A “Somatic Alphabet” Approach to “Sensitive Skin”

Walter Dan Stiehl, Levi Lalla, and Cynthia Breazeal
Robotic Life Group
MIT Media Lab
Cambridge, MA 02139, USA
{wdstiehl & yeomp}@mit.edu, cynthiab@media.mit.edu

Abstract— **The sense of touch is one of the most important sensory systems in humans. This paper describes an initial step toward the realization of a fully “sensitive skin” for robots in which somatic sensors of varying modalities such as touch, temperature, pain, and proprioception combine, as if letters in an alphabet, to create a more vivid depiction of the world and foster richer human robot interactions. We have developed a new “sensitive” hand, covered in a lifelike silicone “skin” to explore the importance of touch and the formation of the somatic alphabet in the context of our humanoid robot, Leonardo. From initial tests the populations of these sensors show the potential for similar performance to both the mechanoreceptors in human skin and the cortical neurons in the somatosensory cortex.**

Keywords-tactile sensing; force sensing resistor; “sensitive skin”; “somatic alphabet”

I. INTRODUCTION

As humans, we often take our sense of touch for granted even though this sensory system has been referred to as the “mother of all senses” [1]. Our skin is not only the largest sensory organ of the body, but also it is the first to become functional in all species [2].

Much of the focus of tactile sensing research in robotics has been on manipulators. While this work is important to the field, it is only one small portion of the potential of how a sense of touch can be beneficial to a robot. Providing the robot with a full-body sense of touch can help to prevent the robot from damaging itself. As was pointed out by Lumelsky, Shur, and Wagner, vision alone is not sufficient due to the problems of occlusion [3]. Tactile information and vision can be combined together to form a stronger percept. A simple example would be to have a robot using visual information (such as color, shape, and location) as well as tactile information (such as softness, roughness, temperature, vibration, or mass) to distinguish between two objects. In the context of human robot interaction, a sense of touch can help distinguish between the situation where a person places his or her hand around the robot’s arm to guide it to an object versus the impact felt by the arm when it bumps into something. Touch can also be employed as part of a control loop. A better controller results if both tactile feedback and force feedback are combined [4]. Tactile information can also be used to help to trace the contours of an object and further understand its shape. These are only a few of the many examples in which a full body sense of touch can be beneficial to the field of robotics and the related field of prosthetics.

In this paper, insights from brain and cognitive neurosciences provide a background as to how we process our own somatic information and how we can apply this understanding to the field of robotics. Central to this discussion is the notion of a “somatic alphabet.” Our perception of the world around us through our somatic senses is not due to a single “somatic sensor” but rather an alphabet made of different types of sensors and methods of processing. These “letters” combine to form the “words” and “sentences” of our somatic perception. Next, we will discuss how a “somatic alphabet” can be applied to robotics in the creation of a fully “sensitive skin.” Finally, we will discuss a current implementation using force sensitive resistors as the first letters of this alphabet on the hands of our humanoid robot, Leonardo.

II. TACTILE PERCEPTION IN HUMANS AND ANIMALS

In order to design a biologically inspired sense of touch system for robots it is important to first understand how humans and animals are able to tactilely perceive the world around them. Human and animal skin can be divided into two main types – glaborous, found on the palm of the hand and sole of the foot, and hairy, found nearly everywhere else. Within each skin type there are different somatic sensors, referred to as receptors. There are four main receptor types – cutaneaous and subcutaneous mechanoreceptors that encode touch; thermal receptors that encode temperature; nociceptors that encode pain; and muscle and skeletal mechanorceptors that encode limb proprioception [5].

Within each of these categories are at least four different types of mechanoreceptors which encode a specific property of that modality. For example, in the modality of touch, the Ruffini ending will largely encode skin stretch, while the Pacinian corpuscle will largely encode vibration [5]. The discriminative touch sensors encode the properties of objects such as size, shape, and texture as well as the movement of these objects across the skin. It is with this class of sensors that much of the discussion of this paper will focus since it most closely parallels the sensors chosen for this work.

