Design of a Therapeutic Robotic Companion for Relational, Affective Touch*

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Abstract **– Much research has shown the positive health benefits of companion animals. Unfortunately these animals are not always available to patients due to allergies, risk of disease, or other reasons. Recently, this application domain has attracted attention of robotics researchers. The Huggable is a new type of robotic companion capable of active relational and affective touch-based interactions with a person. It features a high number of somatic sensors (electric field, temperature, and force) over the entire surface of the robot, underneath a soft silicone skin and fur fabric covering. This paper describes the design and early results in recognizing affective content of touch for this robot.**

Index Terms – "sensitive skin", robotic companion, human robot interaction, "somatic alphabet", tactile sensing, social affective touch

I. Introduction

There currently exists a large body of research indicating the diverse benefits that companion animals offer people. Studies have shown that animals are capable of lowering stress [1], reducing heart and respiratory rate [2], and showing positive changes in hormonal levels [3], as well as mood elevation and social facilitation [4].

Unfortunately, animals are not always readily available for patients. In many nursing homes, animal assisted therapy is a scheduled event; only taking place once or twice a week for a few hours or less per day. Many current nursing homes do not allow this type of therapy due to the fear of disease, bites, allergies, or for other reasons.

For these reasons a new branch of therapy has begun – robot therapy. The goal of robot therapy is to create robots which can act as pet surrogates for those who do not have access to animals. Currently work has been done with Sony's AIBO[5], Omron's NeCoRo [6], and Paro [7].

One aspect that the Paro, AIBO, and the NeCoRo lack is a *full body* sense of touch capable of properly detecting the affective content of touch. AIBO and the NeCoRo feature only a handful of touch sensors located in discrete sections of the body. There are many places in which the robot cannot detect if it is touched. The Paro, features a much more uniform coverage of tactile sensors, but still only features a small number of such sensors. Additionally, these robotic companions lack the ability to actively touch back through nuzzling, hugging, or other communicative touch behaviors.

Touch has many positive benefits [8]. Touch can convey a wide variety of communicative intents, especially in the realm of human and animal relationships. An animal can be tickled, petted, scratched, patted, rubbed, hugged, held in ones arms or lap – just to name a few. Each of these types of interactions conveys a different meaning. Much of this realm of social affective touch is still yet to be explored in robots. It plays a particularly important role for companion animals. And should play a similar role for companion robots.

In this paper, we present the Huggable, which is a new type of therapeutic robotic companion based upon relational touch interactions. In this paper we describe the novel aspects of its design including the design of the sensitive skin for affective interaction [9], voice coil actuators [10], and results from classifying different kinds of social tactile interaction.

II. The Huggable

A. Design Overview

Figure 1 shows a photo of the Huggable. Unlike other robotic companions, the Huggable is based upon an anthropomorphized fantasy animal – the Teddy Bear. This allows for freedom of design of behaviors

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given that it is not based on a real animal. Also, the choice of

Fig. 1 The Huggable.

a Teddy Bear alleviates the concern of "replacing living cats, dogs, etc."

In its full implementation, the Huggable features a full-body sensitive skin, silent back-drivable voice coil actuators, an inertial measurement unit, and an embedded PC with wireless communication capabilities for behaviors, patient monitoring, and data collection. Vision and auditory processing may be added as well to allow for multi-modal interactions.

B. *Mechanical Design*

The Huggable is designed for use in hospitals and nursing homes with a wide range of users from the elderly to small children. As such, it is important to develop a robot that invites users of all ages to interact with it. The form of a Teddy Bear was chosen since it has a wide appeal among all age groups across different cultures. The exterior of the Huggable is a Gund Teddy Bear (Butterscotch model). This bear was chosen for its size as well as its soft fur that is pleasant to touch.

In the current design, the Huggable features a 3-DOF neck, 2-DOF eyebrow mechanism, 1-DOF ear mechanism, and a 2-DOF "Hug" shoulder mechanism. The neck and shoulder mechanisms allow for active touch behaviors such as orienting towards touch, nuzzling, and hugging. The eyebrow and ear mechanisms are used for expression of internal state. Additional degrees of freedom may be added in the future such as body posture or other facial degrees of freedom.

