A "Sensitive Skin" for Robotic Companions Featuring Temperature, Force, and Electric Field Sensors

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***Abstract* - As robots become an everyday part of the complicated environment of the human world it will be important for such systems to feature a *full body* sense of touch capable of detecting a wide variety of tactile inputs. Such "sensitive skins" can provide much benefit in human robot interaction, specifically in the realm of robotic companions for therapeutic or service applications. In this paper we present a set of design criteria for how such "skins" should be designed. Based on this criteria, a "skin" which features temperature, force, and electric field sensing is described. Results from early experiments with this skin show how the sensors of the multi-modal skin complement each other and allow the distinction between social and affective classes of touch to be distinguished from touch with physical objects.**

Index Terms - "sensitive skin," robotic companions, "somatic alphabet," multi-modal processing, tactile sensing.

I. Introduction

The human world is a complex, ever-changing environment. As robots become an increasingly daily part of our lives they must feature technologies which allow them to sense the world around them that consists of both people and objects and adapt quickly. One of these sensory systems required is a *full body* sense of touch.

Humans and animals provide a wonderful inspiration for how such tactile systems should be designed. The sense of touch is the first of our senses to develop in the womb [1]. It is also the largest sensory system of our body with sensors capable of encoding many different properties of the world around us, some social, others physical. Thus, this biological system is one design template for large, full-body, multi-modal sensory systems.

Lumelsky, Shur, and Wagner [2] were the first to coin the term "sensitive skin." They describe such a sensory system as consisting of a large variety of sensors with processing capabilities that cover the entire surface of the robot. Recently there have been other implementations of "sensitive skin." One such system uses surface covers for protection and better control [3]. Another "sensitive skin" is focused on the detection of temperature and pressure in a single flexible skin [4]. Other researchers have focused on the processing capabilities of such skins. A good review of these approaches can be found in [5]. It is important to note, that in all of these cases the goal of these skin designs were primarily to keep the robot from damaging itself or the people around it, or to sense the physical properties of objects. The realm of social or affective touch has been largely ignored in "sensitive skin" design.

In this paper we present a "sensitive skin" which combines force, temperature, and electric field sensing under a soft silicone skin. While the focus of the design of this "skin" is for robotic companion applications, the design can be applied to a wide variety of other applications.

II. Design Criteria For HRI Applications

Human Robot Interaction (HRI) applications pose a specific set of challenges in the design of robotic "sensitive skins." Unlike the world of manipulation in which the robot arm must only deal with objects, in HRI applications the robot must be able to interact with people and objects. This human interaction includes a realm of social touch, such as greeting with a hand shake, and the affective touch, such as petting a robotic companion. These challenges pose a new set of design criteria.

First, the "sensitive skin" must be able to distinguish interaction with a human from interaction with an object. A robotic companion should be able to distinguish if it is sitting on someone's lap or a table top. One solution is the use of a multi-modal approach, in which the skin consists of many different types of sensors – temperature, pressure, etc. This is similar to how human and animal skin is designed. Next, the skin itself must convey the "illusion of life" through a full body coverage of sensors. No matter how lifelike the robot moves, if it is touched and does not respond this illusion is instantly broken. Additionally, this failure to respond can be frustrating to the human and affect the interaction. Closely related to this full body challenge is the fact that the skin itself must be designed to cover the complex geometry of the surface of a robot.

How the skin feels to the person touching the robot is equally important. It should feel pleasant to touch and not distract from the interaction. For example, if the robot is designed to look like an animal, it should not feel hard. Finally, the "sensitive skin" must be able to detect a wide variety of social or affective touch interactions, such as hand-shakes, petting, tickling, slapping, or tapping, among others. To do so, the skin should be designed with fine spatial resolution, on the order of the width of a human finger. With such a resolution the skin should be able to distinguish between interaction with one finger, such as a poking/tapping gesture, and those with a full hand, such as a slap. These interactions must be able to be sensed across a wide variety of different age groups and populations.

III. "SENSITIVE SKIN" DESIGN

"Sensitive Skins" can be applied to a wide variety of applications from surface covers for furniture to prosthetics. Our domain in which this skin is designed is for interaction between people and therapeutic robotic companions such as the Huggable [6](the robot for which this skin is designed). In this section we begin by outlining our biologically inspired approach for the design of our skin and then continue on with a description of the design with attention paid to the design criteria proposed in the previous section.

A. Design Overview: "Somatic Alphabet Approach"

The "somatic alphabet" approach [7] is based upon theories from neuroscience and provides a great theoretical approach toward the design of "sensitive skins." The skin receptors in humans and animals encode four modalities of perception – temperature, touch, pain, and kinesthetic information. Within each of these modalities are sets of receptors, or "letters," which encode a specific property of the stimulus. Thus there is not one single somatic receptor.

