GelTouch: Localized Tactile Feedback Through Thin, Programmable Gel

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Figure 1. ***GelTouch*** **is a thin gel-based layer that can selectively transition between *soft* and *stiff* (up to 25 times stiffer) within seconds to provide multi-touch tactile feedback. Activated areas can be changed continuously and dynamically. We show that *GelTouch* can be applied to touch screens and that screen elements such as buttons, sliders and virtual thumbsticks can be augmented with tactile guides. This can enable eyes-free interaction (e.g., typing) and improve the user experience of tablets, control panels of cars and appliances, and wearables.**

ABSTRACT

We present *GelTouch*, a gel-based layer that can selectively transition between *soft* and *stiff* to provide tactile multi-touch feedback. It is flexible, transparent when not activated, and contains no mechanical, electromagnetic, or hydraulic components, resulting in a compact form factor (a 2 mm thin touchscreen layer for our prototype). The activated areas can be morphed freely and continuously, without being limited to fixed, predefined shapes. *GelTouch* consists of a poly(N-isopropylacrylamide) gel layer which alters its viscoelasticity when activated by applying heat ($>32\,^{\circ}\mathrm{C}$). We present three different activation techniques: 1) Indium Tin Oxide (ITO) as a heating element that enables tactile feedback through individually addressable taxels; 2) predefined tactile areas of engraved ITO, that can be layered and combined; 3) three-dimensional arrangements of resistance wire that create thin tactile edges. We present a tablet with 6x4 tactile areas, enabling a tactile numpad, slider, and thumbstick. We show that the gel is up to 25 times stiffer when activated and that users detect tactile features reliably (94.8%).

UIST '15, November 08 - 11, 2015, Charlotte, NC, USA

ACM 978-1-4503-3779-3/15/11$15.00
DOI: http://dx.doi.org/10.1145/2807442.2807487

Author Keywords
tactile feedback; thermoresponsive hydrogel;

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

Many modern devices such as phones, tablets, car dashboards, and appliances feature large touchscreens, sacrificing physical buttons. Thus, the experience of feeling for buttons using the fingertips is lost. The lack of haptic information makes eyes-free usage and usage for the blind difficult. Further, the experience of interacting could be enriched by providing haptic feedback. Previous approaches have addressed the problem of providing haptic feedback on touchscreens. Electrovibration [4, 22] allows to globally alter the perceived friction of the screen, simulating the sensation of texture. The main limitation of this approach is that it cannot provide multi-touch output, as each finger perceives the same feedback. For soft touchscreens, an array of electromagnets can be used to selectively alter the viscosity of magnetorheological fluids (MR fluids) [20], simulating different levels of *stiffness*. However, this usually requires large electromagnets, and the fluid is not transparent. *Tactus* [8] uses microfluidics to physically expand a polymer layer on top of the screen. This layer is deformed by creating small tangible bumps that resemble physical buttons. While this approach is very effective for rendering predefined shapes such as keyboard buttons, it does not allow for dynamic shapes that are not predefined.

In this paper we present *GelTouch*, a system that allows to selectively alter the stiffness of a soft touch surface, by changing the viscoelasticity of a thin layer of environmentally sensitive hydrogel, covered by an elastic coating. Our system is compact (2 mm thin) and transparent in non-activated state, which allows it to be combined with touchscreens (as shown in Figure 1). In the current implementation, the change in viscoelasticity is induced by stimulating the hydrogel with heat ($>32\,^{\circ}$C). By controlled spreading of heat in the gel, the activated area can be changed continuously and dynamically.

We present three activation techniques, all allowing for continuously sized tactile shapes: 1) *taxels* - dense, uniform, individually addressable tactile elements (similar to pixels in a picture) through a layer of ITO, 2) tactile *areas* through engraved shapes of ITO, and 3) tactile *edges* through thin resistive wires. The tactile resolution is not limited by the gel itself, but by the resolution of the heat stimulation. To our knowledge, the total number of activation cycles is practically not limited, with prior research demonstrating over 1200 activation cycles of similar gels [13].