Voice coil actuators [10] were selected for use, as opposed to the traditional geared DC motors, found in other commercial robotics applications. These actuators were selected because they have smooth motion without backlash, and a more life-like motion. In addition, the actuators are compliant and can be back driven. Thus, if a user tries to move the arms or head of the bear, there is no risk of damage to a gear-train or other transmission or to the person. Finally, the actuators are silent and do not distract from the interaction.

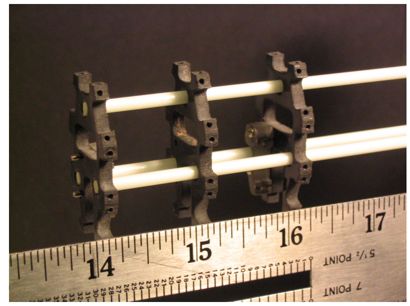

Fig. 2 The Arm Mechanical Understructure.
All dimensions shown are in inches.

The Huggable consists of a series of body regions – the arms, the legs, the head, and body. The body contains an embedded PC, somatic processing sensory circuit boards, batteries, and motor driver circuit boards. Each of the other regions attaches to the body region.

The underlying chassis is designed using a ribbed structure, as shown in Figure 2. This structure consists of a series of 1/8" thick delrin plates connected by a series of fiberglass 1/8" diameter rods. This design allows for high strength while keeping the weight of the mechanical structure low. Because the Huggable is designed to be held in one's arms, it is important to keep the overall weight of the Huggable to less than 5 lbs. Each sensor circuit board is mounted to this structure. No metal could be used in this design as it would interfere with the electric field sensing employed in the Huggable, described in the next section.

C. *Electronics Design*

The Huggable features a "Sensitive Skin" based upon the ideas originally proposed in [11], as well as the organization of the somatosensory system in of humans and animals. Unlike the other robotic companions described in the previous section, the Huggable is designed for affective, relational touch. As such much emphasis was placed upon the design of the sensitive skin.

The somatic receptors in human skin are divided into four modalities – touch, pain, temperature, and kinesthetic information. Within each of these modalities is a set of receptors which encode one specific region. Our somatic sense of the world around us is encoded by these receptors. These receptor outputs are then combined together in higher cortical structures of the somatosensory cortex to form our perception of touch.

We have developed an approach called the "Somatic Alphabet Approach" for the design of robotic sensitive skins [12, 13]. In this approach, each sensor is treated as a "letter" of an alphabet. These "letters" are combined through population coding to form the higher cortical processing, or “words.” Finally these “words”

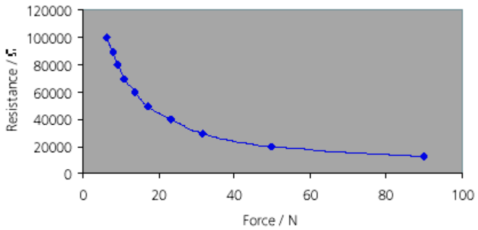

Fig. 3 The Plot of the Resistance vs. Force for the QTC Switch Substrate [14].

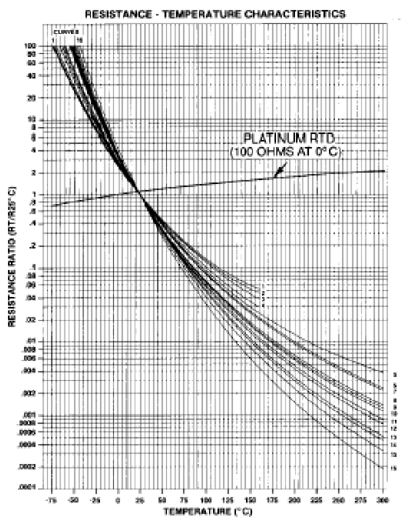

Fig. 4 Resistance Ratio vs. Temperature Characteristics for Thermistors and RTDs [15].

can be combined with other senses, such as vision, to create “sentences.” This approach is based upon the current understanding of the somatosensory system in humans and animals.

