Modular and Deformable Touch-Sensitive Surfaces Based on Time Domain Reflectometry

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ABSTRACT

Time domain reflectometry, a technique originally used in diagnosing cable faults, can also locate where a cable is being *touched*. In this paper, we explore how to extend time domain reflectometry in order to touch-enable thin, modular, and deformable surfaces and devices. We demonstrate how to use this approach to make smart clothing and to rapid prototype touch sensitive objects of arbitrary shape. To accomplish this, we extend time domain reflectometry in three ways: (1) *Thin:* We demonstrate how to run time domain reflectometry on a single wire. This allows us to touch-enable thin metal objects, such as guitar strings. (2) *Modularity:* We present a two-pin connector system that allows users to daisy chain touch-sensitive segments. We illustrate these enhancements with 13 prototypes and a series of performance measurements. (3) *Deformability*: We create deformable touch devices by mounting stretchable wire patterns onto elastic tape and meshes. We present selected performance measurements.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces: Input Devices and Strategies, Interaction Styles.

Keywords: touch sensing, time domain reflectometry, TDR, wearable, deformable, input, capacitive sensing.

General terms: Design, Human factors.

INTRODUCTION

Traditional touch sensing technologies, such as capacitive [4] or resistive sensing [16], require at least *O(n)* cable connections to drive an *n* x *n* sensing grid [1]. Large numbers of cables, however, result in thick and inflexible connections. This becomes an issue when touch-enabling deformable objects, such as smart clothing [20], where deformability, modularity, and form factor are essential.

In this paper, we propose adapting touch sensing based on *time domain reflectometry* (*TDR* [22]) to overcome these limitations. In TDR, a controller injects an electric pulse into a cable. As the impulse travels down the wire, any defect along the cable causes a partial echo, a pulse of reduced amplitude that travels back to the controller.

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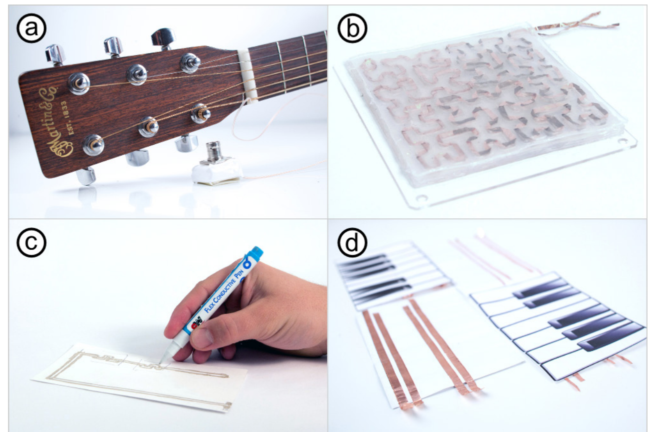

Figure 1: We use time domain reflectometry to touch-enable new devices and form factors including (a) *very thin* objects, such as guitar strings. (b) We use fractal wire layouts to create touch sensors that are *flexible* and *stretchable*. (c) Using conductive ink, we allow users to *sketch* touch-sensitive interfaces. (d) By daisy chaining wires, we create *modular* touch-sensors, such as this paper piano.

This echo allows computing the location of the defect: we obtain the distance to the defect by dividing the time delay between injection and echo by twice the speed of electricity in cables (50-70% of the speed of light, depending on cable type).

While TDR was originally used to diagnose defects in electric cables, engineers discovered as early as 1964 that TDR also responds to a cable being *touched* [22]. A recent US patent [6] proposes using the effect to touch-enable keypads by routing a cable in a serpentine layout behind the buttons. In a recent poster submission [15] Huang et al. propose using the same design on a printed circuit board to touch-enable a letter-size touchpad.

We argue that the possibility of sensing touches along a single pair of wires makes TDR a promising candidate for ultra mobile/wearable devices and smart clothing. To enable this, we present three extensions to TDR, which together allow for a range of new device designs, including the ones shown in Figure 1.

(1) *Thin:* We demonstrate how to use time domain reflectometry on a single wire. This allows us to touch-enable thin metal objects, such as guitar strings. (2) *Modularity:* We present a two-pin connector system that allows users to daisy chain devices. (3) *Deformability*: We create deformable touch devices by mounting fractal wire patterns onto

elastic tape and meshes. Then we demonstrate how to use TDR to allow users to rapidly prototype touch sensitive objects.

We also present selected performance measurements. Using a reflectometer built in 1975 (*Tektronix 1502*), we obtain a precision of one millimeter and a latency of 100ms. Using parallel traces of copper foil, we obtain a signal-to-noise ratio of up to 27 dB, which is similar to common capacitive touchscreen controllers. Applying an adaptive moving average filter we obtain a signal-to-noise-ratio of 37 dB without affecting responsiveness (the filter does introduce lag when recognizing dragging though; we thus recommend the filter for touch recognition only).

While today's high-resolution reflectometers are bulky and expensive, we anticipate that the required functionality may soon be achieved using affordable off-the-shelf time-to-digital converter ICs.

RELATED WORK

The work presented in this paper is related to touch sensing, smart clothing, and time domain reflectometry.

Touch Sensing on Curved or Flexible Surfaces

Today, the two predominant touch-sensing technologies are capacitive [4] and resistive [16] technologies. Unlike resistive touch sensors, capacitive sensors activate even on light touch. According to Dijkstra et al. [8], for example, operating surfaces based on the resistive *Touchco* requires a significant amount of force. Grasping capacitive *Displax* film renders a large part of the surface insensitive to touch [8].

