LOW-COST TOUCH SENSING USING ELECTRIC FIELD TOMOGRAPHY:

Making Touchpad Out Of Anything

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CERTIFICATE

We, hereby, certify that the project titled **“Low-Cost Touch Sensing Using Electric Field Tomography”** is submitted by (Arpit Garg, 2K20/EC/047, and Arpit Yash, 2K20EC/049) students of B.Tech. (Electronics and Communication Engineering), Delhi Technological University, Delhi in complete fulfillment of the requirement for a Bachelor of Technology degree award, is a record of the student's project work under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi — Mr. Piyush Tewari

Date: 22 April 2022

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Candidate's Declaration

We, hereby, declare that the work embodied in this project entitled **"Low-Cost Touch Sensing Using Electric Field Tomography"** submitted to the Department of Electronics & Communication Engineering, Delhi Technological University, Delhi is an authentic record of our bonafide work and is correct to the best of our knowledge and belief. This work has been undertaken taking care of engineering ethics.

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ABSTRACT

Nowadays, most people will have a smartphone, a tablet, or perhaps even a touch-sensitive television. What all of these screens have in common, however, is that they are relatively small and flat. In this project it is possible to make a touchpad out of nearly anything, big or small, flat or irregular, using a variety of conductive materials. In general, they are too expensive to scale to large surfaces, such as walls and furniture, and cannot provide input on objects having irregular and complex geometries, such as tools and toys.

This project is described as "a low-cost and versatile sensing technique that enables touch input on a wide variety of objects and surfaces". To make the surfaces, they combine an electric field tomography with an electrically conductive material. It can enable new interactive opportunities on a diverse set of objects and surfaces that were previously static.

AIM OF THE PROJECT

Nowadays, most people will have a smartphone, a tablet, or perhaps even a touch-sensitive television. This project can be used to make a touchpad out of nearly anything, big or small, flat or irregular, using a variety of conductive materials.

The project is described as "a low-cost and versatile sensing technique that enables touch input on a wide variety of objects and surfaces". To make the surfaces, they combine an electric field tomography with an electrically conductive material. The sensing principle works by injecting a small electrical current into the conductive layer, using a pair of electrodes. The voltage is measured by all adjacent voltage points. When a finger touches the surface, some power is shunted, causing a localized reduction in voltage. By rotating the place the electrical current is coming from, an estimate can be made where the surface is touched, using tomographic reconstruction. With standard blob-tracking techniques, finger locations and movements can be tracked on a computer screen.

We can use a various materials to demonstrate the technique. An example is Velostat, which is a carbon-loaded polyolefin film that can be attached to surfaces with adhesives to make inexpensive touchpads. Carbon-loaded ABS, sold as filament, can also be used to create conductive objects. Using conductive paint, almost anything can be turned into a touchpad, no matter how big or irregular. The team demonstrates that even entire walls can be used as touchpads, as well as shapes made from Jell-O and Play-Doh.

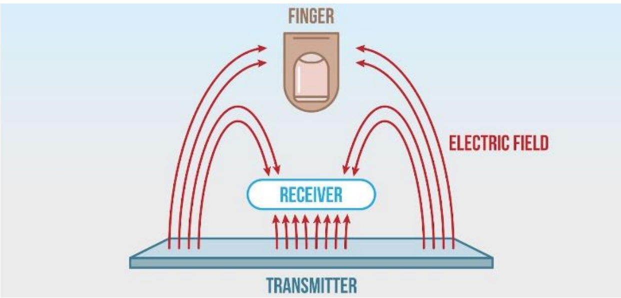
It shows that nearly any object can be 'smart' and interactive if it is made from or covered in a conductive material, once it is hooked up to electrodes and a computer. Watch the video attached to see materials in action.

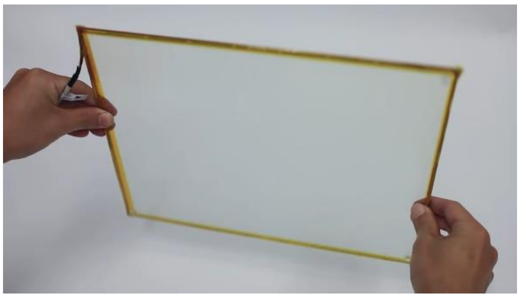
INTRODUCTION

PROBLEM WITH CURRENT TECHNOLOGIES

Today's touchscreen technologies are generally manufactured on a rigid substrate. For example, projective capacitive sensing, like that used in contemporary smartphones, uses a multi-layered, row-column matrix most often deposited onto glass. This means that most touch panels are relatively small and flat. In cases where irregular shapes or large areas have been made touch-sensitive, the price tag is often substantial, and irregular or flexible objects with touch-sensing capabilities are mostly research prototypes unavailable to consumers. This high cost and inflexibility have limited touch interaction from being adopted by a wider array of everyday objects, despite touch being an intuitive and popular input modality.