We implemented a tactile tablet with 6x4 predefined tactile areas. We show three example applications, a numpad, a slider, and a thumbstick. As additional use cases of *GelTouch*, we show a tactile touchscreen-based car dashboard, a control panel for office machines, and a transparent, flexible wearable device. With our work we contribute by:

- Introducing a novel thin, hydrogel-based tactile feedback technology that can be combined with regular displays since it is transparent when non-activated.
- Presenting three different techniques to activate the hydrogel, 1) taxels, 2) tactile areas and 3) tactile edges.
- Showing that 1) the activated gel is up to 25 times stiffer than the non-activated gel, 2) participants can reliably detect tactile features rendered by *GelTouch* (94.8%), 3) participants describe the non-activated gel as *jelly* and the activated gel as *bouncy ball*.

RELATED WORK

Tactile displays

In order to create tactile feedback on surfaces, vibration on the whole (mobile) display (e.g., [6]) and specific areas (e.g., piezo buttons [27]), and different psychophysical phenomena like the squeeze-film effect [5] and the electrovibration effect [35] have been exploited. Systems like *TeslaTouch* [4], *Stimtac* [2], *SurfPad* [7], *Revel* [3] and work by Kim et al. [22] and Saga et al. [31] give users the illusion of dynamically textured surfaces. This allows for rich interactions such as tactile feedback and exploration of differently textured surfaces. However, until now, this type of feedback is only applicable for single-touch applications, as surface properties are altered globally. It is not possible to generate different haptic sensations for individual fingers. In our work, we change the physical properties of the surface *selectively* at certain regions, enabling multi-touch interactions.

Dynamically changing physical texture

Prior research explored various ways for creating physically changing texture, for example through microfluidic technology, pneumatics, shape-memory alloys, motorized pins and ferrofluids.

Microfluidic technology

Tactus Technology[1] develop products to create retractable, tangible buttons on touchscreens. Their technology stack includes a tactile layer containing a fluid, which is added on top of regular touch screens [36, 8]. By mechanically increasing the fluid pressure, predefined areas on the tactile layer can be elevated, resulting in a tactile sensation. The focus of their technology lies in tactile guidance for touchscreens, e.g., physically elevating keys on a virtual keyboard. In contrast to their work, our tactile guidance can be changed continuously and is not limited to discrete predefined areas. Besides, our system preserves the shape of the surface and only alters its tactile properties (e.g., stiffness).

Pneumatics

Harrison and Hudson investigated the usage of pneumatically actuated physical buttons [17]. Follmer et al. [11] created shape-changing user interfaces by low-power pneumatic jamming, which can also be used as haptic feedback by altering predefined shapes. With *PneUI*, Yao et al. [39] used a pneumatic mechanism to change the shape of a surface by inflating and deflating a silicon-based surface. This way, different textures could be created, e.g., for haptic feedback or surface exploration. Stanley et al. [33] used a similar technique for their work *Haptic Jamming*. Hachisu et al. created *VacuumTouch* [15] to provide attractive force sensation (e.g., a suction button) as an additional dimension of user interface feedback. Pneumatic interfaces in general require extensive instrumentation to keep air pressure high, which is necessary for creating the tactile sensation. Additionally, most work focuses on the actuation of predefined areas, whereas our work allows continuously shaped and sized areas.

Motorized interfaces

Iwata et al. created *Feelex* [19], a matrix of linear actuators and one of the first shape changing displays. This work was later adopted and extended by Poupyrev et al. with *Lumen* [30], and Leithinger et al. and Follmer et al. with *Relief* [26] and *inFORM* [12], respectively. These 2.5D shape changing displays are used for haptic feedback as well as for collaboration, communication, and telepresence. In order to digitally augment these displays, projectors are used to display content. Additionally, the often large number of actuators included in these systems requires extensive instrumentation. Hafez and Khoudja took a different approach and created a tactile rendering system based on monolithic Shape Memory Alloy (SMA) micro actuators [16]. Their main usage scenario is to use the tactile display as a braille display.