Most touch-sensitive surfaces in use today are planar. However, interaction on non-planar surfaces has gained interest among researchers [25]. Flexible touch-sensitive films, such as *Displax* and *Touchco*, can be bent along a single axis only. Custom designs based on capacitive sensors allow touch-enabling arbitrary shapes, but their shape cannot be modified later [34]. Also, connecting individual sensors to the controller results in a large number of connecting wires [32].

Also optical touch sensing methods (e.g. [21, 37]) require a number of optical fibers proportional to the desired resolution. Range finders (e.g., *SideSight* [5]) allow sensing touch using a compact form factor, but strongly convex shapes are subject to occlusion. Sensing based on microphone arrays (e.g., *Skinput* [12]), allows users to tap, but offer only limited support for dragging.

Wearables and Smart Clothes

In wearable computing, touch-enabled fabrics allow users to interact anywhere. To allow for optimal integration, touch sensors should to be as compliant as the fabric. So far, there are two layout approaches for touch-enabling fabric: (a) a matrix of orthogonally overlapping conductive strips separated by a non-conductive insulator [14], or (b) arrays of distinct sensors [23]. *Pinstripe* by Karrer et al. [17] detects pinching and rolling of cloth between the fingers by scanning for connections between parallel conductive threads sewn into the fabric. Wagner et al. [35] propose an 'electronic skin' where small rigid subcircuit islands are connected by stretchable thin-film conductors and embedded in a silicone sheet.

Cord input [28] allows using a cord as an input device. However, the membrane potentiometers used in this prototype offer only single-touch tracking and are both expensive and susceptible to bending and force.

Time Domain Reflectometry

As discussed earlier, TDR works by sending an electric pulse along a wire. In reality, TDR uses two wires: One wire is connected to the pulse generator and measurement circuit; the other wire is connected to ground, thereby coupling the sensing wire to ground with a constant capacitance. At discontinuities, where the *characteristic impedance* changes along the cable, a part of the pulse is reflected back to the measuring device.

Such changes in characteristic impedance are caused by changes in the resistance, the inductance, or the capacitance of the wire pair. While initially developed to test cables, this has allowed TDR to also be used to measure soil humidity and detect soil movement [19], to locate microscopic defects in integrated circuits [11], and to recognize strains and fractures in buildings and bridges [31].

Engineers distinguish three termination types of TDR [33]. At the end of the cable, the pulse is reflected at *open ends*; the pulse may disappear when wires are terminated with *matching impedance*; or an inverted pulse is reflected when ends are *short circuited*. As the reflectometer has high impedance inputs, a pulse in a cable with open ends may travel back and forth several times, causing erroneous detection of faults.

In this paper, we use a time domain reflectometer that injects a short electric pulse into the cable. Some reflectometers use a step function instead. While the resulting signal looks differently, it contains the same information.

UNDERLYING PHYSICS & DESIGN IMPLICATIONS

In the remainder of this paper we present several circuit designs for TDR touch sensors. The functioning of these designs relies on optimizing a range of parameters, such as wire thicknesses, minimum distances, and dimensions of insulation layers. Since the aforementioned related work [6, 15] lacks a description of the underlying physics, we provide one here. Throughout the paper, this discussion helps us explain which designs work best and why.

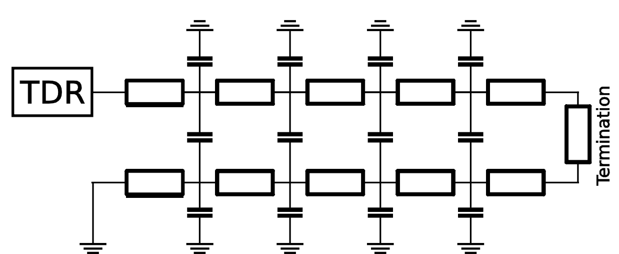

Figure 2: Lumped circuit model of wire pair connected to a time domain reflectometer. Each wire is capacitively coupled to the environment and to the other wire.

Underlying Physics

Figure 2 shows a lumped circuit model of the wire pair. Each wire can be modeled as a series of resistors with very low resistance. In addition, each wire segment forms a capacitor with the parallel wire segment. If the wire diameter, the distance between wires, and the properties of the dielectric between the wires are constant along the cable, the capacitance values between the segments are equal.

TDR touch sensing relies on detecting capacitance changes caused by conductive objects near the wire pair. The user's finger capacitively couples to each wire and thus creates a capacitive shunt between the wire pair. This increases the capacitance at the touch location, causing a partial (inverted) reflection of the TDR pulse (Figure 3). The larger the capacitance change, the greater the amplitude of the reflection. This effect is somewhat similar to *transmit mode* electric field sensing [30], used e.g. by *DiamondTouch* [7]. This allows for simultaneous multi-touch sensing, because only a part of the pulse energy gets reflected back at each touch location.

While it is also possible to measure cables with junctions using TDR, common approaches require simultaneous measurements from multiple ends to distinguish between reflections from different branches [9]. In this paper, we limit our discussion to the case of a single continuous wire pair without junctions.

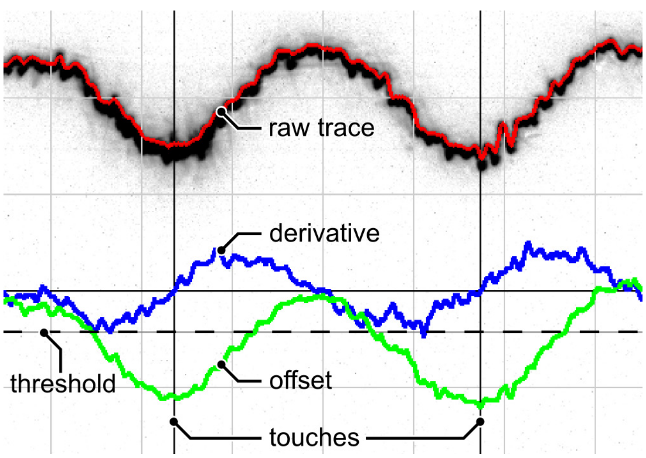

Figure 3: Our approach allows detecting multiple touches on a cable: In this TDR trace two touches were detected by locating negative peaks in the raw trace that also form a local minimum, i.e., derivative is zero.