But due to this most touch panels are relatively small and flat. In cases where irregular shapes or large areas have been made touch-sensitive, the price tag is often substantial – touchscreens above 75" typically cost thousands of dollars. This high cost and inflexibility have limited touch interaction from being adopted by a wider array of everyday objects, despite touch being an intuitive and popular input modality.





In this project, an inexpensive and versatile touch sensing approach is applicable to a wide range of objects and surfaces – including those with large, irregular, and even flexible geometries. To enable it objects must either be made from an electrically conductive material or have a conductive coating. The latter can be easily and cheaply applied through e.g., painting, allowing for large touch surfaces (e.g., walls, furniture).

To track a finger's touch location, electrodes are attached to the periphery of the desired interactive area. A sensor board connected to these electrodes injects an electric field into the conductive substrate and senses changes in the field's distribution resulting from a user's touch. Sensor data can be transmitted wirelessly, allowing the electronics to be fully contained within an object, eliminating the need for external sensing infrastructure. It can enable new interactive opportunities on a diverse set of objects and surfaces that were previously static.

PROPOSED TECHNIQUE

In this project, an inexpensive and versatile touch sensing approach is applicable to a wide range of objects and surfaces – including those with large, irregular, and even flexible geometries. To enable it objects must either be made from an electrically conductive material or have a conductive coating. The latter can be easily and cheaply applied through e.g., painting, allowing for large touch surfaces (e.g., walls, furniture).

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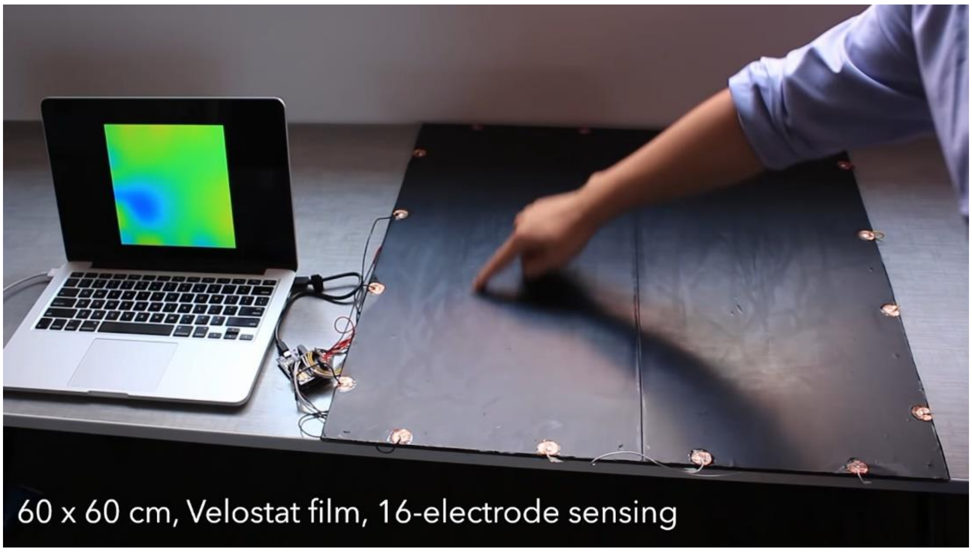


TECHNICAL APPROACH: SENSING PRINCIPLE

The sensing principle is based on the shunting effect, where a human body proximate to an electric field draws a small amount of current to the ground. This phenomenon also called "shunt mode", has been widely utilized in Electric Field (EF) sensing systems. EF sensing generally uses the air as a medium, enabling free-space interactions such as finger tracking, motion sensing, and activity recognition. By using measurements from peripheral electrodes, it is possible to deduce the position of the shunting object.

It is based on a user's finger shunting current. This different sensing mechanism allows us to leverage different (and low cost) materials for our conductive domain, which in turn enables different fabrication methods and use cases.

This project requires objects to have a conductive medium, either as their principal structural material or as a surface coating. The object is further augmented with electrodes placed around the periphery of the desired interactive area. With this configuration, it inserts a small AC current between a pair of adjacent electrodes (the current projecting pair), creating an electric field in the conductive medium. The voltage difference is then measured at all other adjacent electrode pairings voltage measuring pairs). This process repeats for all combinations of current-projecting and voltage-measuring pairs, resulting in a mesh of cross-sectional measurements. This sensing scheme is similar to four-pole sensing in EIT systems.