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[1] `http://tactustechnology.com/`

Ferrofluids and MR fluids

Jansen et al. [20] and Koh et al. [24, 23] explored the usage of ferrofluids, or MR fluids, combined with electromagnetic actuation for haptic feedback. The haptic layer is envisioned to be added to traditional GUI devices. Using ferrofluids allows for selective activation of specific elements of the display. Howerever, ferrofluids and MR fluids are usually not transparent, which does not allow them to be used easily as an overlay to regular displays. We designed *GelTouch* as an additional layer placed on top of regular displays.

CHEMICAL IMPLEMENTATION

The main component of *GelTouch* is a custom hydrogel which alters its viscoelasticity through external stimulation (in our case temperature). A *hydrogel* is a highly absorbent type of gel that consists of hydrophilic polymer chains. *Environmentally sensitive* hydrogels change their viscoelasticity based on external factors (e.g., pH, magnetic fields, light or temperature) [10], and are therefore sometimes referred to as *Smart Gels* or *Intelligent Gels* [29]. A change in viscoelasticity can be perceived as a change in stiffness, enabling dynamically programmable tactile feedback. The sensitivity of hydrogels to a certain type of external stimulation is determined by their composition.

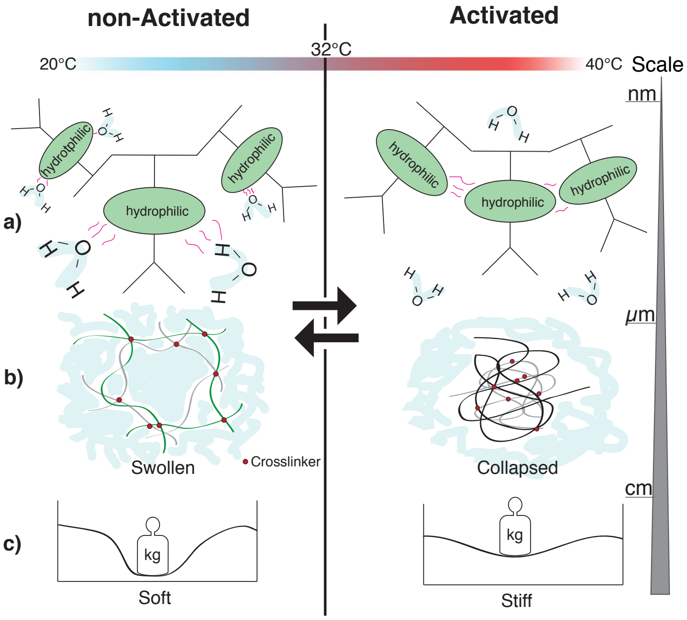

Figure 2. a) Attraction forces of the hydrophilic group of PNIPAM b) Macroscopic conformation of the Gel c) Viscoelastic properties of the gel.

PNIPAM based thermoresponsive hydrogel

For *GelTouch*, we use a thermoresponsive hydrogel, which is a polymeric poly(N-isopropylacrylamide)-based network (PNIPAM). Thermoresponsive hydrogels are polymers with a three-dimensional network that swells in water. They provide unique viscoelastic properties resulting from being an intermediate between solids and liquids [18, 14]. These gels exhibit large conformational changes leading to an expansion or contraction of the network. Due to their responsiveness to external stimuli, these materials can be used as actuators or molecular switches, as well as for tissue regeneration, surface patterning, drug delivery systems or responsive surfaces [38, 21]. PNIPAM gels are hydrophilic and therefore swollen with water molecules at temperatures below 32 °C (see Figure 2). Additionally, in this state the gel is transparent. The temperature threshold is called lower critical solution temperature (LCST). When heated above the LCST, the hydrogen bonds between the polar groups of the polymer and the water molecules break. The water is released from the network resulting in a collapse of the PNIPAM gel. This leads to a phase separation and is accompanied by an increase of the turbidity of the gel [1, 37]. Besides changing the viscoelasticity of the gel, it is also no longer transparent in this state.