Implications for Device Design

The principles discussed above have implications for device designers. By increasing the relative change in capacitance effected by a touch, we can enhance touch sensitivity. This is the case …

(1) with increasing distance between both wires, which also decreases the capacitance between wires,

(2) with decreasing distance between wires and the touching finger, and

(3) with increasing size of the contact area between finger and wire.

This means, for example, that parallel strips of copper foil (Figure 4b) are more sensitive to touch than round wires (Figure 4a). We can also increase touch sensitivity by using wires spaced out more widely—up to a maximum of a human finger width, after which point users cannot make contact with both wires at the same time anymore. However, there is a tradeoff between cable width and flexibility, which needs to be evaluated depending on the application.

Coaxial cable (Figure 4c) is barely touch-sensitive, because the finger causes barely any capacitive coupling between inner wire and shield. Deforming a coaxial cable locally, however, changes its impedance, generating a weak, wide echo.

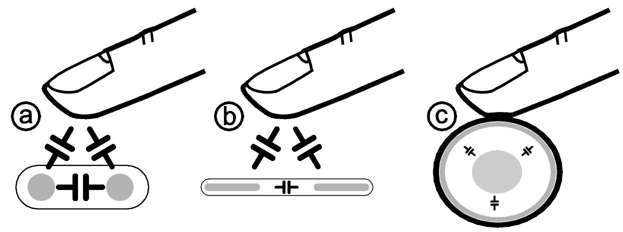

Figure 4: Capacitances between finger and cable: (a) two-wire cable, (b) wide copper traces or foil, and (c) coaxial cable.

Another adverse effect is crosstalk between a wire pair that runs parallel to or crosses another wire pair. A common countermeasure is to employ *coplanar waveguides*, where the active wire is shielded by *two* parallel grounded wires instead of one [15]. Also appropriate spacing of parallel cables mitigates crosstalk. We suggest a spacing of at least twice the distance between the wire pair.

Based on this understanding, we can now discuss our prototypical implementation.

OUR IMPLEMENTATION 1975

The need to process electrical signals in the pico-second range makes reflectometers still comparably expensive to date. However, reflectometers with millimeter resolution have been in use for decades. We conducted the research presented in this paper using a used Tektronix 1502 Reflectometer built around 1975 (Figure 5), which we bought online for €300. The reflectometer was calibrated in 2010.

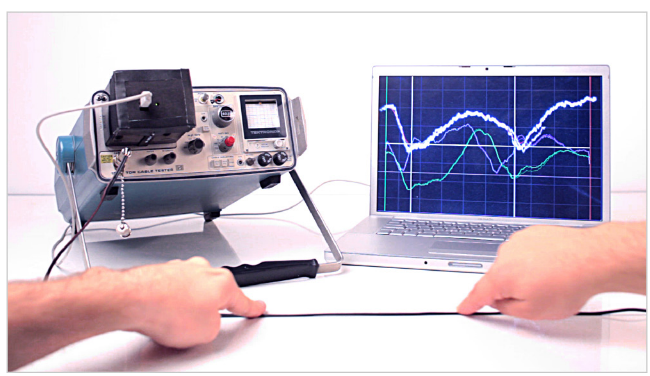

Figure 5: Our experimental setup is based on a *Tektronix 1502* reflectometer built in 1975.

The device offers no digital output and instead graphs the signal on its CRT screen. We bypass the lack of a digital output by capturing the CRT screen using a Point Grey FireFly FireWire camera (640x480px, 20fps). We then reconstruct the graph from the camera image using OpenCV and NumPy by locating the brightest pixel in each column. We extract the delta between current and untouched state by applying background subtraction. Finally, we smooth the signal using a weak low-pass filter over each trace and apply an adaptive moving average filter.

Adaptive moving average (AMA) filters are moving average filters that adjust sample weights dynamically [38]. Our implementation weights samples whose value changes a lot between frames stronger than others. Consequently, the filter smoothes low-amplitude noise strongly, while preserving rapid changes, as they occur during touch events or when users are dragging. The main benefit of AMA filters is therefore that they offer low latency for fast movements while keeping noise low for slow movement.

The screen shown in Figure 3 illustrates how our prototype senses touch. The system reports touches at negative peaks, i.e. wherever the signal (green line) drops below a certain threshold (gray horizontal line) and the first derivative is zero (blue line). In the shown example there are two such points and the system indicates their locations on the cable using vertical lines.

As the Tektronix CRT screen shows only a limited time window, we can see only a limited distance range of the cable. Zooming all the way in, we can capture a 21cm cable segment with a theoretical maximum resolution of 0.3mm. On the other end of the zooming range, we can capture a 400m segment with a maximum resolution of 60cm. Modern digital reflectometers, such as the *Mohr CT100* series, suffer neither of these limitations.

Using this experimental setup we have touch-enabled ultra-thin objects, modular devices, and stretchable 2D surfaces.

ULTRA-THIN TOUCH SENSORS

In this section, we demonstrate how to touch-enable cables and wires and in particular how to do so using a single wire.

Overloading Touch onto Everyday Objects

Touch-enabling objects that already contain a wire pair requires only little effort; we simply overload touch sensing onto the existing wires pair.

