MudPad: tactile feedback and haptic texture overlay for touch surfaces

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ABSTRACT
We introduce MudPad, a system capable of localized active haptic feedback on multitouch screens. We use an array of electromagnets combined with an overlay containing magnetorheological (MR) fluid to actuate a tablet-sized area. As MudPad has a very low reaction time it is able to produce instant multi-point feedback for multitouch input, ranging from static levels of surface softness to a broad set of dynamically changeable textures. Our system does not only convey global confirmative feedback on user input but allows the UI designer to enrich the entire interface with a tactile layer conveying local semantic information. This also allows users to explore the interface haptically.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces. - Haptic I/O.

General terms: Human Factors

Keywords: Haptic I/O, tactile feedback, magnetic fluid, texture display

INTRODUCTION
Touch screen interfaces are increasingly common in both mobile and stationary computers because their user interfaces are intuitive to use and their visuals can be easily changed or re-arranged on the fly. Designing user feedback on these devices, however, is limited by a number of factors. While vibration and sound may be available to acknowledge user input these types of feedback are non-local and generally undirected. Especially on touch devices that allow multiple points of input a richer feedback channel is needed.

Temporary graphical overlays which are often used in these situations can give local visual feedback but still have to be moved out of the fingers' occlusion areas and thus potentially occlude other parts of the interface. Examples of these techniques are the on-screen keyboards of current smart phones. The Samsung i718, e.g., uses global tactile clicks to confirm key presses, the Apple iPhone uses sound and graphical overlays that appear above the pressed keys.

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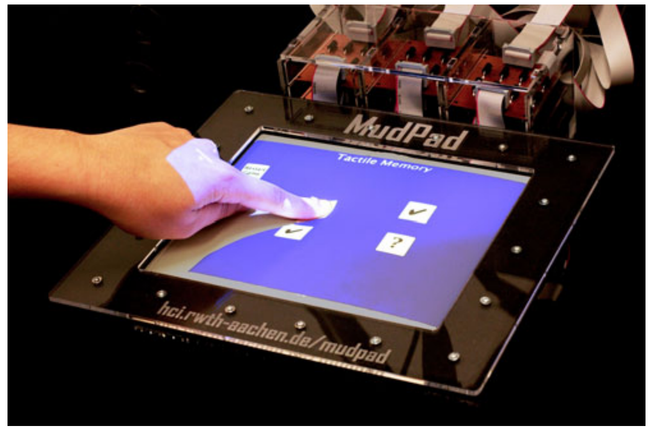


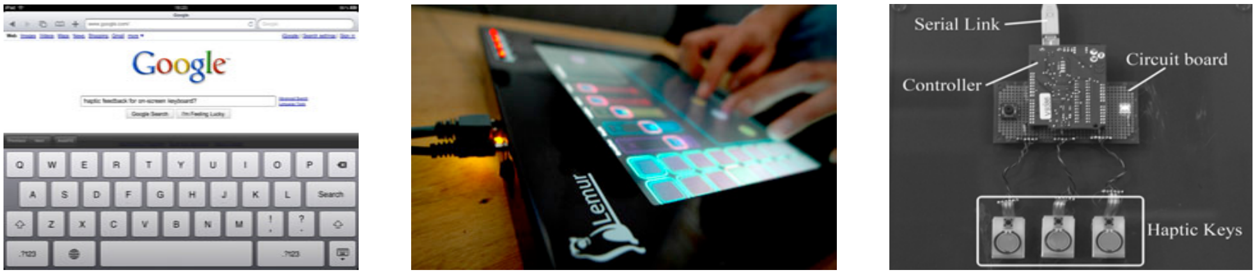
Figure 1: MudPad is a system that provides localized haptic feedback independently at multiple points.

Although these approaches work reasonably well, MudPad combines the advantages of graphical overlays - locality and low latency - with those of tactile feedback - privacy, eyes-free access, and no need for screen real estate. For this, we add a continuous haptic feedback layer to the display that is able to produce a wide range of tactile signals at arbitrary positions. Since every position or area on the surface can be addressed individually, each graphically displayed UI element can be associated with a distinct tactile sensation making MudPad a haptic feedback counterpart for multitouch input.

RELATED WORK
As both the field of haptic feedback and multitouch input is very broad, we will restrict the coverage here to only those systems which lie in the much smaller intersection of these fields.

Until now there has not been a system capable of localized active haptic feedback for touch screens. There are some intersecting projects though. Poupyrev et al. [14] presented Lumen, a low resolution height display capable of displaying an additional layer of information through different pixel heights. As it is based on shape memory alloy its reaction time is slow and not comparable to MudPad.

Harrison et al. introduced inflatable buttons [6] and thus gave virtual buttons a physical shape. However, the placement of



(a) (b) (c)

Figure 2: Possible usage scenarios for localized multi-point haptic feedback. (a) Virtual keyboard of an iPad. (b) JazzMutant Lemur (www.jazzmutant.com) (c) The secure haptic keypad by Bianchi.

the buttons is fixed once assembled. Additionally, each button requires a dedicated pneumatic pump to be able to operate it independently.

