The UnMousePad - An Interpolating Multi-Touch Force-Sensing Input Pad

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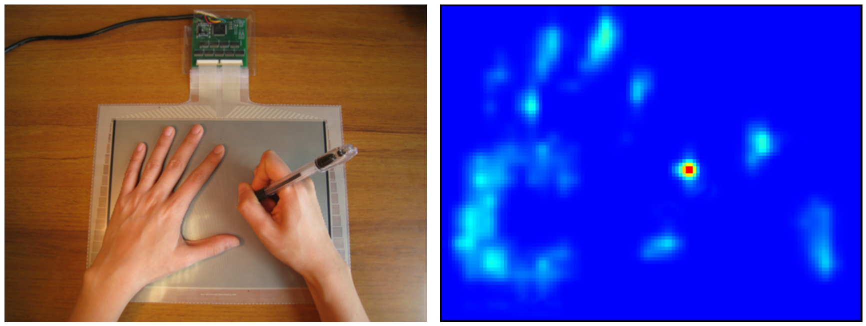

Figure 1: *Writing on an UnMousePad and the resulting force image (warmer colors represent greater pressure). The red dot corresponds to the high pressure point created by the pen tip.*

Abstract

Recently, there has been great interest in multi-touch interfaces. Such devices have taken the form of camera-based systems such as Microsoft Surface [de los Reyes et al. 2007] and Perceptive Pixel's FTIR display [Han 2005] as well as hand-held devices using capacitive sensors such as the Apple iPhone [Jobs et al. 2008]. However, optical systems are inherently bulky while most capacitive systems are only practical in small form factors and are limited in their application since they respond only to human touch and are insensitive to variations in pressure [Westerman 1999].

We have created the UnMousePad, a flexible and inexpensive multi-touch input device based on a newly developed pressure-sensing principle called Interpolating Force Sensitive Resistance. IFSR sensors can acquire high-quality anti-aliased pressure images at high frame rates. They can be paper-thin, flexible, and transparent and can easily be scaled to fit on a portable device or to cover an entire table, floor or wall. The UnMousePad can sense three orders of magnitude of pressure variation, and can be used to distinguish multiple fingertip touches while simultaneously tracking pens and styli with a positional accuracy of 87 dpi, and can sense the pressure distributions of objects placed on its surface.

In addition to supporting multi-touch interaction, IFSR is a general pressure imaging technology that can be incorporated into shoes, tennis racquets, hospital beds, factory assembly lines and many other applications. The ability to measure high-quality pressure images at low cost has the potential to dramatically improve the way that people interact with machines and the way that machines interact with the world.

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1 Introduction

Multi-touch input has been an active area of research for over two decades [Buxton et al. 1985] but has always suffered from the absence of an easily available high-quality touch input device that is accurately responsive to pressure and can scale inexpensively to large or small form factors. For this reason, exciting user interfaces developed in the lab have appeared on CNN [Han 2005], but not on everyone's desks, computer screens, table-tops, walls and floors. What has been needed - and lacking - is an inexpensive, flexible and sensitive *touch imaging* technology, capable of capturing even subtle variations in gesture.

The UnMousePad is a novel form of input sensor that enables inexpensive multi-touch pressure acquisition. It can accurately measure entire images of pressure with continuous bilinear interpolation, permitting both high-frame-rate and high-quality imaging of spatially variant pressure upon a surface.

Though the use of force-variable resistors at multiple points of contact is not new [Malacaria 1998], previous work in this area has focused mainly on arrays of discrete and independent sensors. The key difference between the UnMousePad and previous technologies is the newly developed principle of Interpolating Force Sensitive Resistance (IFSR), which closely mimics the multi-resolution properties of human skin, in which the position of a touch can be detected at finer scale than the discrimination of multiple touches.

The development of the UnMousePad and other IFSR based sensors and an improved understanding of their electrical properties enhances the type and quality of information that may be obtained in situations where entire images of pressure need to be constantly and continuously tracked. IFSR based sensor technology is inherently unobtrusive, inexpensive, and very durable. It has a very wide range of potential applications in many sectors of society, primarily because it enables multi-touch pressure imaging at a low cost in a wide variety of form factors.

2 Prior Work

Multi-touch input technologies fall mainly into three broad categories: optical, capacitive and resistive. Each of these affords a particular set of advantages and disadvantages.

2.1 Optical Sensing

Optical multi-touch sensing generally incorporates a digital video camera behind the touch surface to form an image of a user's fingers and possibly hands. Microsoft Surface [de los Reyes et al. 2007] integrates images captured simultaneously from several digital video cameras to obtain both touch and proximity information. In systems based on Frustrated Total Internal Reflectance [Han 2005] a finger or hand touch disrupts the path of infrared light that is undergoing total internal reflectance [Gettys et al. 1989] inside a glass surface. The scattered light is captured by a digital video camera placed behind the glass.

Recently [Davidson and Han 2008] have demonstrated the ability to determine touch pressure by incorporating a soft light-scattering layer over the touchable FTIR surface. Because of the use of a camera at some distance behind the touch surface, existing optical multi-touch technologies tend to be bulky and are often sensitive to lighting conditions.

2.2 Capacitive Sensing

In contrast, capacitive technologies can assume compact and flat form factors. Currently the most widely adopted capacitive-based multi-touch system is the touch-screen of the Apple iPhone [Jobs et al. 2008], a successful adaptation of research by [Westerman 1999]. The DiamondTouch system [Dietz and Leigh 2001], while not pressure-sensitive, is able to distinguish between different users, by incorporating each user's body into a unique capacitive circuit. Because they are based on capacitance, these systems can only measure the surface area of contact (albeit imprecisely due to variations in skin conductance between individuals). Thus, neither of these system can reliably distinguish different levels of pressure.

Another limitation of the capacitive principle is its reliance on the dielectric properties of the water within the human body – most capacitance-based systems are only able to track a finger, not a stylus or other object. One exception is the N-Trig DuoSense [Perski and Morag 2002], which is able to track both finger and stylus, by making use of a special pen.