These receptors are grouped together into receptive fields. Higher-level cortical cells in the somatosensory cortex respond to specific properties, such as orientation or direction of motion, within each receptive field. In the "somatic alphabet," these higher-level cortical cells are the "words" of the alphabet formed from the individual "letters." Finally these "words" are combined with other senses, such as vision and auditory processing, to form the "sentences" of perception – such as, "The smooth red ball is rolling down my arm."

B. Sensor Selection

Our "sensitive skin" design features 3 different sensor types in 3 of the four modalities of tactile perception. Force information is sensed using Peratech Quantum Tunneling Composite sensors (QTC). These sensors were chosen for their wide resistance range (10 M-ohm to less than 1 ohm) and low cost [8]. Additionally these sensors allowed for flexibility in design as custom sized sensors can be cut from the large A4 sheets. QTC has also been used in other tactile sensing systems, such as the NASA/DARPA Robonaut Hand [9].
Temperature is sensed through the use of Thermometrics NTC thermistors. These sensors are nominally 100 K-ohm at 25°C.

The last sensor in the design of our "skin" is the Motorola/Freescale Semiconductor 33794 Electric Field Sensing IC. This IC was selected because it allowed for 9 input electrodes with a driven shield. Additionally, the use of a single package allowed for the measurement process to run in parallel while other processes were running on the microcontroller. Electric field sensing measures the proximity of a human hand to the surface on an object and this is ideal for human robot applications. A further discussion of this type of sensor can be found in [10].

The modality of pain can be detected by an extreme sensor value in either of the three sensor types listed above.

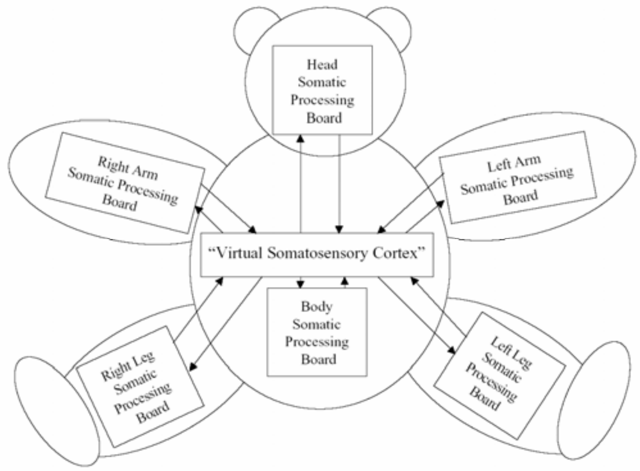

Fig. 1 Division of a robotic companion into body regions for somatic processing.

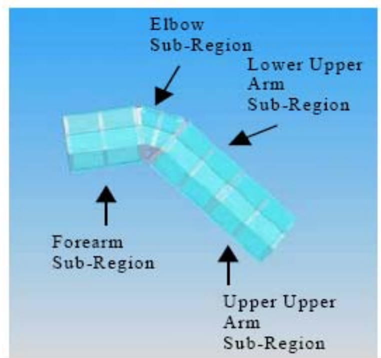

Fig. 2 Division of the left arm into sub-regions. Note the end cap (paw) is not shown in the figure.

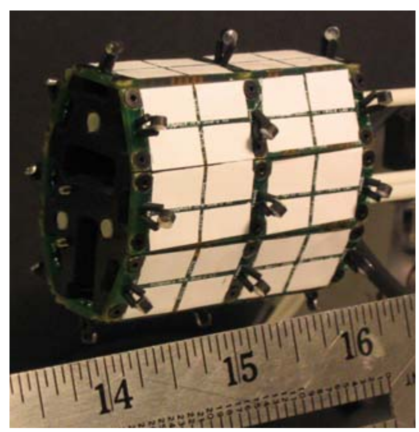

Fig. 3 The forearm sub-region. All dimensions shown in inches.

Additionally, though not sensed in the skin, the modality of kinesthetic information can be encoded by passive potentiometers or other joint angle sensors used throughout the robot.

C. *Flow of information*

The sense of touch in the human and animal systems is arranged in a somatotopic map with different areas of cortex devoted to different parts of the body [11]. Likewise, the “sensitive skin” design for a robotic companion should be arranged in a similar fashion. For simplicity, a robotic companion can be divided into different body regions as shown in Figure 1. Each body region, e.g. the left arm, may consist of hundreds of tactile sensors. Thus it becomes important to reduce wiring as well as perform local processing for each body region. Each body region has a somatic processing circuit board responsible for signal conditioning, low level processing, and analog-to-digital conversion. The output of these circuit boards are then sent via RS-232 to an embedded PC running the “Virtual Somatosensory Cortex” software system. A more detailed description of these systems will be presented later in the paper.