In one instance, we have retrofitted a pair of off-the-shelf headphones with TDR-based touch sensing. This design allows users to pause, play, and skip tracks by squeezing the respective locations on the headphone cable; users adjust volume by sliding fingers or the entire hand along the cable.

We implemented this by connecting the left and right channels of the headphone to the reflectometer. The ground wires, which are connected to the headphone plug, were not used for sensing. We found the capacitive coupling caused by the common ground wires to decrease touch sensitivity only slightly.

We obtained best results with headphones that use standard "ribbon" cables, i.e., two unshielded wires located next to each other. Coaxial cables worked as well, but as discussed earlier were much less sensitive, because touches had less of an effect on local capacitance. The two wires of the cable we used were 2.5mm apart, which worked well.

Another limitation of our outdated reflectometer is that it is not capable of testing live wires (its pulse generator might can get damaged even by small currents). To protect the device, we therefore did not connect the headphone to an actual audio source in this demo. More modern reflectometers do not suffer from this limitation.

Application to Metal Objects—Extension to Single Wire

As mentioned above, TDR generally uses two parallel wires. This works fine for most applications, such as the headphones. However, when we want to touch-enable individual wires, such as a guitar string, the two-wire approach reaches its limit.

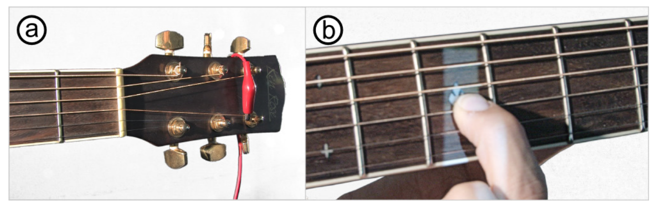

Figure 6: (a) We have touch-enabled a guitar string of an otherwise unmodified acoustic guitar. (b) In the shown demo application, the touch location is highlighted in real-time using a projected white bar.

To address this, we have developed a TDR version that locates touch along a single wire. We demonstrate this by touch-enabling a guitar string (Figure 6). Applied to all strings, this approach could be used to capture the user's grip patterns while playing a guitar without applying any modifications to the instrument itself.

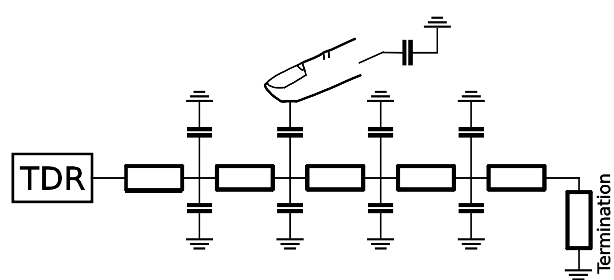

Figure 7: A lumped circuit model of a single wire touch-enabled using TDR. Touching the wire increases its capacitive coupling to the environment at the touch location.

The lumped circuit model in Figure 7 illustrates the underlying physical effect we exploit. A single wire is capacitively coupled to ground via the environment. This coupling is very weak, however. A finger touching the wire will increase the capacitive coupling, increasing the characteristic impedance at the touch location. This works for both bare and insulated wires. Grounding the wire's end prevents spurious touches and the touching object needs to be grounded or offer good capacitive coupling to the environment. Overall, this makes the properties of single-wire TDR similar to those of traditional *loading mode electric field sensing* [30].

Single-wire TDR is subject to two limitations. As most of the pulse gets absorbed by the touching finger, only the touch location closest to the reflectometer can be determined reliably. We therefore modified our algorithm so as to detect only the first touch (Figure 8). Finally, the single-wire approach only works as long as there are no large conductive objects close by, which prevents certain applications, such as touch-enabling the frames of glasses.

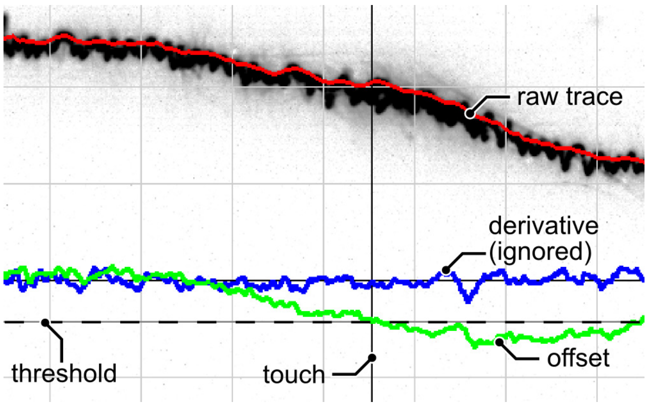

Figure 8: With single-wire sensing, our system detects touch at the location where the characteristic impedance drops below a threshold. Since the signal continues to drop after the touch location, we do not consider the first derivative in single-wire sensing.

MODULAR TOUCH SENSORS

The above examples are exceptions in that they readily offer a set of wires to appropriate. In the more typical case, we touch-enable objects and clothing by applying a touch sensitive strip or sheet.

Tear-Off, Adhesive Touch Strip for Prototyping

To allow users to touch-enable arbitrary objects quickly, e.g., when prototyping touch sensitive devices, we created the *touch tape* shown in Figure 9. It consists of masking tape with two embedded strips of copper foil. The adhesive coating allows users to apply the tape to any flat or curved surface. The tape roller helps users obtain the desired amount.