2.3 Resistive Sensing

Resistive array based multi-touch sensors can have a flat form factor, are inherently inexpensive, use little power and can measure applied force. Such devices are based on the principle of Force Sensitive Resistance [Eventoff 1979]. An FSR device is a continuous electrical switch through which electric conductance increases gradually as external force is applied. In one common configuration, two conductors which have both been coated with FSR ink are placed into mutual contact.

The FSR principle is often used to create discrete sensor arrays. An inherent limitation of such arrays is their inability to track at resolutions finer than the spacing between successive sensing elements, and their inability to track a stylus when it enters the dead zones between sensels. For this reason, the JazzMutant and Stantum sensors [Joguet and Largilliar 2007] are limited to applications such as music remixing that do not require high precision, whereas Tekscan sensors [Malacaria 1998] cost thousands of dollars due to the high cost of electronics required to scan a high-density array. Another approach to creating multi-touch pressure sensors is to combine multiple buttons that can each sense a position and a force [Wessel et al. 2007]. However, these devices still suffer from the inability to track the position of styli and fingers between sensor cells.

To improve tracking, one could put a thick sheet of rubber over existing devices, blurring the force image, and thereby creating a form of positional interpolation. However, per our experiments, such a layer of rubber needs to be approximately half an inch thick to have any appreciable effect. Besides the packaging, weight and aesthetic issues that this creates, the blurring makes it impossible to distinguish a stylus press from hand/finger input. In addition, the damped signal has higher latency and greatly reduced temporal resolution. Our approach allows for high-resolution, high-speed, force-sensitive positional tracking without the expense of a high-resolution discrete FSR array, or the signal losses associated with a mechanical blurring layer.

3 Our Contribution

An all-purpose pressure-sensitive multi-touch input device needs to do at least two quite different things: (i) track a stylus with high resolution, and (ii) distinguish between different fingers of a human hand. These are very different requirements. Fingertips are relatively large, and their centers never get much closer to each other than about half an inch. In contrast, a stylus tip generally needs to be tracked to within a fraction of a millimeter. In addition, while the distance between nearby fingers may be large, fine position sensing is useful for detecting subtle finger movements, such as leaning and wiggling.

What has not been shown previously is a multi-touch input technology that provides, simultaneously, a flat and flexible/bendable form factor, the option of transparency, ability to inexpensively scale up to large sizes, accurate pressure sensing, self-calibration, interpolation between touches, low power and low cost. We have achieved this by revisiting the use of force sensitive resistance in a novel way.

In the remainder of the paper, we discuss the following key contributions:

1. The general principle underlying the sensor.
2. Construction of IFSR sensors.
3. Methods for electrically scanning IFSR sensors.
4. Methods for improving accuracy.
5. Methods for interpreting device output in software.
6. Applications of IFSR sensors.

3.1 Interpolating Force Sensitive Resistance

Interpolating Force Sensitive Resistance (IFSR) is a new and cost-effective method we have developed for using FSR to capture images of pressure upon a surface. With pre-existing arrays of discrete FSR sensors, it is not possible to correctly reconstruct the position of a point touch with a low-resolution grid. In contrast, the IFSR has sensels with overlapping regions of sensitivity (see Figure 2). The spatial drop-off in sensitivity at each sensel of an IFSR is near-linear on both X and Y axes, resulting in a piecewise bilinear response kernel. The bilinear kernel allows the position of any touch, even a very small point touch - such as that of a stylus tip - to be accurately interpolated by calculating the voltage-weighted average of the sensel positions (see Equation 1). Effectively, the IFSR yields an anti-aliased image of the pressure applied to it.

$$(X,Y) = \left(\frac{\sum_i \sum_j i * V_{out}(i,j)}{\sum_i \sum_j V_{out}(i,j)}, \frac{\sum_i \sum_j j * V_{out}(i,j)}{\sum_i \sum_j V_{out}(i,j)} \right) \quad (1)$$

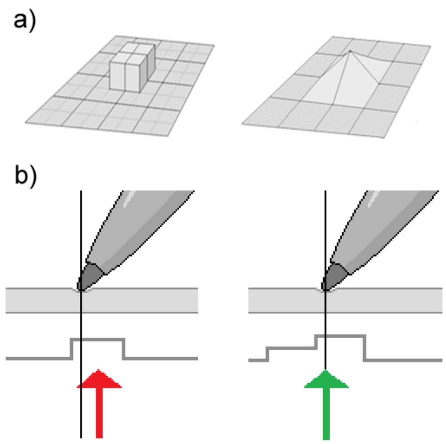

Figure 2: *Discrete versus bilinear sampling. a) Area response of one sensel of a discrete FSR sensor (left) vs. an IFSR sensor (right). b) Reconstruction of pen position with a discrete FSR sensor yields an error in position (left), while an IFSR sensor properly reconstructs position with minimal error (right).*

As a result, the IFSR has two notions of resolution. The first is how close two touches can be before they can no longer be distinguished from each other. We refer to this as *grid resolution*. The second measures the much finer positional resolution at which a single point can be tracked. We refer to this as *positional resolution*. An IFSR allows grid resolution to be much lower than positional resolution. Compared to a discrete FSR sensor, an IFSR sensor with similar positional resolution can be manufactured with relatively inexpensive drive and A/D conversion electronics. Because of the lower grid resolution, IFSR sensors also require less bandwidth to process and transmit the acquired data.

