Leveraging Conductive Inkjet Technology to Build a Scalable and Versatile Surface for Ubiquitous Sensing

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ABSTRACT

In this paper we describe the design and implementation of a new versatile, scalable and cost-effective sensate surface. The system is based on a new conductive inkjet technology, which allows capacitive sensor electrodes and different types of RF antennas to be cheaply printed onto a roll of flexible substrate that may be many meters long. By deploying this surface on (or under) a floor it is possible to detect the presence and whereabouts of users through both passive and active capacitive coupling schemes. We have also incorporated GSM and NFC electromagnetic radiation sensing and piezoelectric pressure and vibration detection. We report on a number of experiments which evaluate sensing performance based on a 2.5m x 0.3m hardware test-bed. We describe some potential applications for this technology and highlight a number of improvements we have in mind.

Author Keywords

Sensate skin surface, flexible electronics, location tracking, distributed sensor network.

ACM Classification Keywords

C.3 Special-Purpose And Application-Based Systems: Microprocessor /microcomputer applications; Real-time and embedded systems; Signal processing systems. H.5.2 User Interfaces: Input devices and strategies.

General Terms

Design, Experimentation, Human Factors

INTRODUCTION

Traditional electronic fabrication techniques are based on rigid planar substrates – namely mass-produced low-cost printed circuit boards (PCBs). This constrains the associated circuitry not only in terms of physical flexibility,

but also in terms of surface area – because they are rigid, PCBs larger than around 30cm x 30cm are typically impractical because they are hard to manufacture, transport and deploy. Research into materials and mechanics for flexible and stretchable electronics [1-4] promise an exciting future but are still far away from full-scale mass production. However, recent advancements in manufacturing based on flexible films coupled with conventional rigid components are opening up new possibilities in the design of a large, flexible and cheap substrate for circuitry. Indeed, flexible substrates with customized printed conductive traces are now becoming readily accessible and have potential applications in a number of ubiquitous computing application scenarios.

In this paper, we explore the use of a recently commercialized technology known as conductive inkjet printing [5] (e.g. conductiveinkjet.com) as an enabler for the goal of building low cost, large area flexible sensate surfaces which can detect and localize users in an indoor environment. We present a prototype sensing 'surface' based on a flexible substrate with custom-printed conductive traces which provide natural electrodes and antennas for capacitive and electromagnetic sensing.

RELATED WORK

Our prior work has explored dense networks of hardwired sensor modules (termed *Sensate Media*) as a scalable sensor substrate [6-7], and low cost, dense sensing environments have been explored by many research groups, often as sensate floors for interactive media applications. Unlike computer vision based tracking, this approach requires minimal computing power, can be quite low cost, and can also provide good range-independent resolution depending on the sensor density. A flexible sensor floor can be quickly rolled out and hooked up anywhere without constraints on lighting or issues of camera occlusion. One of the methods is to use load cells at the corners of a surface that can estimate the changes in weight and position of an object and

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further identify people based on their footstep force profiles [8-9]. Other projects, including the Magic Carpet (piezoelectric wires) [10], Litefoot (optical proximity sensors) [11] and ISA floor (FSR) [12], create pixilated surfaces using larger numbers of sensors. The Z-tiles used Force sensing resistors (FSRs) in networked modular sensing units for easy installation and reconfiguration [13]. Recent projects in the area of floor sensing evolved quickly in the direction of multi-modal sensor fusion, especially those combining vision tracking for off-floor three-dimensional movement and interaction [14-16].

In this work, we want to leverage the latest advances in flexible electronics substrate manufacture to create a sensing floor. Three major types of manufacturing technique can be used to fabricate a flexible sensing surface. The first one is fabrication by roll-to-roll processing [17-18]. Roll-to-roll lithography is capable of very high resolution conductor placement on flexible substrate materials, but at a relatively high cost. Another manufacturing method for fabricating large-area, low cost flexible materials is additive printing of noble-metal conductors, organic conductors, and even semiconductors [17-18]. However, the electrical and mechanical characteristics of the resulting materials do not make them an adequate substitute for more conventional manufacturing techniques. The third approach centers around methods for printing metallic conductors from nanoparticles – these techniques are currently being developed, hence few are yet main-stream. The main contenders appear to be copper-on-kapton substrate (e.g. www.allflexinc.com), conductive inkjet flex technology (e.g. www.conductiveinkjet.com) and metallic nanoparticle inkjet printing (e.g. t-ink.com).

SYSTEM OVERVIEW

Overall Architecture and Construction

Our prototype sensate surface is based on a matrix of sensing 'tiles' that is formed by printing a specific copper pattern onto a thin, flexible plastic substrate using conductive inkjet technology. Each sensing tile is around 0.3m x 0.3m and contains four printed electrodes of approximately 0.12m x 0.12m for capacitive sensing and two additional printed RF antennas – one for detection of cellular GSM UHF electromagnetic radiation and another for Near Field Communication (NFC) pickup in the HF band.

Whilst it is possible to attach surface mount electronic components directly to the printed substrate, using either low-temperature solder or conductive adhesive, this process is not straightforward and does not yield high enough performance to support the circuitry needed to process the signals picked up by the printed electrodes and antennas. For this reason, we decided to implement the required circuitry on a small but separate conventional FR4 glass fiber printed circuit board (PCB). This is reminiscent of the architecture proposed by Wagner et al. [19] for an elastomeric skin that carried rigid islands housing active sub-circuits. In our case, the PCB forms a signal

conditioning and processing module, which is itself attached to the flexible substrate. One such module is attached per tile, in the center of the four capacitive electrodes. Figure 1 shows photos of these components. Details about the operation of the various sensing modes supported by the electronic hardware are described in the following section.