Our gel is prepared in a surfactant-free radical polymerization of the monomer N-isopropylacrylamide (NIPAM) and the cross-linker N,N-methylene-bis-acrylamide (MBA) in water according to the protocol of Wang et al. [37]. The monomer NIPAM can be seen as a single building unit of the polymer chain. The monomer units connect with each other during the polymerization process and form long poly(NIPAM) chains. Additionally to NIPAM monomers, crosslinker units of MBA are built in during the polymerization. MBA enables the growth of branched polymer chains which form complex three-dimensional networks. Thus, the architecture of the gel is mainly determined by the cross-linker. Hydrogels with low amounts of cross-linker will swell more due to less cross-links and a less rigid network. Therefore the amount of cross-linker affects the viscoelastic properties [34, 37, 25]. The polymerization is initiated by ammonium persulfate (APS) at a temperature of 4 °C. In order for the polymerization process to start we add tetramethylethylenediamine (TEMED) as an accelerator [37].

Synthesis

We eliminated several synthesis steps such as nitrogen washing and water washing from Wang et al.'s protocol [37]. This simplified and sped up the production process while having no significant impact on the result of the synthesis. We performed the following steps to prepare about 25 mL hydrogel.

1. Dissolve N-isopropylacrylamide (2 g) in millipore water (20 mL)
2. Add N,N'-Methylene-bis-acrylamide (2 mg) to the solution and dissolve it (ultrasonic bath and vortex)
3. Put the solution on ice for 10 minutes
4. Dissolve APS (50 mg) in millipore water (3 mL)
5. Pour the N-isopropylacrylamide / N,N'-methylene-bis-acrylamide solution in the synthesis container
6. Add TEMED (150 µL) to the container
7. Add APS solution (1500 µL) to the container
8. Put the container into the fridge (4 °C) for about eight hours
9. Wash the hydrogel 3 times with millipore water (500 mL)

Viscoelastic properties

Viscosity in general describes the resistance of a material to deformation by applied forces. Viscous materials flow like a liquid when a force is applied, but do not return to their original shape upon removal of the force. Elastic materials reply with a reversible deformation towards applied force being able to recover to their original state upon removal of the load. The gel used in *GelTouch* is viscoelastic and exhibits both viscous and elastic components in its response towards stress, which means that it first stretches elastically and starts to flow later. Depending on the time of stress release, the deformation can be reversible [28].

The viscoelastic properties are important factors to determine if a material is perceived as stiff or soft [9], while the stiffness of an object is primarily perceived by tactile sensors in the human skin [32]. *GelTouch* creates tactile sensations due to viscoelastic changes of the touched surface. The extent of the viscoelastic response of the gel towards stress is determined by the cross-linker concentration during the synthesis. High concentrations of cross-linker result in a relatively stiff gel. A softer gel is produced by the addition of lower amounts of cross-linker.

We conducted a small test series of MBA concentrations to enhance the difference in viscoelasticity of the two states of the gel. The tested cross-linker concentrations ranged from $0.01\,\%$ MBA to $7\,\%$ MBA. All samples had the same level of stiffness when activated due to a fixed concentration of PNIPAM, but varied tremendously in the viscoelasticity when non-activated. For very small cross-linker concentrations, the gel turned out to be too fluid and did not stay in place. $0.2\,\%$ of cross-linker turned out to be the optimal concentration for our purposes.

Container
Since the solution is liquid before the synthesis, we synthesized the gel in the priorly prepared final container. As a container, we used laser-cut acrylic glass, since we did not observe any chemical reaction between the gel and the acrylic. Alternatively, containers can be prepared using PTFE. For sealing the container we used transparent silicone and acrylic resin varnish which does not react with the gel. Other types of glue (e.g., industrial tape, adhesive foil) damaged the gel.

To keep the hydrogel in place, prevent it from drying out, and avoid direct skin contact, the system is covered with an elastic transparent foil. While PNIPAM is generally not considered harmful, direct contact with the mouth or the eyes should be avoided according to safety recommendations. We used a *Polyurethan* layer of $28\,\mu\mathrm{m}$ thickness, as it provides a good balance between elasticity and transparency. We also experimented with household materials: Plastic wrap (*LD-PE*, $12\,\mu\mathrm{m}$) sticked to the users' fingers, affecting tactile sensation. Gift wrapping foil (*PE* , $25\,\mu\mathrm{m}$) has too low elasticity to pass the viscoelastic properties of the gel to the fingertip effectively.