For purposes of discussion, we will focus on the left arm body region. The implementation of this one region is similar to the implementation of the other regions except for changes in geometry, the number of sensors in the region, and the grouping of sensors within that region. Each body region is then divided into sub-regions. For the arm, there are 5 sub-regions – the end cap (paw), the forearm, the elbow, the lower upper arm, and the upper upper arm. Figure 2 is a diagram of this division. Within each division are sets of sensor circuit boards. The forearm section used for the experiments described in the results section is shown in Figure 3. It is with these sensor circuit boards that the flow of information begins. For clarity, the entire flow of information from raw sensor input to higher level processing is shown in Figure 4.

D. *Sensor Circuit Boards*

In the forearm sub-region there are 8 sensor circuit boards. Each sensor circuit board of the forearm has 8 QTC sensors (shown as white rectangles) and 3 thermistors (extending from the surface of the board). A copper layer on the bottom layer of the PCB is used as an electrode for electric field sensing. A pair of analog multiplexers are placed on the underside of each sensor circuit board to reduce the number of wires. A SN74LV4051 8:1 multiplexer is used for the QTC and a MAX4634 4:1 multiplexer is used for the temperature sensors. These multiplexers share the same control channels as well as power and ground. The QTC and temperature sensors share a common ground.

The electric field sensing is rather slow (~5ms) compared to the other two sensors (~µs). Additionally, there is not the need for fine spatial resolution with this sensor. Lastly the 33794 IC features 9 electrode inputs. Thus for these reasons it was decided to divide each body region into a maximum of 9 different electrode sections. The elbow and end cap sections only have one electrode, and the remaining 3 sub-regions each have two electrodes.

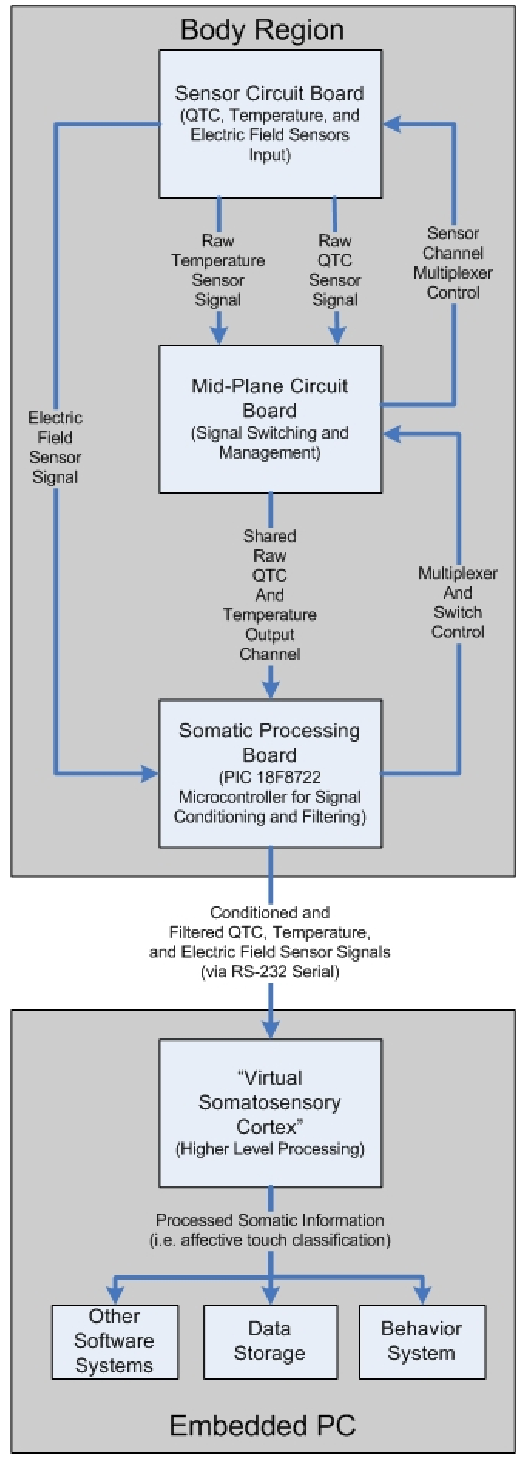

Fig. 4 The flow of information in the “sensitive skin”

The forearm sub-region of Figure 3 is further divided into two groups of four sensor circuit boards (top/left and bottom/right). The common control signals (A,B,C) for the multiplexers of these circuit boards as well as Vcc and GND

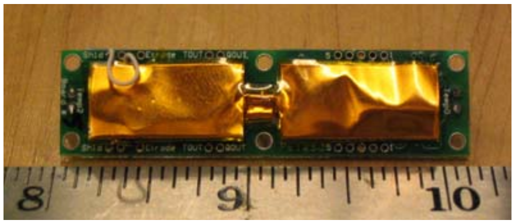

Fig. 5 The copper shield on the backside of each sensor circuit board. All dimensions shown in inches.

are shared among these four boards. Additionally, the copper electrodes of each sensor circuit board are connected together forming one larger electrode. One of the benefits of using the 33794 electric field sensing IC is that it provides a driven shield. A copper shield is placed behind each sensor circuit board as shown in Figure 5. The driven shield signal is shared among the four copper shields of each sensor circuit board group. The electrode and shield are connected directly to a flexible coaxial cable (Cooner Wire CW2040-3050SR) which travels the length of the arm to the somatic processing board for the arm.

