this slider's potential for in-pocket feedback, e.g. a "silent" countdown timer.

As an additional promising location we tested the smartphone's back. We imagined that a circular slider around the centrally placed fingerprint reader would allow for back-of-device interaction while looking at the screen or while eyes-free. Using Rhino's CAD features, we quickly made a circular indent in the back of the case model to offer tactile guidance for interaction. We then 3D printed the modified model and designed a circular slider matching the indent's shape (Fig. 13c). By testing the finished prototype we found it to be suitable for both cases, looking at the screen and eyes-free interaction.

Application case 2: Presenter with tactile feedback

In our second application case, we aimed to explore the design of a new tangible presenter device with tactile feedback (Fig. 3). This served as inspiration for the example we have presented earlier in this paper (Fig. 3-5). We designed a simple 3D model of a presenter shape in Rhino3D. We then 3D printed the model (on an Objet Connex3 260 printer). In our design tool, we designed two buttons and one slider on the front of the device and tested the tactile feedback (Fig. 5a).

During exploration, we found that scanning the progress slider with a finger is difficult without looking at it. In a second iteration, we thus moved the slider to the back edge of the model as additional tactile guidance and tried different slider sizes, as illustrated in Fig. 5b & c. We then 3D printed the final design with embedded electrodes on an Ultimaker S5 printer (Fig. 1c) and implemented an application that interfaces the presenter prototype with Microsoft PowerPoint.

[2] https://www.thingiverse.com/thing:3207361

Lessons learned

For iteratively designing and fabricating the application cases, the Tactlet design tool and printing approach have been extensively used over the course of 8 weeks for a total of 15 design iterations. Here we summarize practical insights and limitations learned:

Rapid iterations: We found a key benefit of the approach for practical use is its rapidity. Being able to physically move a printed interface on the object, instead of re-printing a new design, was an important factor for saving time in day-to-day work, as it turned out that many design iterations relate to iteratively finding the best location for a tactile element on the object. To further speed up early explorations of electro-tactile feedback in initial design phases, we frequently simply placed a printed interface on the table rather than attaching it to an object. The Real-time Design Mode helped to rapidly test different behavior or stimulation parameters of a Tactlet without having to implement an interactive application. However, it is not possible yet in the design tool to directly link events to more extensive application logic. Future versions of the tool could create code stubs and connect to an IDE for implementing application logic. A future version should also include auto routing to facilitate the design process.

Our work allows initial insights into the usage of the design tool and the interaction with Tactlet controls. However, to gain a better understanding, a thorough study should investigate the extended usage of the tool, e.g. with novice makers, and the usage of the controls, e.g. for eyes-free discrimination.

Geometry: Inkjet-printed designs, despite printed on paper and attached onto the object, supported a surprisingly large set of geometries, including surfaces of slight double curvature, e.g. a whiteboard marker and a planter with ridges. Four examples are illustrated in Fig. 7 and 9. For our most challenging case, the indent on the smartphone with pronounced double curvature, we had to cut out the individual electrodes. This made the printed interface compatible with the geometry but introduced a less smooth surface, which affects the tactile feedback during sliding. In contrast, 3D printing allowed realizing a smoother result on this challenging geometry.

Scalability: We successfully inkjet-printed controls as small as a single taxel button (3mm radius, Fig. 7a) and as large as a 15-taxel slider spanning an A4 sheet (28cm length). While inkjet printing can realize electrodes with a separation of <0.5mm, for 3D printing realizing high taxel resolution can be difficult. This is related to printing parameters, where one has to ensure that clean boundaries are printed between conductive and non-conductive material (e.g. prevent stringing of the conductive filament). We were able to achieve a minimum separation of 2 mm.

Real-time refinement is limited within the scope of the printed electrode layout. Future work could address this through additional taxels to activate on demand. This would require a solution to facilitate the connection of more electrodes.

Electro-tactile feedback: From our experience it is important to calibrate a comfortable level of intensity. Too weak or too strong intensity can result in barely noticeable or uncomfortable sensation. We therefore opted against using variations of intensity to create different sensations. Instead, we experienced that variations in frequency offer a wide range of sensations (e.g. poking at 1 Hz vs. vibration at 50Hz). In contrast to mechanical feedback, such as vibrotactile actuators, electro-tactile feedback supports very localized stimuli. However, it requires the user to touch two electrodes simultaneously. This poses limits to the spatial design of taxels and controls; e.g. a button that is only partially touched may not be able to provide feedback. Printing mechanical actuators, e.g. electro-active polymers actuators, is actively investigated in material science. In future work, the Tactlets concept, digital design process, and templates could be transferred to such alternative actuation technologies.

Touch sensing: Our resistive sensing scheme works with the same electrodes used for electro-tactile stimulation, does not require additional components in the controller, and offers the SNR required for touch sensing. As commonly used in touch interfaces that offer no hover state, it relies on timing to distinguish between touch input and touch exploration. Confirming a selection during sliding is thus possible via tapping or double tapping. Additional sensing capabilities, e.g. to sense pressure or hovering, may offer a better scheme for distinction. For instance, capacitive touch sensing has been shown to sense pressure [46, 47] and hover states [9] and to work with inkjet-printed electrodes [9, 33] and conductive 3D printing [46, 47]. Our system can be extended to include a multi-stage multiplexing circuit to incorporate capacitive sensing.

CONCLUSION

In this paper we have presented a novel digital design and fabrication approach for input and output on interactive objects. Tactlets enable rapid prototyping of electro-tactile output and touch sensing in a conformal form factor on various 3D-object geometries. The concept builds on a high-level digital design tool and parametric templates of tactile controls, paired with automatic generation of printable layouts. Interactive objects can be rapidly fabricated through conductive inkjet printing or conductive 3D printing. A real-time design mode supports hands-on testing and design refinement using the physical prototype. Results from an empirical study with users confirm the technical functionality of sensing and tactile output on various object geometries. In practical application cases, we have demonstrated how this new process enables rapid design iterations and quick exploration of various tactile controls for interactive objects. We envision that Tactlets will enable HCI researchers, interaction designers, and makers to explore the use of tactile input and output controls for rapid prototyping of novel interactive objects, tangible interfaces, and ubiquitous computing devices. In future work we plan to explore how to integrate additional sensing capabilities and how to extend the approach to different tactile actuation approaches.

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