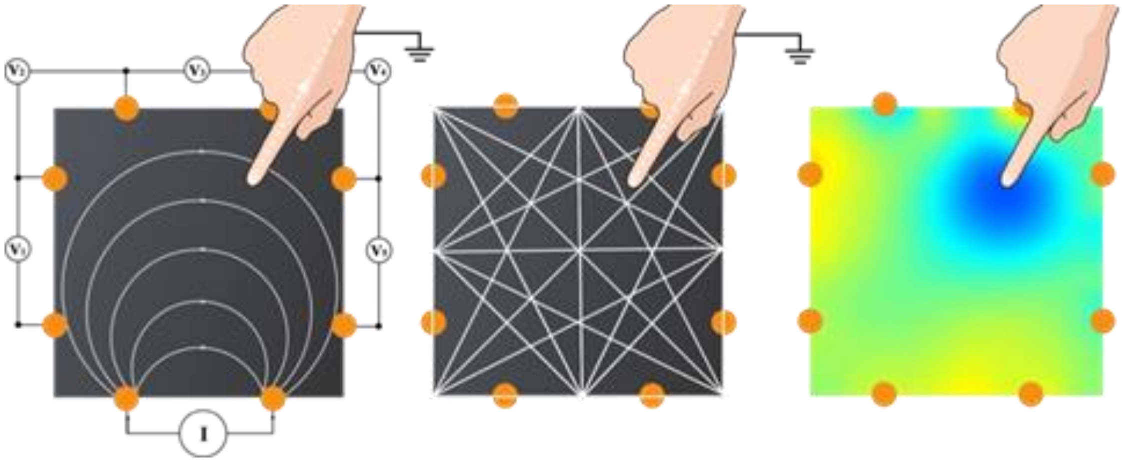


Figure 1. Left: we insert current from one pair of electrodes and measure voltage from other pairs. Center: A mesh of cross-sectional measurements. Right: A reconstructed 2D touch-sensing image. Blue indicates low current density.

As previously mentioned, our approach relies on the fact that a grounded object, such as a user's finger, will shunt some current to the ground when it encounters an electric field through capacitive coupling (similar to surface capacitive screens and in-air electric field sensing). This current is very small, comparable to that induced by capacitive touch-screens found in smartphones. However, this shunting distorts the electric field, characteristically altering the voltages measured at receiver pairs. We can then use our cross-sectional measurements to recover the location of the shunt point.

This can only be used with materials with compatible resistivity. If the resistivity is too high, the electric field will be very weak, making it hard to sense the field signal. However, if the surface resistivity is too low, the current shunted by the finger (a fairly high-impedance pathway) will be negligible, making touches hard to detect. In testing, we found that surface resistivity in the range of 500 Ω to 50 MΩ per square worked best for surface coat materials. The surface resistivity should be higher (10 kΩ to 50 MΩ) for structural materials, out of which objects can be directly 3D printed, milled, or molded.

HARDWARE IMPLEMENTATION

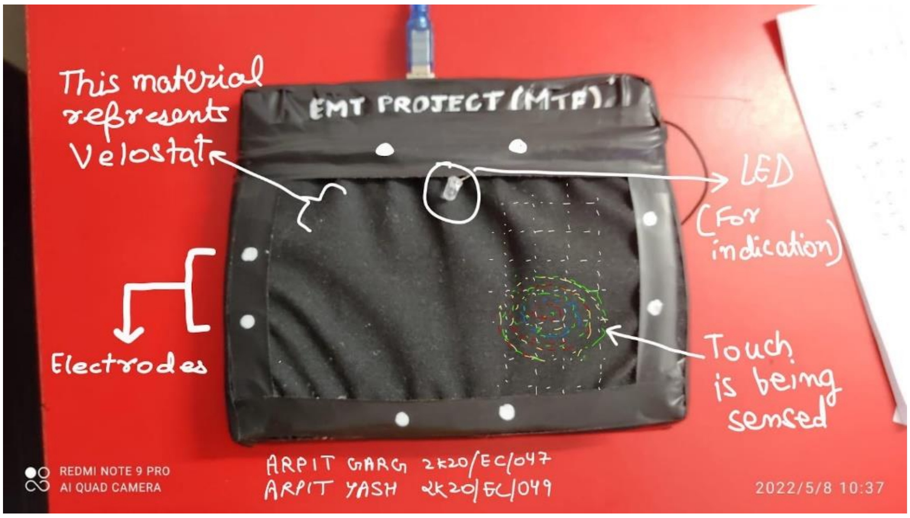


Fig. front representation

We have tried to build a prototype of our project using a capacitive touchpad sensor where we have tried to show the black cloth as the conducting velostat material, the white dots at the periphery as copper electrodes, and tried to show the tomographic reconstruction around the touch sensor.

In our hardware we have taken help of adruino and capacitive touch sensor to make a prototype of the project , what happens is that when someone touches the black cloth (representing velostat) the capacitive touch sensor under it senses the touch and sends the signal to adruino(This process represents the tomography sensing), and then adruino does the work according to the program , for example in our case we have programmed it to "spacebar" and other half of the touchpad is set to light up the led , the following video is attached.

