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Design Considerations for Multimodal “Sensitive Skins” for Robotic Companions

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1. Introduction

The sense of touch is the earliest sensory system to become fully functional in all species. Even as early as nine weeks in the womb, the fetus will close its fingers in a gripping motion if its palm is touched (Montagu 1986). The skin, our largest sensory organ, is capable of detecting skin indentations as small as 1μm (Nolte 2002). It is our sense of touch that helps to protect us by allowing us to feel pain so we do not damage our bodies. We manipulate objects using the tactile sensors of our hands. Additionally, touch has an affective and social component – expressed through hugs, handshakes, and pats on the back. One only needs to look at the interactions between humans and their pets to see these expressions of affective touch in action.

To help motivate this discussion of the importance of touch let’s conduct a thought experiment. Imagine you wake up in bed and have to start your day without using your sense of touch. How far would you get just relying on vision and sound processing alone? Most likely, you would have trouble leaving your room. Now replace yourself with an autonomous robot and you can see why tactile sensing systems are important.

One major goal of robotics research is to produce robotic systems which can exist in the very complex human world. Touch sensing systems can add a great deal to allowing the robot to function autonomously in this world. First, vision alone is not sufficient to function in unstructured environments due to problems of occlusion (Lumelsky et al. 2001). Second, tactile information can be combined with vision and auditory information to form stronger multi-modal percepts. Third, a full body tactile system can help to convey the “illusion of life” in the robot – as no matter how lifelike the motion of the robot may appear, if the robot is touched and it does not respond, that illusion is instantly broken. Fourth, in the context of human-robot interaction (HRI), the sense of touch can carry social, affective, or other information. In addition to these qualities, a well designed skin should feel pleasant to touch and not distract from the interaction.

In many cases, the field of robotics today has focused much of its attention on vision and auditory sensing. If tactile sensors are used, they have primarily been confined to discrete locations, such as those of Sony’s AIBO robotic dog (Sony Product Literature) or have been primarily used in grippers for manipulation tasks, such as NASA’s Robonaut (Martin, et al. 2004). While these uses are important, there exists much potential for full-body, multi-modal, tactile sensing systems – or “sensitive skin” as defined by (Lumelsky, et al. 2001) .

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Such “sensitive skins” consist of a large variety of sensors with processing capabilities that cover the entire surface of the robot.

Today, there are a few “sensitive skin” systems currently in development. There are fabric sensor based systems such as (DeRossi et al. 2002; Sergio et al. 2002) which are capable of potentially being used for full-body sensitive skins, through currently they are not multi-modal. Other approaches have tried to use inductive coupling to eliminate the wires of such “sensitive skins” (Hakozaki et al. 2001) or have looked to use optics to eliminate the wires in the skin (Yamada et al. 2002). Others such as (Someya et al. 2004) have created flexible skins which combine temperature and pressure sensors into a single flexible skin design with the potential for a large number of sensors. In the realm of robotic companions, the traditional approach has been to use a set of discrete touch sensors in specific locations, and thus there is not usually full-body coverage in such systems. Some examples are the Omron Necoro (Omron Corporation Product Literature) and the Aibo (Sony Product Literature). The one exception is the design of the Paro (Shibata et al. 2001) which features a nearly full body “sensitive skin” but has a small number of sensors which are primarily pressure based. Finally, a good review of the processing capabilities of various “sensitive skins,” treating such systems as sensor networks can be found in (Paradiso et al. 2004).

Unlike many previous systems, our approach looks to create a “sensitive skin” designed not just as a patch of skin, but rather to be a fully functional full-body skin on a small robotic companion. Additionally, our emphasis is on social and affective touch and not manipulation. Thus, our desire is to create a multi-modal sensitive skin with a large density of sensors. We believe that the biological design of the human and animal somatosensory cortex provides a great design template for such as skin.

In this chapter I will first present a brief overview of the somatosensory system in humans and animals. Next, using the human and animal system as inspiration I will describe our conceptual approach – the “somatic alphabet.” Next I will spend the bulk of this chapter describing our current sensitive skin design for the Huggable, a new teddy bear robotic companion being developed at the MIT Media Lab. Finally, I will end this chapter with a discussion of future areas of research wide open in the field of tactile sensing for robotic systems.

2. Biological inspiration – the human and animal somatosensory system

The human and animal somatosensory system is a great template for how a robotic somatosensory system should be designed. In this section, I will briefly describe some of the important concepts behind the biological system and I encourage the reader to further study these systems if they are interested by looking at the following references in much more detail - (Heller & Schiff 1991; Kandel et al. 2000; Nolte 2002; Rosenzweig et al. 2002; Sekuler & Blake 2002). In this chapter I will work my way from the skin, through the sensors, and then up the spinal cord, finally completing this discussion in the somatosensory cortex of the brain.

2.1 The mechanoreceptors – the “sensors” of the somatosensory system

There are two major types of skin found in the body of humans and other animals. The first type is glaborous, the smooth skin found on the palm of the hand and the sole of the foot.

The second type, hairy, is found on almost every other part of the body. In addition to the two types of skin, the skin can also be divided into two layers - the epidermis above and the dermis below. The actual sensors of the somatic system are referred to as the mechanoreceptors. Each of these receptors has a specific location and stimulus response. Thus, these different mechanoreceptors are the building blocks of our somatic sensation. What becomes instantly clear is that there is not one single sensor for somatic information in the body, but rather, a set of specific receptors which are combined together encode the wide variety of somatic sensations we feel.

These mechanoreceptors can be first divided into the four modality types of somatic sensation as shown in Table 1. For purposes of our discussion we will focus on the mechanoreceptors of glaborous skin in the touch modality – the Meissner’s corpuscle, the Merkel disc receptor, the Pacinian corpuscle, and the Ruffini ending. For those interested a good discussion of the pain receptors can be found in (Rollman 1991; Kandel et al. 2000). More information on temperature sensing can be found in (Stevens 1991; Craig & Rollman 1999). Finally, a further discussion of muscle and skeletal mechanoreceptors can be found in (Clark & Horch 1986).

The glaborous skin mechanoreceptors for touch can be arranged in a 2x2 grid as shown in Table 2. One axis of this grid corresponds to adaption, which is how the receptor responds to a sustained stimulus. There are two types of adaptation – slowly adapting (SA) and rapidly adapting (RA). Slowly adapting receptors encode static position and can do so over a period of several minutes. This firing rate first indicates how rapidly the pressure is applied to the skin initially and then in steady state the firing rate is proportional to the skin indentation (Kandel et al. 2000). The rapidly adapting receptors fire at a rate proportional to the speed of motion and their duration corresponds to the duration of the motion (Kandel et al. 2000).

The second axis describes the size of the receptive field, i.e. the how big the area on the skin that receptor is sensitive to. This receptive field size is due to both the location and the depth of the mechanoreceptor in the skin. The mechanoreceptors right below the surface of the epidermis have a small receptive field, while those deep in the dermis have a larger receptive field. The terms punctate (small receptive field with sharply defined boundary) and diffuse (larger receptive field with less definition of boundary) can be used to describe each type (Cholewiak & Collins 1991). A more detailed discussion of how the physical properties of each mechanoreceptor influence their stimulus response can be found in (Kandel et al. 2000; Nolte 2002).

The number and type of mechanoreceptors vary throughout the body. Psychophysical tests such as the two-point limen and the error of localization test have determined that there is spatial perception difference on different parts of the body (Cholewiak & Collins 1991). For example, the fingertips can distinguish a difference in location as small as 2mm on the pad while the back can only distinguish a difference as large as 70mm (Sekuler & Blake 2002). Additionally studies have shown that touch also has temporal properties as well and the limit at which tactile stimuli can be perceived as two separate events if spaced in time was 5ms or more, which is slower than hearing (0.1 ms) but faster than vision (25 ms) (Pohja 1996). A further discussion of other findings from psychophysical studies can be found in (Cholewiak & Collins 1991).