There are four main types of mechanoreceptors found in glaborous skin. These receptors can be arranged in a 2x2 grid as shown in Table I. The first axis, adaptation, corresponds to how a receptor responds to a sustained stimulus. The rate that a slowly adapting, or SA, mechanoreceptor fires has been shown to indicate how rapidly pressure is applied to the skin (initially), and then in steady-state shows a level proportional to skin indentation [5 pg 438]. Rapidly adapting, or RA, mechanoreceptors fire at a rate proportional to the speed of motion, and their duration of activity corresponds to the duration of motion [5 pg 438]. The second axis refers to the receptive field size, or how large an area on the skin a receptor is sensitive. Mechanoreceptors at the superficial layers, i.e. closer to the surface, have a smaller, more finely tuned receptive field. The deep layer mechanoreceptors have a larger

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field with a much less defined boundary [6]. These sensors often have a region directly above where they are most sensitive.

Much work has been done investigating how mechanoreceptors at the periphery encode tactile information, specifically in the realm of texture and roughness [7], shape [8], and curvature [9]. Other similar types of peripheral encoding can be seen in temperature, pain, and proprioception as well. Thus it becomes clear that much information is encoded by the receptors at the periphery, and the "alphabet" of somatic sensation begins here.

As tactile information travels from the periphery to the brain, it travels in a somatotopic grouping, i.e. nerve fibers from different regions of the body tend to group together based on location. This somatotopic map is ultimately reflected in the primary somatosensory cortex where the area of cortex devoted to a given part of the map is proportional to the number of receptors in each body location. For example, the fingers, lips, and tongue have a higher density of receptors (and a much larger cortical area on the map), as compared to the trunk (that has a low density).

The cortex itself has a hierarchical structure with many mechanoreceptors from the periphery converging upon the receptive field of a lower-level cortical neuron. These lower-level cortical neurons combine together to form the receptive fields of higher order cortical neurons which may respond to motion, direction, or orientation of a stimulus [5]. This construction of higher order cortical neurons, based upon the combination of lower cortical neurons, can be seen in other modalities of the somatic senses as well. Thus the "words" and "sentences" of the perception of touch are formed by a combination of the alphabet at a lower level of processing.

TABLE I. MECHANORECEPTORS IN GLABOROUS SKIN. ADAPTED FROM [5]

	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

III. DESIGN ISSUES FOR ROBOT SKIN

In [3], Lumelsky, Shur, and Wagner describe a "sensitive skin" as a "large area, flexible array of sensors with data processing capabilities" covering the entire surface of a robot (consisting of a wide variety of sensors) that would allow robots to function without human supervision in "unstructured, unpredictable environments" [3, pg 41]. The use of a wide variety of sensors in this skin parallels the notion of the somatic alphabet introduced previously. This poses a series of design challenges that must be considered.

A. *Flexibility*

The first is flexibility. If the skin and the sensing system of the robot are the same entity, all of the wiring, sensing elements, and local processing, in addition to the material of the skin, must be able to bend around joints, conform to curvature, and stretch while still providing accurate sensor readings. One approach is the design of conductive fabric sensors [10, 11]. Another idea is to eliminate the wiring entirely through the use of inductive coupling [12] or optics [13]. Our approach is to decouple the skin from the sensor. A soft silicone skin covers the sensors that are rigidly mounted to the hand.

B. *Integration of Processing Elements*

Another design challenge is the integration of processing elements into the skin. Some initial work has been done in this area, combining both sensing and processing elements, for both a shear-stress sensor [14] and a fingerprint detector [15]. How the skin processes information from a large number of sensors poses a similar problem to those researching wireless sensor networks. Specifically, how can a network of distributed sensing and processing elements communicate information to each other. Some approaches to this problem are explored in the "Pushpin Computing" [16] project at the MIT Media Lab.

C. *Wide Variety of Sensors*

There currently exists a wide variety of available electronic sensors that could be implemented as part of a somatic alphabet framework. The greater the sensing capability, both in resolution and in number of modalities, the larger the number of percepts can be formed. For example, roughness of an object could be encoded through tactile or vibratory sensors. This and other information could be useful to help a robot perform a task by "feeling" the handle of a tool as it picks it up.

Fig. 1 Our humanoid robot, Leonardo. As can be seen, this robot has an organic appearance. Leonardo was designed in collaboration with Stan Winston Studio. (Photo copyright Sam Ogden. Leonardo chracter design copyright Stan Winston Studio.)

D. *Natural Look and Feel*

As shown in Fig. 1, Leonardo is designed to have an organic look and feel, unlike traditional humanoid robots that are usually made of metal and have a hard exterior. Thus it is important that the robot's skin have a natural look and feel.

