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Mechano Thermo and Proprioceptor Feedback for Integrated Haptic Feedback

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Abstract

Haptic sensation has two complex components; skin (cutaneous) sensing which is mediated by a variety of sensing organs that respond to pressure, vibration, displacement and temperature and kinaesthetic/ proprioceptive sensing (muscles and joints) which responds to motions and forces exerted by the interaction of the body with the external environment. Although haptic interaction has been identified as being crucial for many applications, achieving realism in haptic feedback has not been possible due to physical, understanding and modelling problems.

This paper explores the sensation of touch from a physiological and technological perspective and shows how this can be combined with an integrated touch/force reflecting system to produce a 'realistic' haptic rendering.

1. Introduction

Haptic cues are the form of information that can be acquired by the human sensory system through touching or handling an object [1]. Some cues require active exploration while others are passively received. Touch is perhaps the most complex of all the sensing modalities in terms of the arrays of different nerve types that are identified with it and in its most global form is a whole body experience, as opposed to the other senses which are localised in the eyes, ears, nose and mouth. As such its representation poses unique problems for its development and application in telepresence systems.

Touch can be divided into two subsystems:

i) the somatosensory system and
ii) the visceral sensory system,

with the somatosensory system being further divided into superficial sensibility associated with the skin receptors, and the deep sensibility -associated with internal receptors in muscles, tendons and joints [2]. Superficial sensibility and deep sensibility are often clustered together to form the area known as haptic sensing/perception (the 'sense of touch') where they are usually termed **cutaneous** and **kinaesthetic** sensations respectively.

The neurophysiological and psychophysical mechanisms that underlie tactile perception have been a subject of much research [3-4] and the structure and function of the low-level nervous fibres innervating the skin is reasonably well understood, however, the high-level mechanisms are still an area of speculation [5]. The particular modalities associated with superficial cutaneous skin sensation have, however, been classified as the senses, of touch (mechanoreception), of temperature (thermoreception) and of pain/damage (nocioception). Sensations associated with the mechano and thermo receptors will be dealt with directly in this study together with proprioceptor stimulation.

Inspired by the recent demands from VR/tele-presence applications and longer standing demands for rehabilitation systems a number of systems have been developed aimed at simulating some aspect of human 'touch'. These systems have largely concentrated on one particular aspect of the tactile system. Devices/mechanisms aimed at stimulating the mechanoreceptors include: Air or water jet displays [6-7], Air or water bladder displays [8], Mechanical tactor elements [9-11], Voice coil displays [12], and Electrotactile displays [13], Caldwell et al have combined some aspects of mechanoreception with thermoreceptor stimulation [14]. Devices aimed at replicating proprioceptor sensation have seen similar developments with mechanism such as master/slave systems, arm exoskeletons, hand exoskeletons and more recently force reflecting joysticks such as the PHANToM and the Impulse engine[15-18]. From these studies it can be seen that although research is active there have been no attempts at combining mechano, thermo, and proprioceptor stimulation have not been produced.

This work will study the sensory and technological aspects of haptic sensory requirements. Attention will be focused of global tactile requirements (kinaesthetic) and the local tactile (cutaneous) sensory cues. A model of the sensory stimuli will be presented and this analysis of the grouped sensation of taction will be used in a tactile feedback system combining force reflection from a joystick with touch reflection from a multi- modal TactileGlove to stimulate mechano thermo and proporiceptor nerves. Future requirements for further enhanced tactile rendering will be discussed briefly.

2. Human Sensory Systems

2.1 Proprioception

The ability to be aware of the orientation of our limbs, to perceive the movements of our joints, and to state

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accurately, the amount of resistance opposing any movements constitute deep sensibility. Often the terms proprioception or kinaesthesis are used to describe this stimuli perceived from the body itself and not from this surroundings. Kinaesthesis (proprioception) is the primary source of information for gross object shape, overall stiffness, and object mass which are low frequency signals.

Proprioception consists of three modalities: the sense of position, the sense of movement, and the sense of force [2]. Proprioceptive information is detected by sensory organs, proprioceptors, located at the skeletal joints, tendons and in the muscles [5]. They include but are not limited to the

i). joint receptors, believed to mediate the sense of movement having mainly phasic (dynamic) responses. They may also in some small part contribute to the sense of position.

ii). muscle-spindle receptors

iii) tendon organs. It is likely although not definitely proven that force sensations are detected by stretch sensors in the muscle spindles and tendon organs

iv) labyrinthine receptors (associated with the inner ear and the sense of balance) and not a tactile sensation.

In addition there are other as yet uncharacterised nerve receptors together of course with contributions from cutaneous mechanoreceptors [3].