Analogously, the Huggable features four modalities of somatic information – pain, temperature, touch, and kinesthetic information. For touch, both electric field and force sensors (QTC) are used. Thermistors are used for temperature. For Kinesthetic information, potentiometers are used. Finally, pain is treated as an intense sensor signal of anyone of these stimuli.

Quantum Tunneling Composites (QTC) are materials which normally act as insulators, but when deformed they become highly conductive due to Quantum Tunneling effects [16]. Figure 3 shows a plot of resistance as a function of force for the Peratech QTC switch substrate used in the Huggable. In the current implementation a force range from less than 100 grams to greater than 5 kg can be sensed. This is well within the range of forces from human contact. More information on these sensors can be found at the manufacturer’s website: www.peratech.co.uk.

The change in the resistance ratio of the Thermometrics 100 k-ohm NTC thermistors as a function of temperature is shown in Figure 4. The sensors perform well within the range of room temperature and human body heat, which is the desired application range. They show a longer time constant than the QTC sensors and begin to show change within five seconds after first contact. This longer delay is useful in cases where body heat needs to be measured for prolonged contact such as the Huggable being held in someone’s arms or hugged.

The electric field sensing is done using a Motorola/Freescale Semiconductor 33794 electric field sensing integrated circuit. This sensor is tuned to detect proximity of the human hand within 1 inch from the surface of the electrode. Because proximity is detected instead of force, very light touch, such as gently brushing the top surface of the fur can be detected. This type of light touch would never be detected by the QTC sensors. In addition, the electric field sensors can distinguish between social contact with a person versus contact with an inanimate object. This is useful for the classification of affective touch – e.g. stick would never be capable of tickling the Huggable. Finally, the electric field sensing allows for the anticipation of touch to be detected.

In the arm section shown in Figure 5 there are a total of 8 sensor circuit boards mounted to the ribbed structure of Figure 2. Each sensor circuit board has eight QTC sensors, 3 temperature sensors, and 1 electric field electrode. The arm section is divided into two regions – top/left and bottom/right. The electrodes of each of the four sensor circuit boards of one region are tied together, forming one large electrode. Each sensor circuit board features on-board multiplexers for both the QTC and thermistor sensors to reduce the number of wires.

Each arm section features 8 sensor circuit boards as shown in Figure 3, thus for each arm section there are a total of 64 QTC sensors, 24 temperature sensors, and 2 electric field electrodes. In the entire arm, there are three of these arm sections in addition to an elbow and end cap section. Thus, there are over 200 QTC sensors, 80 temperature, and 9 electric field sensing electrodes in the arm. The Huggable consists of two arms, two legs, a body, and a head section which each have approximately the same number of sensors, thus the entire Huggable has over 1000 QTC sensors, 400 temperature, and 45 electric field sensing electrodes.

Because the electric field sensors would couple into the wires used to connect the QTC and temperature sensors to the somatic processing circuit boards, a mid-plane circuit board was developed. This circuit board has a set of switches to disconnect the power, ground, and multiplexer control wires from the rest of the circuit when that region is in electric field sensing mode.

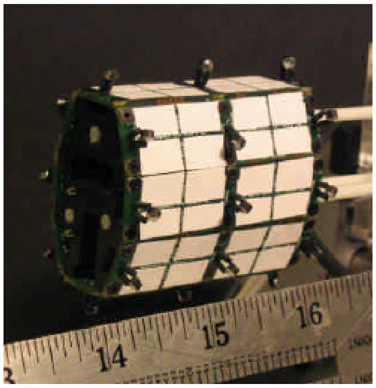

Fig. 5 The Arm Section. Each white square is one QTC sensor. The silver sensors above the surface of the QTC sensors are the thermistors. The electric field sensing electrode, not shown, is located on the bottom plane of the sensor circuit boards. All dimensions shown are in inches

Additionally, there are multiplexers which select the sensor output of each of the four sensor circuit boards in that region. When that region is in electric field sensing mode, the inhibit pin is raised to disconnect the sensor outputs from the common output of the multiplexer, isolating the sensor circuit boards from the rest of the circuit.