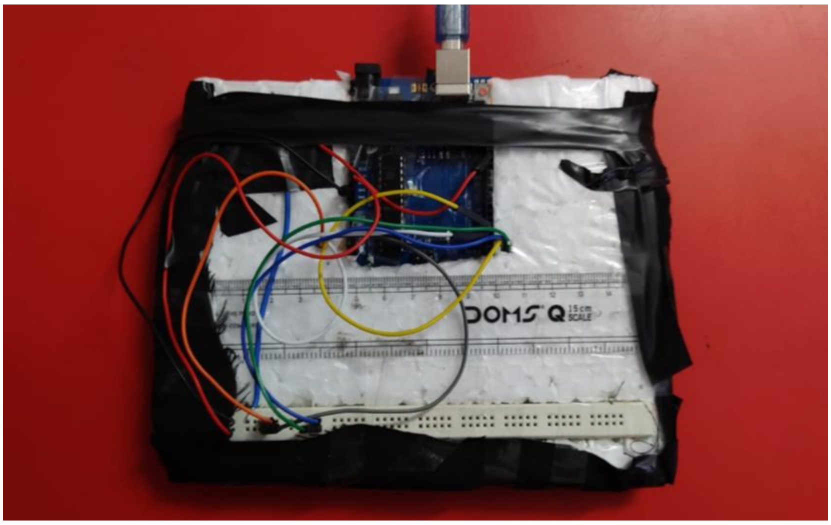


Fig. Back representation and connection with Arduino.

Fig. Dino Game Play

APPLICABLE MATERIALS & FABRICATION PROCESSES

We identified three classes of material of particular utility and interest: solid, pliable, and paintable. These basic material forms are used in a wide variety of fabrication and finishing processes, including subtractive methods (e.g., milling, laser cutting), additive methods (e.g., 3D printing), molding methods (e.g., stamping, casting, vacuum forming, blow molding, injection molding), and coating methods (e.g., brush painting, spray painting, powder coating).

Among many compatible materials, we sought low-cost examples with four key properties:

1. compatible electrical resistivity
2. non-toxicity
3. applied without exotic equipment or facilities, and
4. readily accessible.

We now briefly discuss example materials we identified that fit our four criteria, and how they can be used with our project.

Example Solid Materials

Bulk plastics, such as **ABS and Polycarbonate**, are widely available in mildly conductive formulations (most often by adding carbon or metallic particles). These plastics come in many forms, including blocks (for e.g., milling), sheets (for e.g., forming/stamping), pellets (for e.g., molding/extrusion processes), and filament (for e.g., 3D printing).

Another compatible material is **Velostat, a carbon-loaded polyolefin sheet/film m**ade by 3M. It is primarily used for the packaging of electronic components to mitigate electrostatic buildup. This can be attached to surfaces directly (e.g., to walls), or laminated onto a thermal-formable sheet (e.g., polyethylene) and vacuum-formed into a low-cost, durable shell of almost shape.

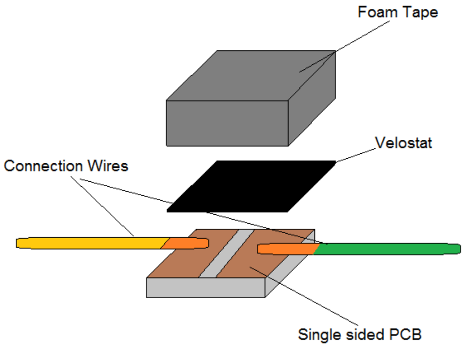
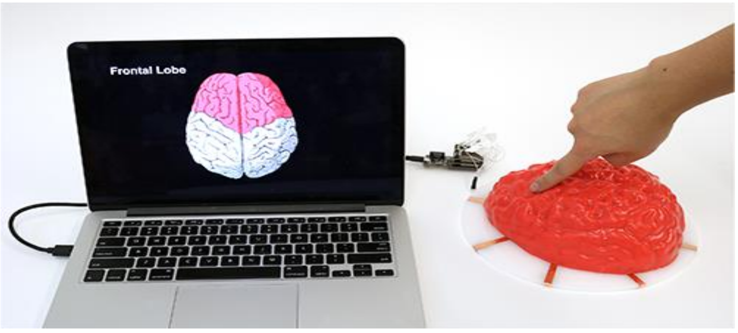


Fig. Velostat

Example Pliable Materials

There are also conductive materials that are soft and pliable. As one example of an easy-to-use, off-the-shelf material, we selected **Jell-O**, which has a surface resistivity of roughly 12 kΩ/sq. **Playdoh** is also compatible with our project.