Receptor Type	Fiber Name	Modality
Cutaneous and subcutaneous mechanoreceptors		Touch
Meissner's corpuscle	RA	Stroking, fluttering
Merkel disc receptor	SAI	Pressure, texture
Pacinian corpuscle	PC	Vibration
Ruffini ending	SAII	Skin Stretch
Hair-tylotrich, hair-guard	G1, G2	Stroking, fluttering
Hair-down	D	Light Stroking
Field	F	Skin Stretch
Thermal Receptors		Temperature
Cool receptors	III	Skin cooling (25ºC)
Warm receptors	IV	Skin warming (41ºC)
Heat nociceptors	III	Hot temperatures (>45ºC)
Cold nociceptors	IV	Cold temperatures (<5ºC)
Nociceptors		Pain
Mechanical	III	Sharp, pricking pain
Thermal-mechanical	III	Burning pain
Thermal-mechanical	IV	Freezing pain
Polymodal	IV	Slow, burning pain
Muscle and skeletal mechanoreceptors		Limb proprioception
Muscle spindle primary	Ia	Muscle length and speed
Muscle spindle secondary	II	Muscle stretch
Golgi tendon organ	Ib	Muscle contraction
Joint capsule mechanoreceptors	II	Joint angle
Stretch-sensitive free endings	III	Excess stretch or force

Table 1. Somatic Sensation Receptor Types adapted from (Kandel et al. 2000)

The four main types of mechanoreceptors of glaborous skin respond to stimuli in different ways. Numerous studies applying stimuli to the finger pad of monkeys and recording from the individual receptors have shown that texture and roughness can be encoded in different ways at the level of the mechanoreceptor. Some examples of stimuli presented have been dots (Johnson & Lamb 1981; Lamb 1983; Connor et al. 1990; Johnson et al. 1991; Connor & Johnson 1992; Johnson & Hsiao 1992; Johnson & Hsiao 1994), raised letters (Vega-Bermudez et al. 1991), and grooved surfaces (Lederman 1974). From these studies, it has been shown that the encoding of form and texture is done primarily by the Merkel disc receptors with the possibility of some encoding by the Meissner's corpuscles (Johnson & Hsiao 1992).

Other studies have been conducted by recording the response of Merkel disc receptors and Meissner's corpuscles to the encoding of shape (LaMotte & Srinivasan 1993) and curvature (LaMotte & Srinivasan 1987; LaMotte & Srinivasan 1987; Srinivasan & LaMotte 1987). These results have shown that the Merkel disc receptors show an increase in firing rate after indentation as the curvature of the presented stimuli increased.

	Slowly Adapting (SA)	Rapidly Adapting (RA)
Small Receptive Field (Superficial Layers)	Merkel disk receptors	Meissner's corpuscles
Large Receptive Field (Deep Layers)	Ruffini endings	Pacinian corpuscles

Table 2. Glaborous Skin Somatic Sensation Receptor Types adapted from (Kandel et al. 2000)

Finally, studies of vibration have shown that three of the mechanoreceptors of glaborous skin fire an action potential at a rate of one spike per cycle of the sinusoidal wave of a presented stimulus. In addition, these three receptors are "tuned" to different frequencies with the Merkel disc receptors showing a preference for signals between 5-15 Hz, the Meissner's corpuscles preferring a range of 20-50 Hz, and the Pacinian corpuscles are active for a range of 60-400 Hz (Kandel et al. 2000).

Thus from this brief presentation is becomes clear that the mechanoreceptors in the skin of humans and animals are the first building blocks of our somatic sensation. Now we will turn our discussion from the individual receptors to the path that each output signal takes as it travels from the mechanoreceptor to the somatosensory cortex.

2.2 The pathway from receptor to cortex – the "wires" of the somatosensory system

A single nerve fiber will receive input from a cluster of Merkel disc receptors or Meissner's corpuscles. Those mechanoreceptors with a larger receptive field such as the Pacinian corpuscle and the Ruffini ending will be connected to a single nerve fiber. Just as there are different types of receptors in human skin as shown in Table 1, there also exist four different types of peripheral nerve fibers each with different diameters, conduction speeds, and sheath. A further discussion of these fibers can be found in (Rosenzweig et al. 2002) and a mathematical model for the conduction of an action potential along these fibers is found in chapter 6 of (Dayan & Abbott 2001).

What is important to note is that there is an organizational structure as to how the sensory information from each type of somatic receptor enters into the central nervous system through the spinal cord. The division of the spinal cord in humans into 8 cervical sections (neck), 12 thoracic sections (trunk), 5 lumbar sections (lower back), 5 sacral sections (pelvic), and 1 coccygeal section (bottom) maps to specific regions of the skin (known as dematomes) that the spinal nerves innervate (Rosenzweig et al. 2002). Each dermatome actually overlaps the surrounding dermatomes and this helps with higher level processing in the somatosensory cortex, discussed in the next sub-section. The actual specifics of how the sensory nerves synapse, and information travels up the spinal cord to the somatosensory cortex is beyond the scope of this chapter. The reader is encouraged to look at (Kandel et al. 2000; Nolte 2002) for a much more in-depth discussion. Additionally, reflexes, which do not leave the spinal cord level, are further described in (Sekuler & Blake 2002).

2.3 The somatosensory cortex – the "high-level processing" of the somatosensory system

The somatosensory cortex has three major divisions – the primary somatosensory cortex (SI), the secondary somatosensory cortex (SII), and the posterior parietal cortex (Kandel et al. 2000). A full in-depth discussion of the actual physical layout of these systems and their interconnections is beyond the scope of this section and the reader is encouraged to read (Kandel et al. 2000; Nolte 2002) for a greater detail.

The study of the somatosensory cortex has yielded a few interesting results which are particularly important for the design of "sensitive skins" for robotic systems. First, each region of the primary somatosensory cortex is arranged in a somatotopic map. This map shows the number of receptors in each region with areas such as the fingers and lips which have a high density of receptors having more cortical area than those such as the trunk which have a lower density. This map has also been presented in a different fashion, known as the Homunculous, or "little man," where the body form is distorted to reflect the number of receptors present in that region.

A second important fact is that cortical neurons receive input from a large number of mechanoreceptive fibers and inhibition methods (such as surround or lateral) are used to help result in finer modes of discrimination and feature detection (Kandel et al. 2000). In addition, as information moves from lower level to higher level cortical regions, the size of the receptive field increases, but the processing becomes more complex. For example a single lower level receptive field might encompass only a single fingertip, but a higher-level would include the finger pads of all four fingers. Thus, these higher level neurons have been shown to encode such properties as motion, direction, and orientation (Hyvarinen & Poranen 1978). In addition, beyond the somatosensory cortex, other brain regions are integrated with touch to yield multi-modal forms of processing. This discussion is beyond the scope of this chapter, but the reader is encouraged to see (Calvert et al. 2004) for a further discussion.

3. The "Somatic Alphabet Approach"

In the previous section, the biological somatosensory system in humans and animals was described briefly. The goal of this section is to present one approach we have created to help abstract a design methodology for the field of robotics in creating "sensitive skins." We call this approach the "Somatic Alphabet" (Stiehl 2003; Stiehl & Breazeal 2004; Stiehl et al. 2004). Figure 1 shows a diagram of this approach.