IV. DESIGN OF TACTILE SENSATE HANDS

To explore the creation of a fully "sensitive skin" for an anthropomorphic robot, our emphasis was first to create a set of hands for Leonardo.

Leonardo’s current hands are covered by a foam latex glove as can be seen in Fig. 1. These gloves pose an important design constraint as they fixed the exterior of the palm of the hand to less than 36 mm long x 48 mm wide x 11 mm high. Due to the small size of the hand, all sensor processing in the initial hand design (shown in Fig. 2) happens on a separate circuit board away from the hand itself. In addition, this first generation hand was approximately 1.5 times larger than Leonardo’s actual hands.

The modality of touch, specifically pressure, is the first somatic sensor we chose to begin the development of our “somatic alphabet.” Many of the robot’s interactions with people and objects are based upon touch, and less upon vibration and temperature. Leonardo also has a sense of proprioception through the feedback provided by the potentiometers and encoders on each motor. A sense of pain is encoded as too much pressure on the sensors. For a more in-depth description of the ideas and implementation of the first generation hand described in this paper see [17].

A. Sensor Selection and Layout

The sensors used in the hand are force sensing resistors (FSRs) part #400 obtained from Interlink Electronics. These sensors were selected because of their fast response rate, high sensitivity, small drift, and wide force range. A summary of the specifications of these sensors appears in Table II.

The FSR lead lengths were reduced and hand crimped from a length of ~31mm from the base of the diameter of the sensor to a total length of ~19mm to allow for maximal sensor placement. Using the body’s somatic sensor layout as a guide, it was determined that groups of sensors should be clustered together to form the higher cortical cells, whose receptive fields consisted of many mechanoreceptors. In the implementation of the first generation hand, ten FSRs were combined together on the palm. Another ten were combined on the back of the hand. Three FSRs were placed on the side of the hand. Each of the four fingertips has five sensors, one on each surface. Thus the total number of FSRs on the first generation hand totals 43 sensors. Fig. 2 shows the entire hand with sensors mounted.

B. Lower Level Processing

The sensory information from each sensor enter into a custom designed 64-Channel Analog-to-Digital Conversion Board. This board takes input from the right hand and fingers. One can imagine the creation of a full-body somatotopic map of sensation using a series of these A/D conversion boards with each board mapping to a specific body part.

Each tactile sensor enters the circuit through a voltage divider with the FSR at the base of the divider and a 50 kilo-ohm potentiometer at the top. The potentiometer is used to adjust any sensor to measurement differences due to the hand crimping process. After this initial preprocessing, a series of 4 dual 8-channel MAX307 analog multiplexers are used to select which sensor is activated for A/D conversion. A PIC16F877 microcontroller is at the heart of this circuit and does the 10-bit A/D conversion. Finally, a MAX233 RS-232 driver/receiver is used for serial communication. The baud rate used for serial communication is 19200.

TABLE II. INTERLINK FSR PART #400 SPECIFICATIONS ADAPTED FROM [18]

PARAMETER	VALUE	NOTES
Size of Active Area (part #400)	0.5 cm diameter	
Thickness	0.30 mm	
Pressure Sensitivity Range	<0.1 to > 10 kg/cm^3	Dependent on Mechanics
Force Resolution	Better than 0.5% full scale	
Break Force	20 g to 100 g	Dependent on Mechanics and FSR build
Stand-off Resistance	>1M	Unloaded, unbent
Switch Characteristic	Essentially zero travel	
Device Rise Time	Resistance instantaneously tracks force	
Sensitivity to Noise and Vibration	Not significantly affected	
Temperature Range	-30°C to +70°C	Dependent on Materials

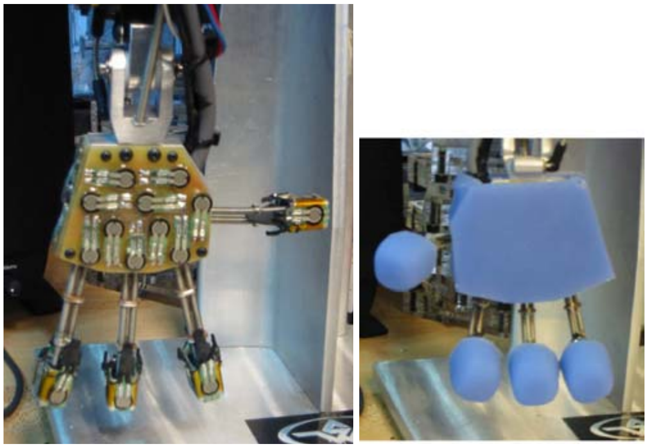

Fig. 2 The Assembled First Generation Hand – Back of Hand View at left; Palm view of Silicone skin at right