Example Paints

Liquid paint and spray coatings are particularly versatile, as they can be added as a postproduction step to almost any object or surface – small or large, flat or irregular, regardless of how the underlying object was manufactured. In addition to total paint coverage, paints can also be masked (e.g., stenciled, silk-screened) to define interactive areas.

Coatings

As previously discussed, the shunting effect of a user's finger occurs through capacitive coupling; direct contact is not required. This permits the use of an optional (thin) topcoat, which can be used to add color or alternate finish to an object.

IMPLEMENTATION

This project implementation requires the development of custom hardware and software, which we now describe.

Electrodes: Once an object has been created or coated with a compatible conductive material, it must then be instrumented with electrodes around the periphery of the intended interactive region. A copper tape, to which we solder a wire that runs to our sensing board. It is also possible to reverse these fabrication steps, attaching the electrodes first, and then covering the electrodes with e.g., over-molded materials or paint.

Sensing Board: The board has a voltage-controlled current source (VCCS), direct digital synthesis (DDS) IC, and ADC preamp. The board also features multiplexers that allow for the cross-sectional measurements as well as a Bluetooth module to transmit data for wireless applications

Multiplexing: A pair of 32-to-1 multiplexers connect the VCCS terminals to two electrodes, forming the current-projecting electrode pair. Another pair of multiplexers connect two other electrodes (the voltage-measuring pair) to the preamp buffer terminals. This electrode selection flexibility also affords us the flexibility to vary the number of electrodes used (i.e., 8, 16, or 32).

Analog Sampling: The measured signal is amplified with a preamp to maximize the dynamic range of our ADC. We also implemented a 79.6 kHz high pass filter to dampen ambient EM noise, chiefly fluorescent light ballasts (i.e. 50 kHz) and powerline noise (i.e. 60 Hz).

Data Acquisition: After our board selects the appropriate electrodes using its multiplexers, it waits 100 µs for the DC bias on the AC coupling capacitors to stabilize. The board then collects 200 samples (roughly 10 periods of our 200 kHz excitation signal) for a root-mean-square (RMS) computation. This constitutes a single measurement (taking ~137 µs in total).

The board then moves to the next voltage-measuring electrode pair, reconfiguring its multiplexers accordingly. After collecting all measurements for the current-projecting configuration, the board then moves to the next current projecting pair and repeats the above procedure. Once it completes one full frame of measurements (all current projecting pairs), the board sends the values over Bluetooth or USB to a laptop for further processing.

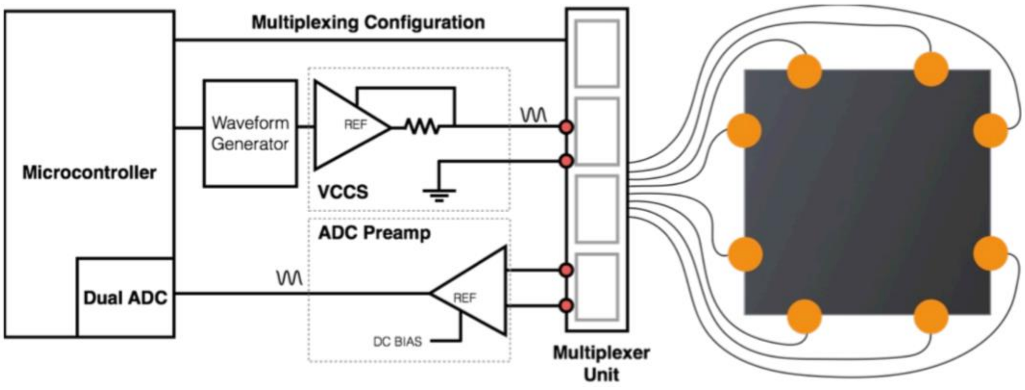


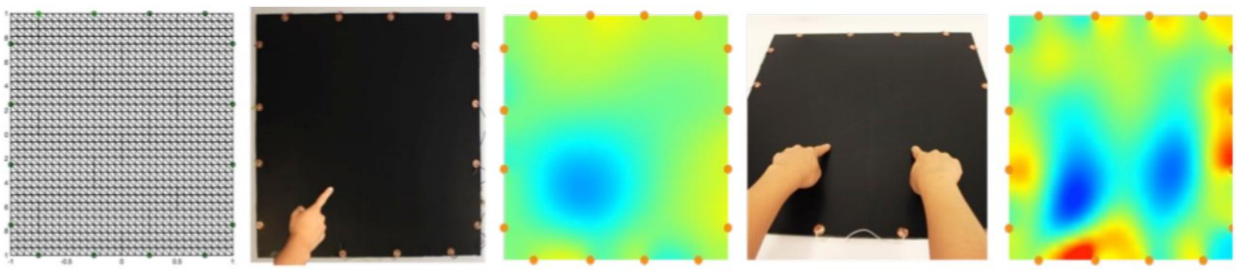
Fig. A schematic view of our system with e.g., 8 electrodes.

