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Development of a Carbon Fiber Knitted Capacitive Touch Sensor

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ABSTRACT

Textiles, in combination with advances in materials and design, offer exciting new possibilities for human and environmental interaction, including biometric and touch-based sensing. Previous fabric-based or flexible touch sensors have generally required a large number of sensing electrodes positioned in a dense XY grid configuration and a multitude of wires. This paper investigates the design and manufacturing of a planar (two-dimensional, XY location) touch fabric sensor with only two electrodes (wires) to sense both planar touch and pressure, making it ideal for applications with limited space/complexity for wiring. The proposed knitted structure incorporates a supplementary method of sensing to detect human touch on the fabric surface, which offers advantages over previous methods of touch localization through an efficient use of wire connections and sensing materials. This structure is easily manufactured as a single component utilizing flatbed knitting techniques and electrically conductive yarns. The design requires no embedded electronics or solid components in the fabric, which allows the sensor to be flexible and resilient. This paper discusses the design, fabrication, sensing methods, and applications of the fabric sensor in robotics and human-machine interaction, smart garments, and wearables, as well as the highly transdisciplinary approach pursued in developing medical textiles and flexible embedded sensors.

INTRODUCTION

Touch-sensitive interfaces offer unique and robust levels of interaction between users and touch-enabled devices. In the last 10 years, human-computer interaction (HCI) reaped tremendous benefit from the design and development of such interfaces, now ubiquitous in smartphones and tablets. Other HCI areas, such as robotics and wearable technology, could benefit from sensors that detect touch—especially soft and flexible ones.

In the field of robotics, soft touch sensors could improve the quality of human-robot interaction (HRI). Low-cost depth cameras have revolutionized aspects of HRI in terms of environment mapping and kinematic planning. However, tactile sensing, which directly correlates to the robot's dynamics, is often neglected. This is due in part to rigid construction and control schemes that ease proprioception, but cannot account for unplanned collisions. Soft sensors would alleviate some of these issues by allowing deformation at contact points that may relax tighter kinematic constraints and further enhance the ability for robots to function well in a wide range of environments [1].

Several groups have already begun conducting research on the production of soft, flexible touch sensors. Recently, Google's Project Jacquard developed a method of using industry standard jacquard machinery to produce textiles with integrated sensors for use in bespoke smart garments [2]. Georgia Tech's Healthcare Robotics Lab developed silicone sensors with "taxels"—tactile pixels—used to characterize force applied to a robotic arm [3]. Many other methods have also been investigated such as using conductive rubber [4], layering of piezo-resistive and conductive textiles [1], combinations of conductive knit or woven textiles [5] and threads [6] [7], screen printing [8] [9], splicing of optical sensors into individual fibers and knitting of structures containing silver coated nylon [10], stainless steel [11] [12], and carbon or polymeric conductive yarns [13]. Sensors knit with carbon fiber filament show promise for improving the sensitivity of wearable devices. The knitting process ensures repeatability of the design, while the carbon fiber has been shown to function well in a wider range of conditions [14].

While great progress has been made, many of these solutions still face a number of challenges with respect to manufacturability and robustness. Hard and fragile embedded electronic components and the need for bundles of wire leads often diminish the feasibility of these solutions [15]. Human factors can change the efficacy of these devices [16], for instance the need to recalibrate antenna components that can function at different frequencies on the human body than they do in free space [17]. In the case of sewn sensors, the production process is lengthy, complex, and cannot easily conform to exact measurements. Additionally, the need to wash and clean these textile sensors may arise, adding complexity to the design and production [18].

Like the authors of "Textile-Based Weft Knitted Strain Sensors: Effect of Fabric Parameters on Sensor Properties," we also believe that knitting is a highly advantageous method of producing soft, flexible sensors that address some of the challenges mentioned above. Knitting is a method of fabric production that has existed for thousands of years and has been successfully mechanized over the past several hundred years [19]. Weft knitting is the intermeshing of horizontal rows of loops to create a fabric that can stretch in both the horizontal and vertical directions. Digital knitting provides a number of manufacturing advantages. A wide range of materials in the form of yarn have already been tested and established for use in knitting machines, and garments can be knit with multiple materials seamlessly within the same textile. If only a small quantity of a material is available for testing, it can still be incorporated in small segments. Seamless knitting also eliminates potential points of structural weakness and provides a platform for the development of continuous soft circuitry. When combined with techniques such as knitted spacer fabrics, knitting can be used to create 3D forms that are suitable for electronic devices while remaining soft, flexible, and comfortable for use in garments.