In addition to performing the necessary signal processing, the PCB modules also contain a microcontroller unit (MCU), which is able to sample the detected waveforms and communicate this information with a PC over a shared I^2C bus that runs along the length of the substrate. In order to minimize any cross-coupling between the data lines, each is separated by a grounded trace. The MCU can also be instructed to excite the electrodes with a predefined waveform – for this, synchronization between the adjacent squares is required, and this is achieved using one additional line that distributes a global clock to all tiles and their associated MCUs.

Power is distributed to each PCB using dedicated power and ground lines running along the left and right edges of the substrate. Wider tracks are used for this to lower trace impedance and hence power drop. The conductive inkjet printing process results in a sheet resistance of printing 200 mΩ per square, and the resulting power drop across each sensing tile was measured at ~0.18V with all sensing modules fully powered on. The power rails run at 18V nominally (for 8 units), and a smoothed linear regulator fitted to each PCB is used to generate a 5V supply locally.
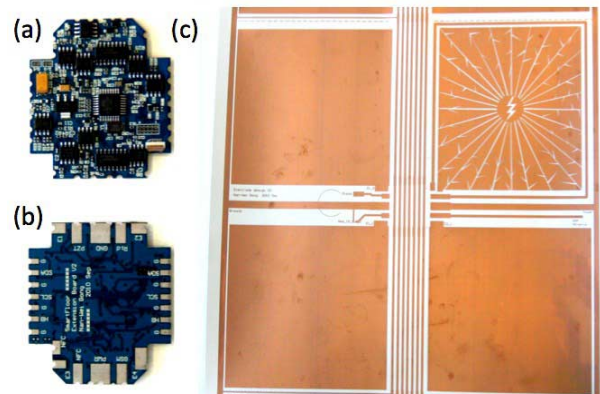

Figure 1. (a) The top view of the signal processing PCB module shows the electronic components, whilst (b) shows the surface-mount pads on the underside of the PCB module, which are used to connect with the substrate below. (c) The substrate is made up from sensing tiles like the one shown. The 2x2 matrix of printed electrodes is clearly visible; note that the top-right electrode incorporates a pattern of breaks in the copper designed to minimize Eddy currents because the NFC HF antenna is printed around it (just visible in the photo). The GSM UHF antenna is just above the bottom-right hand capacitive electrode.

Figure 2 shows what the sensing floor looks like when the PCB modules are attached to the flexible substrate. Our test-bed is based on a 2.4m length of 0.3m wide printed

film, which has 8 tiles along its length. In our prototypes the width of the substrate was limited to a single tile because the conductive inkjet process was only available to us on a 30cm wide roll at the time of manufacture, although our supplier's manufacturing facility is theoretically capable of printing on substrate up to around 2m wide. The length of substrate is only constrained by the size of the roll; a single piece tens of meters long is entirely feasible. The PCB modules are soldered to the substrate with low temperature solder (we used $Sn_{42}Bi_{58}$ tin-bismuth solder: melting point 138°C, tensile strength 55.2 MPa). We also attached a piezoelectric pickup element directly to the substrate.
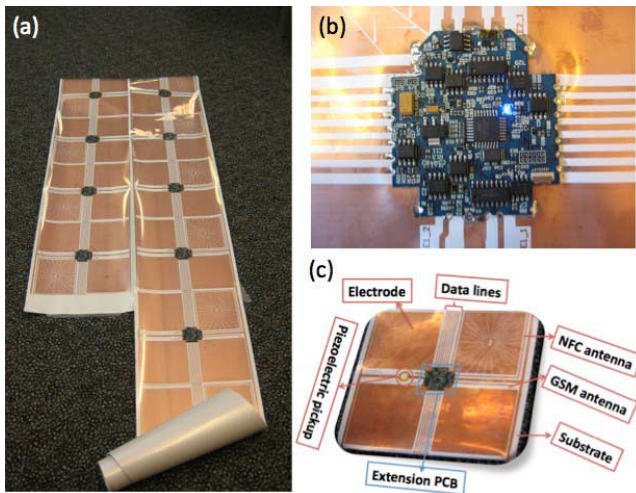

Figure 2. (a) A roll of the substrate with multiple sensing PCB modules fitted and (b) a close-up of one PCB module. (c) A single sensing tile consists of the substrate plus the corresponding PCB module.

PCB module circuitry

Having made the decision to mount the electronic components on a 'PCB module' rather than directly to the flexible substrate, we decided to make the circuitry as versatile as possible. To that end, each PCB module in the system uses an Atmel Atmega368 microcontroller to coordinate global and local communication, manage sensor I/O and perform basic data processing. Global communication is achieved by a two-wire I^2C protocol that is coordinated by a master microcontroller, which interfaces between the end of the substrate and a PC.