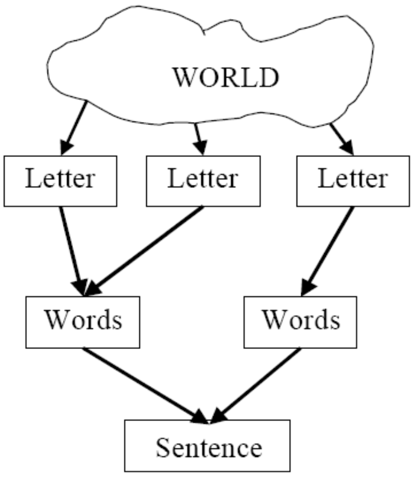


Fig. 1. The Diagram of the "Somatic Alphabet Approach"

The first building blocks of our somatic perception of the world around us are the actual skin receptors in the four modalities of pain, proprioception, touch, and temperature as shown in Table 1. These receptors are designed to encode a specific aspect of a specific type of somatic sensation. Thus nature has created a set of primitives. In the “Somatic Alphabet” approach these primitives are the “letters” of the alphabet.

Just as there is not a single somatic sensor in our skin, thus we should not build “sensitive skins” for robots relying on only one sensor to encode all the properties of the world encountered through touch. From a practical standpoint, it is possible to build a “sensitive skin” using commercially available sensors. For example temperature can be sensed using thermistors, RTDs, or thermocouples. Potentiometers can be used to measure kinesthetic information of joint angle motion. Force sensitive resistors, capacitive sensors, load cells, or vibration sensors can measure touch information. Finally, pain can be encoded as the extremes of temperature or touch information. Additionally, each sensor can be tuned using analog electronics to detect different levels of sensitivity to different input ranges. For example, a voltage divider can be used to change the response of a force sensing resistor (FSR) to different applied inputs. Thus, these hardware sensors act as the “letters” of the “Somatic Alphabet.” This approach is similiar to the original concept of a “sensitive skin” consisting of a collection of different sensors as proposed by (Lumelsky et al. 2001).

The next building level of the “Somatic Alphabet” combines the individual “letters” into “words” which now hold a specific meaning. In the biological system, data from the receptors in the skin travels up through the spinal cord to the somatosensory cortex. Here in this cortex, these receptors are combined into receptive fields for higher order cortical process such as orientation, direction of motion, etc as was previously discussed.

In our robotic “sensitive skin” the location and type of the sensors are known due to the specific design layout of the skin. The information from each of these low-level sensors travels from the periphery of the robot to a central processing computer and at each time step this information is aggregated to ascribe somatic meaning to the interaction. This higher level processing, i.e. the creation of the “words” of the “Somatic Alphabet,” is the first step towards building meaning about the interaction the robot is having with people and its environment.

Our perception of the world around us consists on not only touch, but rather we combine data from all of our senses to created a much richer understanding of the world around us. For example the smooth surface texture, the color, and the scent all tell us that the object we are holding is an apple and not an orange. Thus the “sentences” of perception can be formed by combining “words” from different modalities in our robotic system. In the next section we will show how we are applying this approach to the design of a multi-modal “sensitive skin” for a robotic companion called the Huggable.

4. The design of a multi-modal “sensitive skin” for a robotic companion

4.1 The huggable robot platform

In January of 2005, our research group began the development of a new type of robotic companion called the Huggable (Stiehl et al. 2005). The Huggable, shown in Figure 2 is designed to function both as a fully autonomous robot as well as a semi-autonomous robot avatar (Lee et al. 2008). We are particularly interested in using this robot to explore how robotic companions for healthcare, education, family communication, and entertainment should be developed. In addition we are developing this system to function as a research platform that can be used by experts in robotics as well as other fields such as eldercare (Stiehl et al. 2008).

The Huggable is being designed with a pair of cameras in the eyes (one color and one black and white), an array of microphones in the head based on (Miaw 2008), and a speaker in the mouth. In the body, the Huggable features an inertial measurement unit based upon (Morris 2004), passive potentiometers in the hips and ankles for joint angle position detection, and an embedded PC with wireless networking. Additionally, the Huggable features a set of 8 quiet, backdrivable actuators using a hybrid belt/gear drive system. These degrees of freedom (DOF) are a 3 DOF neck (nod, tilt, and rotate), a 2 DOF shoulder mechanism in each arm (rotate and in/out), and a 1 DOF ear mechanism. Currently, the Huggable robot runs tethered to a 12V power supply and will ultimately be wireless. The huggable is also being designed with a full body, multi-modal, sensitive skin with over 1500 sensors all over the surface of the body underneath a layer of soft silicone rubber and fur (Stiehl & Breazeal 2006). This skin is the subject of the following sections.

A full discussion of the hardware and software architecture of the Huggable is beyond the scope of this chapter and the reader is encouraged to see our other publications for more information (Stiehl et al. 2005; Lee 2008; Lee et al. 2008; Stiehl et al. 2008; Toscano 2008). Before transitioning to describing the "sensitive skin" system being developed for the Huggable robot, it is important to first motivate this discussion by mentioning a few important design considerations for the Huggable which directly impact the "sensitive skin" design.

Fig. 2. The Current Huggable V3.0 Prototype (in development) (right) and the Concept Plush by Tammy Hendricks (left). In the current prototype only the underlying mechanics of the robot are shown. The sensitive skin system, soft silicone rubber synthetic skin, and final cosmetic fur exterior are not shown in this photo. When fully finished the Huggable robot will look like the concept plush at left.

4.2 Important design considerations for the huggable's "sensitive skin"

The Huggable is designed to look and feel like a soft teddy bear. Thus, in addition to its furry look, the Huggable when touched must feel soft and organic as to not distract from the interaction. Other robotic companions such as the Omron NeCoRo (Omron Corporation Product Literature) place fur over hard plastic coverings or use only plastic covers without fur such as Sony’s Aibo (Sony Product Literature). While these are approaches, the feeling is very different for the person interacting with these robots than that of a real animal, soft teddy bear, or other soft skinned robots such as the Huggable and the Paro (Shibata et al. 2003). In the next section we will discuss how we are creating a soft silicone rubber synthetic skin for the Huggable to accomplish this lifelike feel.

Another important design consideration is that the Huggable must feature a full body “sensitive skin” to help promote the illusion of life. No matter how lifelike the Huggable moves or interacts, if a person touches the robot and it does not respond that illusion of life is instantly broken.

Ultimately, we want the “sensitive skin” of the Huggable to be capable of distinguishing a large variety of tactile interactions. Thus we have employed a “Somatic Alphabet Approach” in our design. Our current skin design is capable of detecting aspects from the four modalities of somatic sensation. We use electric field sensing and quantum tunneling composite (QTC) force sensors (Peratech 2004) to detect touch, thermistors to detect temperature, potentimeters to detect joint angle position, and finally pain can be determined as a high value above a determined threshold in each of the previous sensors. In addition to the multi-modal combination of sensors in the skin, we have a high spatial resolution of sensors in the skin – with QTC sensors the width of 1 finger tip in close proximity to one another. This size (width of 1 fingertip) was selected as most of the tactile interactions people will have with the Huggable will involve human touch on the robot in a petting, tickling, or scratching gesture, to name a few. Thus the smallest unit in size is approximately the width of one finger tip.

Finally, from a practical standpoint, the size of the Huggable, approximately 18 inches tall, means that whatever skin that is designed must be developed in a small form factor with much care given to wire management. A bundle of 400 wires would be larger than the arms of the Huggable and thus is not an option. To help reduce the number of wires and make the system as compact as possible, the Huggable features a tree like structure which will be discussed in the next section.