Research and development of these textile touch sensors is being conducted at the Expressive and Creative Interaction Technologies (ExCITe) Center at Drexel University through collaboration between The Shima Seiki Haute Technology Lab, a smart textile research lab, and the Music Entertainment Technology Lab (MET-lab). The touch sensor we have developed combines the efforts of designers, computer scientists, and multiple fields of engineering including mechanical, electrical and materials. Together, these groups work at the intersections of disciplines incorporating both design and engineering to create textile-based sensors.

Combined with our transdisciplinary approach at the onset of research, we also design with manufacturability of our envisioned product in mind and consider the Manufacturing Readiness Level (MRL) [20] of the product through all stages of development. MRL, a metric developed by the United States Department of Defense, is used to help assess a product in terms of real-world viability. The scale ranks a new product or technology from level one, "basic manufacturing implications identified" [20], to level ten, "full rate production demonstrated and lean production practices in place" [20]. This metric is also used in conjunction with the Technology Readiness Level (TRL) [21], an assessment used to look at capabilities and requirements of a technology that is being developed and how it will ultimately translate into a manufacturable product. Through the platform of mechanized knitting, we are able to design, fabricate, and rapidly prototype a soft, flexible capacitive touch textile sensor using a well-established manufacturing process. Knit programs are developed so that minimal hand fabrication is required and careful consideration is given to the prototype design, enabling it to be effectively scaled up for full production.

THEORY

Theory of capacitive sensing

Projected-capacitive sensors are among the most commonly used touch sensors in computing and mobile devices [22]. A capacitive sensor is a measurement device that converts a measured change in capacitance into a continuous or discrete output. In the case of detecting human touch, a capacitive sensor will measure the induced capacitance of the human body through the change in the dielectric coefficient to detect whether or not a touch has occurred. A basic capacitive sensor uses a resistor (R) and capacitor (C) in series to form a circuit (figure 1). The input is driven by a simple on-off DC voltage generator, Vin, and the output is the change in the voltage waveform across the capacitor, Vout [23]. The circuit is modeled as a first-order linear ordinary differential equation. The capacitor is sensitive to changes in charge (proportional to voltage) and the resistor is sensitive to changes in current (derivative of voltage). Moreover, because only one branch current is present in the circuit, only a single measured point (time-voltage pair) is needed to determine the value of the capacitance given a known input voltage and resistance. As the values of both R and C increase, the time constant, τ, increases. τ is defined as the resistance multiplied by the capacitance of the circuit. In the case of measuring the capacitance of human touch, the induced capacitance is very small—in the range of 10's of Pico-Farads. Thus, a large series resistance is needed to measure the rise time while using a modest sampling interval (figure 1).

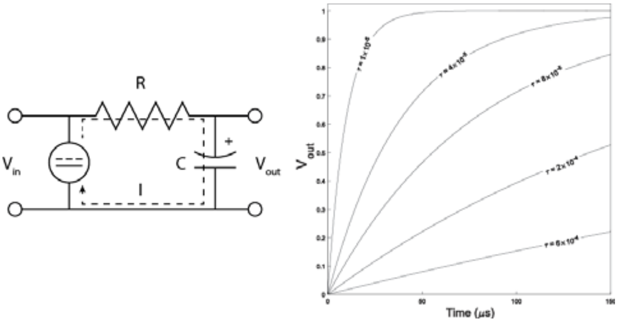

Figure 1. Rise Times of simple RC circuit.