Figure 3 shows a block diagram of the sensing operation of each unit. There are five major modalities: passive capacitive sensing, active capacitive sensing, GSM UHF detection, NFC HF detection, and vibration/pressure sensing from the piezoelectric sensor. This wide range of approaches was chosen to allow us to explore the use of printed conductors for sensing as extensively as possible. The raw signal from each printed detector is passed through some signal conditioning circuitry and then into a

multiplexer (CD4052) for selective analog to digital conversion (ADC) sampling on the microcontroller. The sampling rate was set to fast mode (400 kHz) with 6 channels of 10-bit ADC. The electrode size in our design (~12cm x 12cm) seems to work well for resolving detail down to the size of a human foot. It would be possible to design a higher or lower resolution floor to match different needs for tracking and localization.
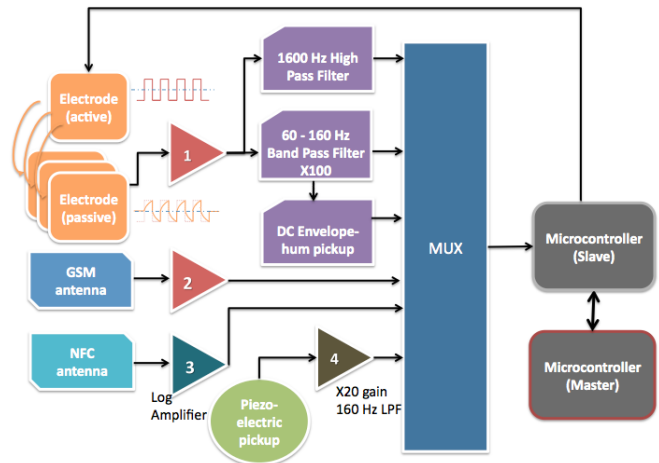

Figure 3. Block diagram of operation for each sensing tile. From left to right, signals picked up by the electrodes/ antennae are then filtered by analog circuits and finally sampled by the microcontroller. Each microcontroller acts as a slave device to a master microcontroller, which controlled the entire floor via a two wire communication protocol.

Figure 4 below illustrates the basic operation of the firmware for power management on each slave sensor unit. Each operation starts after receiving "start" command from the master MCU and then enters Idle mode after it successfully joins the I^2C network. Idle mode is the low power mode where the MCU stays in sleep state and the most power-hungry analog circuits (e.g. the NFC log amp) are disabled to save power. The slave units will wake on interrupts from the passive sensor signals, piezo pickup (or optionally on the passive capacitive or GSM/NFC signals), indicating nearby activity. If verified, every unit in proximity wakes up and enters passive capacitive sensing mode.

In the passive capacitive sensing mode, we can easily locate the presence of a person and start the active (interaction) mode. If nothing is detected (event completion), passive mode will eventually time out in favor of idle mode. However, if presence is detected, the operation enters active sensing mode. In this stage, the slave MCU repeatedly excites one of the electrodes with a 5V square wave pattern and samples adjacent electrodes for coupled pick-up, transmitting signal strength information back to the master node. It also samples for signals that are potentially generated by mobile devices the detected user may be carrying or interacting with, namely GSM and NFC signals.

After the interaction stops, the master node sends out a stop command, and slave units return to low power mode until further movements are picked up. Details about how each sensing modality works are described in the following section.
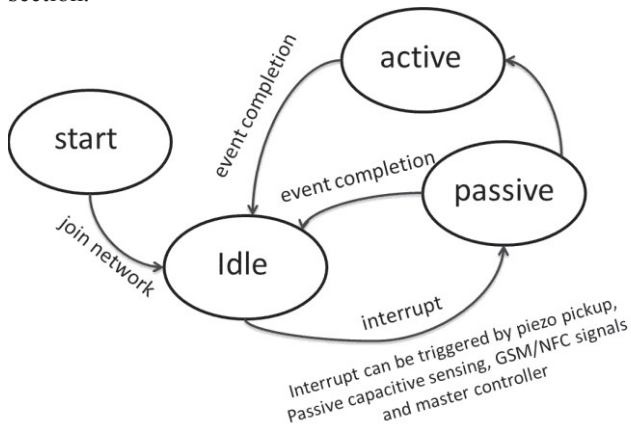

Figure 4. Basic operation of each slave sensor unit.

Physical topology

As mentioned above, our prototype is based on a relatively narrow roll of substrate due to current limitations of the production process we used, as shown in Figure 2(a). In order to cover a wider area with a single strip of sensing substrate, we explored the use of folding – which is possible given the flexible nature of our prototype. In this way, it is possible to cover large areas and also non-flat geometries without the need to cut or re-connect different pieces of the substrate. Examples of this are shown in Figure 5.
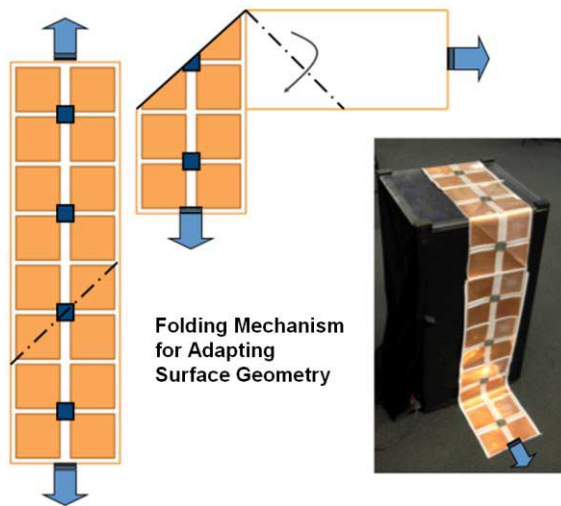

Figure 5. Example folding schemes that allow wider and non-flat areas to be covered using a single piece of the substrate without any cutting or joining. Blue arrows indicate the direction of connecting units.