E. Mid-Plane Circuit Board

The use of electric field sensing poses a few design challenges. First, the mechanical structure to which the circuit boards are attached must be made of a non-conducting material. In the current design, delrin and fiberglass rod are used. Second, the wires which leave the sensor circuit board also carry the electric field sensor signal. Thus it becomes important to isolate these wires from the rest of the signal pathway. For this purpose, the mid-plane circuit board is used. This circuit board sits inside the arm sub-section as shown in Figure 6. A schematic diagram of the mid-plane circuit board is shown in Figure 7.

As shown in Figures 6 and 7, the mid-plane circuit board is divided into two sections. On the top surface of the circuit board are two pairs of connectors. The 5 pin connector transmits the multiplexer control channels as well as Vcc and GND to each set of four sensor circuit boards corresponding to the two electrodes (top/left and bottom/right). The 8-pin connector is used to receive the QTC and temperature multiplexer outputs from each sensor circuit board corresponding to the electrode grouping. Thus the inputs and outputs of each set of four sensor circuit boards, corresponding to the two electrodes, are separated.

The four QTC and four temperature multiplexer signal outputs from the four sensor circuit boards corresponding to the top/left electrode are connected to a SN74LV4051 8:1 multiplexer. A separate SN74LV4051 is used for the signals from the sensor circuit boards in the bottom/right electrode grouping. The output of these two multiplexers then passes through a Fairchild Semiconductor NC7SBU3157 SPDT analog switch. Thus, for the forearm sub-region consisting of 64 QTC force sensors and 24 temperature sensors, a single cable is used to carry this sensor signal information to the arm somatic processing board.

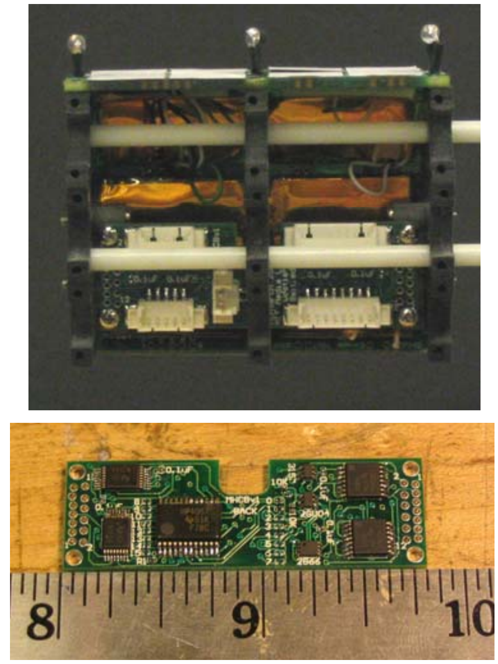

Fig. 6 The mid-plane circuit board. At top is shown the top view of the circuit installed inside the forearm sub-section. At bottom is the back side of the circuit board. All dimensions shown in inches.

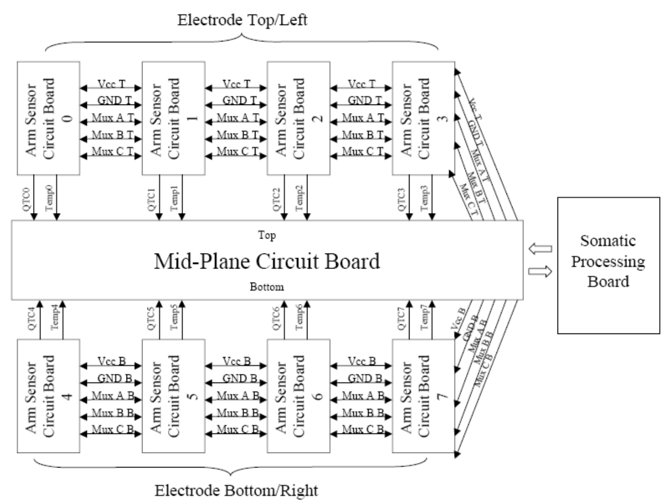

Fig. 7 The schematic diagram of the mid-plane circuit board.

The three multiplexer control channels and common power and ground are connected directly to a pair of bilateral switches (SN74LV4066A and SN74LVC2G66). When in force/temperature sensing mode these switches are closed providing power and control logic to the sensor circuit board multiplexers. When that electrode grouping is in electric field sensing mode, these switches are opened and the SN74LV4051 multiplexer is inhibited. Thus that cluster of four sensor circuit boards is isolated from the rest of the arm. Because of this isolation, it is still possible to read the force/temperature values from the remaining sub-sections of the arm while the electric field sensor value is being calculated.

