Sensing Touch Using Resistive Graphs

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ABSTRACT
In early design, instrumenting an object with touch sensing capability, especially one with complex surface geometry, can be problematic. In this paper, we show how resistive graph patterns—or *resigraph*s—can be used to quickly fabricate multi-touch sensors tailored to an object's shape. In very early ideation, resigraphs can be drawn using conductive ink. In later refinements they can be silk-screened or laser cut from off-the-shelf materials. A resigraph uses a commonly available microprocessor (e.g. Arduino), requires only three wires, and enables touch input on non-planar and non-developable surfaces.

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INTRODUCTION
Working with a three-dimensional interactive form adds complexity to the design process, making building an interactive object quite laborious. This puts greater demands on touch technology; sensors that were once flat must be repurposed to quickly fit around a broad set of curves, shapes, and topologies. Although an active research area exists [7,11,13,16,19,20,25], these novel touch solutions demonstrate a tradeoff between resolution and ease of use. As resolution increases, so does the copper, cabling, plastic, and the complexity of a sensor's software. Traditional touch sensors often have fixed dimensions and—unlike the expressiveness of clay, plastic, and wood sculpted by an industrial designer—cannot be tailored to an object's shape. These constraints limit the quick and timely exploration of a design idea, both tenets of Buxton's interactive sketching [5].

The material properties of touch sensors are critical when instrumenting and sketching spherical surfaces [3], deformable interfaces [17], and, in general, Organic User Interfaces [10]. Also important is how easily and often a non-technical designer can fabricate, interface, and employ a sensor to achieve a design goal [5]. Motivated by this problem, this paper reports on the use of resistive graph patterns to craft touch sensors across a broad set of curved, non-planar, and irregular shapes (see Figure 1).

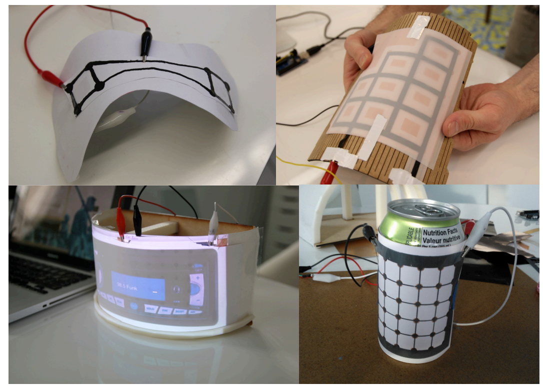

Figure 1. Using conductive ink, a resigraph with eight touch points is painted directly on an interactive sketch of a paper craft game controller (top left). The metal frame underneath (not shown) contacts a designer's hand and is used to acquire the touch signal. A similar pattern is laser cut from conductive vinyl for the deformable tablet sketch (top right). Note, the radio and coke cans reuse the same silk-screened resigraph (bottom).

A resistive graph pattern is a highly parallel and mesh-like circuit. It uses electrical resistance to distribute current such that the voltage at each junction is unique. The structure of these resistive graphs—which we refer to as *resigraphs*—can be modulated to form a touch sensor that is sampled using only three wires. This is an approach that allows touch sensors to be fashioned by a designer using pencil, silk-screening, or by laser cutting carbon-doped vinyl [14]. In early design explorations, a designer can paint a resigraph directly on a surface.

RELATED WORK - TOUCH SENSING
As commercial examples of capacitive and resistive touch sensors tend to be rigid, planar, made of glass, and require dense cabling, there are many new examples of touch interaction on non-planar forms [3,11,19,20,21,22,25]. We briefly discuss previous work concerning resistive graph techniques, non-planar touch input, smart textiles, computer vision, and, specifically, touch sensing that is geared for ideation and rapid prototyping.

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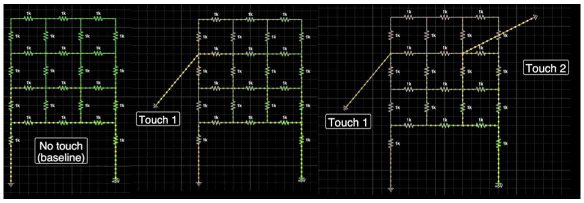

Figure 2. An illustrative resigraph with 1K Ohm resistive connections and the amount of current flow displayed (green indicates high activity). The baseline electrical behavior when no touches are present and +5V and ground are attached two corners (left). When a touch is present, a new parallel circuit is formed (middle). A second touch occurs, changing the circuit once again (right).

Resistive Graph Sensing Techniques

Using an analog-to-digital converter to measure a number of digital inputs is a known technique. A common example is the remote control found in earphones [9], a method that maps resistance values to play/pause, forward, and back buttons. This approach does not scale to more complex graph patterns or multi-touch input without more intricate cabling. R/2R ladders address these limitations using a binary ladder [6], yet achieving the necessary uniformity of edge resistance is problematic when painting with conductive ink or cutting from carbon-doped materials.