C. Synthetic Silicone Skin

Human and animal skin is viscoelastic. A “soft skin” is necessary for tactile sensing to protect the sensors from damage, to allow for better grip by conforming to the objects’ surface, and to allow for significant deformation in the medium to distribute localized pressure. This serves to activate the sensors in a way that provides them with enough resolution [19]. The skin must be flexible and stretch around joints. If a robot and human are to interact together, the skin must have an organic feel as well.

Silicone rubber, specifically those used in the special effects industry, was chosen to create a synthetic skin over the first generation hand because of their low durometer, high elongation, and their ability to be colored and finished to give a realistic look. Fig. 2 shows the hand with the 7mm thick silicone cover (made of Walco V-1082 Silicone with 20% DC-200 silicone fluid) attached. The hand is not cosmetically finished in this version.

V. RESULTS

A. Peripheral Coding

As was discussed in the beginning of this paper, our perception of touch is encoded by a variety of sensors, each encoding a specific type of stimuli. One of the main divisions of the four touch mechanoreceptors in human skin is based upon how quickly they adapt to changes in stimuli, either rapidly adapting or slowly adapting. Fig. 3 shows the response of a single FSR to finger taps applied to the silicone skin directly above it.

In this figure, the sensor shows the logarithmic response of the FSR. Values decrease with increasing pressure due to the voltage divider relationship described earlier. The sensor functions in a similar manner to a slowly adapting mechanoreceptor, encoding pressure sensed in the silicone skin above. By taking the derivative, as shown in the lower plot, a rapidly adapting profile emerges. The sign of the derivative implies the direction of motion, either increasing or decreasing indentation. Thus one sensor signal can represent two different types of sensory information encoding this portion of the somatic alphabet.

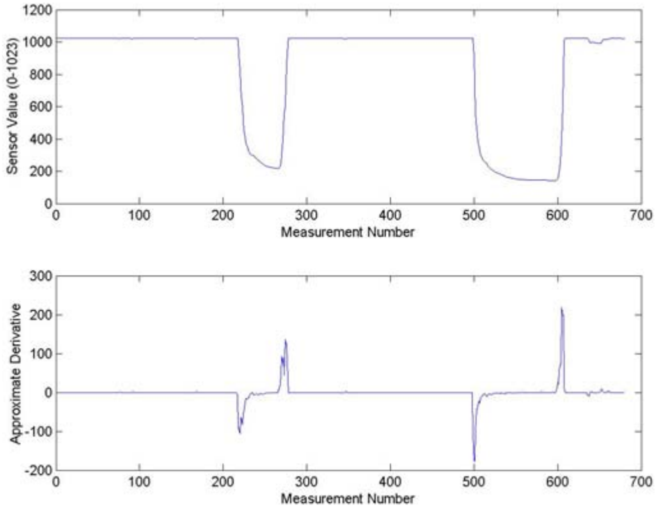

Fig. 3 The Response of a Single FSR to Finger Taps. The top graph shows the FSR 10-bit sensor value as converted from the analog signal. This raw value is later subtracted from 1023 to make 1023 a maximum pressure value. Below is the approximate derivative of this raw stimulus as calculated using the diff function in MATLAB.

The other division of the mechanoreceptors in glaborous skin are classified according to the size of their receptive field. While not studied quantitatively here, the receptive field does appear to expand beyond the center of the sensor due to the silicone skin. Finger taps were applied to the area of skin around the sensor and the response was observed on an oscilloscope. The FSR showed an increased response as the finger taps were applied closer to its center. However, further testing and quantification of this process will be necessary, as the silicone skin chosen will most likely affect the area of the receptive field.

B. Higher Level Cortical Processing

As discussed previously, cortical neurons are formed from populations of lower level neurons. Thus our “virtual somatosensory cortex” employs a similar method by creating receptive fields from populations of sensors for a similar body region.