SENSING MODALITIES

Analog active filtering circuits were designed to detect all of the supported signal types mentioned previously. Each is described in more detail here.

Passive Mode Capacitive Sensing

Passive mode turns out to be both the simplest and the most power-efficient mode for tracking people moving across the surface. In passive mode, the floor detects signals from the environment, such as power line hum (usually 50 or 60 Hz). These signals are coupled into electrodes much more strongly when a person stands on them. We implemented circuits for detecting and sampling this electric hum. The raw signal was first fed into a band-limit filter, made from a pair of first-order filters - a 50Hz high-pass followed by 160 Hz low-pass with x100 gain. The filter output can be selected for ADC sampling by the microcontroller, or alternatively it is also passed through a DC envelope-detector that gives an easily-sampled smooth output reflecting hum amplitude. Because there was a 2.5 V offset on the electrodes, they worked as condenser microphones, and were very sensitive to impacts. Although this was mainly filtered out by our conditioning circuitry, it could be used as another sensing modality as well.

Active Mode Capacitive Sensing

In active mode, one of the floor electrodes on each tile transmits a signal that is detected by adjacent electrodes when a person's body bridges any two of those electrodes. Any of the four electrodes can serve as the transmitter by emitting a 0V to 5V square wave. The other three electrodes are set up as receivers via trans-impedance front-end current-voltage converters that amplify coupled transmit signals. This process is illustrated in Figure 6.
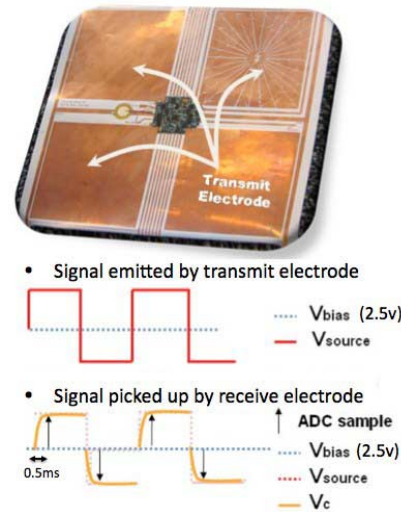

Figure 6. Active capacitive sensing: one of the electrodes serves as a transmitter by way of a series of rising and falling edges that act as an excitation waveform (Vsource). The neighboring electrodes pick up this signal (Vc). The amplitude of Vc is proportional to the capacitive coupling between transmit and receive electrodes.

Signals from the receive electrodes were connected to a high pass filter (1600Hz cut-off frequency) with 10x gain and then sampled by the built-in microcontroller ADC after each changing edge of the transmit electrode (ADC sampling rate ~9600Hz), once the receive signal stabilized (around 0.5ms in our case). As seen in Figure 6, we sampled the charging and discharging amplitude change (voltage) for 32 cycles and averaged their difference.

It is important to note that with a tiled setup like our floor system, there is very likely to be cross talk between tiles during active mode. This means the transmit electrode of any one tile is likely to generate a signal that is picked up by electrodes on neighboring tiles. In our prototype, we alleviate this issue by ensuring all tiles operate in sync when running in active capacitive sensing mode. We do this by running a global clock synchronization line to each tile. Accordingly, with proper synchronization, sensing between a transmitter attached to one microcontroller and receiver on an adjacent microcontroller is possible.

There are two possible scenarios when a user's body comes into the electric field between transmit and receive electrodes – these are known as transmit mode and shunt mode [20-21]. In transmit mode, the signal is coupled through the person, effectively increasing the amplitude of the signal on receive electrodes. The user or object has to be very close to the transmit conductor, hence is acting like an extension of the transmit electrode. Conversely, in shunt mode, the object or body of the user is not connected to the transmit electrode. Instead, it blocks the electrical field between electrodes, i.e., the coupling between the person and the room ground dominates.

The relative dominance of transmit and shunt modes depends on aspects of the physical configuration of the floor and the user walking across it – things like the position of the user's foot relative to the transmit electrode and the distance between the somewhat dielectric floor surface and the capacitive electrodes below it. In transmit mode, the strength of the detected signal will increase as the foot approaches the floor, and in shunt mode it will drop. Nonetheless, it is possible to use either to detect the user's presence.

In addition to localization and identifying people, an active capacitive sensing floor can be further used as a platform for communication between different devices or users by transmitting signals through the user's body as in [23-24]. For example, we have demonstrated this with a small circuit clipped on a shoe with inner side electrode to local ground (against the body) and outer electrode transmitting/receiving a digital signal to and from the floor (Fig. 15).

UHF and HF Sensing
We implemented two antenna designs to pick up signals from a cellular phone. The first type is a ¼ wave GSM antenna, which is designed to pick up both 900MHz and 1800MHz emissions from a GSM cellular handset. The

design is a simple 8 cm by 0.3 cm trace on the flexible substrate that feeds a Schottky diode detector followed by a low-pass filter with gain.

NFC signal detection was achieved by constructing a square loop antenna designed to be resonant at 13.56 MHz around one electrode. The electrode was cut into sectors as shown in Figure 1(c) in order to eliminate Eddy currents that would decrease performance. The signal is amplified and detected with an AD8307 log amp in order to produce an easily sampled output response.

Piezoelectric pickup
In addition to printing electromagnetic pick-ups on the substrate in the form of capacitive sensing electrodes and UHF/HF antennas, we also integrated flat contact piezoelectric pick-up sensing elements onto the substrate, adjacent to each PCB as shown in Figure 2(c). Each sensor was soldered onto the ground line of the substrate and was also glued in place to ensure it would be physically coupled to any vibration around the area, as well as responding to dynamic pressure applied from above. Signals were conditioned with a 160Hz active x20 gain low pass filter.