Resistive Touch Sensing

UnMousePad is an example of a multi-touch resistive sensor that senses non-planar touch input [20]. Doing so results in a large amount of circuitry and a fixed extent. While it uses a sheeted resistive vinyl, its dense dual-sided row and column circuitry trades precision for material flexibility. Its thin-film plastic covering makes it hard to wrap around some non-planar surfaces without falsely registering a touch event.

Capacitive Touch Sensing

Rekimoto's SmartSkin exemplifies the use of capacitive sensing to enable multi-finger sensing across an array of surfaces [18]. Sung et al.'s MTPen [22] wraps around the shaft of an artist's digital pen, enabling grip-based gesture commands. The shape of the capacitive foil, however, is fixed. Proposing a new industrial design for the pen, one that, for example, explores the pen's ergonomics by reducing its radius for a better grip, would require a new custom capacitive matrix and possibly even a new circuit design for its controller.

Smart Textiles

Touch-enabled textiles are constructed on highly deformable substrates that maintain their original pliability even after hardware integration. Pinstripe [13] senses pinching and rolling of a garment between the fingers by registering connections between parallel tracks of conductive thread. If necessary, a resigraph could be made out of conductive thread, but we focus on the use of a laser cutter or conductive ink as a time saving measure in early design.

Computer Vision

Although a depth-sensing camera can be used to sense touch on curved and static objects [7, 24], this requires wearing or positioning the camera, calibrating, and managing occlusions.

Prototyping Touch

A significant amount of work has been done to minimize the time needed to prototype interactive systems [1, 4,8,11,12,15,23,25]. Recently, touch solutions have emerged specifically for use in interactive sketching and prototyping. Tactiletape [11] is a variable length resistive tape used to sense one-dimensional touch on curved surfaces. Wimmer et al.'s [25] time domain reflectometry (TDR) is a novel technology that affords sensing multi-touch points on copper tape by recognizing touches as the echoes of a pulsed signal, a technique used to find faults in undersea cables. In both cases, covering a surface in these conductive tapes has practical time limitations, particularly during intense iterations when a surface must be repeatedly re-instrumented.

Customizable Touch Sensors

To allow greater customizability in touch sensor design, Midas offers a software and hardware toolkit that supports the design, fabrication, and programming of custom capacitive touch sensors for physical prototypes [21]. Though the motivation behind Resigraph, to fluidly enable touch sensor construction, is closely aligned to Midas, a resigraph uses a resistive sensing media instead of capacitive, changing the source materials that can be used to make a touch sensor. Second, resigraph only requires three wires, even as the number of touch points increase. Midas's capacitive approach, on the other hand, requires cables to run to each touch area.

This dense cabling is also the case with Olberding et al.'s cuttable capacitive multi-touch sensors [16]. As both Olberding et al.'s sensors and Midas use sheeted source materials, they are limited to curve-planar surfaces only (i.e. developable). A painted resigraph, for example, can be applied to both developable and non-developable surfaces.

RESIGRAPH SENSORS

In its simplest embodiment, a resigraph is painted directly on an object and requires only a light amount of force to operate. In this arrangement, a designer's hand contacts a grounded material, such as a metal wire or copper tape, and the touch signal passes through it. This fabrication method is quick to construct but limited to a lower resolution (i.e. less than ten touch points) because the deposit of the conductive ink is less uniform than other methods, such as silk-screening. In a more complex embodiment, a resigraph consists of three layers: conductive copper fabric, a spacing layer, and a resistive mesh. The copper contacts the mesh through a gap in the spacing layer, requiring slightly more force than a painted resigraph.

In general, the graph pattern of either embodiment directs current flow and causes the current passing through each node to be unique (see Figure 2). When a touch is present, the current is disturbed and this change can be mapped to its corresponding location.

Sensing Touch Events

When no touch is present, a resigraph is an open circuit that establishes a baseline pattern of current flow. A positive voltage (+5V) is attached to one corner of the graph while the other corner is grounded. When a finger deflects a resigraph, its grounded top layer presses against a junction. This disturbs the baseline, is detected as a voltage change, and forms a new parallel circuit. The potential difference is measured between the positive voltage attached to one corner and the Arduino's analog input. This potential differences changes for each touch location because when a junction is activated, it forms a unique parallel circuit (or path in the resigraph).

When a second touch is present, the voltage sample again jumps to a new value and forms a distinct parallel circuit, an event that is detected as a discontinuous change in the voltage sample. Had the initial finger moved off the surface, the resigraph would have returned to its baseline. This method can also be extended to sensing three, four, or more touch points.