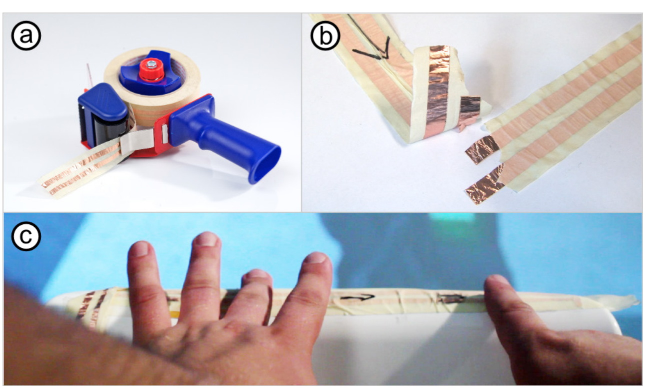

Figure 9: (a) *Touch tape* is masking tape with embedded copper traces. (b) Users can join multiple strips by connecting the trace pairs. (c) We used this setup to control a first person shooter and a racing game in an impromptu gaming session. Note the bimanual use.

Application designers link touch locations to actions by entering a calibration mode, tapping an area on the tape, and then picking the action to be executed on the computer. To give users a sense of where to touch, the application designer may also mark locations or draw widgets such as buttons or sliders onto the tape.

Using thin strips of copper foil with a distance of about 1cm, we minimize capacitance between strips and maximize capacitive coupling to the finger, resulting in a better signal-to-noise ratio. Therefore, the shown parallel strip design is so sensitive that it allows sensing a hovering finger up to about 1cm above the strip. This allows detecting and locating gestures before the finger actually touches the tape (similar to e.g., *PreSense* [24]).

Daisy-Chaining TDR Touch Sensors

Touch tape allows users to (re)assemble multiple pieces of tape into a larger piece by pressing one wire pair onto the other (Figure 9b). This allows creating larger touch-sensitive surfaces or changing their configuration.

As a first proof-of-concept prototype, we applied parallel strips of copper foil to paper piano tiles (Figure 1b). The prototype allows users to add additional octaves by attaching additional 12-key tiles to the end of their keyboard.

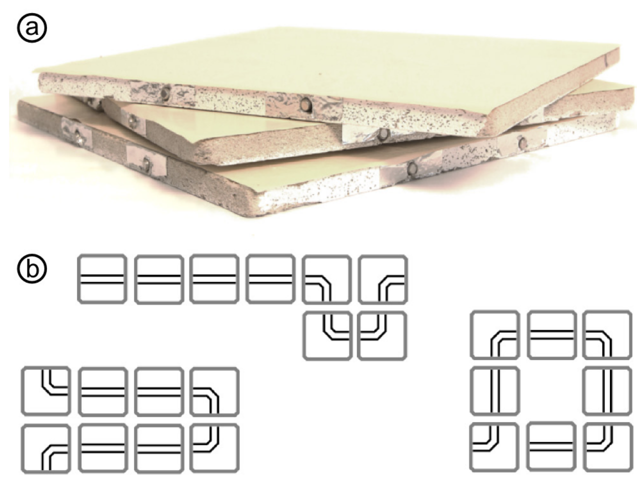

Figure 10: (a) Each floor tile bears electric contacts and magnetic connectors on each of its four sides. The magnets help users connect tiles quickly. (b) Three example layouts created using the same eight floor tiles. Only the first tile needs to be connected to the reflectometer.

We have obtained best sensing results using a short circuit termination. Alternatively, we have achieved less accurate but acceptable tracking using “open ends” (i.e., no termination) which saves users the effort of attaching the terminator.

Floor Tiles

Figure 10 shows a set of eight floor tiles measuring 30cm x 30cm each. Each tile contains a pair of straight or curved metal strips. This design allows users to assemble differently shaped touch-sensitive surfaces. Magnetic connectors hold the tiles together and act as conductive bridges between tiles.

Cable Identifiers Allow Auto-Configuring Device Sets

To allow the system to recognize how a set of modular segments is currently reconfigured, we provide each segment with a unique arrangement of "markers". Markers are simple pieces of copper foil wrapped around the cable segments at object-specific intervals. In the signal trace, markers show up as dents. This allows the system to identify cable segments attached to the reflectometer and, if we avoid symmetries, to determine which side of the segment is connected.

A cable segment's marker pattern remains largely visible when segments are daisy chained. We have exploited this in order to distinguish different 'devices' plugged into a headphone jack (Figure 11). In the shown example, markers were placed at multiples of 14 cm along the wire.

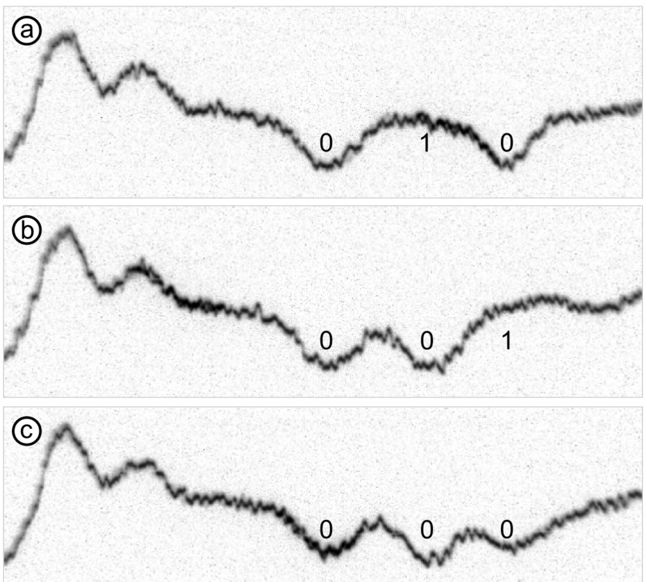

Figure 11: We identify cables by unique patterns of discontinuities. These raw traces belong to three different modules, each of which was marked with a different 3-bit sequence. Binary values are encoded by wrapping short strips of copper foil around the wire pair.