3.2 UnMousePad Construction

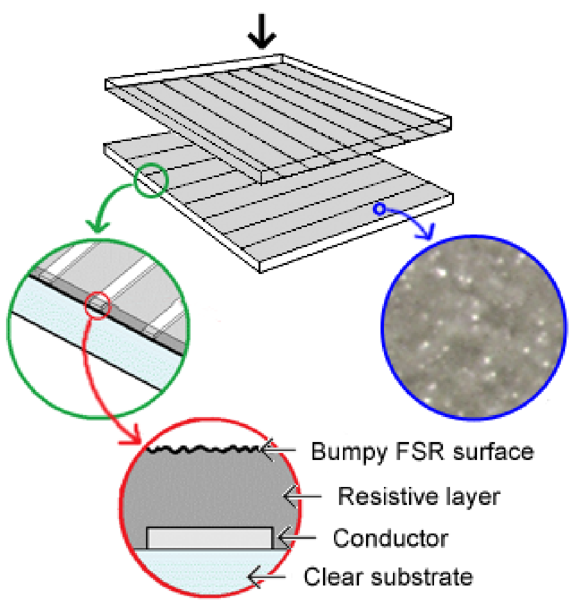

Figure 3: *The UnMousePad is constructed by sandwiching together two sheets with electrodes at right angles. The electrodes are covered with a thin continuous layer of FSR ink. A contrast-enhanced image of FSR material at 20x magnification is provided.*

We have built IFSR sensors in various form factors including credit-card sized sensors, large disk-shaped sensors, transparent sensors, and 12" x 16" sensors for two-handed operation. We affectionately call our 8.5" x 11" form factor IFSR device (shown in Figure 1) the *UnMousePad*. It is conveniently sized like a page of standard letter paper. It has an 6.85" x 9.21" active sensing area consisting of a 40x30 grid of sensels spaced at 6mm intervals – sufficient to obtain two samples per finger width, and therefore to reliably distinguish between two fingers even when those fingers are very close together.

The UnMousePad consists of two paper-thin 8.5" x 11" sheets of PET (polyester) plastic attached together at the edges. On the inner side of the top sheet is a circuit pattern consisting of 40 parallel active column electrodes spaced at 6mm (with non-active drone electrodes in-between at 1mm intervals). The circuit pattern is coated with a thin, solid layer of FSR ink. As this ink dries, its exposed surface hardens to form microscopic bumps (see Figure 3). Because the sensor uses a solid layer of ink, it is easy to align it with the electrode layer, reducing manufacturing cost. A printed wire runs from each electrode to a connector area that is provided on one side for interfacing with electronics. The inner side of the bottom sheet has a similar pattern with 30 row electrodes which are perpendicular to the column electrodes. A circuit board is connected to the top and bottom layers which contains electronics that read from the UnMousePad and send pressure images to a computer via USB.

3.3 Scanning the UnMousePad

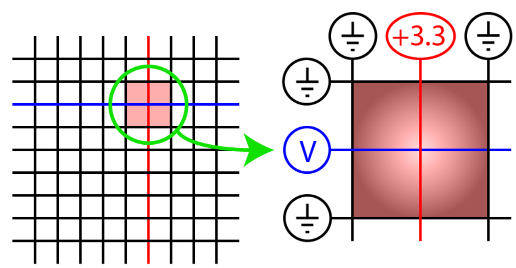

Figure 4: *One time-slice during a sensor scan. Red wire indicates powered column electrode, blue wire indicates metered electrode, and black wires indicate grounded electrodes. Pink area illustrates bilinear sensitivity in metered region.*

A micro-controller on the circuit board scans all row/column intersections in succession. At any given moment of the scan, some column i is connected to a positive voltage source (+3.3V for our micro-controller) and some row j is connected to an A/D input port on the micro-controller, which measures output voltage. Meanwhile, all other rows and columns are connected to ground (see Figure 4).

Consider the highlighted (pink) region in Figure 4. If the sensor is not being touched in this region, a steady stream of current will flow from the positive voltage source to the neighboring grounded electrodes to the left and right along the top FSR surface, but no current will flow between the top and bottom surfaces.

When a user touches the UnMousePad in the highlighted region, current is able to flow through to the bottom surface. Some of this current goes to the nearest grounded electrodes on the bottom surface above and below, and some of it goes through the metered electrode to the circuitry that is measuring voltage (Figure 4). As the position of the touch moves nearer to the intersection between the positive voltage source and the metered output line (i.e. toward the center of the highlighted region), the measured voltage increases.

3.4 Avoiding False Positives

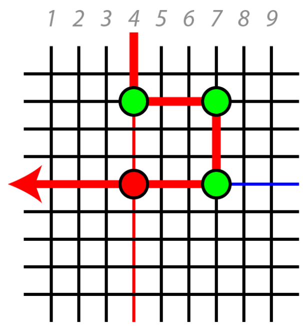

Figure 5: *False positives are avoided by grounding. Green dots indicate real touches. The thick red line indicates a current path that would result in the detection of a phantom touch (red dot) if the non-active electrodes weren't grounded.*

It might seem that a multi-touch device with passive junctions (as opposed to a transistor at every wire intersection) would produce false positives. In Figure 5, green dots indicate three touches where wires cross, and the red dot and path indicate an erroneous phantom touch that might result when input voltage is applied to column 4 and output voltage is measured at row 5.

The UnMousePad does not suffer from this problem because at any moment during the scan, all conducting lines that are not set to either the positive voltage source or the metered output are set to ground. In the above example, the current would simply drain to ground at both row 2 and column 7, rather than at row 5.

3.5 Interpolation Linearity

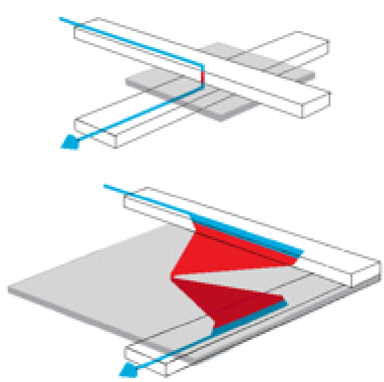

Figure 6: *Touch sensitivity at corner (top) and center (bottom) of a 6mm cell. In both diagrams, current traveling through low-resistance metal is shown in blue, and current that travels through high-resistance FSR ink is shown in red.*

Ideally, the drop-off in response with respect to distance from a row/column intersection should be linear in both the X and Y directions. However, our early generation of UnMousePad prototypes had very poor interpolation behavior – sensitivity as a function of distance from the active intersection fell off much faster than expected.