Through the use of the mid-plane circuit boards, the number of wires is greatly reduced – only one sensor output wire, two coaxial cables for electric field sensing, and a single 13-conductor cable for common control are needed for each arm section. These cables connect to the somatic processing board.

Each body region – left leg, right leg, left arm, right arm, head, and body – has its own somatic processing board. The somatic processing circuit board receives inputs from each of the electric field, QTC, and thermistor sensors and converts the analog value into a digital signal which is then passed to the embedded PC. The somatic processing boards also multiplex each sensor for efficient processing. This design is based upon the somatotopy of the human and animal somatosensory system [17].

There are five pathways of signal conditioning on the somatic processing board. The QTC signal is conditioned in three different ways. In the QTC light touch pathway, the sensor signal is placed in a voltage divider with a 2 M-ohm potentiometer. The output of the divider is then amplified so that very light touches can be detected. The QTC moderate touch pathway uses a voltage divider with a 1 M-ohm potentiometer without the added amplification. The QTC hard touch pathway uses a voltage divider with a 50 K-ohm resistor. The thermistor signal is processed in a similar manner as the QTC light touch signal with extra amplification. The electric field sensor electrodes are connected to a Motorola/Freescale Semiconductor

Fig. 6 The Finished Arm Test Section. At top is the silicone skin. In the middle is the completed assembly. At bottom shows the layered structure.

33794 electric field sensing integrated circuit. The output of the 33794 is then amplified.

D. *Synthetic Skin*

The feel of the Huggable's skin is very important. The Huggable must feel soft and "fleshy" like a creature, not hard like the traditional robot. A silicone skin was chosen to provide this soft feel. Silicone skins have been used in other robotic platforms [18, 19], prosthetics, and the animatronics of the special effects industry. Silicone rubber can be formulated to be as soft as human skin and pigmented to have a very realistic look [20]. In addition, the silicone skin serves a functional purpose. The skin helps to distribute the forces applied to the top surface across multiple sensors. The skin also protects the sensors from damage. The skin has a high elongation and tensile strength which make it appropriate for robotic applications, especially in areas of high movement. It also functions as a thermal and electrical insulator.

Using the original 3D solid model of the bear arm a silicone mold was created. This mold was printed in 3D using a Z-Corporation 3D printer. The cavity of this mold was roughly 1/8”, which results in a skin of the same size.

A set of slits were cut into the silicone skin to allow for the thermistors to poke through the skin. The silicone rubber acted as a thermal insulator and thus, the temperature sensors would not detect any changes if placed below the silicone and fur. Figure 6 shows the completed assembly. The fur arm sleeve is then placed over the silicone rubber as shown in the figure.

III. RESULTS

The use of the three different sensor types provides the ability to distinguish a wide repertoire of social and affective touch. The electric field sensor is used to distinguish between contact with a human versus with an object. This becomes important in the classification of affective touch, as one would only expect a person to affectively touch the bear. Figure 7 shows the results of contact with a human hand compared to contact with three inanimate objects placed on top of the electrode.

The QTC sensors can be combined into receptive fields to infer the direction of motion, or the size of contact. In addition, the electric field sensor first detects the presence of the human hand prior to the QTC sensors being activated. This proximity detector can be used to allow the Huggable to detect very light touches which could not be detected by the QTC sensors, such as the guard hairs on an animal.

The temperature sensors have a slower time constant than the QTC and electric field sensors – on the order of 5 seconds. Thus they only show change during prolonged contact. This information is useful in cases such as squeezing, or hugging in which there is a long period of contact, such as through holding. By combining the temperature and electric field sensors with the QTC sensors, a “person” estimate can be formed. If all three sensors are active, then it implies that the force on the QTC sensors is from a person as opposed to an inanimate object, such as the table top the Huggable is sitting on. Additionally, these sensors can be combined with the inertial measurement unit inside the bear to allow the Huggable to know how it is being held as well as where the person is in relation to itself. For example, the Huggable can know that it is being hugged and can hug back, or nuzzle into a person’s chest if held in someone’s arms.