Hoffmann et al. presented a haptic keyboard [7] that prevents the user from accidentally pressing keys by increasing their resistance. While this approach is related to MudPad, it is also a special purpose system limited to keyboard entry.

Marquardt et al. introduced the haptic tabletop puck [12] that allows a one-point access to an additional layer of haptic information on a multitouch table. Even though it is possible to use several of these pucks simultaneously, each one occludes part of the interface.

Recently, Leithinger et al. presented with Relief [11] a low-cost height display using rods combined with top projection. Even though the system provides multi-point sensing and feedback, as a height display it mainly addresses visual perception.

Block et al. introduced touch-display keyboards [3], unmarked keyboards supplemented by top-projection and a camera to detect touch positions. Such a physical keyboard has excellent tactile feedback, but it also restricts interaction to discrete key-based input.

Hook et al. [9] presented a system using ferrofluid for multi-touch sensing. While this approach is similar in construction to MudPad, it is an input device without active haptic feedback.

Bau et al. [1] recently presented TeslaTouch, a touchscreen using electrovibration. The device produces a subtle tactile feedback when a user moves his fingertips over the surface.

USAGE SCENARIOS

Before diving into the specifics of the proposed design, we introduce some possible scenarios to illustrate the benefits of localized active haptic feedback.

Virtual Keyboard

Adding feedback to virtual keyboards (like Figure 2a) is probably one of the most intuitive applications for localized tactile feedback. Virtual keyboards are in general much harder to use than physical ones as either constant visual attention or very accurate muscle memory is necessary to operate them [8, 4]. Being able to distinguish keys from each other and to feel whether intended input was recognized by the system would be an enormous improvement.

Music Sequencer

A special purpose application would be touch based music instruments or sequencer applications. The use of touch input for music creation became popular with the ReacTable [10] where tangibles provide physical controls. In general, musicians benefit from touch input devices (see Figure 2b) for music production purposes as they offer the flexibility of a digital recording environment without the need of special hardware for different kinds of controls. Being able to also feel the music in the controls or at the touch surface would further help musicians to stay ‘in touch’ with the music they are producing.

Secure Touchpad Input

The idea of a secure touchpad [2] (see Figure 2c) is to allow users to enter sensitive information on a touch input device while being protected against shoulder surfing. The haptic sense is a private channel where physical contact is necessary to receive information. A secure touchpad therefore gives tactile feedback to tell a user that, e.g., the next entered character will be ignored and should be chosen at random.

SYSTEM DESIGN

MudPad consists of four layers as shown in Figure 3 with the bottom layer *(d)* being an array of electromagnets similar to the Actuated Workbench [13]. Each magnet can be addressed individually to build up a localized magnetic field. Directly

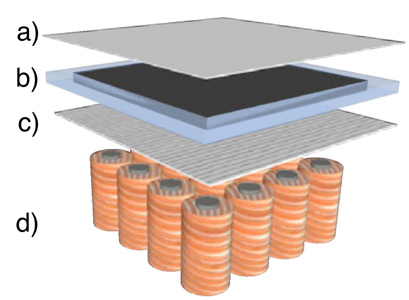


Figure 3: Exploded view of system design: a) latex touch & projection surface, b) MR fluid pouch, c) resistive touch input pad, d) array of electromagnets (projector omitted in this schematic).

on top is a thin resistive high-resolution touch surface *(c)* ideally capable of multitouch sensing (e.g., an UnMousePad as proposed by [15]). The touch surface is covered by a thin (3–5 mm) fluid-filled pouch *(b)* with flexible top and bottom sheets so that pressure from user input can be detected by the touch surface. A white latex cover *(a)* is used as a top-projection surface.

Magnetorheologic Fluid

The liquid inside the pouch *(b)* is a smart fluid, i.e., its physical properties can be controlled. For our purposes we use a magnetic fluid the viscosity of which can be linearly controlled by applying a magnetic field. Viscosity levels range from fluid like water (Figure 4a) to viscous like peanut butter (Figure 4b). The liquid is a suspension of a carrier fluid

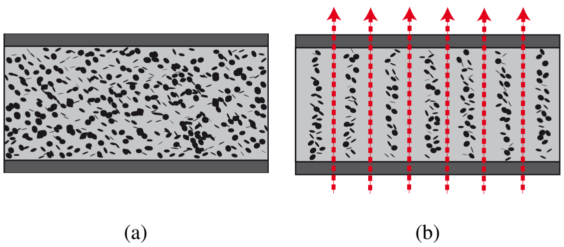


Figure 4: Magnetorheologic fluid under the influence of a homogeneous magnetic field. (a) Off state: free flowing particles within the carrier fluid, i.e., low viscosity. (b) On state: particles arrange along the flux lines, i.e., high viscosity.

(we use glycerin as it is chemically compliant with the latex cover) and free flowing carbonyl iron particles[1] sized 3μm in average. When a magnetic field is applied, the particles align in chains along the flux lines, thereby increasing the viscosity—the fluid stiffens. Removing the field allows the fluid to return to its original state.