Theory of materials/yarns

Carbon fiber is a material widely used in resistors due to its high impedance and durable enough to be extruded as a yarn. It is ideal to create the resistance needed by the sensor to measure the induced capacitance of human touch. During development of our knitted touch sensor, we considered both the material properties of the carbon fiber yarn as well as the knit structure. In this initial design, the touch sensor structure combines resistive and non-resistive yarns to create an alternating grid-like pattern. The main body of the knit structure (non-resistive) is made from two ends of Primaloft® yarn, (50% Primaloft, 50% wool, 3.5 twists per inch) and the sensing element is made from a filament carbon fiber yarn with a linear resistance of approximately 1

MΩ/in. The linear resistance of the yarn was tailored to match specific values by twisting multiple filaments together. The carbon fiber yarn used in this sensor is made from a commercially available carbon fiber monofilament (Resistat, Type F901, Merge S022, 22 Denier, 24 Dtex from Shakespeare Conductive Fibers). To produce a yarn with the desired resistance, 32 ends of carbon fiber monofilament are twisted together using a Simet Twisting Machine following the steps illustrated in figure 2A.

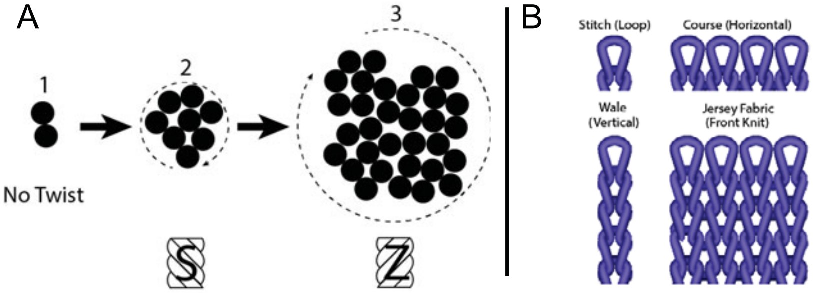

Figure 2. A. Carbon fiber yarn twist pattern.

1. Two ends of carbon filament were wound together onto four individual cones.
2. The four cones from step one were S-twisted together and wound onto four new cones.
3. The four cones from step two were then Z-twisted together onto one cone.

Figure 2. B. Knitting terminology.

Theory of knit structures

While changing the monofilament density of the carbon fiber yarn can change its overall resistance, changing the knit architecture of the sensor can also alter the resistance both selectively and as a whole. This can mean increasing the number of courses (the horizontal dimension of the knit) and/or wales (the vertical dimension of the knit). Increasing the length of the courses increases the resistance, while increasing the wales decreases the resistance (figure 2B).

Changing the knit architecture can also mean changing the contact arrangement of the yarn by creating an interlock pattern. Interlock patterns create thicker courses by drawing more yarn across the needle bed (figure 3A). The pattern "floats" yarn between knit stitches to deposit more

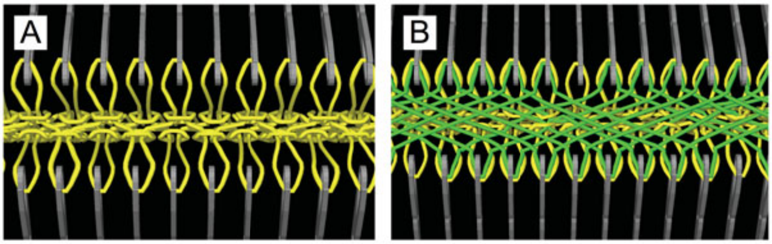

Figure 3. A: Interlock knit stitch pattern (yellow); B: Spacer knit stitch pattern (green). Simulations created on Shima Seiki SDS-One Apex Software.

material over multiple passes. Another technique to increase the thickness of the pattern itself involves the use of “spacer yarn” that tucks between the front and back needle beds to fill in the gap (figure 3B). The spacer yarn “bulks up” the fabric to create a spongy texture—an ideal architecture for touch sensors.

Design of sensing pattern

Weft-knitting machines use continuous strands of yarns to form knitted structures. Therefore, each yarn used in the sensor—including the resistive yarn—is continuous throughout the structure. The routing of the resistive yarn traverses the face of the sensor in an S-shaped pattern to maintain electrical separation (figure 4). Because the trace does not intersect itself, the linear touch position output of the sensor maps to a pair of XY points.