4.3 The electromechanical design of the “sensitive skin” of the huggable

As was previously described in Section 2, the human and animal somatosensory system provides a great template for the design of robotic sensitive skins. In Section 3, the “Somatic Alphabet” approach was presented as a way to create such sensor systems. In this section we will discussion how we have applied lessons from the human and animal somatosensory system and the “Somatic Alphabet” approach to design the “sensitive skin” of the Huggable robot.

As is shown in Figure 2, the current version 3.0 prototype of the Huggable has it’s “sensitive skin” design currently under development. For purposes of discussion, in this section we will be presenting the design of the “sensitive skin” of the previous Huggable robot prototype – version 2.0. Lessons learned from this design are currently being applied to the design of the somatic system for our current version 3.0 prototype.

Our “sensitive skin” design decouples the sensors from the actual soft synthetic skin material. This design decision allows for us to not have to make the sensing system flexible, as the silicone skin is capable of large elongations greater than 100%. A further discussion of the synthetic silicone skin appears later in this chapter.

Figure 3 shows two different examples of the “sensitive skin” for two different sections of the Huggable – a section of the arm and the body. Each green circuit board is the first level of the sensing tree and is analogous the skin of the human body. On these sensor circuit boards, the three main sensor types of the Huggable’s “sensitive skin” system are found. The white rectangles and squares are the QTC material used for force sensing. These Peratech Quantum Tunneling Composite sensors were chosen for their wide resistance range (10 M-ohm to less than 1 ohm) and low cost (Peratech Product Literature). Additionally the switch substrate material came in A4 sheets which could be cut to any specific size which allowed for much flexibility in our design. There are close to 1400 of these sensors in the current version 3.0 skin design and they are used primarily for high spatial resolution force detection.

The silver circles above the arm sensor circuit board are the Thermometrics NTC thermistors (Thermometrics Product Literature) used for temperature sensing. Ultimately it was decided to replace these through hole sensors with surface mount sensors in the rest of the sections of the “sensitive skin” due to the risk of the small sensor leads breaking during prolonged interaction. Currently we are exploring methods of improving the thermal conductivity of the silicone rubber to get better performance from the surface mount thermistors. However, the slow time constant of these temperature sensors is not a huge problem. We do not require fast temperature sensing but rather monitor the temperature rise in a region of contact with a person’s body due to body heat.

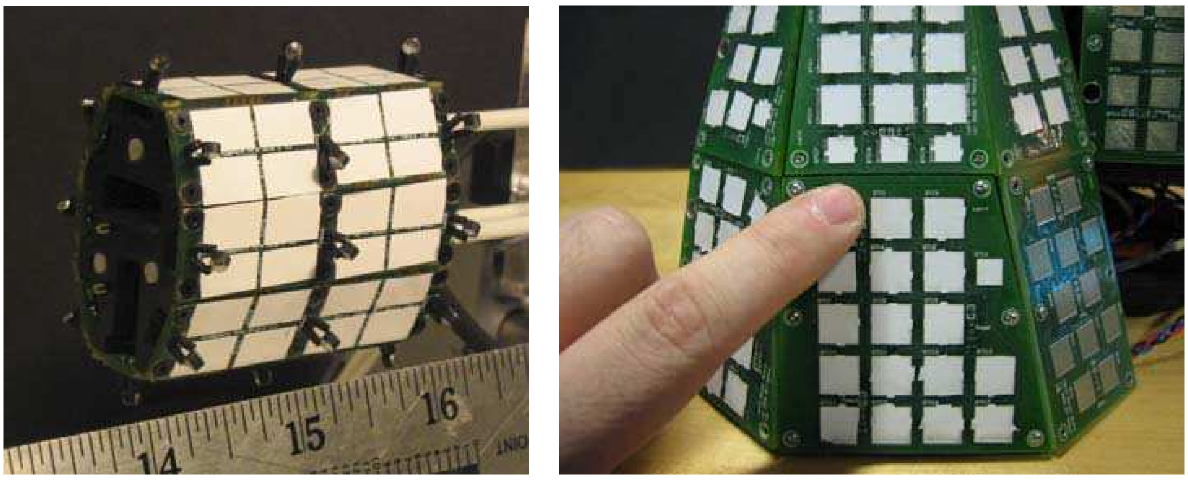


Fig. 3. Two Examples of the “Sensitive Skin” designed for the Version 2.0 Huggable Robot. At left is a section of the arm with units shown in inches. At right is one of the four body region panels with a human finger shown for scale. In each case the silicone skin and soft fur coverings are removed to show the sensor circuit boards.

Finally, the electrodes for the electric field sensors are embedded inside each of the sensor circuit boards on an internal layer. A Motorola/Freescale Semiconductor 33794 Electric Field Sensing IC is used for processing the electric field signal connected to each electrode. This IC was selected as it allowed for 9 input electrodes with a driven shield. The driven shield is connected both to the shield of the coaxial cable carrying the signal as well as a copper shield on the backside of each sensor circuit board (not shown). Additionally, the use of a single IC package solution allowed for the measurement process in one body region to run in parallel while other processes were running on the microcontroller. We currently tune these electric field sensors to be preferential to human contact and thus use them to measure the proximity of a human hand to the surface of the Huggable. This has great human robot applications, as using this sensor we can distinguish between the Huggable sitting in a person’s lap or sitting on a table top due to the differences in dielectric material properties and conductivity between a plastic or wood table top and human skin. Another benefit of using this sensor in our skin is that our robot has a soft fur covering of approximately ½″ in thickness. Thus, if a child or adult were to gently stroke their hand across the top surface of the fur, they would actually not be applying a force to the skin, but rather just displacing the fur. Ideally, we would want a similar receptor to the hair mechanoreceptors of Table 1. While some have used small piezo sensors with mounted fibers as used in the Tribble project (Paradiso et al. 2004), we felt that given the size limitations and potential places for people to gently brush the fur, it was better to use a proximity sensor for this purpose. The electric field sensor allows us to detect such proximity to about 1″ above the surface of the sensor circuit boards and can be read through the silicone rubber sensitive skin. For those who are interested in further reading, a much further discussion of electric field sensing can be found in (Smith 1999).

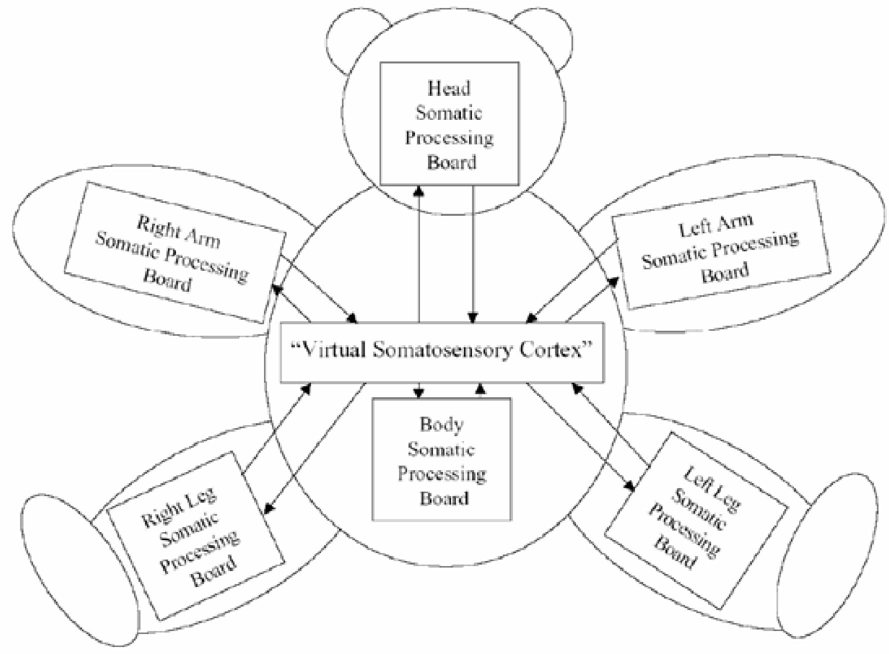


Fig. 4. The Division of the Huggable Robot into Body Regions. As shown in the figure, each body region has its own Somatic Processing Board with the output of each of these circuit boards being sent to the “Virtual Somatosensory Cortex” software system running on the Embedded PC inside the Huggable robot.