EVALUATION
Here, we report the capability of our system operating under various types of inputs and conditions. We seek to demonstrate the potential of printed conductive technology as a basis for sensing the presence and location of users in a low-cost, highly flexible sensing system.

Detecting users with passive mode
First, we evaluate the ability of our system to sense users via the electric hum, which is coupled into the electrodes using the passive capacitive sensing circuit outlined above. Without any stimulus, the output from the signal conditioning circuitry is centered at the bias voltage of just under 2.5V. When a user steps on the sensing surface, different intensities of electric hum coupled via the body were picked up based on the contact area and proximity.

In Figure 7, we demonstrate footstep detection over time on 4 individual sensing units. As we can see from these traces, the interaction patterns are clean and consistent. It is also worth observing that we can detect the user's foot approaching from a range of 15-20cm in passive mode.

In Figure 8, signals from each of the electrodes in a single tile are plotted separately. Three major signatures of the three typical signal patterns – heel strikes, forefoot strikes and mid-swings between steps – can be differentiated.
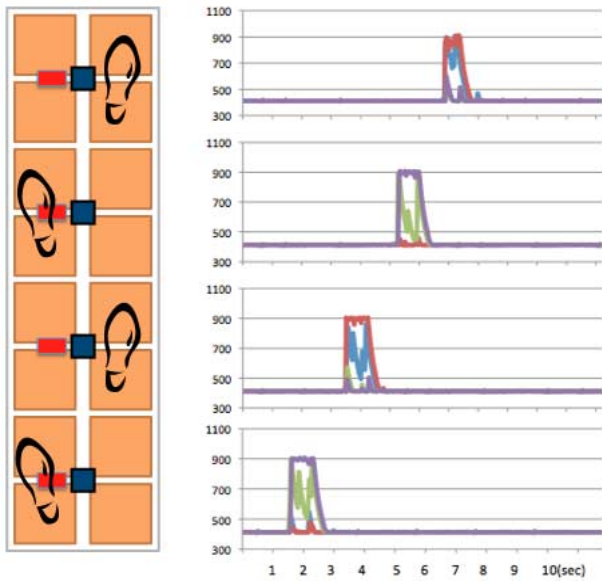
Figure 7. Footstep patterns detected by electrodes embedded in the floor in passive capacitive sensing mode. The four different colors in the right-hand figures represent the signals from the four different electrodes in one sensing tile.
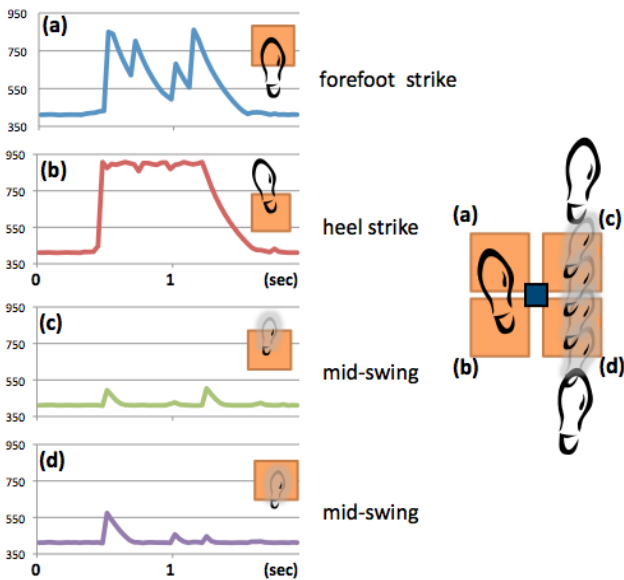

Figure 8. Different signatures typically detected with the passive capacitive sensing method. (a) Forefoot strike, (b) heel strike pattern (left feet), (c) and (d) mid-swing between steps (right feet), detected by adjacent electrodes. The decay time is from the RC response of the envelope detector.

Sensing with active mode

As mentioned above, depending on the distance between users' body and the transmit electrode, two possible effects can be observed during active capacitive sensing, namely transmit mode and shunt mode. We therefore tested the active mode in these two conditions.

Firstly, a user interacted with one unit by directly touching the transmit electrode (4) and approaching the receive electrode (1), see Figure 9(b). From the resulting signal distribution in Figure 9(c), it can be seen that adjacent electrodes picked up the signals as well. To demonstrate the range versus signal response of transmit mode, we tested and plotted signal strength based on 5 sets of interactions per sensing distance. The result shown in figure 9(a) indicates that signal strength decays smoothly with distance. This not only demonstrates transmit mode, but also suggests that signals can be easily capacitively coupled into and out of the body, enabling the body to be used as a conduit for electronic messaging via touch.
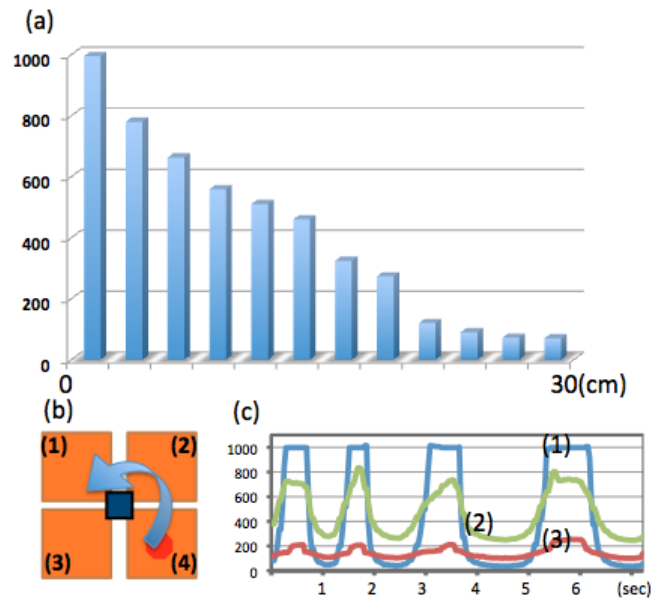