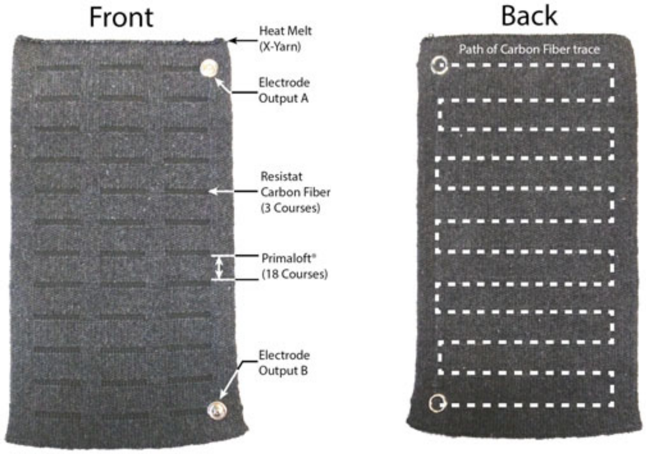

Figure 4. Diagram of knitted sensor.

Material characterization

In order to determine the knit structure based on a desired physical layout, test swatches were knitted using silver-plated nylon. The end-to-end resistances of the swatches were measured and used to determine the number of courses and wales, the type of interlock needed, and the density of the carbon yarn required. For the desired number of lines (12 lines spaced ½" apart) and the desired resistance (1 MΩ ± 200 kΩ) the number of courses that yielded a satisfactory match was found to be three courses. The final linear resistance of the sample was measured at 1.10 MΩ, which satisfied the aforementioned tolerance.

Theory of sensing and operation

The sensing circuit depicted in figure 5 models the touch pad as having a continuous linear resistance, RK. When the sensor is touched at a point on the trace, a pathway to ground is created between the circuit and the human body. The continuous resistance is then split into two resistances, RKx and RK(1-x) that are proportional to the normalized touch location, x, where x ∈[0,1].

The sensor detects the linear touch location by measuring the charge and discharge times of the voltage outputs, Vout,A and Vout,B, which change significantly depending upon touch location at either end of the knitted fabric sensor. A square wave pulse is generated at the sources, Vin,A and Vin,B, and passes through current limiting resistors, RA and RB. The values of RA, RB, and RK should match as closely as possible to provide the best range of output. Inexact matching of resistors RA and RB will cause skewed voltage readings and the reported touch location will be biased towards the higher value resistor.

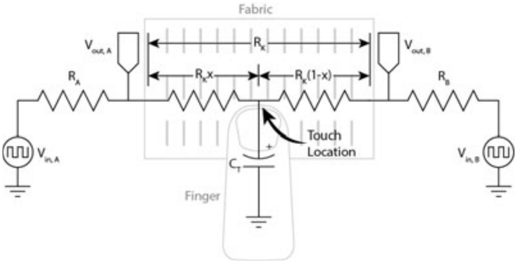

Figure 5. Fabric circuit sensing diagram.

The voltage sensing is performed by an external microcontroller (Atmel SAM3X8E). The microcontroller generates a 500 Hz square wave input with a 50% duty cycle to both input leads of the current limiting resistors. The pulses are timed to charge and discharge synchronously. Capacitance and position are measured by recording the time needed to charge the circuit to ½ of the microcontroller's reference voltage (3.3V). These times range from 10 to 70 microseconds depending on the touch pressure and relative charge of the individual. Touch interactions induce oscillations in the output waveform and skew the measured rise time. Filtering is performed on the rise time data through a simple moving average. The operation steps are listed in table 1.

Table 1. Fabric circuit sensing procedure.