TOUCH-ENABLING DEFORMABLE 2D SURFACES

Touch-enabling surfaces using TDR requires covering the area with the wire pair in a space-filling pattern. Replacing the serpentine pattern proposed by Huang [15] (Figure 12a) we use a Hilbert Curve layout [13] in most of our prototypes (Figure 12b). In our prototypes, we use Hilbert Curves with mitered corners instead of rounded or straight corners. This avoids signal reflection at corners and keeps the diameter—and thus the impedance—of the trace approximately constant.

Hilbert curves offer several benefits:

(1) They offer consistent touch resolution in x and y directions, whereas serpentines offer high resolution along the main direction of the wire, but not perpendicular to it. (2) Hilbert curves ensure that successive wire segments are also close together on the surface. This limits the x/y error resulting from sensing inaccuracies along the wire. (3) Hilbert Curves allow for better differentiation between adjacent touches, as the probability of two adjacent touches falling onto the same wire segment is lower than with the serpentine layout. (4) Hilbert Curves support modularity. Since they are self-similar, users can (repeatedly) cut a Hilbert Curve in half, always resulting in a functional touch-sensitive surface. Similarly, tiles made from Hilbert Curves can be combined to form larger touch-sensitive surfaces. (5) Hilbert Curves result in stretchable layouts, as we discuss in the following section.

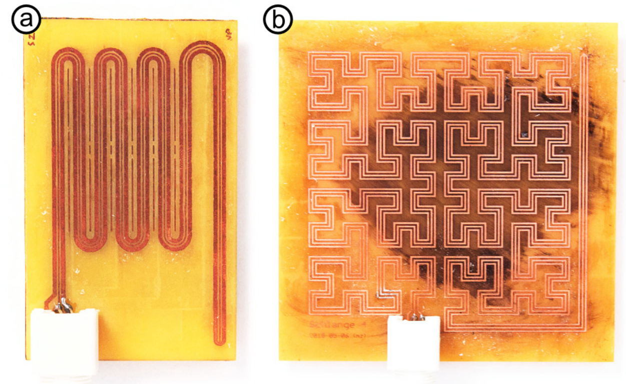

Figure 12: We touch-enable surfaces not (a) using serpentines but (b) using Hilbert curves. In both prototypes, traces are spaced 5mm apart, so that a finger touches at least two different locations along the trace.

Stretchable Strips

A serpentine layout also works fine, as long as the touch-enabled object is stretched along only a single dimension. Figure 13 shows a prototype of a stretchable wristband that we have used to temporarily touch-enable arbitrary objects of different sizes. It is made of conductive thread embedded into a stretchable mesh material.

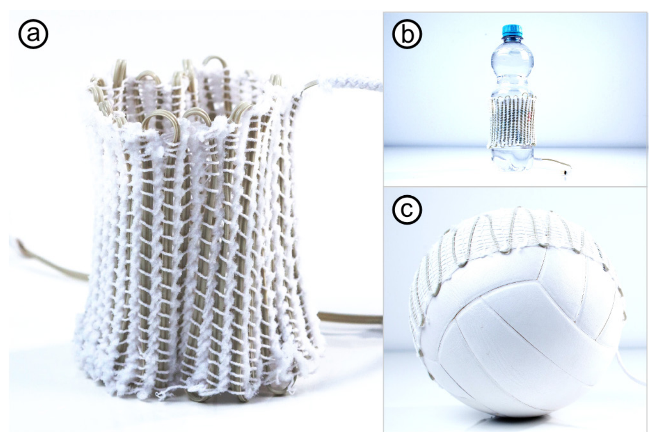

Figure 13: Embedding a cable laid out in a zigzag pattern into a strip of stretchable mesh allows mounting the strip to objects of different sizes.

Note how spatial resolution decreases when the mesh is being stretched, and increases when it is released.

Figure 14 shows a similar prototype, only this time we used conductive thread embedded into strips of a soft silicone support material. When the strip is stretched, the thread is pulled to its full length; upon relaxation, the thread crinkles.

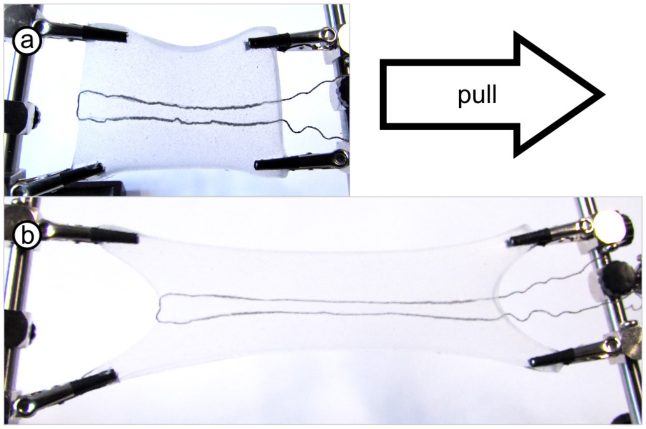

Figure 14: Conductive thread embedded into a silicone strip: (a) relaxed, (b) stretched

Figure 15 shows a touchpad based on the Hilbert Curve; unlike the serpentine designs, it is stretchable in both x and y.