Figure 9. The effectiveness of active capacitive sensing mode. (b) Shows the electrode pattern of a single tile, where the electrode marked by the red dot served as the transmitter. The user was bridging two electrodes, namely transmit electrode (4) and receive electrode (1). (a) The user was touching the transmit electrode and moved from towards electrode (1). The strength of the signal pick-up is plotted as a function of distance. (c) Signal pickup on all the receive electrodes as a function of time, as the user repeatedly bridges electrodes (4) and (1) – significant signals are picked up by adjacent electrodes (2) and (3) as well as electrode (1).

The second condition involves detecting walking signals on the floor in shunt mode. The testing environment was set up on the floor, with ~4cm of high-dielectric constant foam on top of the sensors. The test subject walked over the receive electrodes as indicated in Figure 10, thereby avoiding transmit mode. Again, the red dots in the figure represent the transmit electrodes, and the results plotted show how the signal picked up by the electrodes adjacent to the transmit electrode demonstrate a noticeable attenuation through the shunt effect. Although this effect is less marked

than the passive sensing results, it none-the-less shows around 4 bits of resolution. Signals from each electrode are marked with numbers – patterns from the steps were consistent across four units: (a) heel strikes and (b) mid-swings. Better shunt-mode response can be attained by lifting the electrodes a few cm above a conducting floor (e.g. by putting a piece of wood below the sensing strip).
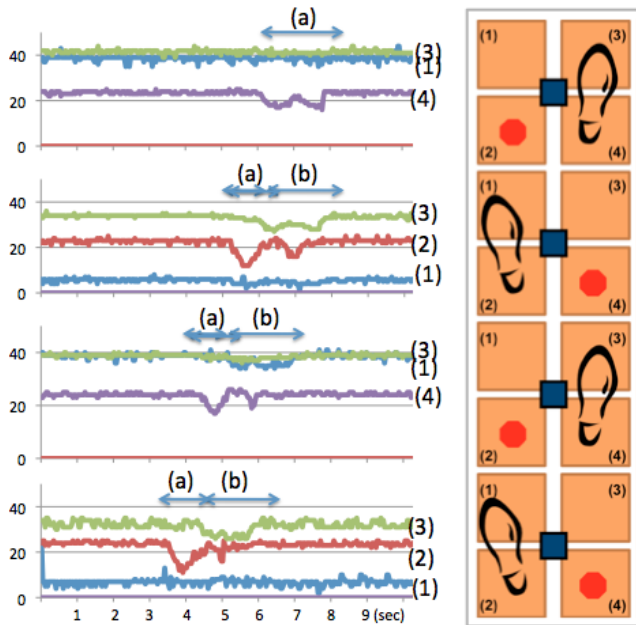

Figure 10. Walking patterns detected by shunt mode. During each step, the user effectively blocks the electromagnetic field flux, hence the signal drop: (a) heel strikes and (b) mid-swing. The red dots mark the transmit electrodes.

Piezoelectric sensor

We integrated piezoelectric sensors into our system for several reasons. First, like passive capacitive sensing mode, piezoelectric sensors do not require active pulsing, and can therefore be operated with relatively low power consumption. Additionally, a piezoelectric sensor can sense vibration and strain on the surface, so activity at distance can be detected as well as dynamic pressure applied directly to the sensor. In this way, we can easily use the signal from a piezoelectric element to trigger wake up of the microcontroller from a low power sleep mode. The piezo signal also yields dynamics that might roughly infer the weight of a person and provide insight into gait dynamics [27].

We evaluated the effectiveness of vibration and pressure detection in a similar manner to the previously reported tests of capacitive sensing. Figure 11 shows the signals picked up by our system. When a user walks along the floor, vibrations that match their footsteps are detected by the nearest sensor; smaller amplitude vibrations are also detected by adjacent sensors.
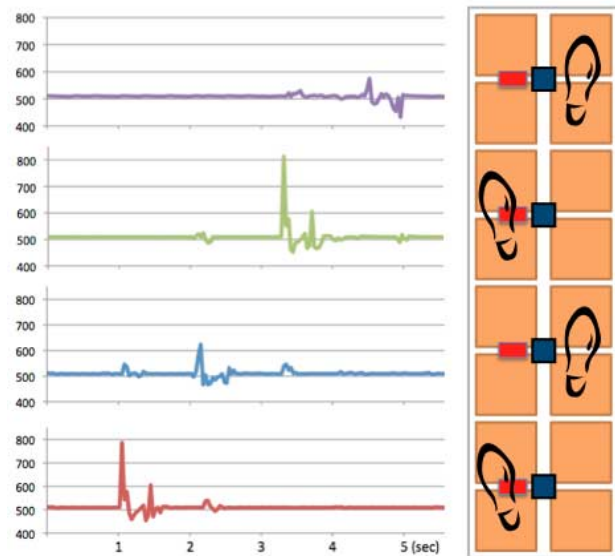

Figure 11. Signals picked up from the piezoelectric sensors. Red rectangles mark the location of each sensor within the sensing surface. Walking patterns were consistent with the other experiments reported in this paper. Note that vibration from adjacent units is also perceptible.