Touch Tracking

Initially, our finger-tracking pipeline used a fully realized tomographic reconstruction, to which standard computer vision "blob" tracking techniques can be applied. Specifically, we used a single-step Gauss-Newton method using a maximum a posteriori estimator to produce our tomographic.

This approach is capable of high accuracy and even multitouch segmentation. However, it requires the construction of a finite element model (FEM) for each object before use. This is relatively straightforward for planar circular or rectilinear surfaces but is a significant obstacle for ad hoc uses and complex geometries (which would require 3D scanning equipment). We also found this method to be sensitive to small fabrication/manufacturing variances, such as electrode size, adhesion, and conductive coating thickness.

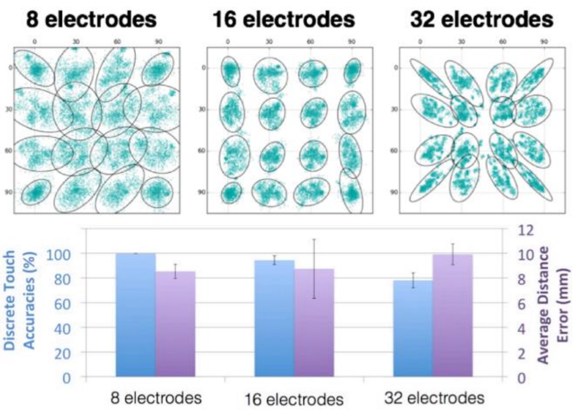
Fortunately, machine learning offers a robust and practical alternative, one that offloads much of this variability. A schematic view of our system with e.g., 8 electrodes. complexity from users to computers. Instead of having to model an object's geometry, users can perform a simple one-time calibration on the object itself, from which machine learning models can be initialized. In addition to permitting arbitrary geometries, this process also innately captures and accounts for variances in fabrication. For input features, one can simply use our raw cross-sectional measurements with no additional featurization.



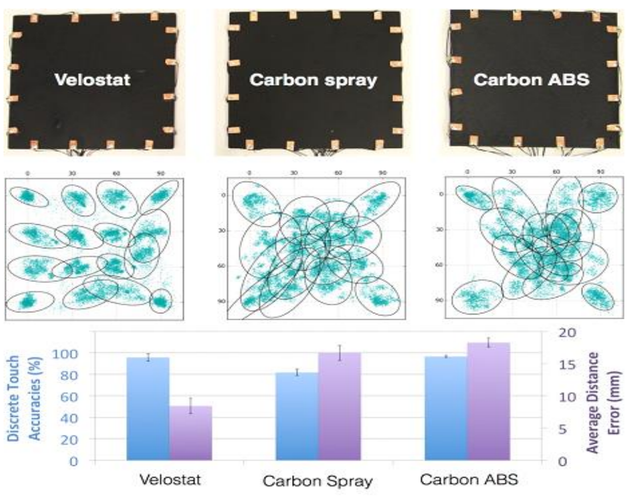
Multitouch: Tomographic techniques output a 2D reconstruction of the sensed medium. As such, localizing multiple finger touches is immediately possible. Standard computer vision techniques, most notably blob detection, can be applied. However, due to the low resolution of the reconstruction, there must be a substantial separation between finger contacts for robust tracking.

EVALUATION

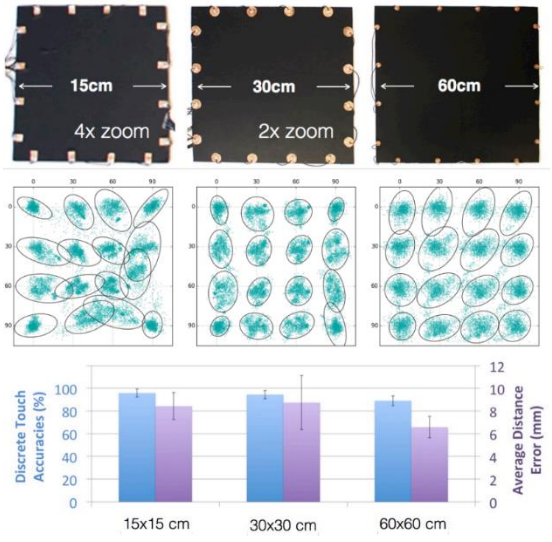
The versatility of this project meant there was a range of factors we wished to investigate: the performance across different electrode counts (8, 16, 32), materials (Velostat, carbon spray, carbon ABS), surface sizes (15×15, 30×30, 60×60 cm), surface geometries (flat, curved, angular), and coatings (bare, paper, spray paint). Within each evaluation tested the performance of this discrete touch sensing and continuous tracking approaches