2.2 Mechanoreception

Mechanoreception is concerned with the detection of mechanical stimuli at the skin. This modality comprises four qualities [2]. These are: the sensation of pressure, the sensation of touch, the sensation of vibration,
and the sensation of tickle

The human fingertips (primary tactile sensing sites) are covered with ridged glabrous skin, innervated by about 17,000 tactile units with at least four types of pressure/vibration sensitive nerve endings: Meissner corpuscles, small fluid-filled sacs found in the papillary layer of the dermis close to the surface; Merkel disks, an expanded dislike nerve terminal extending into the epidermis; Ruffini organs, large uniform capsules found below the papillary dermis; and Pacinian corpuscles, large capsules of layered lamellar cells with a sub capsular space filled with fluid. Figures 1a and 1b shows the structure and position of mechanoreceptors in glabrous skin.

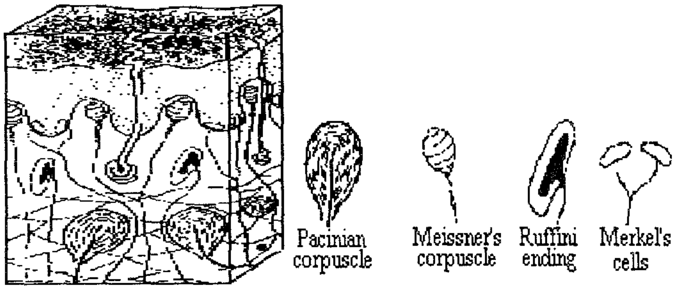

Fig 1a and b Structure of mechanoreceptors and position in skin

Mechanoreceptive nerve fibres can be categorised by two criteria. These are: the size of their active areas (receptive field), and the speed of their adaptation to static stimuli. Mechanoreceptive nerve fibres with small receptive fields are called type I units, while those with large fields are called type II. Nerve fibres that respond to static stimuli are called SA (slowly adapting, while those with no static response are called FA or RA (fast or rapidly adapting) [5].

Physiologic research has identified four functionally distinctive groups of mechanoreceptive afferent nerve fibres in this type of skin. These are: slowly adapting, small receptive field mechanoreceptive afferents (SA I), slowly adapting, large receptive field afferents (SA II), rapidly adapting afferents (RA), and Pacinian afferents (PC). Based on morphological observation (receptive field characteristics (area within which an applied stimulus can excite the receptor), adaptive properties of the fibres to stepwise indentation and frequency response to sinusoidal vibration), attempts have been made to associate RA with Meissner corpuscles, SA I with the Merkel disks, SA II with Ruffini organs and the PC with Pacinian corpuscles[2-4].

Probable Receptor	Class	Receptive Field(mm^2) (median)	Skin type	Frequency range(most sensitive)	Probable Sensory correlation	Receptors /cm^2 (palm)
Pacinian Copuscles	PC	10-1000 (100)	G.H	40-800Hz (200-300Hz)	Vibration Tickle	21 (9)
Meissner's Corpuscles	RA	1-100 (12.6)	G	10-200Hz (20-40Hz)	Touch tickle Motion Vibr	140 (25)
Hair follicle Receptor	RA	?	H	?	Touch Vibration	
Ruffini ending	SA II	10-500 (60)	G.H	7 Hz	Stretch Shear Tension(?)	49 (16)
Merkel's Cells	SA I	2-100 11.0	G	0.4-100Hz (7Hz)	Edge(?) Pressure	70 (8)
Tactile disks	SA	3-50	H	?	?	?

G-Glabrous Skin
H-Hairy Skin

Table 1. Skin Tactile Receptors

These characteristics have been shown in table 1, together with the probable correlation between the receptor and the sensory input.

2.3 Thermoreceptors

As with mechanoreception, thermoreception is not believed to be due to inputs from one type of nerve and has been divided into two separate systems; warm and cold, based on both objective and subjective findings. The distribution of these cold and warms spots varies across the body surface, but there appear to be more cold than warm spots [3]. As with mechanoreception and indeed nocioception there is as yet no absolute certainty as to the identity of the end organ responsible for thermal sensations. The basic behaviour of thermal sensors can be summarised as [3]:

i). Thermal fibres detect rate of change of temperature rather than the absolute temperature.

ii). The surface of the finger is at about 32°C under 'normal' conditions but can vary over a large range.

ii).The reaction time for cold sensations for a temperature drop of greater than 0.1°C/sec, is 0.3-0.5 sec.
iii). The reaction time for hot sensations with a temperature rise of greater than 0.1°C/sec is 0.5-0.9 sec.
iv). Thermoreceptors can sense rates of change of temperature as small as 0.01°C/sec (0.6°C/min), i.e. relative temperature sensing is accurately measured. The rate of change required to elicit sensation is smaller if the skin temperature at the time of stimulation is close to 20 °C or 40 °C.
v). For small areas of skin the temperature range that skin can adapt to is from 20°C-40°C i.e. most of the absolute range is adapted to, but it cannot be accurately gauged. Changes are most noticeable above 30°C and below 25 °C.
vi). Below 20°C there is a constant cold sensation (full adaption does not occur) which gives way to cold pain below 3°C.
vii). Above 40°C there is a constant hot sensation that gives way to burning sensation/pain above 48°C.
viii). Thermal cold pain is produced at a threshold of 3°C although some researchers have put the cold pain threshold as high as 15°C.
ix). The spatial threshold for the cold stimuli is lower than that for warmth.