In theory, this non-linearity could be compensated for in software, by use of a look-up table or by analytically solving for position of a point given the signal from the sensor. However, we found that a non-linear response reduced the sensor's signal-to-noise ratio, making this approach impractical. After careful analysis and experimentation, we found that there were two sources of error. We discuss each one in turn, together with methods to reduce them.

3.5.1 Radial Spread Non-Linearity

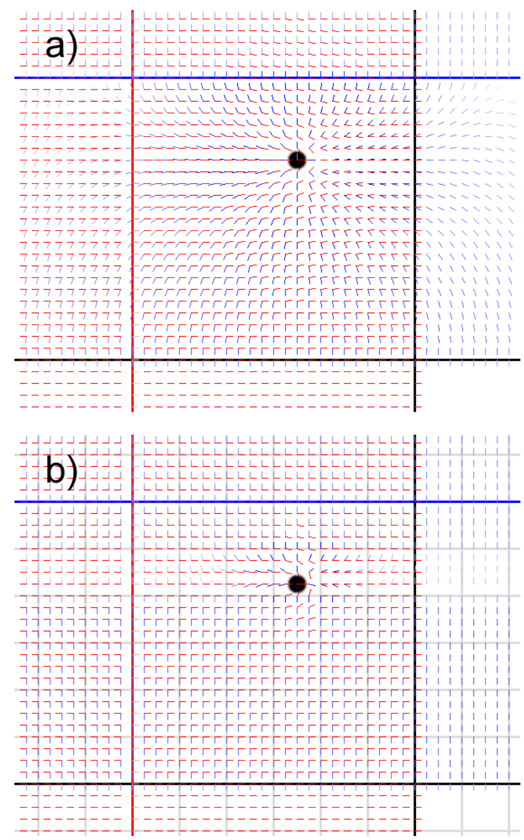

Figure 7: *Potential field for a 100g point touch on a sensor with and without drone wires (computed with field solver). Thick red, blue and black lines represent powered, metered and grounded electrodes respectively. Red and blue vectors correspond to gradients on the top and bottom surfaces respectively. a) Without drones, potential field is curved, leading to non-linear response. b) With drones, linearity of potential field is greatly improved.*

Touching where two wires cross (top of Figure 6) requires very little travel of current transversely through the high-resistance FSR paint, whereas touching far away from the nearest conductor (bottom of Figure 6) requires a significant distance of current travel within each paint layer. Because the current spreads radially around the touch point, the resistance increases non-linearly as the touch point moves farther away from the area where conductors cross. Using a field-solver that we implemented to precisely simulate the flow of current through the layers of the UnMousePad, we can see the radial pattern in the gradient of voltage around a touch point (top of Figure 7). This pattern occurs consistently with touches of varying force and size, and is greatest for a touch near the center of a cell.

We addressed this issue by altering the printed conductor pattern to insert, between every pair of active wires, numerous parallel "drone wires" (bottom of Figure 7). These passive wires have the effect of greatly shortening the maximum effective path that electric current needs to travel through the resistive paint in one direction, effectively creating an anisotropically conductive surface. This shapes the voltage potential field to vary mostly along the direction perpendicular to the wires in a given layer. As the number of drone wires increases, the scale at which the radial spread of current occurs proportionately decreases, and would approach zero for an infinitely fine drone conductor pitch. With our current manufacturing technique, we can reliably print electrodes with 1mm spacing. Thus, we place five drone wires between each pair of active electrodes. This greatly improves the tracking resolution for fingers and styli and the accuracy of force measurements (see Section 4.5).

3.5.2 Voltage Divider Non-Linearity

While it is possible to completely eliminate the non-linearity due to the radial spread of current by introducing a large number of drone wires, there is a second form of non-linearity that results from the fact that when a touch occurs, the current flowing from the top layer of the sensor to the bottom layer disrupts the voltage gradient between electrodes on both the bottom and top layers of the sensor. This effect would not go away even if there were an infinite number of drone wires. Furthermore, this effect cannot be fully compensated for in software because error in position and error in force are difficult to distinguish.

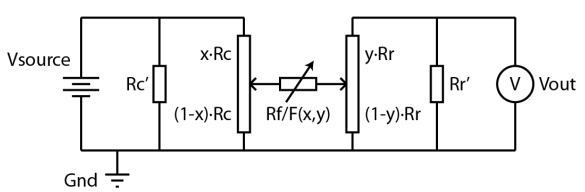

Figure 8: *Schematic of effective circuit at one grid cell for a single point touch.*

To understand the impact of this effect and find ways to reduce it, we created a simplified electrical schematic that models the behavior of a sensor cell in response to a single point touch (Figure 8). In this model, V_{source} is the voltage applied to a powered column. V_{out} is the voltage measured at the metered row. x and y are the positions of the touch and vary from (0, 0) to (1, 1). R_f is the resistance between the top and bottom layers of FSR material. We refer to this as the "through" resistance. $F(x, y)$ is the force applied at point (x, y). R_c is the resistance between two adjacent column electrodes of the sensor. R_r is the resistance between two adjacent row electrodes. R_c and R_r depend on the "transverse" resistance across the surface of the FSR material (R_{fsr}), the length and spacing of row and column electrodes (L_r, L_c, S_r, S_c), the density of drone wires (D), and the thickness of FSR material (T_{fsr}) (see Equations 2 and 3). R'_c and R'_r are the resistances of all other current paths to ground from a row and column electrode, respectively, and are equal to Rc and Rr in our sensor. Equation 4 results from solving for $V_{out}(i, j)$ for a given pressure distribution $P(x, y)$ over the modeled sensor area A:

$$R_c = \frac{R_{fsr} * S_c * (1 - D)}{L_c * T_{fsr}} \tag{2}$$

$$R_r = \frac{R_{fsr} * S_r * (1 - D)}{L_r * T_{fsr}} \tag{3}$$

$$V_{out} = \iint_A \frac{a * V_{input} * x * y}{b(x - x^2) + c(y - y^2) + R_f/P(x, y)}\, dx\, dy \tag{4}$$

$$b = \frac{1}{1/R_c + 1/R'_c} \approx R_c/2 \tag{5}$$

$$a = c = \frac{1}{1/R_r + 1/R'_r} \approx R_r/2 \tag{6}$$

According to this model, if b and c were both zero, V_{out} would be perfectly linear with respect to the magnitude and position of an applied pressure distribution. However, in practice, reducing these values results in decreased output voltage and increased consumption of power by the device. Thus, the best we can do is find a ratio of b and c that is low with respect to $R_f/P(x, y)$, and yet high enough to allow the external electronics to read the sensor. Luckily, there are two factors that work to our advantage, producing a desirable ratio. The first is that in the useful range of operation for a human operator, the FSR inks we use tend to have a fairly high through resistance between 1.2 MOhms and 2.2 kOhms for forces between 5 grams and 200 grams. The second is that with proper selection of FSR inks, we can attain values of b and c that are approximately 300 Ohms and 400 Ohms respectively. Thus, we have approximately an order of magnitude difference between the "through" and "transverse" resistance. The result is a nearly linear sensitivity (see Figure 9), which allows the electronics to read signals having a high signal-to-noise ratio.

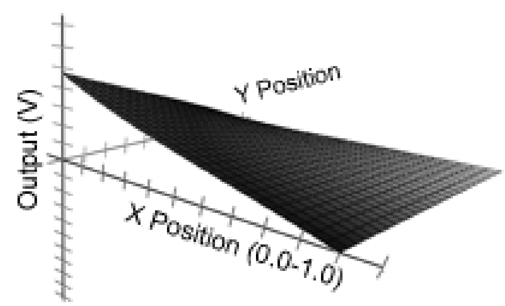

Figure 9: *Calculated response of a single row/column intersection of the UnMousePad sensor resulting from a point touch of 100 grams at different (x, y) locations. Voltage decays in a linear fashion along X and Y axes.*

4 UnMousePad Characteristics

4.1 Electronics

The main component on the UnMousePad circuit board is a PIC24H micro-controller produced by Microchip Technology, Inc. which uses five M74HC595 shift registers to power one column electrode at a time while grounding all others, then reads analog voltage values from each even row, followed by each odd row, while four other M74HC595 shift registers are used to alternately ground the odd or the even rows respectively. The micro-controller then switches to the next column and repeats for the remaining columns. The micro-controller converts those analog voltage values to a digital value via an onboard 12-bit analog-to-digital converter. Finally, the micro-controller sends the complete frame of data to the host computer.

4.2 Scan Rate

The data stream from the UnMousePad consists of 1200 pairs of bytes forming a 40x30 image of force on the sensor. Each frame is followed by a terminating sequence. Whenever a run of successive zeros is encountered, a special code followed by the number of zeros is sent, effectively run-length-encoding long strings of zeros for areas of the sensor not being touched. The computer then receives, decompresses, and processes these pressure images at approximately 60 frames per second. The measured latency is 1/60th of a second. Currently, the rate-limiting factor is the USB transceiver chip which restricts the data rate into the computer to 900kbits/sec. Because the A/D converter on the micro-controller is capable of up to a million samples per second, we are confident that we will be able to attain sample rates of over 500 frames per second once we switch to a faster USB transceiver.

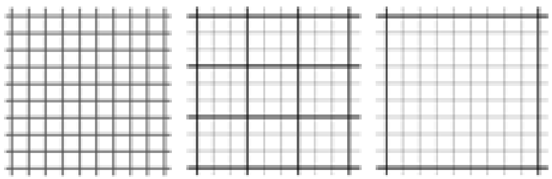

Figure 10: *Scan resolution can be dynamically varied. Left: all active lines are scanned; Middle: every third active line is scanned, other lines effectively become drone conductors (gray); Right: sensor is scanned at the lowest possible resolution, effectively turning it into a single-touch sensor.*

It would appear that this method of scanning would not scale well to larger sensors, and would be insufficient for applications such as musical instruments where scan rates over 1000 Hz are necessary, or for mobile devices that need to draw as little current as possible. However, the IFSR architecture has a useful property which allows a dynamic trade-off between spatial resolution on the one hand, and faster scan rate and lower power consumption on the other.

Spatial resolution can be lowered simply by disconnecting sets of column or row electrodes from both power and ground, effectively turning them into drone conductors (the disconnection can be done using commonly available electronic logic that has a high-impedance mode). For instance, if we disconnect every other column and row electrode, the grid resolution goes down by a factor of two, and the scan rate goes up by a factor of four. Taking this further, if every column and row electrode is disconnected except the first and last ones on each side, the sensor acts as a single bilinear cell which can only measure the centroid and sum of pressure exerted over the entire sensor surface (see Figure 10). Finally, it is possible to adaptively scan the sensor with finer detail only in areas where contact is made or where fine detail is required. This allows for the best of both worlds - providing high resolutions in areas where there is contact, while providing high speed and low power usage over areas with no contact.

This variable resolution allows for the scanning of the sensor at many thousands of frames per second in order to detect very short duration impacts. It also permits a "sleep mode", whereby battery-powered devices that need to conserve power can idle without drawing significant power as they wait for a touch event to awaken them. Finally, it permits us to build large, high resolution sensors without significantly impacting electronics cost.