Just as the human and animal somatosensory system divides up the skin into dermatome regions, we divide the Huggable’s “sensitive skin” into body regions and then sub-regions. First the Huggable is divided into six body regions as shown in Figure 4 with each body region having its own somatic processing circuit board. This circuit board will be discussed in more detail later in the section. This division allows faster processing time for the entire skin system. Additionally, each body region is further divided into independent body sections. Each body section is further divided into a set of sensor circuit boards with each circuit board having a discrete set of temperature, QTC, and electric field sensors. For example, the arm section shown in Figure 3 is one of five arm sections which make up the arm region. As shown in the figure, the arm section shown consists of eight sensor circuit boards with each sensor circuit board consisting of eight QTC, three temperature, and one electrod for the electric field sensor inside the circuit board (not shown). This tree-like structure mirrors the design of the nerves of our somatosensory system.

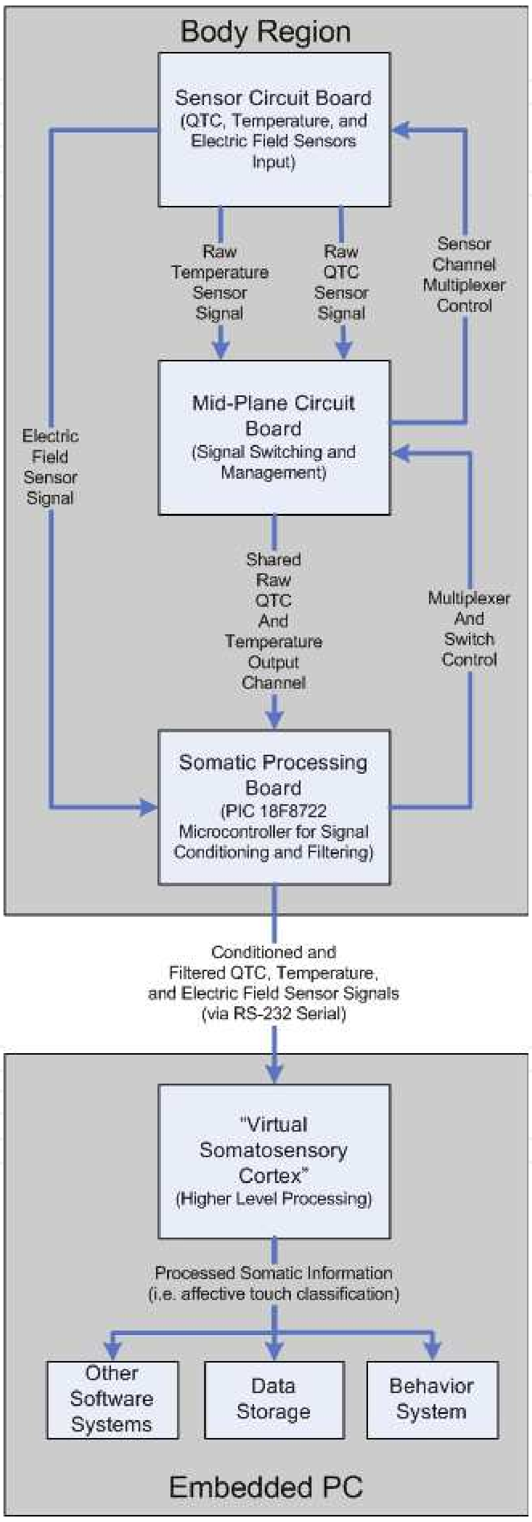


Fig. 5. The Flow of Information in the Huggable's "Sensitive Skin."

To help reduce the overall number of wires we employ a three layered approach of circuit boards in each body region as shown in Figure 5. The first layer is the actual sensor circuit board shown in Figure 3. A pair of on-board multiplexers is used to switch between each QTC and temperature sensor. The electric field sensors have their own path direct to the somatic processing circuit board via a shielded cable to prevent interference. Additionally, in the arm each arm section's set of eight sensor circuit boards are divided into two electrodes with each set of four sensor circuit boards forming one electrode.

The QTC and temperature output of the multiplexers on the sensor circuit board travels to the next layer – the mid-plane circuit board. The mid-plane circuit board has a dual purpose. First, this circuit board mutiplexes the QTC and temperature outputs of each sensor circuit board in a given body region to further reduce the overall wire count.

Second, the mid-plane circuit board features a series of on-board switches to isolate each sensor circuit board from the rest of the system during electric field sensor readings. This isolation is needed to prevent the electric field signal from coupling into the other wires of the system and which carry power, multiplexer control, and ground to the sensor circuit boards. A more in-depth discussion of this design and the isolation process can be found in (Stiehl 2005; Stiehl & Breazeal 2006). Finally, the mid-plane circuit board also acts as a pass through for power, ground, and multiplexer channel select to each of the sensor circuit boards in that body section.

The final layer in each body region is the somatic processing board which is responsible for the control of the entire "sensitive skin" body region, the signal conditioning of the raw sensor values for the temperature, QTC, and electric field sensors, the A/D conversion of these sensor values, and finally the output of these digitized values to the Embedded PC's "Virtual Somatosensory Cortex" software system for higher level processing. Figure 6 shows a schematic overview of the somatic processing circuit board. As shown in this diagram, the QTC sensors are processed in three different ways – light, moderate, and hard. Each processing method was done using a different voltage divider resistor value to sense a different part of the exponential sensor range of the QTC switch substrate (Peratech Product Literature). In addition, though not shown in Figure 6, each signal conditioning system featured a set of digital potentiometers which were designed to be used as part of an auto calibration function. Further work has been done on the auto calibration approach and the description can be found in (Wang 2008). A more detailed description of the somatic processing board is beyond the scope of this chapter, but the reader is encouraged to look at (Stiehl 2005; Stiehl & Breazeal 2006) for more information.

4.4 Synthetic silicone skin

As shown in Figure 7, the Huggable features a soft silicone rubber skin between the soft fur exterior and the hard sensor circuit boards of Figure 3. This synthetic skin helps to provide the Huggable with a more life-like organic feel while helping to protect the sensors. As we wanted to use a soft silicone rubber, a series of tests using professional special fx silicone rubbers were conducted. The details of these tests can be found in Chapter 13 of (Stiehl 2005). The final formulation chosen was Silicone's Inc XT-298 with 20% silicone fluid. This rubber was cast into 3-D printed molds to ensure a proper thickness of 1/8" to ¼" depending on the body location. A full discussion of the casting and pigmentation of silicone rubber is beyond the scope of this chapter, but the reader is encouraged to see (McLaughlin 1999) for more information.

