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The Design of the Huggable: A Therapeutic Robotic Companion for Relational, Affective Touch

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Abstract

There have been numerous studies which have 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. One potential solution for cases in which animals are not available is use the use of companion robots as pet surrogates. The Huggable is a new type of robotic companion capable of active relational and affective touch-based interactions with a person. It features a full body "sensitive skin," silent voice-coil actuators, and an embedded processor for data collection and networking. This paper describes the design of this robot and presents some early results from the "sensitive skin."

Introduction

Many countries of the world are facing the crisis of a large elderly population. In the United States, the largest increase in population (55%) in the 2000 Census was for 50-54 year olds. In Japan, currently 1 senior citizen is supported by 3.9 members of the labor force. By 2050, this number is expected to be only 1.5 members of the labor force supporting 1 senior citizen (National Institute of Population and Social Security Research 2002).

The current trend in nursing homes is one of larger facilities with a low number of empty beds. In a recent survey by the CDC and NCHS, 80.5% of nursing homes in the US had between 50 and 199 beds (CDC/NCHS). In addition, 34 of the 50 states and the District of Columbia had greater than 80% nursing home occupancy rates (Gibson, Gregory et al. 2004).

Hospitals and Nursing Homes can be stressful places, especially during the first few days. As nursing homes become larger and more crowded, this stress level is expected to increase. Currently, in many nursing homes, the residents have become over-medicated and often suffer from loneliness and lack of care (Thomas 1996).

One solution, for this problem of loneliness, helplessness, and boredom, has been the use of companion animals, or animal assisted therapy (AAT). 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 (Allen, Blascovich et al. 1991), reducing heart and respiratory rate (Ballarini 2003), and showing positive changes in hormonal levels (Odendaal 2000), as well as mood elevation and social facilitation (Collis and McNicholas 1998).

Ideally, an animal is the best solution. Unfortunately, these companion animals are not readily available. Concerns of dog bites, allergies, or disease have led to many nursing homes and hospitals to ban this therapy. When this therapy is offered it is a very regulated experience. The animal must be in the company of a trained professional at all times. Additionally, these sessions are a scheduled activity and only occur for a few hours or less each day, once or twice a week.

As a result of these restrictions a new form of therapy, robot therapy, has emerged. 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 (Tamura, Yonemitsu et al. 2004), Omron's NeCoRo (Libin and Libin 2004), and the Paro (Wada, Shibata et al. 2002). Initial results show that such platforms can provide benefit to an elderly population in nursing homes – increasing social facilitation, or improving mood.

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

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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 (Field 2001). 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 (Stiehl 2005), voice coil actuators (McBean and Breazeal 2004), and results from classifying different kinds of social tactile interaction.

The Design of the Huggable

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 given that it is not based on a real animal. Thus, there are no preconceived notions of how the bear should behave. Also, the choice of a Teddy Bear alleviates the concern of "replacing living cats, dogs, etc." Additionally, the Teddy Bear is a universal symbol of comfort across many different cultures and countries.

In its full implementation, the Huggable features a full-body sensitive skin, silent back-drivable voice coil actuators, an inertial measurement unit (Morris 2004), and an embedded PC with wireless communication capabilities for behaviors, patient monitoring, and data collection. Additionally, vision and auditory processing allow for multi-modal interactions.

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 use of a Teddy Bear was deliberately chosen. The Teddy Bear is a symbol of comfort across many different age groups, cultures, and countries. 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.


Fig. 1 The Huggable, Currently in Development.


Fig. 2 The Neck Mechanism.

The interaction with the Huggable is based upon the ways people interact with lap animals (such as rabbits, cats, and small dogs). Thus, the motion of the Huggable is focused on expression and orientation and not locomotion. In the current design, the Huggable features a 3-DOF neck (shown in Figure 2), 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.

One concern with the use of robotics with an elderly population is the risk of injury. Robots have motors and moving parts which could potentially hurt an individual. In many commercial robotics applications, geared motors are used. These motors usually cannot be back-driven and rely upon a control system to prevent injury to the person or damage to the robot. In addition, these motors have backlash in the gear train and are often noisy.

The Huggable features voice coil actuators (McBean and Breazeal 2004). These actuators, used in the neck mechanism shown in Figure 2, 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.

The Huggable consists of a series of 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. The head also will contain microphones for audio input, a speaker for audio output, and two small video cameras for simple visual processing. These systems are still in development.

The Huggable is designed to be held in one's arms, thus, it is important minimize the overall weight. The mechanical structure is made of lightweight, strong materials such as plastics and fiberglass. The sensor circuit boards and actuators are 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.

"Sensitive Skin"

Much of the interaction between humans and animals is based on touch. Skin receptors cover the entire surface of an animal and can detect a wide variety of stimuli such as temperature or pressure. The animal is then able to infer the affective content of the tactile interaction by processing the outputs of these receptors.