Figure 8 shows a plot of the raw sensor outputs for one receptive field to a series of 10 pats with a human palm to the top of the arm section of Figure 6. As shown in the figure, the temperature sensors do not convey much information during short contact times. However, the electric field sensors clearly show changes that mirror the response of the QTC sensors indicating that the contact was due to a person and not an object. The electric field sensors are activated both before and after contact with the QTC sensors. Thus

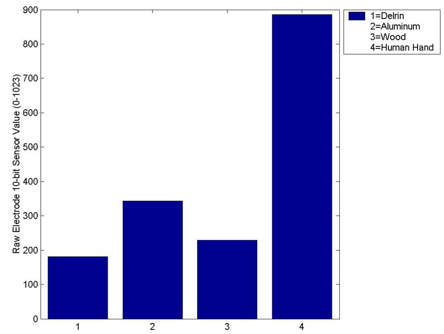

Fig. 7 The Response of the Electric Field Sensor to Contact with Delrin Bar(1), Aluminum Bar (2), Wood Bar (3), and Human Hand (4).

the distance of the hand to the surface of the Huggable’s arm can be detected.

Figure 9 shows the response of the same sensor circuit board of Figure 8 to a petting gesture from a Human hand. The direction of motion can be clearly shown in the figure. The peaks that emerge are due to the gaps between each finger moving across the surface of the skin. Again, due to the short time frame of the interaction, the temperature sensors do not show much response.

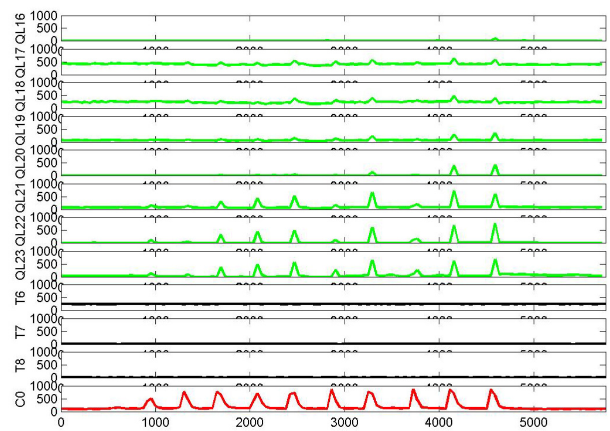

Fig. 8 The Response to a Series of Ten Pats by a Human Hand. The eight green lines are the response of the QTC sensors from one sensor circuit board. The next three black lines are the response of the temperature sensors of the same sensor circuit board. The red line at the bottom is the response of the electric field sensor.

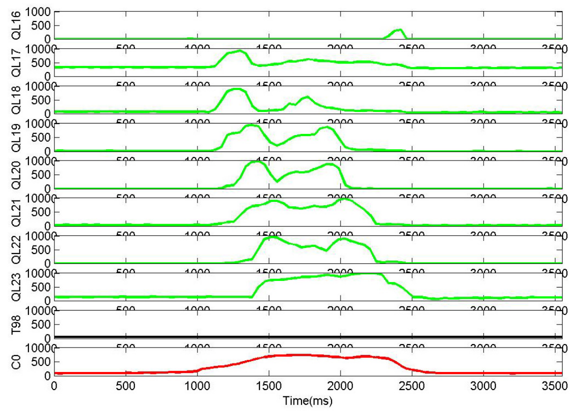

Fig. 9 The Response to Petting Motion by a Human Hand. The eight green lines are the response of the QTC sensors from one sensor circuit board. The next three black lines are the response of the temperature sensors of the same sensor circuit board. The red line at the bottom is the response of the electric field sensor.

An initial experiment was conducted to assess the ability to classify the affective content of touch. Each sensor was not calibrated individually due to time constraints. A total of 199 trials of affective touch with the arm section of Figure 4 were divided into 9 classes – tickling, poking, scratching, slapping, petting, patting, rubbing, squeeze, and contact. Each of these classes were again combined into 6 response types – teasing pleasant, teasing painful, touch pleasant, touch painful, punishment light, and punishment painful. The response type is how the Huggable interprets what behavior to perform. For example, a pleasant touch should signify a happy reaction while strong punishment should result in a pain response. Table 1 is the result of classification by a neural network for each class of affective touch. Table 2 is the result of classification for each response type.