For purposes of illustration, an initial test was conducted using a delrin circular rod as the stimulus. A palm circuit board from the first generation hand was placed on standoffs and covered with a 7 mm layer of Walco V-1082 silicone skin with 20% silicone fluid. The bar was applied by hand and no recordings of force or actual orientation of the bar were made. This test was simply to observe the performance of the sensors and determine if the formation of cortical neurons, as described in this section, would be possible. Fig. 4 shows the results from this initial test. The algorithms used will be described in more detail in a forthcoming paper [20].

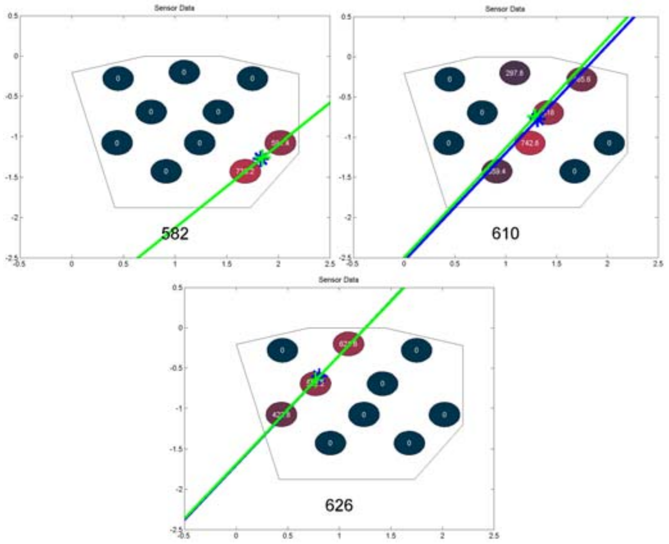

Fig. 4 An Initial Evaluation of the Possibility of the Formation of Cortical Neurons from Individual Sensors. The delrin rod was rolled from the lower right corner (upper left image) to upper left corner (bottom image). Each filled-in circle corresponds to the size and location on the first generation palm circuit board of an FSR sensor. The color of the circle corresponds to a 10-bit sensor value (0-1023), as shown in Fig. 3, with a bright red indicating maximum. The two lines indicate the calculated orientation of the delrin rod based on the logorithmic raw (green) and linearized (blue) sensor values. The calculated centroid of motion is shown for the logorithmic raw (green plus sign) and linearized (blue asterisk) sensor values.

As can be shown in this figure, there exists the potential for cortical processing of a population of sensors. We can compute the location of the centroid of a stimulus through a weighted average of the active sensors as shown in (1). In figure 4, the centroid is indicated by a green plus sign for the logarithmic raw sensor value and a blue asterisk for the linearized value.

$$CentroidLocation = \frac{\sum_{i=0}^{N}\left(SensorValue_i SensorLocation_i\right)}{\sum_{i=0}^{N} SensorValue_i} \qquad (1)$$

In a similar fashion, we can also calculate the orientation of a stimulus from the population of FSRs. First, the endpoints which define the orientation line are calculated using (2), (3) and (4).

$$Radius_i = SensorLocation_i - CentroidLocation \qquad (2)$$

$$OrientEnd_1 = \max\left(\left\{\frac{SensorValue_i Radius_i}{1023}\right\}\right) \qquad (3)$$

$$OrientEnd_2 = \max\left(\left\{\frac{SensorValue_i Radius_i}{1023}\right\} - \{OrientEnd_1\}\right) \quad (4)$$

The angle of orientation is then calculated using (5).

$$\theta_{orientation} = \arctan(slope\{OrientEnd_1, OrientEnd_2\}) \quad (5)$$

Once the orientation and location of the centroid are determined, motion can be calculated. Motion can be first encoded by observing the responses of the rapidly adapting sensor values, calculated using the methods discussed in the previous section. The sign of the rapidly adapting sensor value implies direction, since the raw FSR sensor value increases as a stimulus is removed, and decreases as a stimulus is applied as shown in Fig. 3. Thus a negative derivative value implies movement out of the receptive field. In addition, the position of the centroid can be used to determine motion across the skin in any direction by comparing the current position to the previous one in time. Thus the "words" and "sentences" of the "somatic alphabet" can be formed by this higher level process – encoding motion, direction, and orientation of a stimulus.

VI. SECOND GENERATION HAND

In order to explore the realm of *active touch perception* with Leonardo, a new set of hands were developed. Based on what we learned from the first generation hand, a stiffer finger design based on torsional springs at each joint was created to improve the pressure sensing at each fingertip. Using a stiffer hand with precision motion control, material characteristics such as softness can be encoded by combining tactile information with proprioceptive information.