In a similar way, the Huggable features a "Sensitive Skin." This full body coverage of sensors is based upon the ideas originally proposed in (Lumelsky, Shur et al. 2001), as well as the organization of the somatosensory system in of humans and animals (Kandel, Schwartz et al. 2000). Unlike the other robotic companions described in the previous section, the Huggable is designed for affective, relational touch. As such much emphasis is 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 (Stiehl 2003; Stiehl, Lalla et al. 2004). 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" 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 (Motorola/Freescale Semiconductor 33794 electric field sensing integrated circuit) 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. A more detailed description of these sensors and the ways in which these signals are processed can be found in (Stiehl and Breazeal 2006).

The combined use of pressure, temperature, and electric field sensors allows for a wide variety of interactions to be sensed. The electric field sensors are tuned to detect the proximity of a human hand to within 1 inch from the surface of the electrode. Thus very light touches, such as gentle brushing of the surface can be detected. These interactions would not be detected by force sensors alone. Such a sensor is ideal for populations, such as the elderly and small children, who may not have the strength to activate the force sensors.

The combination of the three sensor types allows for interactions with a human to be distinguished from interactions with an object. This distinction is useful for the classification of affective touch as only a person is capable of tickling the Huggable. The electric field sensors are tuned for contact with a human, who provides a ground path for the signal. Similarly, the presence of body heat sensed by the temperature sensors is an indicator of contact with a human.

Currently, one of the arm sections has been prototyped. This arm section, shown in Figure 3, has a total of 8 sensor circuit boards mounted to the ribbed mechanical understructure. 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.

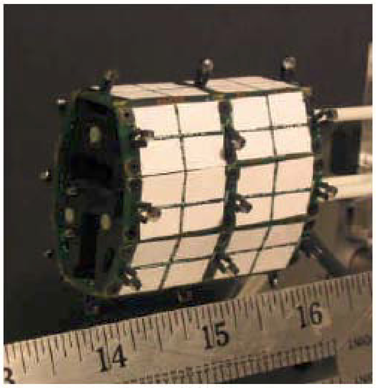

Fig. 3 The Arm Section. Each white square is one QTC sensor. The silver sensors above the surface of the QTC sensors are the thermistors. The electric field sensing electrode, not shown, is located on the bottom plane of the sensor circuit boards. All dimensions shown are in inches

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.

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 (Kandel, Schwartz et al. 2000).

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 (Hara and Kobayashi 1997; Breazeal, Brooks et al. 2003), 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 (McLaughlin 1999). 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 5 shows the completed assembly. The fur arm sleeve is then placed over the silicone rubber as shown in the figure.

Visual and Auditory Systems

In the previous sections much of the focus of the discussion is on the "sensitive skin." While this sense of touch is important, it is limited to interactions in which the person is in physical contact with the Huggable. Thus it becomes necessary to include other sensory systems which allow for interactions without direct contact. The ideas presented in this section are still in the process of being implemented but serve as a roadmap for some of the types of interactions we are designing.

When an animal sees a person come towards them in their field of view, they get excited and want to play. Similarly, the Huggable should show an excited and playful response to a person coming towards it. Additionally the Huggable should be able to look at people and objects in the scene as well as to follow their motion. The Huggable features two cameras, one in each eye, for these tasks. A color camera (Supercircuits PC229XP) is used in one eye while a black and white camera (Supercircuits PC224XP) is used in the other eye. Each camera has 470 lines of NTSC resolution with the black and white camera performing well in low light situations.

Another important aspect of the interaction between humans and companion animals is through sound. People affectionately speak to an animal as they are petting it or call its name to get its attention. The Huggable is being designed with these interaction patterns in mind. The Huggable will include a set of microphones with the goal of not only using them for orientation but also to detect the affective content of the persons voice through vocal prosody using a similar method described in (Lockerd Thomaz, Berlin et al. 2005).

Embedded Processing and Networking

The early focus of the Huggable design is on creating a platform with much flexibility for a wide variety of different age groups in various different facilities. Thus, the processing techniques and behavior for an elderly woman may be vastly different than those for a young male child. An Advanced Digital Logic PC-104+ embedded PC (ADL855PC) was selected for its small size and computational power. The processor is a 1.8GHz Pentium M with 1GB of DDR RAM. An 8GB compact flash card is used for local data storage. 802.11g is being used to connect the Huggable to a base station computer which would reside either in the room of the resident or with the nursing staff.

There currently exist two modes in which we anticipate that the Huggable will be used in the nursing home or hospital setting. The first is as a robotic companion in which the Huggable will execute a series of behaviors based upon the interactions it has with the person. These could include nuzzling or hugging behaviors or a series of games which the person could play with the Huggable.

The second mode of use will be as a team member in the care of the person. It is this mode that differentiates the Huggable from other robotic companions. The Huggable can gather data about the interaction pattern, such as the affective content of the interaction or the level of activity the person is having with the Huggable. This information is then relayed to the base station computer for analysis by the nursing staff. One potential benefit is that a drop in activity or change in the way a person interacts with the Huggable may be a precursor to a more severe problem or change in mood. Another benefit is that the video from the cameras in the eyes of the Huggable and audio from the microphones can be transmitted to the nursing staff.