Number of Electrodes: Intuitively, we expected higher electrode counts to produce a finer mesh of cross-sectional measurements and thus offer more accurate touch tracking. However, we found the opposite effect this reduction in accuracy is chiefly due to the reduced distance between projecting/measuring electrode pairs. A shorter electrode separation means that the electric field does not project as far into the conductive medium, which reduces the signal-to-noise ratio (SNR). Furthermore, the reduced distance between measuring electrode pairs similarly decreases terminal resistance, resulting in smaller voltage measurements, again reducing SNR. This result suggests that electrode count should be tuned according to surface size; e.g., for smaller interactive areas, lower electrode counts are likely to work better.



Material: There is a significant difference between Velostat and the other two test materials as a result of Velostat's superior homogeneity (compared to our other two conditions), as it is an industrially manufactured material. This makes the electric field projection more linear, whereas small non-linearities in our Carbon Spray and Carbon ABS conditions thus tracking regressions could not accurately interpolate interior touches. A more controlled coating process would likely yield improve accuracy.



Surface Size: Larger surfaces tend to have more linear regression results, though there was no significant difference between our three conditions. This is probably not directly related to size per se but rather tied to an earlier observation about electrode separation (i.e., as surface size increases, so does electrodes electrode separation, improving accuracy).

Surface Geometry: No statistically significant differences between the different surfaces. The continuous touch tracking means distance error was 15.7 mm (SD=3.5).

Coatings: Encouragingly, spray paint and bare performed equally well, suggesting some coatings are immediately compatible with our project, opening a range of finish and color options. However, the paper covering resulted in significantly worse performance as the paper is thicker than a spray coat, and thus impacts capacitive coupling more substantially.

EXAMPLE APPLICATIONS

To demonstrate the expressivity and versatility of this project, a variety of fully functional, interactive, example applications can be shown. These were selected to include a range of sizes, geometries, materials, fabrication processes, and use domains:

Desk: Using a roller, we can carbon paint a desk and attach eight electrodes to the sides of the desktop, allowing the whole surface to become touch-sensitive. As an example application, users can place paper stickers anywhere on the table, and register them to an application (e.g., browser) or function (e.g., mute), after which the stickers can be pressed to quick launch items.

Wall: We can carbon paint a sheet of drywall. By using 16 electrodes, we can create a touch surface. Then apply an off-white latex wall paint. Pervasive touch-sensitive walls could enable innumerable applications. As one example, we can create a light control application; tapping the wall anywhere near a sconce light toggles it on/off; dragging up or down allows the user to control the brightness.

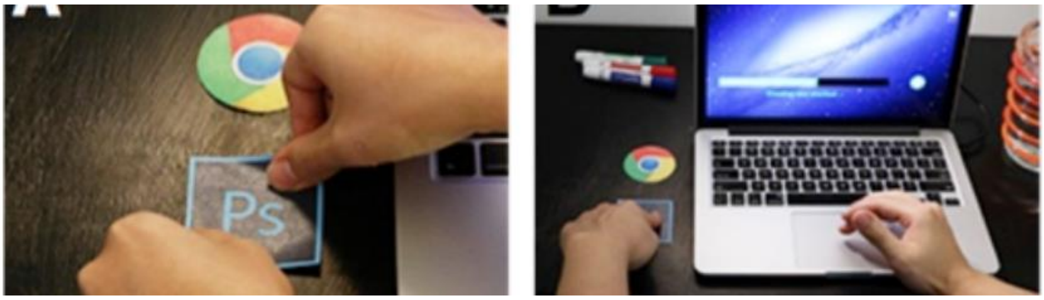


Fig. Stickers can be placed and bound to laptop functions

Fig, A user can turn on/off a light by tapping the wall.

Toys: The low-cost nature of toys has largely precluded the integration of touch surfaces. As an example, one can carbon spray a dog toy and then hand-paint it in colored acrylic paints. With this setup, touches on different locations trigger different audio effects. One made similar apps for toys molded from conductive ABS and silicone.

Play-doh: Play-doh can also be made interactive, allowing a user to sculpt a figure or object, and then bind interactive functionally to different touch locations. To achieve this, the finished object is placed onto an 8- electrode base, with small pins that penetrate the play-doh. A snowman example, is where different phrases are spoken when touching the nose or belly.

Fig. A Play-doh snowman is made interactive.

Fig. A guitar with dynamically configurable controls

Guitar: In this demo, a user can add virtual controls (e.g. volume, filters, and effects) to the surface of a guitar through a drag-and-drop design application on a computer. To achieve touch tracking, carbon sprays an electric guitar and use eight electrodes running along the edge of the instrument.