Step	Procedure
1	The circuit is discharged; the input signal is pulsed HIGH.
2	The system time is recorded as the starting time of the rising signal.
3	Hardware interrupts trigger for each output terminal that measures when the signal crosses the low threshold.
4	The interrupts return the system time at the instant upon reaching ½ rise time as the ending time.
5	The microcontroller returns the difference of the starting and ending times.
6	The circuit is charged; the input signal is pulsed LOW.
7	The system time is recorded as the starting time of the falling signal.
8	Hardware interrupts trigger for each output terminal that measures when the signal crosses the high threshold.
9	The interrupts return the system time at the instant upon reaching ½ fall time as the ending time.
10	The microcontroller returns the difference of the starting and ending times.

Modeling and simulation

In order to verify the observed circuit behavior, the circuit and touch interactions were modeled using MATLAB Simulink and Simscape Electrical Foundation Library (figure 6). A relationship was sought that decouples the touch location and capacitance given two output rise times. This relationship is useful for creating a capacitance-invariant touch position model to sense touch location from different users, each with their own baseline charge.

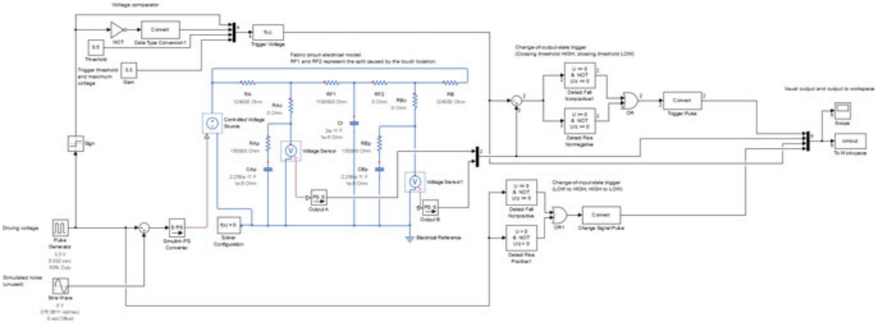

Figure 6. MATLAB Simulink model of the fabric circuit.

A model of the physical circuit and microcontroller functions was simulated over a range of touch positions and capacitances spanning from 1 to 200 pico-Farads to determine a model that decouples the touch location and touch pressure from the output rise times. Though a 30 to 60 Hz oscillation was present in waveforms observed from the physical circuit, no attempt was made to replicate this noise in the simulated model.

Graphical user interface

A graphical user interface (GUI) was created to indicate the registered touch location and pressure to provide visual feedback during testing (figure 7A). The GUI indicates the touch location on the vertical black bars by means of a red indicator. The program uses a simplistic algorithm to determine the touch location by taking the difference of the A and B electrode readings and dividing by the sum of the readings. This value indicates the offset from the center

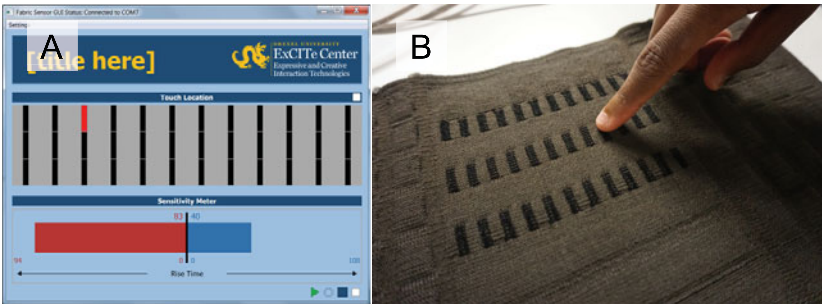

Figure 7. A: Fabric touch sensor GUI; B: Fabric touch sensor in useq

of the pad. For instance, if readings A and B are equal, the output value will be close to the center of the pad. If reading A is much greater than reading B, the value will skew towards the position of electrode A and vice-versa. The sensitivity meter displays the raw readings from the electrodes along with the maximum readings from each to assess imbalances in the sensing circuit.

Results and discussion

To verify the modeled data, the simulated output was compared against real world data. Data was collected from six individuals who were asked to press on all 36 discrete sensor pads (figure 7B). 100 data samples were taken per individual per pad, amounting to 600 data points per pad for 36 pads. To convert the pad locations to a real numbered position, the data was labeled with the normalized distance between the two endpoints, ranging from 0 to 1 in divisions of 35. Aside from a simple moving average applied to the data within the microcontroller, no additional filtering was applied. Only the position information was recorded during testing. The touch capacitance was not measured. This was due, in part, to the inability to accurately measure capacitance in the experimental setup, but also to verify the hypothesis that the measured touch location would be invariant to the touch capacitance. No calibration procedure was performed on the sensor in between testing to simulate the effect of real world use.