The features used as inputs to the neural network included the changes in direction of motion, average sensor value, change in sensor value, number of sensors active among others. The 199 trials were divided into a training and validation data set of approximately equal size. MATLAB was used to train and test the three layer neural network with 100 inner layer. The "logsig" transfer function was used with the "trainrp" transfer function for all three neural networks. The learning rate was 0.001. The maximum number of epochs was 1000. The error tolerance was 1e^-3. Due to time constraints, only one neural network was trained for the class and response classifiers. Currently, the neural networks are not done in real-time, but will be in future implementations. A more in-depth discussion of the neural networks and features used will be discussed in [21].

Table 1. The Results of the Neural Networks for Class Classification 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

Table 2. The Results of the Neural Networks for Response Classification. PPV = positive predictive value, NPV = negative predictive value

Response	PPV	NPV	Sensitivity	Specificity	Chance
Tease Pleasant	0.40	0.93	0.25	0.97	0.17
Tease Painful	0.66	0.94	0.53	0.96	0.17
Touch Pleasant	0.77	0.90	0.74	0.90	0.17
Touch Painful	0.70	0.91	0.70	0.91	0.17

The neural networks show promising results given the un-calibrated, raw data. The negative predictive value and specificity are related to the number of true negatives. In the majority of the data used for training and validation, there was either a no-contact situation or another type of contact was occurring. Thus, the class or response would be classified correctly as being negative. As a result, the ratio of true negatives to true positives is rather high as shown in the tables.

Slap, not shown in Table 1, was not classified well, which indicates an error in the feature extractor. As such, the punishment response, not shown in Table 2, was not well classified since only slaps are classified as punishment. One possible reason for this is that in the current design, the QTC and temperature sensors are read once the electric field sensor is finished. Thus there is a delay between sensor readings, as the electric field sensor needs 4-5 ms for signal conditioning while the QTC and temperature sensors need less than 10 µs. The slaps occur very quickly and thus with the long delay, there could not be enough sensor information for proper classification. In the final design, there will not be this long delay as while the signal from one capacitive electrode is being conditioned, the remaining QTC and temperature sensors in the arm will be read. With calibration, improved timing, and improved feature extraction, the performance of these neural networks should improve.

IV. Conclusions and Future Work

The current prototype arm section of the Huggable shows that with a combination of temperature, electric field, and QTC force sensors a wide classification of social affective content of touch can be detected.

Initial use of neural networks have shown that these types of interaction are separable from one another based upon the sensor data described in this paper. The next steps will be to improve these networks as well as experiment with other pattern classification methods for real time detection of the affective content of touch.

The motor control and behaviors will further enrich the interaction for the user as the affective content of touch will have a change in the bear's response. Additionally, because the Huggable will know both its body orientation, from the inertial measurement unit, and the location of the person, form its "sensitive skin", relational touch can be implemented. Much like an animal that will nuzzle into its owner's arm, the Huggable will be able to show a similar response.

Finally, the goal of this project is to place a series of Huggables in real world settings of hospitals and nursing homes. With the ability to record and monitor the patient's activity with the Huggable, and report this information to the staff of the nursing home or hospital, the Huggable can become an important team member in the end-goal of improving the well-being of the nursing home resident or hospital patient. Over the next year, the first robust prototypes will be deployed to nursing homes for focus group testing. After this initial testing period a set of clinical trials will be conducted to evaluate the Huggable's usefulness.

These clinical trials will address the following questions: Does the Huggable provide a measurable health benefit in stress reduction, mood mitigation, recovery rate, or social facilitation? What is the benefit of extended interaction? Unlike therapy animals which only stay with a person for a short time, the Huggable could stay with a child the entire time it is in a hospital. By performing these controlled studies, we are interested in understanding specifically what kinds of interactions can improve the health and quality of life of those in nursing homes and hospitals. The bear has been designed to do so many different things in order to be a useful tool in better quantifying the science behind health and touch, and the health benefits of companion animals.

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