Cellular signals versus localization and identification

In our system, we included two types of RF antennas, namely 13.56MHz NFC and 900/1800MHz GSM. We used a Nokia 6212 phone to test the signal strength of both NFC and GSM emissions across the platform. Figure 12 shows the typical signal patterns picked up by our system.

The signal response from the NFC output of our logarithmic amplifier circuit is consistent and can be mapped to the distance – Figure 13(d) shows this. GSM signals are both stronger and more complex. The signal versus distance relationship can be related more easily by filtering & averaging the signal patterns.

Figures 13(b) and 14(b) show the experimental setup. We tried to evaluate the effectiveness of our platform in terms of identifying the exact unit the user was standing on or near, and the detection range over which cellular signals could be used. Each data point was taken and averaged according to five measurements.

To demonstrate signal propagation across the whole floor system, we plotted the signal response across the tiles in Figure 13(a) when the NFC device was held 30 cm away from the surface. The peak value was reported from the tile directly under the NFC reader as expected, and the signal strength drops off in all directions, enabling the location of the handset to be determined via the NFC signal. We further tested range versus signal strength by taking data from only one tile, recording measurements at various distances. The red circle in figure 13(b) indicates the location of NFC antenna used for this. Results are shown in Figure 13(d). The NFC signal is good for detecting short-range signal emissions, up to around 90 cm in our tests.
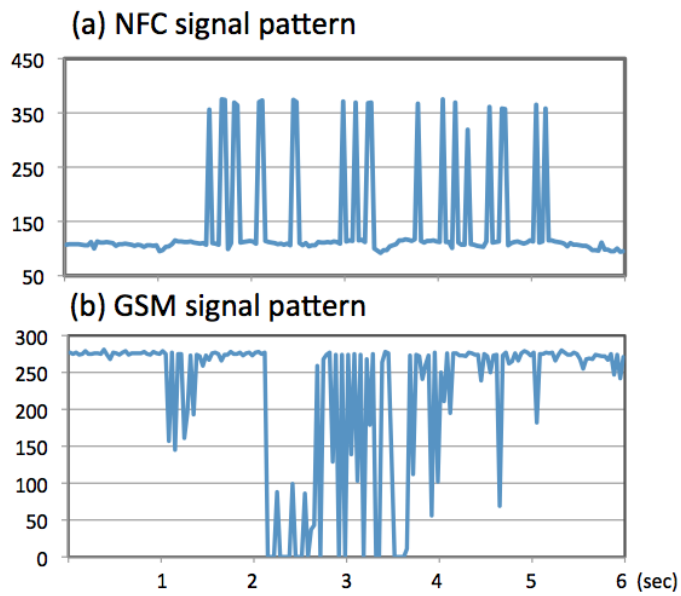
Figure 12. Signals picked up by antennas printed on the sensing substrate. (a) NFC signal pattern. The pattern and signal strength of NFC are consistent and can easily be used to determine range by measuring peak thresholds. (b) GSM signals have stronger signal response that can infer longer distance tracking by integrating and averaging the signal patterns.

We performed a similar experiment with GSM signal detection. When communicating with the cell tower, a cellphone generates a strong signal in the GSM band, which turns out to be readily detectable by the floor tiles from some distance via our simple circuit. Figure 14(a) shows the signal strength distribution across our platform when the mobile device is held about 1m away from the sensing surface as shown in Figure 14(b). The signal strength was integrated and averaged from a 6-second long GSM connection. As seen in figure 14(a), the peak value fell off in adjacent tiles in a similar manner to the NFC signal. We again recorded signal strength versus range as described above, and illustrated the result in Figure 14(d). This shows that the GSM signal strength drops off with distance in a similar manner to NFC and it is apparent that either could be used as a basis for determining range.

Both NFC and GSM signal strengths are directionally sensitive and could be affected by the way a user holds the mobile device. We have seen the GSM pickup to be fairly resilient, however, and the NFC detection range has been over a meter when the NFC antennae on the floor are isolated from magnetic material below – e.g., by putting a piece of magnetic shielding under the antenna or raising the floor up by a cm or two atop a nonconductor (e.g., piece of wood).
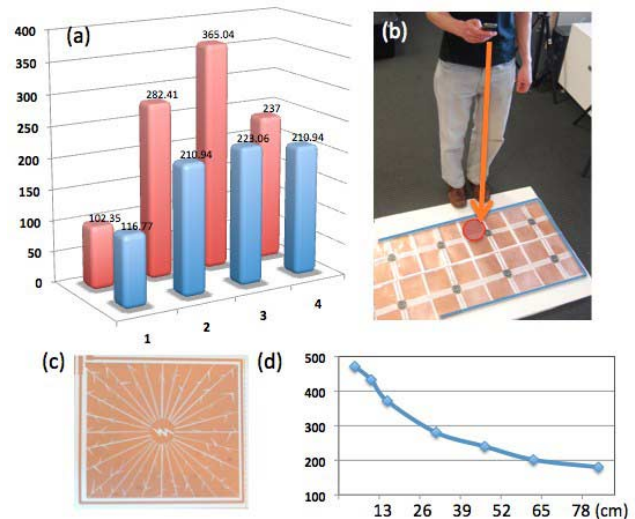