ACTIVATION TECHNIQUES
One key property of *GelTouch* is that the tactile features are not predefined (i.e., dynamic in shape and size, and individually addressable), since the gel provides a continuous medium. The spatial resolution is determined by the ability to locally apply heat to the gel. We present three example activation techniques that can generate taxels (dense tactile elements), predefined tactile areas and tactile edges (Figure 3). With all heating techniques, the size of the activated areas can be controlled continuously by adjusting the time during which voltage is applied.

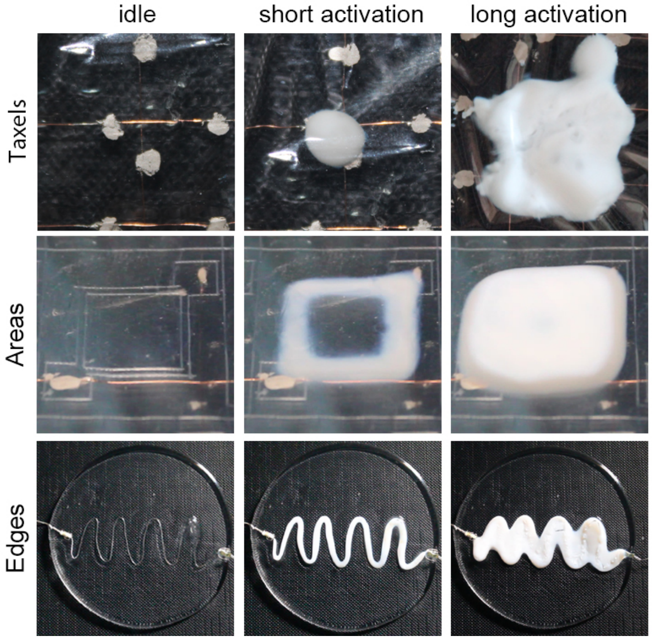

Figure 3. Overview of activation techniques. Heat can be applied through ITO (taxels, tactile areas) or resistance wire (tactile edges). The hydrogel is soft in non-activated state and stiff in activated state. The size of the activated areas can be continuously increased by applying more heat. Neighboring activated areas can also be merged.

Taxels on ITO Layer
Indium Tin Oxide (ITO) is a transparent conductive material that is coated on a thin polymer/plastic layer. By connecting electrodes to the layer, the area where current flows between the electrodes is heated. Figure 3 shows the electrodes distributed on the ITO and their activation (top row). We created a 6x6 multiplexing matrix of pairs of anodes and cathodes, placed $4\,\mathrm{mm}$ apart. The electrodes are connected through coated copper wire, which we glued to the ITO with conductive ink. We believe that through industrial processes, such as direct printing of conductors, the resolution of electrodes, and thus the density of taxels, could be increased substantially. Additionally, the resolution could be increased by stacking multiple layers of taxel rasters. This heating technique has the benefit that it can render arbitrary shapes (like raster graphics, but with continuously controllable pixel size). However, the resolution of the shapes is limited by the density of taxels.

Tactile Areas through engraved ITO
Our second heating technique allows to render predefined tactile areas (see Figure 3 - center row). By laser-engraving shapes into ITO, and attaching electrodes to their extremes, various shapes can be created. We created a 6x4 array of square key hints, which we also used for the tablet prototype. The engraved ITO sheets can also be layered, as heat

is transmitted through ITO acceptably well. Thus, applications could render superimposed and compound shapes from different shapes on different layers.