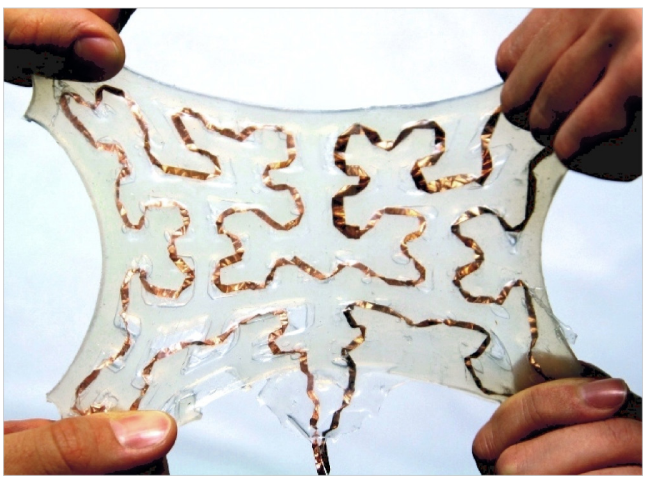

Figure 15: Wire layouts based on the Hilbert Curve are stretchable in x and y direction.

In addition to sensing touch, the design shown in Figure 15 also detects pressure. We achieved this by embedding *two* Hilbert Curves made from copper foil into the silicone, using a technique proposed by Slyper et al. [29]. The two copper foil layers are separated by a thin silicone layer. When a finger applies force to the pad, the two copper layers are pressed together, locally increasing their capacitive coupling. This shows up in the TDR trace. Again, the Hilbert Curve is a beneficial layout, as deformations stay locally confined.

Sketching Touch Sensors

To provide even more flexibility when rapid prototyping interfaces using TDR, we have created interfaces using conductive ink (*Circuitworks CW2200MTP pen*). As illustrated by Figure 16a, this approach allows users to touch-enable an arbitrary surface by drawing parallel conductive traces on a sheet of paper and connecting these to the reflectometer. This allows sketching arbitrary touch-sensitive shapes, allowing designers to create exactly the shapes required by the application (Figure 16b). As we only track impedance changes over time, minor fluctuations in line width and spacing have no effect on sensitivity. Actions can be mapped to touch locations using the same approach as described for the masking tape.

The resulting widgets continue to work when users touch the backside of the paper. We exploit this in order to achieve better affordance: we let users flip the paper around and draw or print GUI widgets that explain the desired interaction onto the sheet. The result is an interactive paper prototype.

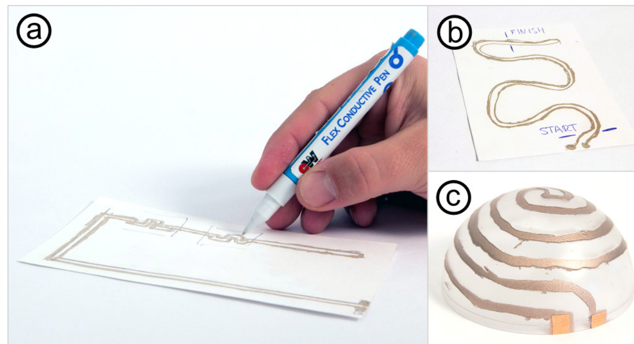

Figure 16: (a) Sketching a TDR touch interface using conductive ink. (b) This allows creating ad-hoc UIs like this path-following game. (c) Using conductive spray paint and hand-cut stencils, arbitrarily shaped objects can be touch-enabled.

Conductive paint is also well suited for making non-planar surfaces touch-sensitive, such as the one shown in Figure 16c. This version was created using a stencil, offering additional precision: (a) Draw rough traces onto the surface using a sharpie pen, (b) apply a thin silicone layer, (c) cut parallel lines into the silicon, following the drawn trace. (d) remove the silicone from the traces, (e) spray-paint the surface with conductive paint (*CRC Industries EMV35*), and finally (e) pull off the remaining silicone.

Using appropriate printing techniques [36], touch-sensitive paper based on TDR might also be mass-produced, e.g. using transparent indium tin oxide (ITO) for the traces.

MEASUREMENTS: SENSITIVITY, PRECISION, LATENCY

To obtain a better understanding of the accuracy and limitations of our approach, we conducted a series of measurements using the following five cable types.

A: flexprint ribbon cable, 0.8mm wide, 0.5mm gap, 0.5m

B: copper foil traces, 8mm wide, 10mm gap, 0.5m long

C: copper foil traces, 20mm wide, 20mm gap, 0.5m long

D: ribbon cable, ∅0.4mm, 0.9 mm gap, length 2.5m long

E: loudspeaker cable, ∅1.5mm, 1.2mm gap, 11m long

We report amplitude changes in a TDR trace in units of mρ (millirho). Here, $\rho = V_{reflected} / V_{pulse}$, i.e. the relation between the amplitudes of reflected pulse and injected pulse. As our reflectometer emits 300 mV pulses, 1 mρ $\triangleq$ 0.3 mV.

Figure 17: Cable types tested in our evaluation of sensor characteristics. A-C consist of flat copper foil traces, D and E use stranded wires.

Setup

Cables A to D were connected to the reflectometer using a 95cm cable with alligator clips. Cable E already had a BNC connector. Cables were laid out in a straight line, as shown in Figure 17.

For consistency, we simulated touches using metal weights placed across the cable's wires or traces: For cables A to C we simulated the touch of an index finger at 1 Newton using a 10g 28mm x 14mm x 8mm ferrite block. For cables D and E, we simulated a finger slightly enclosing the cable using a 10g 22mm x 26mm x 3mm steel plate. Weights were placed 250mm from the start of the cable/traces, which was located 1200mm from the reflectometer's input.

In order to reflect the noise levels *along* a cable segment, we calculated the root-mean-square (RMS, similar to standard deviation) changes in mρ for a single trace of 400px width. We then took the maximum noise level of 200 frames. For a discussion of signal to noise ratios, see Atmel's Touch Sensor Design Guide [1]. To give a better overview of the expected performance, we computed all results without filtering (respective first row) and using a 32 sample adaptive moving average filter (respective second rows).