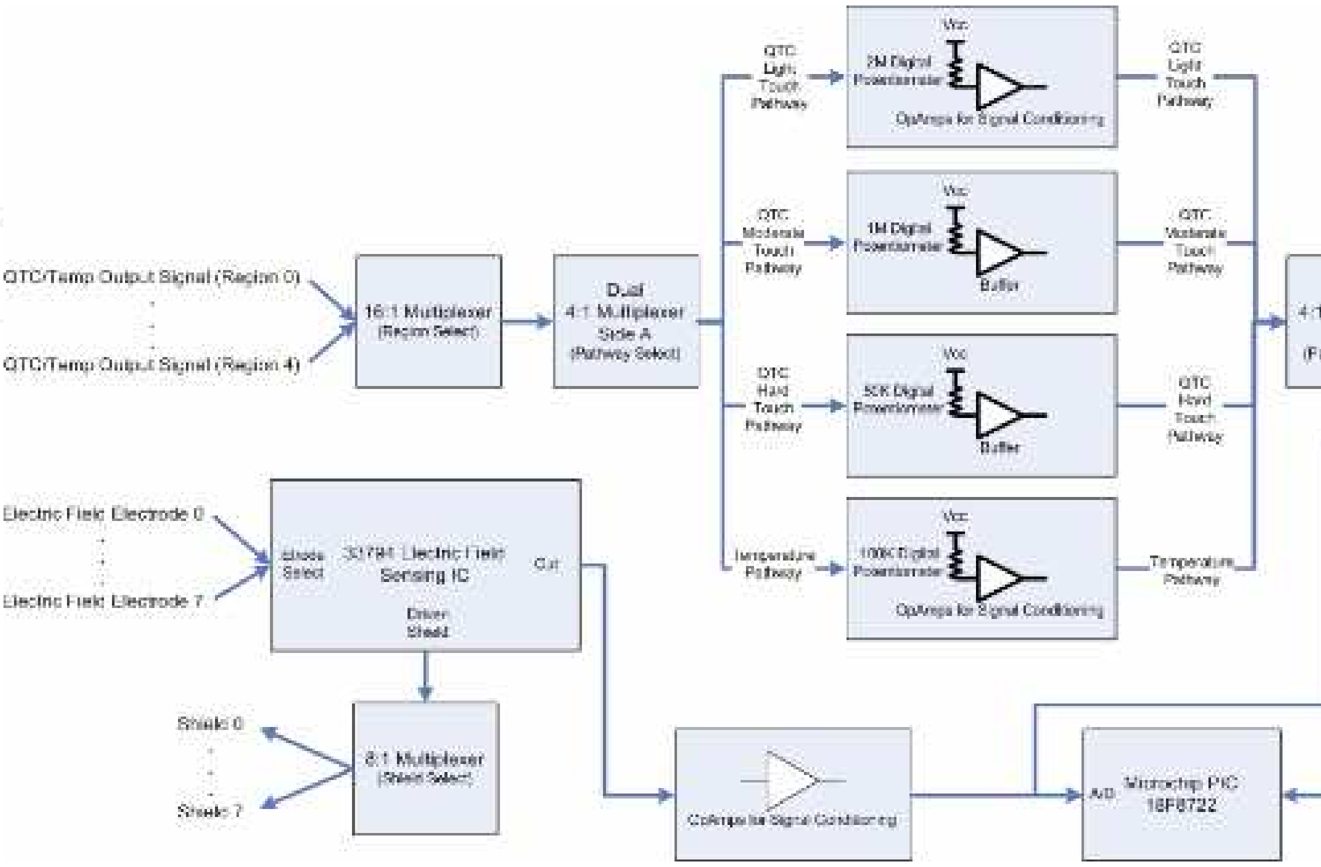


Fig. 6 The Schematic Overview of the Somatic Processing Circuit Board. Note the auto calibr
shown.

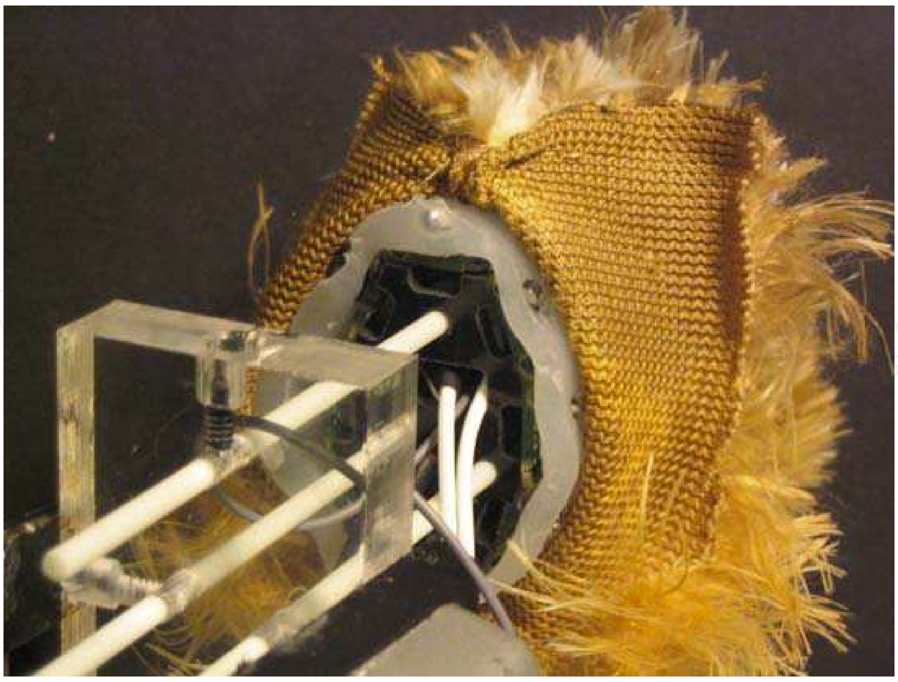


Fig. 7. The Arm Section of the Huggable “Sensitive Skin” showing the layered structure of soft silicone rubber sandwiched between a fur exterior and the sensor circuit boards.

4.5 The “virtual somatosensory cortex”

The somatosensory cortex of humans and animals contains cells which use population coding to arrive at higher levels of processing, as was previously described in section 2. In the population coding approach cells respond to a specific feature with in a given receptive field. This receptive field is formed by combining a set of individual receptors. The outputs of these cortical cells form the inputs to higher levels of processing further on in the somatosensory cortex. In the “Somatic Alphabet Approach,” the “words” are formed by this process.

We employ a similar approach in the design of our “Virtual Somatosensory Cortex,” which is the name of our somatic processing software system which runs on the embedded PC of the Huggable robot. Our current approach is an extension of work originally done in the early design of a pair of tactile sensing hands for the Leonardo robot at the MIT Media Lab (Stiehl 2003; Stiehl & Breazeal 2004; Stiehl et al. 2004; Stiehl 2005). Just as with the biological system, we employ a population coding approach. Here individual sensor outputs which have been conditioned, filtered, and digitized by the Somatic Processing Circuit Board are combined into receptive fields which are formed in a hierarchical tree. This tree has the smallest unit of a single sensor circuit board, and these sensor circuit boards are combined into larger and larger receptive fields for higher levels of processing, as is the case in the human and animal somatosensory system. From a computational approach, this ability to have multiple levels of receptive fields allows for different interactions to be encoded. For example, a “look at where touched” behavior would only need to know the rough location where the robot was touched, but a more complex behavior needs to not only know where, but also how the robot is being touched, for example giggling if tickled. Finally, the processed outputs of the “Virtual Somatosensory Cortex” system are then fed to the behavior system and integrated with other sensor data, such as the IMU, vision, or sound.