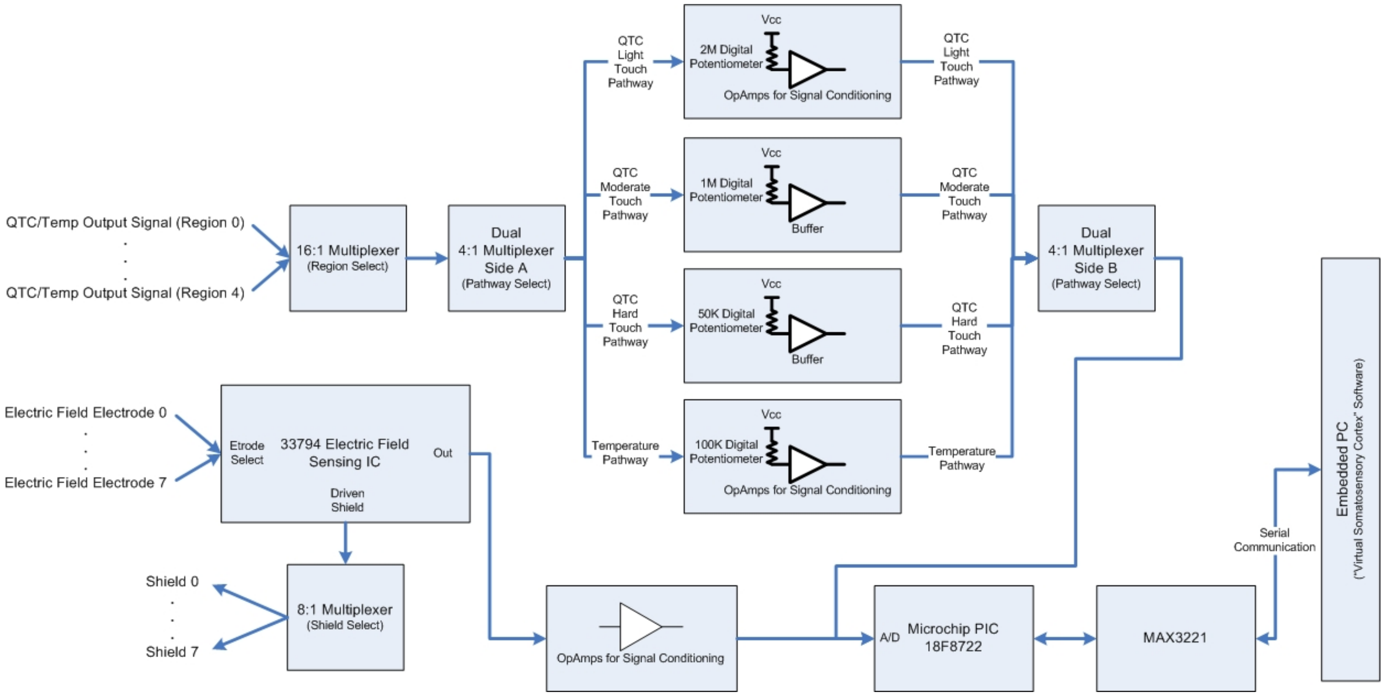

Fig. 8 The Schematic diagram of the somatic processing circuit board. Note the autocalibration functionality is not shown.

The 13 holes on opposite ends of the board shown in Figure 5 are used to transmit common information such as multiplexer and switch control information as well as power to the whole arm. Each mid-plane circuit board is connected to one another and to the somatic processing board for the arm via a Cooner Wire CW6264rev1 13-conductor flexible cable.

F. Somatic Processing Board

Each mid-plane circuit board has one output (shared QTC/temperature output) and 13 inputs. Additionally, each of the 8 electrode groups has a single output wire. Thus for an entire arm consisting of approximately 200 sensors there are only 12 output wires and one common input wire. The last stage of this multi-level approach prior to the embedded PC running the "Virtual Somatosensory Cortex" software system is the somatic processing board. Figure 8 shows a schematic diagram of the flow of information in the Somatic Processing Board.

The somatic processing board uses a Microchip PIC18F8772 microcontroller. This package was chosen for its large program and data memory, large number of I/O pins, and speed. In the current design a 40 MHz oscillator is used, but because the PIC18F8772 requires 4 clock cycles per instruction the actual speed is approximately 10 MHz.

The main functions of the somatic processing board are to select the sensor, condition the sensor signal, convert this conditioned analog value into a 10-bit digital value, and finally send this value to the embedded PC. A MAX3221 RS-232 serial driver/receiver is used at a baud rate of 57600 for communication between the PIC and embedded PC. This value can be doubled in future implementations.

As discussed throughout the paper, there are three types of sensors used in the design of this "sensitive skin" – QTC force sensors, thermistors, and electric field sensors. The 33794 electric field sensing IC provides 9 electrode inputs and a single driven shield output. The driven shield output is multiplexed using an Analog Devices ADG408 high-performance single 8-channel analog multiplexer. The shield signal is greater than the 5V range of the SN74LV4051, thus requiring the selection of a different multiplexer with a higher maximum voltage. Each coaxial cable connecting the sensor circuit boards to the somatic processing board carries the electrode signal surrounded by a driven shield. This electrode signal is passed directly to the electrode input of the 33794.