4.3 Power Consumption

The shift registers mentioned above are used because they are capable of sourcing/sinking much more current than the micro-controller – up to 35mA. We found that the sensor could draw instantaneous currents of as much as 30mA when scanning a row/column intersection where the applied force was over 5kg. However, because 1200 points are scanned every frame, even when a great deal of force is applied to the sensor, the average current draw during the span of one sample frame remains very low. During full speed operation, the sensor and shift registers which drive it consume on average less than 1mA. This allows the UnMousePad to be powered entirely from the USB bus.

4.4 Sensitivity

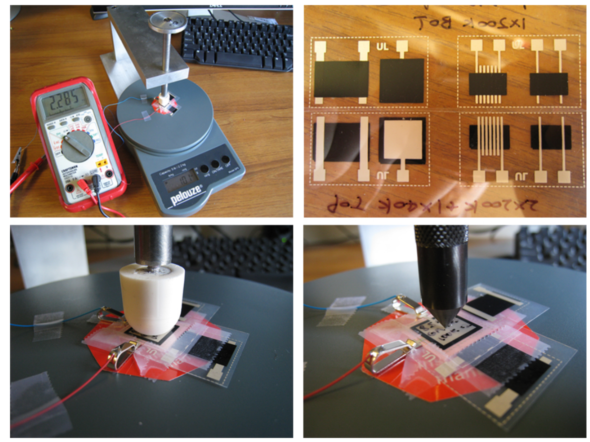

Figure 11: *Sensitivity testing. Upper Left: setup showing sensor on scale, plunger, and ohm-meter connected to sensor; Upper Right: closeup of test areas cut from sensors; Lower Left: finger-shaped silicone rubber plunger; Lower Right: plunger fitted with pen-tip*

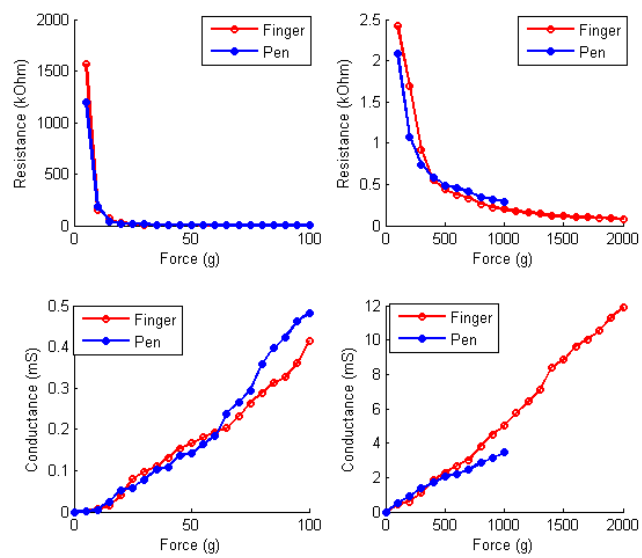

Figure 12: *Force vs resistance (top) and force vs conductance (bottom) at various force ranges (0 to 100 grams on the left, and 0 to 2000 grams on the right) for a point touch and an area touch.*

Using a calibrated force gauge and weights (Figure 11), we found that the lightest force the UnMousePad can reliably detect is 5 grams, and the lightest touch that can be reliably tracked as it moves over the UnMousePad is in the range of 15-30 grams. By comparison, the force needed to press down a typical computer keyboard key is about 65 grams, and for a typical mouse button, about 90 grams. There is a near-linear electrical conductance response to forces between 5 grams and 5 kg (Figure 12). Furthermore, comparing the response to a finger and pen touch, we see that the sensor measures force accurately for touches with different contact areas.

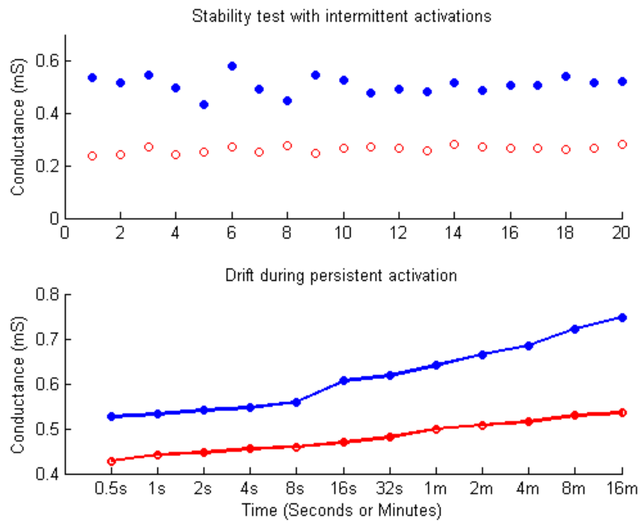

Figure 13: *Sensitivity drift over time with intermittent activations at one-second intervals (top), and with persistent activation over a period of 16 minutes with a logarithmic time scale (bottom).*

We also measured the repeatability of sensor force measurements (Figure 13). We found that with repeated activations, performed at one-second intervals, the measured force had a 5% standard deviation with very little drift. However, we found that with steady pressure at a single point, sensitivity increased over time. Although the increase was 5% over the first five seconds, we found that the rate of increase decayed exponentially with time. After removing the force and reapplying, the exact same pattern repeated. The authors suspect that this is due to the FSR surfaces intermeshing ever closer at a microscopic level over time, and that this effect can be removed in software. In practice, the inaccuracy due to this effect is dwarfed by the lack of precision in human ability to apply constant pressure over time.