A detailed discussion of the various methods we currently employ in the calculation of our sensitive skin is beyond the scope of this chapter and the reader is encouraged to read the indicated references for more information. Our current system design first normalizes all sensor values with respect to a baseline to account for small changes in individual sensors. Then a set of low-level features, including determining the centroid of force in a given receptive field, the orientation, the direction of motion, timing characteristics, and other information is calculated following the steps outlined in (Stiehl & Breazeal 2004; Stiehl 2005; Stiehl & Breazeal 2005). As a first test to verify that affective processing was possible using our skin, an off-line neural network approach using MATLAB was done as described in (Stiehl & Breazeal 2005). This approach focused on just a small section of the arm and we are currently expanding our methodology to the full skin and we are currently experimenting with various new pattern classification techniques such as HMMs in the design of our new "sensitive skin" for the Huggable Version 3.0, currently in development. A discussion of these new techniques can be found in (Knight 2008).

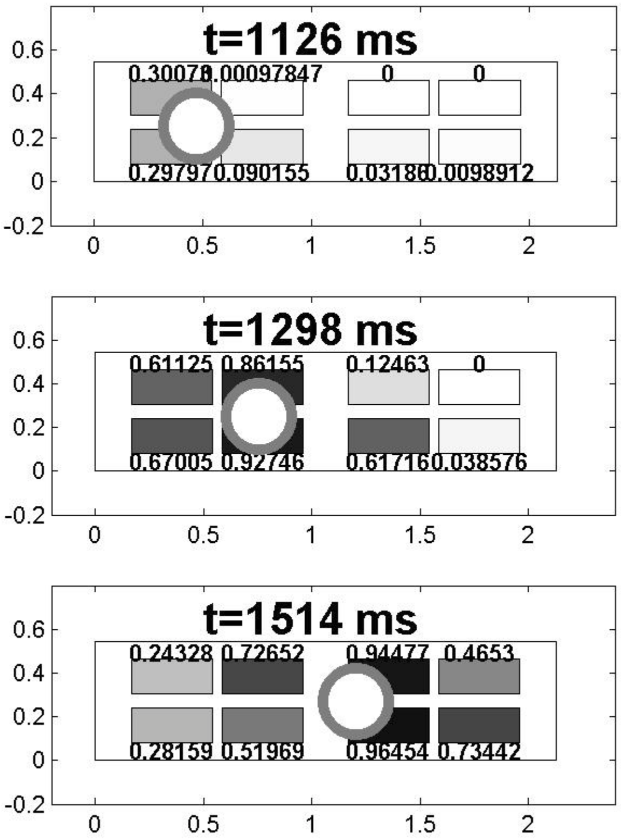
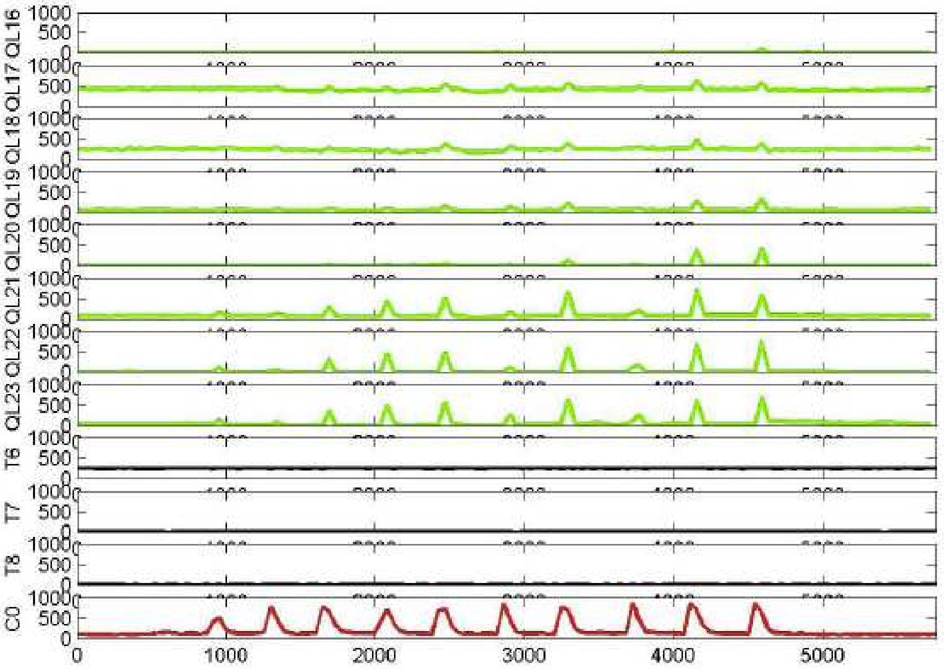


Fig. 8. The calculation of the QTC sensor centroid location for a petting gesture applied by human hand to the top surface of a sensor circuit board. The sequence in time is shown from top to bottom. Each sensor value is indicated both numerically above or below the sensor, and in greyscale with black as maximum value. The white circle with grey edge is the centroid location.

4.6 Results

To help illustrate the performance of our sensitive skin we include the following figures originally published in (Stiehl 2005; Stiehl & Breazeal 2006). A detailed discussion of these results is beyond the scope of this chapter, but we highlight only a few figures to show the power of a multi-modal sensitive skin. Figure 8 shows the calculated centroid of force during a petting gesture. Figure 9 shows the raw sensor response to two types affective

10 Pats



Squeeze

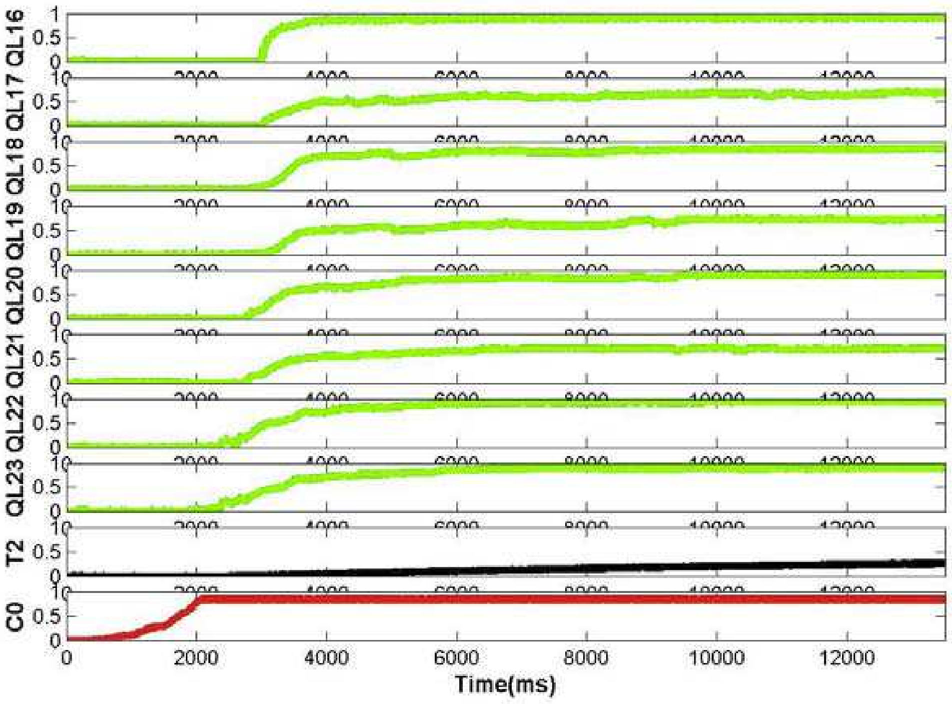


Fig. 9. The response of the QTC (QL, green), temperature (T, black), and electric field sensor (C, red) of one sensor circuit board to two different interactions. At top is a series of 10 pats with sensor values shown as their raw 10-bit value. At bottom is a response to a squeeze with sensor values normalized from 0 to 1.

touch – a series of 10 pats and a squeeze. In both figures, the stimulus was applied by a human hand to the top sensor circuit board in the arm section shown in Figures 3 and 7.