Tactile Edges through Resistance Wire

Our third heating technique renders predefined tactile outlines, as depicted in Figure 3 (bottom row). In order to achieve this, we embed multiple thin resistance heating wires in the gel. Due to their high resistance, these wires heat up when connected to a power source. Since the wire can be placed directly into the gel, 3D structures are also possible. We used a FeCrAl alloy ribbon of Kanthal D resistance heating wire with $0.2\,\mathrm{mm}$ diameter. This technique is best suited if the device should only switch between a limited number of outlined shapes (like vector graphics). Unlike ITO, the resistance wire is bendable in all directions. Additionally, the gel can be activated faster and with less loss, as the heat is generated directly into the gel and does not have to be transmitted through a coating.

EVALUATION

To evaluate *GelTouch*, we conducted two force measurements to identify the force needed to dent the gel and the modules of viscosity and elasticity of our hydrogel. We also conducted a preliminary user study to show that people can reliably distinguish between activated and non-activated state, and to collect qualitative feedback on the tactile sensation of the gel.

Force Measurements

We performed a basic indentation force measurement to determine the force needed to dent a gel of $0.2\,\%$ cross-linker concentration in its two states. The measurements were performed with the VersaTest set-up from Mecmesin. A $4\,\mathrm{cm}$ long gel sample was intruded to a depth of $2\,\mathrm{cm}$ by a probe of oval surface of $19.2\,\mathrm{mm}^2$ at a speed of $500\,\mathrm{mm/min}$. In the case of the non-activated gel a force of $0.72\,\mathrm{N}$ was needed for $2\,\mathrm{cm}$ indentation, whereas for the activated gel a force of $18.09\,\mathrm{N}$ was needed. Thus, the activated gel proved to be about 25 times stiffer than the non-activated gel. Secondly, we identified the viscosity module and elasticity module of a $0.75\,\mathrm{mm}$ thin gel sample with a Rheometer. We used $25\,°\mathrm{C}$ for the non-activated gel and $50\,°\mathrm{C}$ for the activated gel. Results show a 6 times higher elasticity ($437.4\,\mathrm{Pa}$) of the activated gel compared to the non-activated gel ($72.78\,\mathrm{Pa}$). The gel is 3.8 times more viscous when activated ($111.4\,\mathrm{Pa}$) than when non-activated ($111.4\,\mathrm{Pa}$). Both measurements show a clear change in the viscoelastic properties of thick and thin gel samples when activated vs. non-activated.

Preliminary user study

We invited 6 participants (3 male) aged between 22 and 27 years ($mdn = 24$), all right-handed. The goal of this study was twofold. First, we aimed at finding a subjective description of the haptic sensation created by *GelTouch* in both states. Secondly, we investigated how accurately people can detect tactile edges rendered using *GelTouch*.

For the first experiment, participants equipped with disposable gloves were instructed to prod the gel with their index fingers and then asked to describe the perceived tactile sensation. A sample of $2\,\mathrm{mm}$ thin hydrogel was presented to them in a petri dish placed behind a visual barrier, out of sight of the participants. The non-activated gel was described as “slick, creamy, viscous”, and “soft”. The participants compared it to a “gel, creme, jelly, aspic, hair gel, cooling pads”, and “jelly fish”. The activated gel was described as “hard gel”, “hard to deform” and was compared to a “wet piece of cloth, glue, rubber, gum”, and a “rubber ball”.

For the second experiment, we created a $2\,\mathrm{mm}$ thin *GelTouch* layer with tactile edges using 4 vertical resistive wires placed $3\,\mathrm{cm}$ apart from each other. The sample was again placed behind a visual barrier, so the participants could not see but only feel it. They were asked to move their index finger horizontally on the surface from left to right. Participants were allowed to move back and forth and asked to indicate the location of edges. As an independent variable, we controlled the activated edge (outer left, inner left, inner right, outer right). As dependent variable, we measured error rate. Each participant executed 16 fully randomized trials. Some participants were sliding from left to right, others pressed and released their finger in small steps in order to locate the stimuli. We measured a mean accuracy of $94.8\,\%$ (std= $5.6\,\%$). While all participants (6) perceived the edges, 5 also perceived the warmth after having noticed the edges.