Car Steering Wheel: This is a perfect example of a large, irregular object that has yet to be instrumented with rich touch functionality, despite offering an immediately useful surface for user input. As an example, add 8 electrodes to a carbon-sprayed Chevy Aveo steering wheel; it can track the position of both hands, as well as detect gestures, such as swipes.

Fig. augmented steering wheel can track hand location and gestures.

Phone Case: We can vacuum-formed a rear cover for a smartphone. It can be used to detect various grips, to e.g., quickly launch apps, such as the camera or messaging.

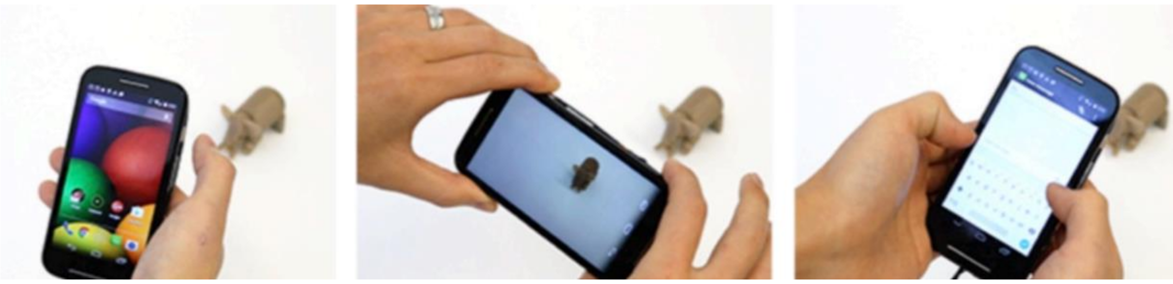
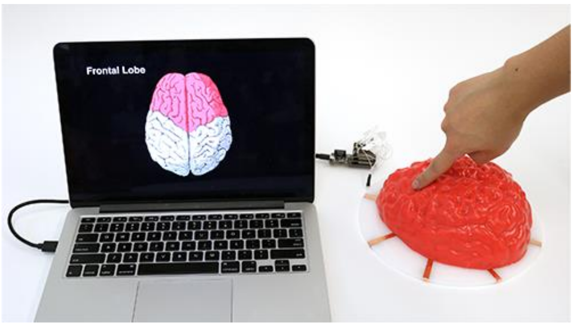


Fig. augmented phone enclosure allows different grips to launch apps

Instructional Aids: Physical props are often useful in learning the visual-spatial subject matter. As an example, a model of a brain using Jell-O, simulates the organic feel. By placing the model onto an 8-electrode acrylic base, students can touch different regions of the brain to summon information Such a base could be reused for any number of low-cost instructional objects. Similarly, US topographical map with carbon spray can be used to find information about different geographical regions with a user's touch.



Game Controller: A Velostat layer and eight electrodes. With the surface now made touch-sensitive, players or developers can pick (or customize) different interface layouts by overlaying different templates. Not only are buttons supported, but also analog inputs, like sliders and joysticks. Obviously, this design flexibility has immediate implications and applications in the rapid prototyping of physical interfaces.

DISCUSSION

One potential concern with this is durability, especially in coatings. There are many more materials that are compatible with it – such as conductive rubbers, foams. Transparent coatings may even be possible. And of course, conductive material composites can often be made in the home or lab by mixing conventional and conductive materials (e.g., carbon powder). Environmental electromagnetic noise, e.g., fluorescent lights, running appliances, and power lines, can affect tracking accuracy. Not only does the conductive object act as an antenna, but so does the human body, which upon touch, introduces more noise. As discussed previously, one can use a high pass filter to combat this interference, though standing underneath a fluorescent light reduced performance. Finally, perhaps the biggest limitation stems from the grounding condition, which is a universal issue for Electric Field Sensing systems. In this project, both the sensor and the user's body capacitively couple to common ground (the Earth) to complete the circuit. Bigger sensor ground planes have stronger capacitive coupling, and thus bigger shunting current and SNR. When a smaller sensor ground is used (e.g., running from a small LiPo battery), the shunting current will be reduced. Although the sensor has a high input impedance, this decrease in shunting current will inevitably lower the SNR. This may preclude the ability to use in small form factors, such as wearables, though it can be made to work in devices as small as smartphones.

CONCLUSION

We have presented this project as a low-cost and versatile touch-sensing technique that can be scaled to large surfaces and irregular geometries. The technique can be used to bring touch interactivity to rapidly prototyped objects, including those that are 3D printed. Results show that it can accurately track both discrete and continuous touch input under various test conditions, materials, shapes and sizes. It is also robust over time and across users. This work can bring touch interactivity to new classes of objects, as well as enable designers to rapidly prototype objects with innate interactive capabilities.

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