The output of the 33794 is a 0-5V analog signal. Currently, the raw output prior to signal conditioning of the top/left electrode of the forearm sub-region of Figure 3 is 1.75V with a 30mV change between the no contact (min) and contact with a human hand case (max). This raw signal is then passed through a series of differential amplifiers and non-inverting amplifiers based on the Burr-Brown OPA2340 dual channel single supply operational amplifier to boost the signal to the full 0-5V range. Finally this signal is low-pass filtered and passed into the 10-bit A/D of the PIC for conversion.

As discussed previously, the QTC sensors have a wide resistance range. To improve sensor performance these signals are processed in three different ways – light touch, moderate touch, and hard touch. One can imagine many interactions where the type of touch could fall within at least one, if not all, of the sensing regimes.

The QTC and temperature outputs from each mid-plane circuit board are carried via a single wire and pass through two multiplexing stages. In the first multiplexing stage a CD74HC4067 16:1 analog multiplexer is used to choose the mid-plane circuit board output. The choice of a 16:1, as opposed to an 8:1 multiplexer, allows for maximum flexibility in design. Once the mid-plane circuit board output is selected a Texas Instruments SN74LV4052 dual 4:1 multiplexer is used to select how this signal is to be processed – temperature, QTC light touch, QTC moderate touch, and QTC hard touch. The output of the first multiplexer stage is sent off along one of the four pathways for signal conditioning through the first 4:1 multiplexer in the SN74LV4052 package. The conditioned signals then pass through the second 4:1 multiplexer and into one of the A/D inputs of the PIC.

The QTC light touch pathway is processed using a voltage divider with a 2M-ohm potentiometer as the upper resistor in the divider and the QTC sensor as the lower resistor. The output of the voltage divider passes through a voltage follower as well as a series of differential and non-inverting amplifiers all based on Burr-Brown OPA2340 package to boost the analog signal to the full 0-5V range. Finally, this signal is low-pass filtered. The QTC moderate and QTC hard pathways also use a voltage divider for signal conditioning with a 1 M-ohm potentiometer for the moderate pathway and a 50 K-ohm potentiometer for the hard pathway. The outputs of each divider pass through a voltage follower and a low-pass filter.

As discussed previously, the thermistors selected have a nominal value of 100 K-ohm at 25°C. Much like the QTC pathways, a voltage divider with a fixed 100 K-ohm resistor is used for the temperature pathway. The output of this divider is then passed through a voltage follower and a series of differential and non-inverting amplifiers to boost the signal. The output is then low-pass filtered.

The somatic processing board also features the ability to auto calibrate. Each of the analog potentiometers used in the voltage dividers and the amplifiers of the electric field, QTC, and temperature pathways can be switched to a set of digital potentiometers with a series of jumpers. An Analog Devices AD5235BRU dual 250 K-ohm 1024-tap digital potentiometer is used for the non-inverting opamp feedback and differential threshold potentiometers. The 50 K-ohm voltage divider used for the QTC hard pathway uses the same AD5235BRU digital potentiometer, but in a dual 25 K-ohm package with the first potentiometer placed in series with the second one. The 1 M-ohm potentiometer for the QTC moderate pathway is formed by placing the potentiometers of two AD5235BRU dual 250 K-ohm packages in series with each other. Finally, the 2 M-ohm potentiometer for the QTC light pathway is created by placing a 1 M-ohm fixed resistor in series with the potentiometers of an Analog Devices AD5263 quadruple 200 K-ohm and an Analog Devices AD5262 dual 200 K-ohm digital potentiometer packages. The values of each of the digital potentiometers are set via SPI communication from the PIC.

A series of switches (Maxim MAX4636 dual SPDT CMOS analog switch and a Fairchild Semiconductor NC7SBU3157 SPDT analog switch) are used at the various points in each pathway to isolate the output of one stage from the input of the next stage. These switches are normally closed, but during calibration they can be individually opened or closed by the PIC. When in the open state, the output of that stage is connected to another of the A/D input pins of the PIC through a multiplexer.

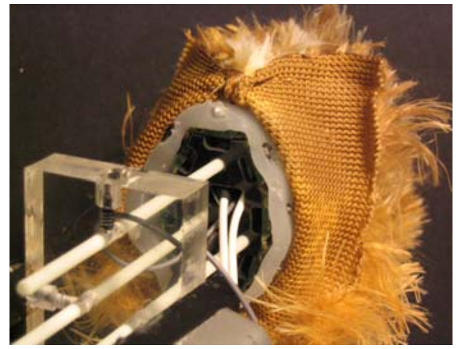

Fig. 9 The layered structure of the synthetic skin. The outer layer is the furry fabric. The middle layer is the synthetic silicone skin. The inner layer is the forearm sub-region of Figure 3.