For each cable we also recorded 800 samples of the touch location and determined the jitter. We also determined the minimum distance of adjacent touches by placing *two* weights on the cable, and decreased their distance until our algorithm started to merge the two peaks into one.

For determining the latency of our setup, we simultaneously captured the cable and our visualization on video with 25 frames per second. Touch latency was determined as the time between the finger first touching the cable and our software detecting a touch. Dragging latency is the time between the finger stopping at a defined point and our software reporting a touch at that point. The speed of slow touches (1Hz), fast touches (2Hz), slow dragging (12.5cm/s), and fast dragging (50cm/s) was defined by audible clicks at intervals of 1s and 0.5s. We measured 20 instances of each touch and dragging movement, ignoring a total of 4 instances where no touch was detected.

Results

Table 1 shows our results for the five different cable types. Overall, we got a very good signal-to-noise, especially for cable types B and C, which also provided very good precision. Touches were between 1-5mm (RMS) off.

Due to their plastics coating, cables D and E are significantly less sensitive. The minimum distance between touches consequently depends greatly on the cable type and is limited by the ~140ps risetime of the Tektronix 1502. Newer reflectometers like the Mohr CT100HF generate pulses with half the risetime. Note that the values in the table may be understood as lower bounds; touches with a force of more than 1 Newton or users holding the cable between two fingers result in much larger signal changes and thus better recognition.

In addition, we measured the impact of position (= distance from reflectometer) onto touch recognition with cable E in 50cm steps. We found amplitude to decrease in a linear fashion. At a distance of about 6m, the peak started to blend with the background noise. When grasping the cable with the whole hand, we were able to recognize touch at distances of up to 20m.

Cable	Resistivity Signal change on touch (mρ)	Noise RMS (mρ)	Signal to noise (dB)	Error offset RMS (mm)	Min. touch spacing (mm)
A	30	5	15		
		2	23	5	150
B	220	9	27		
		3	37	1	25
C	150	7	26		
		3	34	1	25
D	40	7	15		
		3	22	1	40
E	30	7	12		
		3	20	4	20

Table 1: Sensitivity and spatial resolution of five cable types. Second rows are results after applying a 32-sample adaptive moving average filter. $\rho = V_{reflected} / V_{pulse}$,

The base latency of our specific setup is about 120ms. This is the result of the 20fps update rate of the camera (on average 25ms delay) and about 100ms for transferring, buffering and processing the camera image. The delay is the result of our low-cost implementation; the reflectometer itself reacts instantly to changes.

For cables B and C, signal-to-noise-ratio without filtering is comparable to that of standard capacitive touchscreen controllers (25:1, [3]). For touches, latency is roughly comparable to standard touchscreen setups (80ms, [1]) and seems adequate for many applications [1]. We can stabilize the recognized touch location using the aforementioned filter without adding any latency.

For dragging, in contrast, only light or no filtering should be used. In earlier versions, we experimented with a 32-sample filtering window, i.e. a filter looking back 1.5 seconds. For slow dragging this added about 700ms of latency and about 300ms for fast dragging. Both were quite noticeable, which is why we do not recommend using the filter for dragging.

BENEFITS AND LIMITATIONS

The sensing approach presented in this paper offers four benefits:

1. Touch-enable non-planar and deformable objects. Since cables are compliant and robust, our approach allows us to create stretchable and deformable touch sensitive objects and bringing touch input to novel form factors.

2. In particular, the proposed approach allows *touch-enabling single-wire devices,* such as guitar strings, by switching to single-cable sensing.

3. Easy to prototype and rearrange. TDR allows chaining modular sensors without the need for additional controllers. Extensions require only additional cable; touch-sensitive fabric can be mass-produced inexpensively.

4. *Suitable for large installations.* While the prototypes shown in this paper were limited by our outdated reflectometer hardware, devices with higher power and digital interfaces allow applying the concept to installations of much larger scale. In particular, the concept allows tracking a large number of contact points using a single cable. While sensitivity decreases over distance, generating pulses with greater power and shorter risetime can counter this effect.

Limitations

1. Traditional TDR sensing is *susceptible to radio interference*. Mobile phones and other wireless devices (GSM, CDMA, 3G/UMTS, Wifi/Bluetooth) transmit in the GHz range, which can add noise to the TDR signal, reducing sensitivity. Future devices might evade interference by listening to traffic and actively waiting for pauses between packets for sensing. Additionally, TDR variants like spread-spectrum TDR are more robust against noise [10].

2. Time domain reflectometers with high spatial resolution are still *bulky and expensive*. Prices and size can be expected to drop with wider distribution, however. Another alternative might be to make the required hardware from off-the-shelf time-to-digital converter ICs, such as the *acam TDC-GP21*, which already offers a resolution of <50ps, which could enable TDR resolutions of <1cm.

CONCLUSIONS AND FUTURE WORK

In this paper we have demonstrated how to apply time domain reflectometry in order to create thin, modular, and flexible touch strips and surfaces for use in wearable computing and to allow rapid prototyping touch sensitive surfaces. Unlike existing solutions, all sensing takes place over a single pair of wires (or even a single wire), enabling a multitude of new shapes for touch-sensitive surfaces.

As future work, we plan to investigate touch sensing using *optical* TDR. We are also working on a low-cost TDR sensing circuit that can be used for applications where limited resolution is acceptable.

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NOTES & SUPPORTING DOCUMENTATION

Source code and further documentation can be found online at http://tdr.wikia.com

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