Actuation

Particle alignment and dealignment in the MR fluid happen very quickly. Typical response times are less than 2 ms. This allows us to locally actuate the fluid using frequencies up to 600 Hz covering the full range of human tactile perception (highest sensitivity for vibrations at about 250 Hz, see, e.g., [5]). Since arbitrary waveforms can be used, we are able to create a rich set of dynamic haptic textures at any location on MudPad in real-time. Also, different static levels of stiffness can be achieved by applying a pulse width modulation (PWM) signal at a much higher frequency. This way, the fluid's viscosity can be linearly controlled via the PWM duty cycle without incurring any perceivable vibration.

Electronics used to control the magnets

As we mentioned before a reasonably strong magnetic field is necessary to actuate the fluid. Accordingly each of the custom made magnets draws up to 400 mA at 35 V and is controlled by a motor driver IC (ST L6219).

Limitations of the approach

As the fluid contains iron particles it is opaque. Therefore, we can only use top projection for now. A thin and highly flexible display could be used instead of the latex cover but we are not aware of a currently available, suitable product.

Touch Input Technology Most of todays touch screen devices use capacitive sensing. While this technique is very reliable, it cannot be used for MudPad due to the metallic particles in the MR fluid. Also, we want to offer the user a way to haptically explore the interface, requiring a touch technology that can distinguish between a 'hover state' with haptic contact, and active inputs. By using a resistive technology, we allow for user to lightly rest the fingers on the surface and just explore the tactile feedback without invoking an event, or push down to indicate an action. Due to the fluid pouch the force necessary to trigger an event is higher than on capacitive screens but comparable to the force necessary when using a FTIR based touch screen. Our current prototype uses a plain 4-wire resistive touch input pad that can be easily exchanged for a multitouch pad such as an UnMousePad [15] or a pad as offered by Stantum[2].

Resolution The output resolution of MudPad is primarily determined by the size and number of the magnets used to activate the MR-fluid. The magnets have to be strong enough to line up the particles, hence we used relatively large magnets (⌀ 2 cm) for our prototype. This limited the number of magnets for a 10″ tablet to an array of 12 by 7. Although this means that the sources of the magnetic field are sparsely distributed, creating haptic feedback at arbitrary positions is still possible by superimposing fields of multiple magnets (cf. [16] for details on calculating magnetic forces for specific locations). We call any of these groups of magnets that are responsible for a given location the *actuation domain* of that location.

Note that for a single finger per actuation domain the output resolution is still only bounded by the input resolution since the haptic feedback signal in the domain's area will vary according to the exact position of the finger. If, for example, several UI elements with different feedback patterns are placed within a single actuation domain the feedback of the domain changes when the user moves her finger from one element to another.

We cannot yet, however, trivially isolate the effect to such small areas as a fingertip like it would be desirable. Two fingers placed right next to each other at the same time would thus receive a mix of their respective haptic feedback signals.

FEEDBACK CHARACTERISTICS

The different actuation signals compiled in Table 1 can be used as building blocks when creating different tactile patterns by combining them with varying parameters. Possible parameters are duty cycle, frequency, and uniformity to influence stiffness, texture, and roughness.

Dynamic variation of parameters even allows to simulate the haptic impression of interacting with tangible UI elements, e.g., pressing a mechanical button. While the latter allows for rich feedback on virtual keyboards, varying the viscosity can be used to implement a typo prevention algorithm as proposed by [7] by stiffening unlikely keys and thereby making

[1] BASF CEP SQ carbonyl iron powder.

[2] www.stantum.com

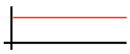
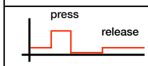
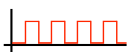
Magnet Signal	Fluid State	UI Mapping (System View)	UI Mapping (User View)
	stiff	inactive areas, i.e., no user input possible	prevent interaction
	quick on/off transition	active UI elements, e.g., buttons	acknowledge user input
	(rapidly) changing vibrating	active areas, demanding user attention	communicate system processes, e.g., progress bar
	fluid	active areas, allow Interaction	neutral

Table 1: Elementary building blocks from which feedback patterns can be constructed.

it harder to press them.

Due to the fast response of the fluid, the lower frequency part of audio signals can be 'played back' by the magnets, letting the user feel the rhythm of the music as described in one of the usage scenarios above. Thus, with MudPad, each slider in a music sequencer could play the signal it controls.

As a user's fingers can rest on the surface we can also use subtle ambient patterns to convey context information. Indicating running background tasks such as downloads or making the current system volume perceptible on media playback controls are just some possible examples.

FUTURE WORK

We are currently designing user tests to formally evaluate the system. We are also planning to investigate user preferences for mappings of tactile parameters and learning efforts to distinguish different widgets by touch. For example, we are interested to learn if it is possible to haptically distinguish an *OK* button from a *Cancel* button.

CONCLUSION

We proposed a haptic overlay for a resistive touch surface that is capable of rich tactile feedback. It uses controlled magnetic fields to effect the local viscosity of a smart fluid, simulating different haptic textures. This way, the system is able to produce localized actuation signals covering the full frequency range of human perception and to vary the softness of the surface. The ability to produce this kind of localized multi-point actuation allows users to explore an interface by touch and opens up new possibilities for feedback design.

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