In the current design, the 64 Channel A/D sensor board is now inside the hand (see Fig. 5). A redesign using surface mount components with the inclusion of an extra multiplexer and digital potentiometer caused the circuit to be drastically reduced in size. Much of the original sensor layout is carried over from the first generation hand. The major changes due to the smaller size are having 9 sensors on the palm and on the back of the hand, 2 sensors on each side of the hand, and 5 sensors per fingertip (currently not shown).

VII. NEXT STEPS: "VIRTUAL SOMATOSENSORY CORTEX"

We are developing a framework for a "virtual somatosensory cortex" implemented using this second generation hand. It is important to isolate reflexive actions from those which will require more processing, such as goal-directed behavior. The framework shown in Fig. 6 allows for important reflex information to pass from the "virtual somatosensory cortex" directly to the motor cortex to quickly halt motion of the robot to prevent damage. In addition, proprioceptive information, (i.e. joint angles), pass from the motor cortex (where they are used for control) to the "virtual somatosensory cortex" where they can then be integrated with other somatic inputs.

Our larger objective is to give Leonardo a fully "sensitive skin" that will be made of hundreds of sensors. This large networked processing system within the body of Leonardo must gather this data in an efficient fashion. In our current design, each sensory processing board is capable of up to 64 Channels of A/D conversion and is given a unique board identifier based upon its corresponding region of the body. Combining these boards together into a hierarchical structure, from individual sensor up to cortical groups, allows for each system of the "brain" of Leonardo to access information from different levels. For example, the vision system does not need to map to an individual sensor level to look at the location on the skin where Leonardo was touched. But a reflexive system may need this information to know in which direction to pull the arm away from an encountered obstacle. Fig. 7 is a diagram of this structure.

Fig. 5 Second Generation Hand currently in Development. Front and Back views.

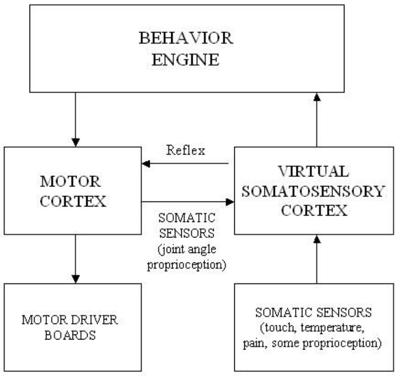

Fig. 6 The Theoretical Location of the "Virtual Somatosensory Cortex" in Leonardo

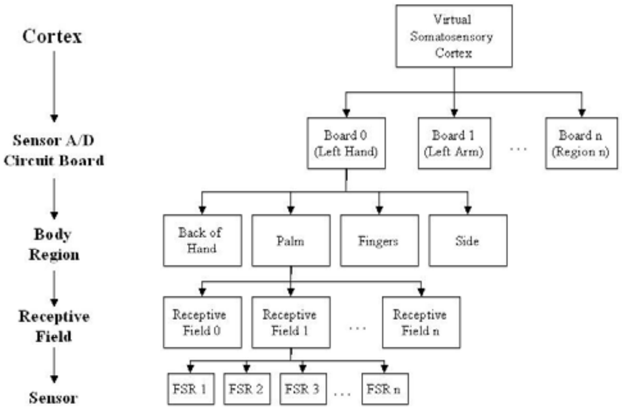

Fig. 7 Hierarchical Organization from Sensor Level to Cortex.

VIII. CONCLUSIONS

This paper provides an overview of initial work towards an ultimate goal of creating a fully "sensitive skin" for a robot based upon a "somatic alphabet." We have created a sensate hand to explore our theoretical framework for giving robots a sense of touch. We have implemented part of the peripheral "somatic alphabet," through FSR sensors, that perform similarly to slowly and rapidly adapting mechanoreceptors. Some higher-level cortical processing has also been implemented through a combination of groups of FSR sensors into receptive fields. Specifically, we have been able to determine the centroid of an object as it moves across the palm from this cluster. We are currently improving algorithms to infer direction, orientation, and motion as well. Future work will involve the addition of different sensors from different modalities, such as temperature and vibration, to expand the "somatic alphabet" of Leonardo. We shall also extend our framework to the entire robot's body.

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