APPLICATIONS

To demonstrate *GelTouch*, we built a prototype in a small tablet form factor. The thermoresponsive hydrogel is included in a $2\,\mathrm{mm}$ thin layer serving as overlay on a 7” resistive touch screen. An ITO layer with 6 (vertically) × 4 (horizontally) engraved squared tactile areas is used as activation technique. Each element of the activation layer can be addressed individually, controlled by an Arduino Nano. We demonstrate three different applications for the *GelTouch* tablet.

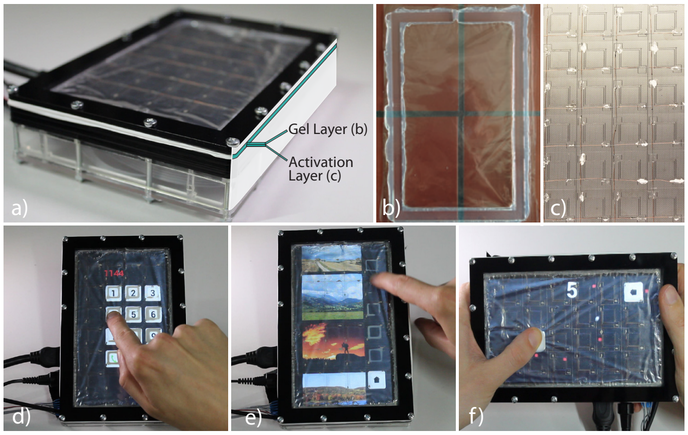

Figure 4. Our a) prototype tablet includes the b) gel layer and c) activation layer on top of a resistive touchscreen. With 6x4 tactile areas, we can render tactile d) buttons, e) sliders, as well as f) solid thumbsticks.

Tactile Buttons

The rectangular tactile areas are used as tactile hints for virtual buttons on the touch screen (see Figure 4d). By sliding their fingers across the surface, users can physically feel the boundaries of the buttons. Since we use resistive touch screen technology and the gel itself absorbs some of the pressure of a slight touch, the screen only reacts after a gentle push. This allows users to explore the screen using their fingertips, without accidentally triggering touch events. Possible applications include eyes-free calling of phone numbers. PIN codes for unlocking the phone or similar can also be entered with the display covered or in a pocket, protecting from shoulder surfing.

Tactile Slider

We designed a tactile slider by placing five rectangular tactile shapes next to a picture gallery (see Figure 4e). These can help to guide the scrolling movement when navigating through the presented pictures. Moreover, the frequency of the perceived tactile hints during the scrolling movement provides haptic feedback on the scrolling speed. In our prototype, sliding across one tactile shape maps to scrolling one picture further in the gallery. This slider might also be used for eyes-free adjustment of audio volume or similar.

Tactile Thumbstick

Finally, we designed a solid tactile area by heating one element longer (see Figure 4f). The resulting shape represents a virtual thumbstick. This provides an indication of the stick location and its neutral position, allowing users to completely focus, e.g., on a game they are playing. The tablet can thus also be used as a *second screen* input device more efficiently (e.g., as game controller for a TV), as it does not require the user to look back and forth between two displays.

Further Applications

In order to show the general applicability of *GelTouch*, we demonstrate usage in a car control panel, a photocopier and as a wearable (see Figure 5). The car and the photocopier use the same hardware as the tablet. In the car, drivers can turn on music, pause it and change songs, all while keeping their eyes on the road. The photocopier provides a dynamic touch panel, while improving experience for the sighted and enabling usage for the blind through haptic feedback. The wearable is a flexible transparent armband ($1\,\mathrm{mm}$ thin) that can be worn over clothes or the skin. Phone and mail icons are included through resistive wire, providing tactile, eyes-free notifications to the user.

LIMITATIONS

Activating a single tactile button (approx. $64\,\mathrm{mm}^3$ of hydrogel) requires $1.7\,\mathrm{W}$ ($58\,\mathrm{mA}$ at $30.15\,\mathrm{V}$ in our case). The current has to be maintained for at least two seconds, resulting in a required charge of about $1\,\mathrm{m}$Wh per activation. With typical battery capacities of current mobile devices, one button could be activated a few thousand times. It takes another two seconds for the activation to be reversed, after the current is removed. Note that the measured values depend on various factors including the resistance of the shape ($520\,\Omega$ in our case), surrounding temperature, size of the activated area, duration of activation, etc. With a multiplexing energy distribution logic, tactile button arrays can be activated simultaneously. Also the efficiency of the activation technique itself influences the required energy. Currently, the ITO is not directly embedded into the hydrogel, but separated through coating.