This ability to auto calibrate in hardware is very important for a variety of reasons. First, the complex geometry of the surface of a robotic companion results in different sensors being of different sizes. Next, the large number of sensors (upwards of a thousand sensors in some platforms) makes calibration of each individual sensor a time intensive process. Finally electric field sensing and temperature sensing are subject to different environmental conditions that may change from day to day or location to location.

G. *Synthetic Skin*

One important factor of any "sensitive skin" is how it feels to a person touching it. Specifically with robotic companions, the focus of our design, how the robot feels when it is petted, scratched, or tickled can greatly affect the quality and length of the interaction. To improve the tactile feel a synthetic silicone skin was created. The thermal properties of the silicone required that the temperature sensors are flush with the top surface of the silicone skin to improve sensing. This silicone skin was placed under a furry fabric exterior as shown in Figure 9.

In addition to providing a soft feel, the silicone skin helps to distribute the forces applied to the top surface of the robot's skin. The skin also helps to protect the sensors from damage.

III. Results

By combining three different types of sensors in one "sensitive skin" design, a greater understanding of the type of interaction can be determined. Specifically, for robotic companions, this design can be used to distinguish a wide array of social and affective touch. In this section we present a series of early experimental results which validate these claims.

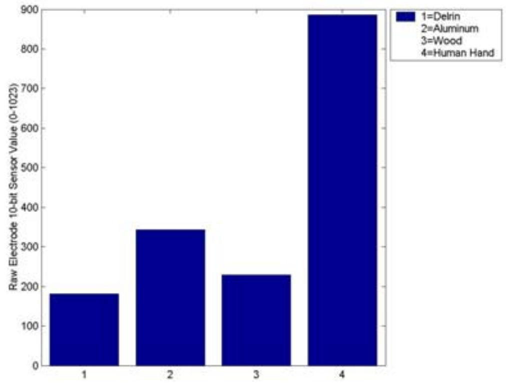

Fig. 10 The response of the electric field sensor to contact with four different objects. From left to right – delrin bar, aluminium bar, wooden bar, and human hand.

One important distinction in any human-robot interaction is the ability to recognize a touch as coming from a human as opposed to an object. Figure 10 shows the response of the raw, unfiltered electric field sensor signal to contact with four different items – delrin bar (1), aluminum bar (2), wooden bar (3), and a human hand (4). As shown in the figure there is a clear distinction between contact with a human hand and contact with an object. The conditioning of the electric field sensor was tuned so as to maximize the response of human contact. It is important to note that the measurement of capacitance is not only based upon material properties but the size and mass of the object to be sensed. Thus in some cases it may be possible to falsely detect the presence of a person, however in the case of the Huggable, the robot for which this skin is designed, such false detections will be rare. Additionally, the presence of the temperature to detect body heat from the person touching the skin can be used to verify the electric field sensor's "person detection."

Figure 11 shows the combined response of the QTC (QL, green), temperature (T, black), and electric field sensors (C, red) to a set of two interactions – patting and squeezing. A petting interaction is shown in Figure 12. These forms of touch are often seen between pets and their owners.

The electric field sensor measures the proximity of a person's hand to the surface of the robot, thus it acts as an anticipatory signal to contact. This can be clearly shown in B of Figure 11 as the electric field signal occurs before and after the contact with the force sensors. Additionally, as shown in Figure 11 A, the electric field sensor can measure contact even if the force applied to the surface is too small to be detected by the QTC sensors. Thus for applications with robotic companions for the elderly and small children who may not have much force, the use of electric field sensing can provide important tactile information.

The temperature sensors have a long time delay (order of seconds) and thus only show change in the presence of prolonged contact. However this lag is beneficial as shown in the case of squeezing (Figure 11 B) where the QTC and electric field sensors reach their maximum value. The

A)

B)