Finally, the Huggable can be used to call the nursing staff. One potential example of this application is a young child undergoing cancer treatment who has just moved into the facility. He or she may be scared their first night and hug the Huggable tightly or rock it back and forth. This information can be transmitted to the nursing staff to indicate that they should check on the child.

These are only a few of the many examples of flexibility that the powerful embedded processing system allows. Other applications may include linking medical sensors to the Huggable or allow a grandmother on one coast to play with her granddaughter through the internet using the Huggables.

Results

As previously discussed, 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 as shown in Figure 5.

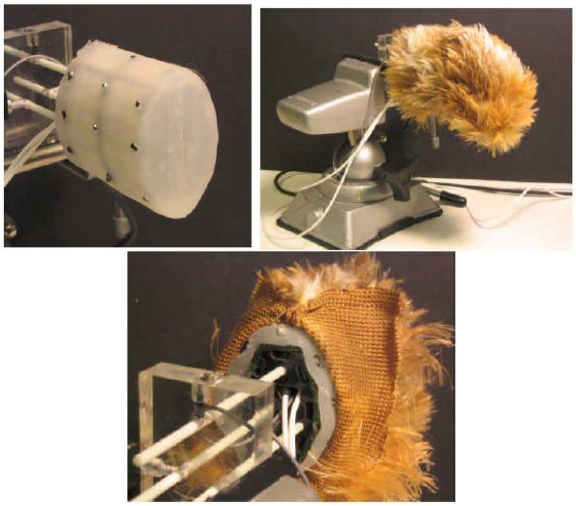

Fig. 4 The Finished Arm Test Section. At top left is the silicone skin. At top right is the completed assembly. At bottom shows the layered structure.

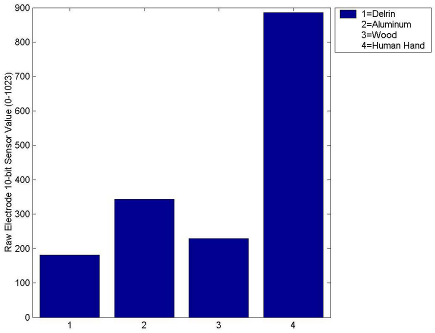

Fig. 5 The Response of the Electric Field Sensor to Contact with Delrin Bar(1), Aluminum Bar (2), Wood Bar (3), and Human Hand (4).

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.

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 a 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 6 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 Figures 3 and 4. 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.

Figure 7 shows the response of the same sensor circuit board of Figure 6 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.

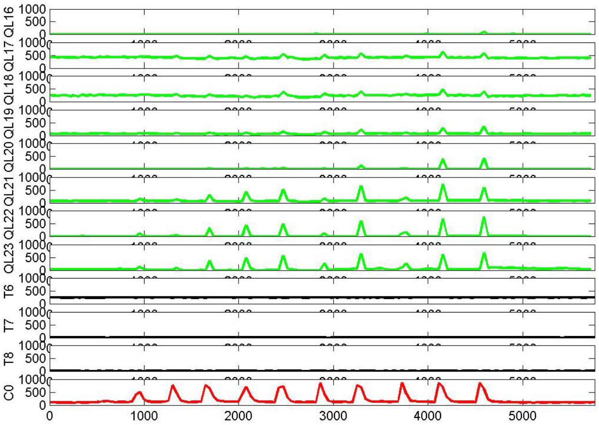

Fig. 6 The Response to a Series of Ten Pats by a Human Hand. The eight green lines are the response of the QTC sensors from one sensor circuit board. The next three black lines are the response of the temperature sensors of the same sensor circuit board. The red line at the bottom is the response of the electric field sensor.

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.

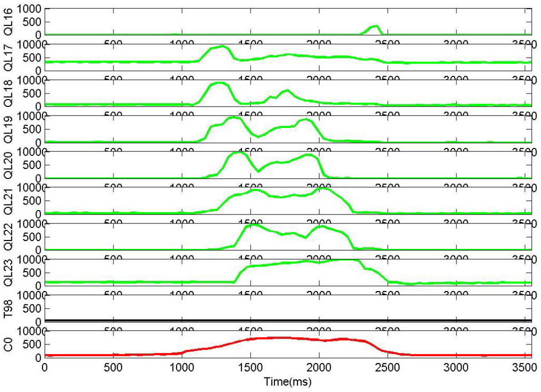

Fig. 7 The Response to Petting Motion by a Human Hand. The eight green lines are the response of the QTC sensors from one sensor circuit board. The next three black lines are the response of the temperature sensors of the same sensor circuit board. The red line at the bottom is the response of the electric field sensor.

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 (Stiehl and Breazeal 2005).

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.

Conclusions and Future Work

In this paper, we have described some early work in the design of the Huggable, a therapeutic robotic companion for relational, affective touch. As the elderly population in the United States and other countries of the world grows larger such technologies may provide benefit.

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.

With the addition of vision and audio processing more enriching interactions without direct contact can occur. For example, the Huggable can show excitement when a person comes into a room or calls out to it. These systems also allow the nursing staff to see and hear what is happening in a person's room through the eyes and ears of the bear.

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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