As shown in Figure 8, it is clear that across the time sequence the centroid location is moving in a direction from left to right, as is the case for a petting gesture. In the case of the 10 pats gesture of Figure 9, a few interesting aspects emerge from the figure. First, the QTC sensors directly under the patting gesture (QL21-23) show a larger response than the other sensors, which convey the location that the gesture was applied. Next, it becomes clear that the patting gesture did not have constant force, but all ten peaks are visible in time. Third, the temperature sensors, with their long time constant, do not show any effect. Finally, the electric field sensor (C0) clearly shows all 10 pats as it is a measure of proximity and not force.

The squeeze gesture of Figure 9 demonstrates a different behavior. With the squeeze, the entire sensor circuit board indicates a maximum value. In this case, the QTC light pathway is only shown, and thus all QTC sensors are close to being fully saturated. What is different in this case is that unlike the short interaction of the patting gesture, the squeeze has a much longer interaction time. This longer length allows the temperature sensors to show a gradual increase over time due to the body heat from the person being sense by these sensors. Thus, for longer interactions where the electric field and force sensors may saturate, the slow time constant of the temperature sensors may yield additional information. Finally, the electric field sensor actually responds prior to the onset of touch. As this sensor measures the proximity of contact, the anticipation of touch can be recorded.

While we currently have much more work to do with this system, these early results from the Huggable Version 2.0 "sensitive skin" are encouraging. We believe that the multimodal nature of these skins allow for more types of interactions to be sensed. With a larger potential feature set due to the different types of sensors and methods of processing, we hope that our pattern recognition algorithms will show improved results.

5. Conclusion

The goal of this chapter has been to present the reader with a brief introduction to some of the design considerations for multi-modal "sensitive skins" for robotic companions. In order to motivate how such systems should be designed, a brief discussion of the human and animal somatosensory system was presented. Central to the design of the biological system is the notion that our sense of tactile perception consists of four main modalities – pain, proprioception, touch, and temperature. Within each of these modalities are a set of receptors specifically designed to respond to and encode a specific set of stimuli. These building blocks are then grouped into receptive fields in the somatosensory cortex of the brain where higher lever processing is conducted. Finally, this somatic information is integrated with other sensory systems to form the perception of the world around us.

Using this biological model, the "Somatic Alphabet Approach" was then presented. This approach treats specific sensors as the building blocks or "letters" of our perception. These "letters" are then combined through higher level processing into the "words" which hold the somatic meaning. Finally, these somatic "words" are combined with “words” from other sensory systems to form the “sentences” of the perception of the world around us.

Next, using the “Somatic Alphabet Approach” as inspiration, the design of the multi-modal, “sensitive skin” for the Huggable robotic companion was presented. This “sensitive skin” system featured sensors across the four modalities of somatic sensation – touch, temperature, proprioception, and pain. In addition this system consisted of a dermatome like mapping of the individual QTC, temperature, and electric field sensors into specific body regions, sections, and specific sensor circuit boards. A brief discussion of the electromechanical design and some of the processing methods used in this system followed to show how the design of this system was inspired by the somatosensory system of humans and animals. Finally, the brief results presented show that such multi-modal “sensitive skins” hold great potential for improved interaction processing capabilities and thus could allow for a much richer human robot interaction.

6. Future work

The Huggable is very much an active ongoing project. Over the past year, our focus has been on the final mechanical design of the Huggable Version 3.0 robot as well as the development of the semi-autonomous robot avatar system (Lee et al. 2008; Toscano 2008). As we move back to the “sensitive skin” design for this new robot, we expect to explore new methods to improve this current design. This includes the potential for fully implementing the entire “sensitive skin” with auto calibration functionality, following the method proposed by (Wang 2008). Additionally, Heather Knight in the Personal Robots Group has been exploring the potential for inferring social touch as part of her upcoming MEng Thesis (Knight 2008). Unlike the affective touch approach which looked primarily at analyzing the tactile interaction in a specific region, the approach Heather is taking will integrate tactile information from all across the body of the robot to infer things such as hugs and other types of social touch. Finally, we are going to be expanding the “Virtual Somatosensory Cortex” software system. One current goal will be to allow the Huggable to integrate full body touch with joint angle information and the inertial measurement unit to understand how it is being held, where the person is in relation to its body, and then using this information allow the Huggable to show relational touch behaviors such as nuzzling into the persons body or looking up at them.

Beyond the Huggable, the design of “sensitive skins” for robotic companions holds many open research questions. As shown in Table 1, our human skin features a large number of receptor types. Our current robotic skin with three sensors is a small fraction of the potential a more sensor rich, multi-modal skin could achieve. Thus, there are the engineering challenges of densely packing a large number of different sensor types into one system. Additionally, if such skins were created, they hold a series of processing challenges. Finally, would it be possible to include sensors not in the human system that could benefit robots where they have deficiencies, even by adding features from other sensory systems into the somatic skin. For example, can a “sensitive skin” be designed which functions as a crude vision system to help improve upon a robot’s capabilities in the human world?

Lastly, when robots with full body, multi-modal, “sensitive skins” become common place, what new applications could emerge? Could these systems be used for therapy applications where the type of touch imparted to the robot or object is measured and recorded? One example is the notion of play therapy, if a child plays with a toy in the therapy session and it records how that toy is being interacted with through its “sensitive skin,” could new methodologies and treatments emerge? Can these “sensitive skins” be combined with prosthetic systems and potentially give an amputee a synthetic sense of touch? Can these skins be applied to furniture to create large surface covers that detect many things about their environment and expand the notion of robot to include furniture? One can clearly see that when we give robots a sense of touch that begins to approach or exceed our own human system, entirely new doors will open in human robot interaction.

7. Acknolwedgements

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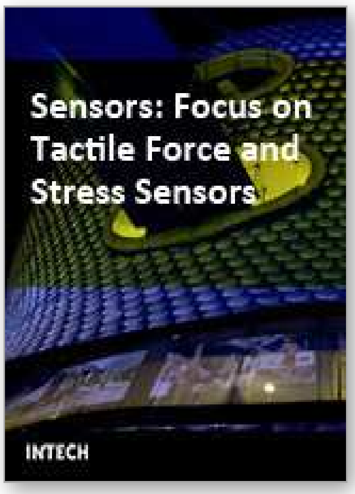

Sensors: Focus on Tactile Force and Stress Sensors
Edited by Jose Gerardo Rocha and Senentxu Lanceros-Mendez

ISBN 978-953-7619-31-2
Hard cover, 444 pages
Publisher InTech

This book describes some devices that are commonly identified as tactile or force sensors. This is achieved with different degrees of detail, in a unique and actual resource, through the description of different approaches to this type of sensors. Understanding the design and the working principles of the sensors described here requires a multidisciplinary background of electrical engineering, mechanical engineering, physics, biology, etc. An attempt has been made to place side by side the most pertinent information in order to reach a more productive reading not only for professionals dedicated to the design of tactile sensors, but also for all other sensor users, as for example, in the field of robotics. The latest technologies presented in this book are more focused on information readout and processing: as new materials, micro and sub-micro sensors are available, wireless transmission and processing of the sensorial information, as well as some innovative methodologies for obtaining and interpreting tactile information are also strongly evolving.

Walter Dan Stiehl (2008). Design Considerations for Multimodal "Sensitive Skins" for Robotic Companions, Sensors: Focus on Tactile Force and Stress Sensors, Jose Gerardo Rocha and Senentxu Lanceros-Mendez (Ed.), ISBN: 978-953-7619-31-2, InTech, Available from: http://www.intechopen.com/books/sensors-focus-on-tactile-force-and-stress-sensors/design_considerations_for_multimodal_sensitive_skins_for_robotic_companions

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