When all six data sets are plotted together (figure 8), it is possible to qualitatively assess the similarities to the simulated output. While each individual exhibited a different base charge per dataset, the overall spread of the data matched the expected output provided by the simulation. Data from individuals who had a higher touch capacitance showed a more pronounced spread between discrete touch points. This matches the predicted distribution of the position as touch capacitance increases. The separation of data between the left, middle, and right regions of the pad is distinct and indicates that coarse touch location can be accurately performed.

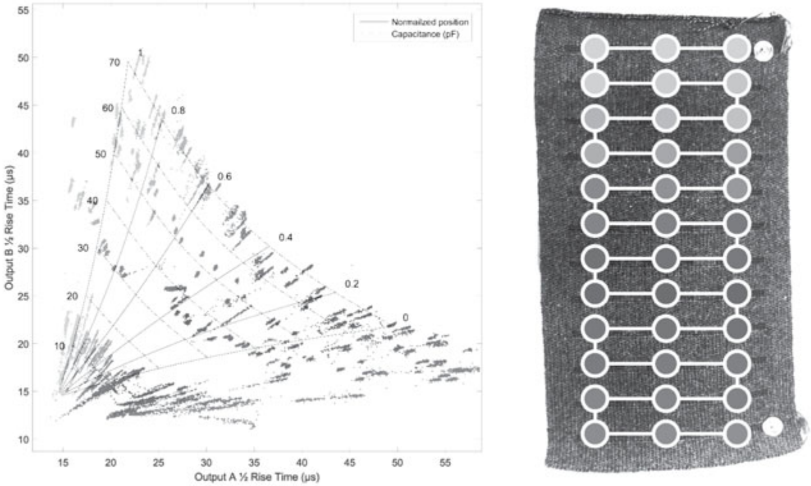

Figure 8. User data plotted against the simulated expected output (solid lines).

Quantitatively, the data had a root-mean-square error value between the expected and observed values of 0.225. This error physically correlates to a misclassification of the normalized distance of approximately one-fourth of the length of the sensing element. The discrepancy between the model data and the data collected is likely a result of the induced noise and the differences in the model's assumed resistance versus the actual resistance.

Though the accuracy of sensing touch falls short when attempting to discriminate fine positions, the sensor is still useful. Capacitive touch sensors that measure single points of contact often require dozens of wires that sense discrete positions across the surface of the sensor. While their accuracy is much greater, the complexity of the design is compounded when increasing the area of coverage of the sensor, specifically in routing the needed wires. In comparison, the design uses only two wires to sense linear touch that is then mapped to a 2D plane.

In applications such as full-body tactile sensing for a humanoid robot, being able to localize touch to a general area such as the lower or upper forearm is more important than sensing precise touch over a large area. Additionally, touch gesture recognition would not benefit from extremely precise touch localization as much as it would benefit from the detection of the change in coarse touch direction. Lastly, the sensor has the potential to sense pressure as a function of capacitance by identifying a baseline charge. Though still at the prototype level, by changing the carbon yarn density, our sensor design is scalable to different sizes without a decrease in functionality.

CONCLUSIONS

The authors of this paper presented a novel, knitted planar capacitive touch sensor and method to detect touch location. The design and construction of the sensor was discussed as well as the theory of capacitive touch sensing. An electrical model of the fabric was constructed and the accuracy of the model was discussed both qualitatively and quantitatively using real world data. Further work will be pursued in increasing the accuracy of the sensor by characterizing and filtering noise, in designing and evaluating an analytical mathematical fabric sensor model, and in working to define a model based on user data. Future research will examine methods to detect multiple touch inputs for natural swipe/gesture recognition and in improving the general design of the sensor to integrate into clothing for wearable applications.

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