4.5 Resolution

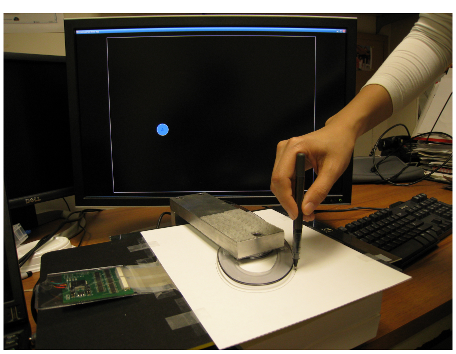

Figure 14: *Resolution test setup. UnMousePad captures curve drawn on paper above.*

To experimentally determine the point-tracking resolution of the UnMousePad, we record the (X, Y) positions of our point tracking algorithm over time, as a curve is drawn on a sheet of paper placed over the UnMousePad. A "French Curve" mounted $1/4$" above the sensors is used as a guide. Next, we scan the reference curve drawn on the paper with an optical scanner at 600dpi and use a thinning algorithm to find the line passing through the center of the curve. Finally, the curves are registered by shifting and the error

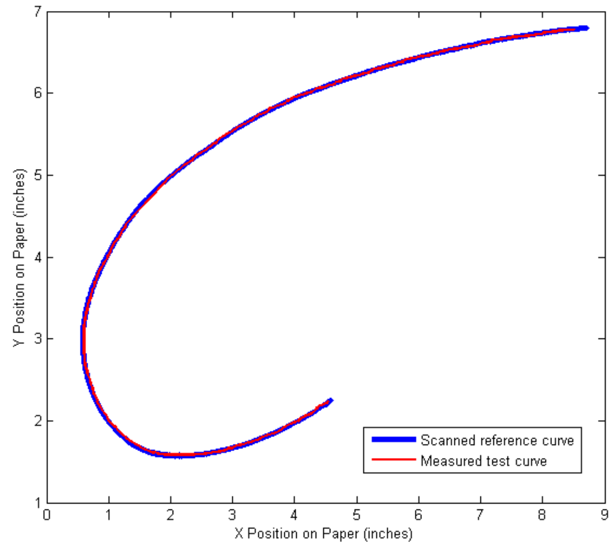

Figure 15: *Resolution test result. Curve captured by the sensor is overlaid onto the thinned reference curve scanned from the paper.*

is computed as the root mean square of the distance from each point in the test curve to the closest point on the reference curve. Using this procedure, we determined that the UnMousePad can track a fine point such as a pen-tip with a resolution of 0.2934 mm (about 0.0115 inches, or 87 dots per inch). Note that no calibration of the UnMousePad was needed to achieve this result.

5 Data Processing and Touch Tracking

For most graphics and HCI applications of the UnMousePad, rather than using raw images of pressure, it is often useful to work with a higher-level representation of the user's interaction with the device. In our driver-level code, we process the raw images to find touches which are tracked from frame to frame. Each touch consists of a unique identifier, an (x, y) position, the total force of the touch and the shape of the oval that encircles the touch, as well as lower level data such as the pixels that comprise the touch. A list of touches is provided to applications, as are change events such as "touch up", "touch down" and "touch moved". Furthermore, we can detect when two touches come so close together that they are no longer distinguishable (which can happen when a user pinches two fingers very close together) and when a single touch splits into two (the opposite of the first event). We call these two events "touch merged" and "touch split" respectively.

In order to get the full benefit of the UnMousePad's pressure imaging capability, the data must be properly processed. This processing consists of several stages of filters. Many of these filters operate on 2D images of force using standard image processing techniques. Because of the interpolating nature of the device, these images are inherently low-resolution and can be processed efficiently in real-time on a micro-controller or a CPU using a small amount of processing power. The processing consists of the following steps:

1. *Force Image Acquisition and Compression:* Micro-controller captures a frame of data, and compresses it for transmission over a USB bus.
2. *Force Image Decompression:* Data is decompressed into a 40x30 image and normalized to grams.
3. *Time Domain Smoothing:* Noise is reduced by averaging current frame with last smoothed frame.