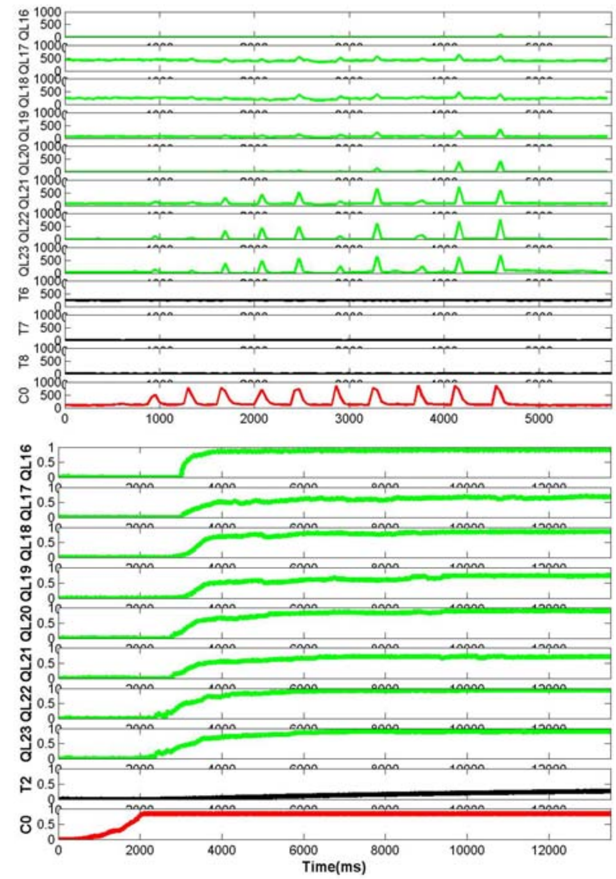

Fig. 11 The response of the QTC (QL,green), temperature (T,black) and electric field sensors (C,red) of one sensor circuit board to three different interactions. At top is the response to a series of 10 pats. At bottom is the response to a squeeze.

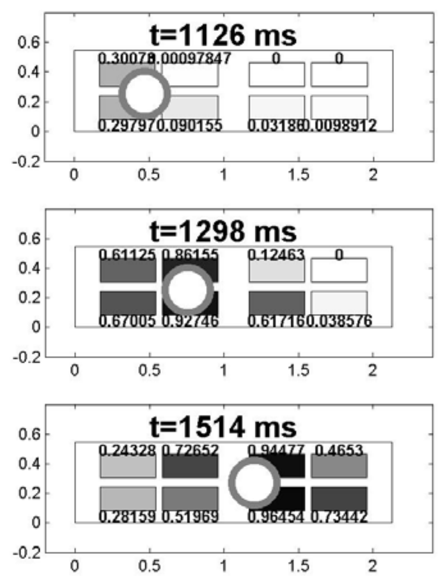

Fig. 12 The calculation of the centroid location for a petting gesture by a human hand. The sequence in time is shown from top to bottom. Each sensor value is indicated both numerically, above or below the sensor, and in greyscale with black as maximum value. The white circle with grey edge is the centroid location.

TABLE I
NEURAL NETWORK CLASSIFIER PERFORMANCE FOR AFFECTIVE TOUCH FROM [13]. PPV = POSITIVE PREDICTIVE VALUE. NPV = NEGATIVE PREDICTIVE VALUE.

Class	PPV	NPV	Sensitivity	Specificity	Chance
Tickle	0.67	0.94	0.57	0.96	0.11
Poke	0.41	0.95	0.29	0.97	0.11
Scratch	0.67	0.94	0.65	0.94	0.11
Pet	0.58	0.97	0.26	0.99	0.11
Pat	0.23	0.99	0.20	0.99	0.11
Rub	0.72	0.98	0.73	0.98	0.11
Squeeze	0.84	0.97	0.73	0.98	0.11
Contact	0.81	0.98	0.84	0.97	0.11

temperature information provides another way to distinguish contact with a human and contact with an object through the detection of body heat.

The QTC sensors are useful in many cases. First, they react to force and thus respond to both contact with a human as well as an object. This is important to protect the robot from damage. Second, they form the largest percentage of the sensors in the “sensitive skin” design described in this paper. Thus these sensors can be combined together in receptive fields for higher level processing, such as calculating the centroid location, shown by the white circle in Figure 12, using a weighted sum. These calculations are described in [12]. Such receptive field level calculations as the centroid location, direction of motion, orientation, and other features can then be used with higher level classifiers such as neural networks or other pattern recognition techniques to determine the affective content of touch, as shown in Table I. We have already shown good results in preliminary work using these techniques [13].

IV. CONCLUSIONS AND FUTURE WORK

In this paper we have presented the design of a “sensitive skin” for robotic companions. The combination of force, temperature, and electric field sensors allows for a wide variety of tactile interactions to be detected. Most importantly, the use of electric field sensing and temperature help to distinguish between contact with an object and with a human. This information is important for the categorization of touch as only a person can interact with a robotic companion through petting, patting, or slapping.

Currently, the results presented in this paper were from only one sub-section of the arm. As the rest of the “sensitive skin” is built it will be possible to explore ways to quickly, and efficiently process such a large number of sensors. Additionally, the “virtual somatosensory cortex” software system for this “sensitive skin” design is still in its initial stages. Over the next few months as more of the “sensitive skin” is developed much of the focus will go to processing this information and extracting important features from the data in real time.

Additionally, one current problem with this design is that the silicone skin used is a thermal insulator. Thus, the thermistors must poke through holes in the silicone skin in order to be an effective sensor. This poses a problem both in longevity of the sensor, as over time the leads may break, as well as it effects the force sensing as the force sensors are not the highest point of contact in the skin. We currently are experimenting with new thermally conducting silicones which will allow us to place the temperature sensors flush with the surface of the sensor circuit board.

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