Figure 13. (a) Signal response versus sensing unit location when a NFC device is held 30cm from the surface. (b) Illustration of the experimental setup. (c) Close up of the NFC square loop antenna printed on each tile. (d) NFC signal strength versus distance.
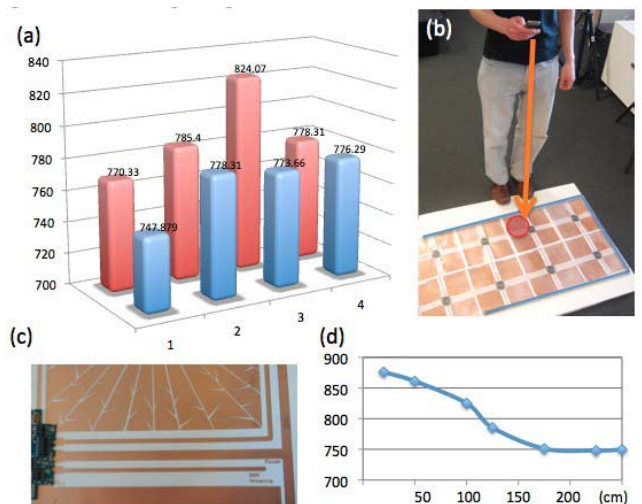

Figure 14. (a) Signal response versus sensing unit location when a GSM device is held 1m from the surface. (b) Illustration of the experimental setup. (c) Close up of the tile GSM antenna. (d) GSM signal strength versus distance.

OBSERVATIONS, EXTENSIONS AND APPLICATIONS
Passive mode is the simplest sensing method to integrate and implement with minimum electronic components, and it is yet one of the most powerful modes for localization. Crosstalk between different electrodes was unnoticeable. The received signal patterns could be used to distinguish walking direction, strikes and mid-swing – all useful information for gait analysis.

In order to minimize system power consumption (in our full system deployment, each unit consumes ~25 mA when it's actively scanning for each sensor input), we combined both

active and passive modes as a low power hybrid mode. The floor defaults to sleep mode and interrupted only when a vibration occurred at the nearby surface and immediately entered passive mode. Upon confirmation from the passive mode, the floor switches to active mode (see Figure 5). Interrupts can also be triggered by the passive capacitive sensing mode or GSM or NFC pickups. It is possible to form a larger network if the current drain is managed properly to avoid excessively loading the power bus lines.

Whilst the sensate floor described in this paper can detect and locate users, it is not intrinsically capable of identifying specific users. However, substantial studies of locomotion and especially gait structure analyses [24-26] suggest that it is possible to use the difference in a person's unique walking motion for identification. Given the gait data presented in Figures 7, 8 and 10 we believe these techniques may be applicable here. It may also be possible to combine additional sensing and identification modalities. For example, if a user is positively identified when they are logged into a desktop computer or when they make use of an electronic access control system, it may be possible to track them subsequently using the floor and maintain the correct association between identity and current location.

Besides localizing and identifying people, it may also be possible to use this technology to sense hands interacting with a surface such as a desktop or wall, and to associate these with the corresponding feet using active transmit mode coupling between the two surfaces through the user's body in a DiamondTouch–like manner [23]. It may also be possible to instrument more complex surface structures by folding or forming a conductive printed substrate in more sophisticated ways than we have presented here. In active capacitive sensing mode, the signal strength is strong enough to be used as a way of transmitting digital information from a body-worn device to the floor sensing system. For example, it would be possible put small tags on users' shoes that transmit unique identification signals for each person with a transmit electrode outside and local ground electrode inside against one's sock and sending the ID of a user (see Figure 15).

Figure 15. Illustration of transmitting/receiving into the floor – from clip on shoe to floor.

Our future work will focus on integrating this system into a building environment to form a ubiquitous computing platform. In addition to evaluating and extending the system further, this will give us an opportunity to investigate potential applications, including smart floor sensing for motion tracking, localization, identification, gesture recognition, gait analysis and a variety of human-computer interaction and ubiquitous computing scenarios.

CONCLUSIONS

In this paper we have presented what we believe to be a scalable and versatile distributed sensate surface based on a new conductive inkjet printing technology, which we believe will become increasingly well established. We constructed a 2.5m x 30cm hardware test-bed to demonstrate and evaluate the potential of this approach. Our design incorporates many different sensing capabilities based on the ability to create a large-scale non-rigid substrate with conductors printed onto it at a relatively low cost. This was not previously practical - it now opens the possibility of easily deploying a large-area surface sensing system. We described the design and implementation of passive and active capacitive sensing, coupled with GSM and NFC RF signal pickup – all based on copper electrodes and antennas printed on the substrate. We also demonstrated a way of incorporating piezoelectric sensors into the system.

Whilst we have not yet built or deployed any real-world applications of this technology, we have presented the results of our extensive evaluation of a range of sensing modalities that we built into our first prototype. We feel that we have proven the possibility of using conductive printing technology to build scalable and versatile generic surfaces for ubiquitous sensing. We also believe that it will be possible to further simplify the electronic circuitry which we currently use in conjunction with the flexible substrate through a design-for-manufacture process. Ultimately we believe that this technology has the potential to change the way we think about covering large areas with sensors and associated electronic circuitry – not just for floors but potentially desktops, walls and beyond – and we seek to inform such work with these early results.

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