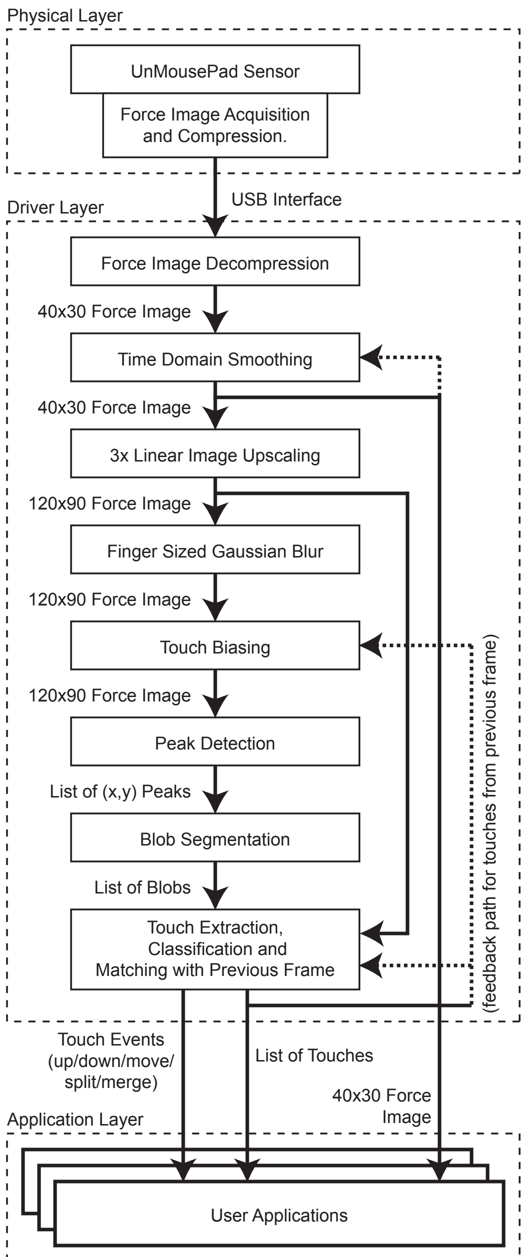

Figure 16: *Illustration of data flow from sensor to application.*

4. *Force Image Upscaling:* To enable accurate segmentation into touch events, upscale resolution by 3x. Reduce forces correspondingly by factor of 9.
5. *Gaussian Blur:* To improve finger tracking and remove singularities introduced by linear upscaling, perform a gaussian blur approximately the radius of a finger touch.
6. *Touch Biasing:* When force is near minimum touch threshold, or when touches merge or split, there can be oscillation between touch/not-touch in successive frames. To avoid these instabilities, bias blurred image by adding a small gaussian-shaped force signature wherever touches were detected in previous frame.
7. *Peak Detection:* Each pixel of biased image is compared against neighbors. Mark any pixel with a higher force than all neighbors as a peak.
8. *Blob Segmentation:* Segment image into areas around each peak by seeding each blob with peak location, then iteratively expanding each blob to encompass neighboring pixels with lower force value than pixels in blob. Stop growing at zero-valued pixels or when blob reaches a pre-set max size.
9. *Touch Extraction:* Compute position, size, total force and surrounding oval for each blob (using both blob data and unblurred image). Position is computed as the force-weighted average of the positions of pixels within each blob.
10. *Touch Classification:* Classify each touch as either *(i)* noise if below minimum touch force threshold, *(ii)* point touch (stylus) if ratio of force to area is above a predefined threshold or *(iii)* area touch (finger, palm or object) if ratio of force to area is below threshold.
11. *Matching with Previous Frame:* Match up touches with those in previous frame having corresponding position and size, giving each touch the same unique id as in previous frame. First time touches generate touch down events, and touches that disappear generate touch up events. When two touches of force a and b merge to a touch of force $a + b$, generate a merge event; vice versa for a split event.
12. *User Applications:* Send pressure images and touch events to user applications.

6 Applications

6.1 Bendable Sensors

Our current generation of UnMousePad is physically bendable. Its bending radius depends upon what material is used for the plastic - thinner is more bendable. We currently use either 3mil or 5mil thick plastic substrates, which permit bending radii of approximately 0.5” and 1.0”, respectively. We have taken advantage of this flexibility to create applications that call for the UnMousePad to be wrapped around a cylindrical grip. An interesting related feature of the UnMousePad is that it can be used as an accurate bend sensor.

6.2 Sensing Through Paper, OLEDs and e-ink

We have found that the UnMousePad can read quite well through one or more sheets of paper. For example, when the UnMousePad is placed behind a pad of paper, the user can draw, write or scribble on the top sheet of the pad, and we can use the information that comes through to the UnMousePad to reconstruct the drawn image.

Similarly, the UnMousePad can read quite well through emerging thin flexible display technologies such as OLED and e-ink. Because such displays are often manufactured on substrates similar to those used for the UnMousePad, it can readily pick up pressure through them. This allows for the addition of touch sensing without any loss of display brightness or contrast.

6.3 Integration with Rigid Displays

In addition to opaque UnMousePads, we have made UnMousePads with transparent FSR material. Opaque FSR inks are typically composed of a carbon-infused polymer, whereas transparent FSR inks are made of a clear polymer infused with a transparent conductor. We have found the transparent versions to be well-suited for use over LCD displays. The conductive electrode lines can be either transparent or opaque.

Transparent conductors are typically made of ITO (indium tin oxide). Unfortunately, due to the high resistance of ITO, sensors with transparent conductors cannot be made very large. Opaque conductors, made of silver, copper or aluminum, have much better conductance than any known transparent conductor, and they can be made so thin as to be virtually invisible, especially if properly aligned with the opaque conductors between the pixels of an LCD screen.

In addition to plastic, we have also found that thin (6 mil) glass is suitable as a substrate for IFSR sensors, with no appreciable loss of spatial resolution. Glass can be advantageous over plastic for transparent touch-screen applications, since many people prefer the feel of glass.

6.4 Pressure-Sensitive Interaction

The availability of fine resolution in pressure makes it possible to distinguish between gestures in interesting ways. This property distinguishes the UnMousePad from capacitive input sensors such as the iPhone's screen which only measure contact area. Fine pressure resolution is needed to correctly interpret many pressure-dependent gestures. For example, lateral movement of a finger that is pressing down indicates wiggling, whereas the same lateral movement of a lightly touching finger indicates displacement by sliding.

Fine pressure resolution also permits highly accurate isometric control. For example, we have found that users of the UnMousePad quickly become proficient at manipulating virtual 3D objects with seven degrees of freedom by placing their fingers upon the pad to translate, rotate and scale an object. In another application we have used isometric pressure of fingers on the UnMousePad to simultaneously manipulate the eight faders of a BCF2000 MIDI controller, mapping pressure directly to fader settings.

In all of the above examples, the control scheme can be effective only because we are using an input device capable of simultaneously tracking all finger touches with fine pressure resolution. These and other examples of unique applications of our device can be seen in the supplemental video.

7 Conclusion

In ongoing work, we are improving our driver-level algorithms to add useful features such as the ability to automatically distinguish the pressure profiles of palms, wrists, the side of the hand, and other objects. We are also building transparent devices for use over LCD screens, and are integrating the UnMousePad drivers with Microsoft Windows 7, which recognizes multi-touch devices. We have also begun to research combining the UnMousePad with various forms of active haptic response, notably arrays of piezoelectric transducers.

In future work we plan to explore a variety of form factors, including flexible inserts for shoes and clothing, non-flat IFSR skins for such devices as game controllers, tennis racket grips and robots, as well as continuously extendable IFSR coverings for floors, tables and walls. We are particularly interested in capturing the subtle dynamics of human foot placement, as this capability opens up a wide range of applications, from dance to physical therapy. Furthermore, we believe that the core principle of the IFSR device – the anti-aliasing of physical phenomena before conversion to digital signals – is an exciting principle applicable to the transduction of sound, electro-magnetic waves and many other types of signals.

In conclusion, IFSR technology has the potential to revolutionize the field of multi-touch interaction by providing a low-cost, high-quality, flexible pressure imaging device. As the availability of IFSR devices increases, and their costs continue to drop, we anticipate that they will find a myriad of new uses, and will come to play an important role in many aspects of everyday life.

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