Description of the Sensing Technique

Establishing a useful baseline mesh pattern is critical: each junction must map to a unique voltage. The method of creating a resigraph is adapted from our early explorations with hand drawn pencil graphs.

To create a resigraph, the first step is to select conductive material with low sheet resistance (Bare Conductive paint [2] is suitable). The low resistance ensures that the current can travel easily throughout the entire graph (and through the designer's hand). This step also requires selecting an ampere and supply voltage; the 5V and 40 mA upper limit of the Arduino is appropriate for a resigraph.

The next step is drawing the touch points on any matte surface. In Figure 1, this corresponds to the black circles grouped at either end of the game controller. In practice, each node is connected such that it has a degree of at most four. The final step is to adjust the location of the grounded wire such that the voltage measurements are sufficiently spread out. This adjustment compensates for the variation in edge resistance between individual nodes, a result of the stochastic deposit of ink and graphite on a surface.

To strengthen this approach, time multiplexing is used to produce a two-dimensional vector that represents the voltage at each touch point. Switching the polarity of the positive voltage in and ground achieves this effect. This produces a voltage tuple and provides a lookup table that maps this multiplexed measurement to a location. This multiplexing also prevents corner touch points from being masked, as current flow is inhibited to them in the simpler, non-multiplexed scenario.

Calibration & Software

To map a node's voltage sample to a touch ID, a designer starts with an uncalibrated graph and then simply touches and holds a location on it. If a dwell time of three seconds is reached and the voltage sample has not been previously observed, a new touch ID will be generated. This method extends to multi-touch input; if a second finger touches a node, while the first one is still touching, a new touch ID will be generated for this multi-finger combination. This entire routine is coded in Arduino and when a touch event occurs, its ID is printed to the serial port at 25Hz, making it available to other applications.

Limitations of Resigraphs

In theory, the number of touch points that a resigraph can sense is limited to an analog-to-digital (ADC) converter's input resolution. For example, an Arduino's ADC has an input resolution of 1024 states. In practice, imperfection in conductive source materials introduces a practical limit. The redundancy introduced via time-multiplexing addresses this problem, as the tuple helps to better identify one touch from another than one measurement alone. A tolerance can be introduced that allows each value in a tuple to deviate from a junction's calibrated values. In practice, we found a tolerance of 10% to be usable.

The densest resigraph we have fabricated has thirty touch points (a curved keyboard concept). This number represents a practical limit that resulted from creating specialized graph patterns during design exploration (see Figure 1), most sketches required far less than twenty touch points. Although the ADC determines the theoretical limit of a resigraph, the practical input resolution is difficult to calculate because it depends on the type of substrate used (pencil, conductive paint, Linqstat, etc) and the size of the junctions. Further testing and exact measurement in left for future work.

Resigraph patterns

Furthermore, resigraphs cannot be symmetrical with regard to the placement of the positive voltage and ground; these corner connections are typically placed along the same edge. If they were across from each other and the resigraph were symmetrical, two different touch points could have the same resistance values. However, when painting a resigraph, the stochastic deposit of ink ensures a variation of edge resistance values, so a symmetrical graph is theoretically possible. This is not necessarily the case with the off-the-shelf Linqstat, as seen in the deformable tablet's asymmetrical graph in Figure 1. Nevertheless, it is possible to change the individual length and thickness of the edge connections in a Linqstat-based resigraph. This would modulate sheet resistance and could maintain a symmetrical graph. This level of control is unnecessary for early design and was not explored in this work.

Accuracy of Resigraphs

It is important to consider Resigraph's intended usage scenario: *interactive sketching* [5]. Even so, accuracy is a critical measurement; how repeatable are the touch events in a resigraph? With the time multiplexing and tolerance allowance, resigraphs are robust enough for a designer to quickly explore non-planar and non-developable interactive shapes (see Figure 1). This is a direct result of using accessible materials, a low wire count, and a common hardware platform (i.e. Arduino). However, resigraphs do not have a long lifespan and their repeatability will degrade. The paint from a resigraph wears off during repeated usage, which requires repeated calibration or reapplication. Similarly, the layered materials will relax after prolonged deformation. That said, resigraphs are intended to be disposable touch sensors [5].

CONCLUSION

Although the demos are not exhaustive, we hope that designers who need to create custom touch sensors rapidly, simply, and with materials and tools that are near at hand will adopt this sensing technique. Using a resistive graph technique, a designer can explore touch interactions according to an interface's shape.

In future, we plan to further explore resigraph using a circuit printer. This machinery will offer much greater control over sheet resistance, allow for more complex graph patterns, mathematical simulation, and more precise performance and reliability testing. It will also be important to move beyond carbon-based conductive materials in future work. Indium Tin Oxide, for example, is transparent and could be sprayed directly on a surface to form a resigraph.

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