Figure 5. We built three additional demonstrators of *GelTouch* as a haptic a) car control panel, b) photocopier control, and c) transparent wearable armband.

GelTouch is not transparent in activated state. This raises challenges for interface design on touch screens, as interface elements might be occluded at times. To our knowledge there are no hydrogels so far which maintain their transparency while crossing the LCST. We currently follow an open-loop activation approach. Such open-loop approaches are naturally not well-suited for exactly keeping activated shapes over prolonged time and changing environmental conditions. Since the hydrogel used in *GelTouch* is activated when the temperature exceeds the LCST of $32\,^{\circ}\mathrm{C}$, it is possible that it is activated inadvertently by the environmental temperature, device temperature or the user's body temperature.

DISCUSSION AND FUTURE WORK

A closed control-loop design using sensing of gel temperature or activation state could provide more precise control over the gel and reduce environmental influences. The LCST can be adjusted, for example by adding co-monomers, salts or using a different basis (e.g., NIMAM instead of NIPAM). Ideally, the gel should be kept just below or above the LCST, to ensure quick activation and deactivation. This could be achieved by controlling the introduced heat, or a dedicated cooling layer. Using a solvent with less thermal capacity (e.g., ethanol ($2.4\,\mathrm{kJ}/(\mathrm{kgK})$) than water ($4.2\,\mathrm{kJ}/(\mathrm{kgK})$) would result in faster activation and deactivation of the gel. Another way to speed up activation would be to directly include the heating elements into the gel. Other hydrogels use different stimuli besides temperature, such as pH, electromagnetic fields, or light.

With high pressure, the activated gel can currently be temporarily displaced. Various cross-linkers (like N,N-cystamine-bis-acrylamide, CBA) could be explored to optimize the compliance of the gel. Adding acrylic acid during the synthesis of gels shows an increase of the elastic properties of different hydrogels. This should increase the difference in viscoelastic properties between the activated and non-activated state of the gel.

Our system includes a protective foil covering the gel. The foil's elastic properties influence the perceived stiffness of the gel and may also lead to wrinkles reflecting ambient light. While this was not the focus of this project, alternative materials such as a thin layer of silicone or a graphene layer would enable a fully transparent protection film with high elasticity.

While thin wires are currently visible in our prototype, transparent printable conductors based on silver nanowires, graphene, or similar technologies might replace them in the future. While our current prototype uses a resistive touchscreen, initial trials using capacitive touchscreens let us believe that *GelTouch* could be used with a custom or modified capacitive touchscreen. This could also allow us to activate *GelTouch* when fingers are hovering above the display.

CONCLUSION

GelTouch is a tactile feedback technology that provides different feedback to individual fingers, with a thin and flexible layer, while allowing dynamically shaped and sized tactile elements. We believe that *GelTouch* can be a very interesting alternative or addition to other tactile feedback technologies in applications where these properties are relevant. We demonstrated how it can be used in tablets, control panels of cars and appliances, as well as wearables. The three activation techniques of taxels, tactile areas and tactile edges allow a multitude of different applications. We do believe that smart gels hold great potential for human-computer interaction and can inspire a research area of organic and flexible interfaces.

ACKNOWLEDGMENTS

This research was funded by the German Federal Ministry of Education and Research (grant number 01IS12056) and ERC (grant ERC-2010-StG 259550 *XSHAPE*). We thank Lucas Kuhrts for assistance with the chemical implementation, Constantin Schmidt, Dieter Eberle and Klemen Lilija for prototyping and development, Martin Schüssler and Ines Ben Said for video editing, Johannes Hellwig and Lutz Rautenberg for force measurement assistance, as well as Tiare Feuchtner and Andreas Fender for general support.

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