Cutaneous sensation provides local information necessary for good task performance such as surface texture, slip detection, thermal conductivity/safety and local stiffness.

3. Integrated Tactile Feedback System

The following sections will consider the mechanism needed to produce a combined tactile feedback mechanism with enhanced haptic realism.

3.1 Mechano-receptor Stimulation [19-20]

The TactileGlove developed to stimulate a range of mechanical and thermal sensations will be discussed in the following sections. These modules have been designed to fit inside a glove which can be worn by the operator without restricting motion or comfort, figure 3.

3.1.1 Low Frequency Mechanoreceptor Feedback: To achieve the higher force sensations needed to simulate contact and grasping, an air bladder system based on a TELETACT device [8] has been used, with modifications to improve performance:
i). The original lycra glove has been replaced by a leather glove, providing a stretch resistant medium and thereby maximising the bladder 'push' towards the skin.
ii). The number of active points has been increased to 30, providing stimulation of all the palmar surface and the lateral portions of the 1st and 2nd finger and the thumb, figure 2.
iii). The maximum operating pressure has now been increased to up to 300kPa (although this is seldom needed).

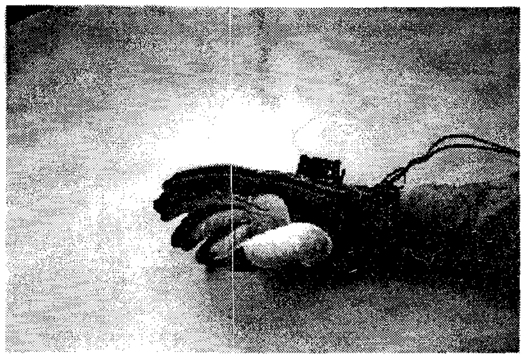

Figure 2. TactileGlove

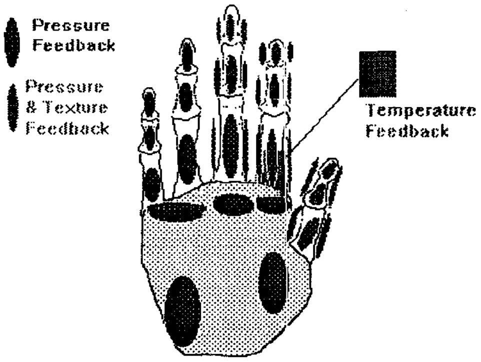

Figure 3. Location of Feedback Modules

iv). A new pulse mode of air flow regulation has been implemented using high speed Matrix valves. This can give air flow pulses at up to 50Hz (if required) although for this system frequency responses, never exceed 1Hz.
v). Closed loop force feedback has been incorporated into the glove. Force Sensitive Resistors (FSR) mounted within the glove under the pneumatic pockets compare the pressure at each individual finger point with the desired pressure at that point and modulate the input to maintain the desired contact parameters.

3.1.2 Medium Frequency Mechanoreceptor Feedback: The medium frequency feedback system was designed to simulate the actual contact surface of an object in terms of motion over surface details such as edges and ridges. To achieve this a piezo electric bi-morph was used. This is based on Braille reader systems but the size has been reduced (25mm in length but only 1mm in depth and 2.5mm wide) by modifying the drive circuitry. With these dimensions mounting onto the finger tip of the feedback glove is possible, and the mass of the unit is low enough that it does not unduly load the hand. The bimorphs have been arranged as a 4 x 4 array.

3.1.3 High Frequency Mechanoreceptor Feedback: typically in the frequency range 50-500Hz (although frequencies as low as 1Hz and as high as 1000Hz can be generated) are produced using a piezo-electric pulse unit constructed from a

PZT (lead zirconate titanate) ceramic discs. These sensors are mounted under the distal pads (tips) of the 1st and 2nd fingers and the thumb, figure 2. The mass of these modules is less than 2g each. These modules are primarily used to simulate textural, slip and edge initial contact sensations.

3.2 Thermoreceptor Stimulation

3.2.1 ***Thermal Feedback:*** The thermal feedback unit has been constructed using as a basis a Peltier Effect heat pump with heatsink and forced air cooling. This combined unit weighs less than 20g with overall dimensions of 15mm x 15mm x 3mm. Very rapid cooling and heating (20°C/sec) in response to stimuli can be achieved. Closed loop thermal control is achieved by mounting a rapid response thermocouple (response 10mSec) on the face of the Peltier module in contact with the operator's skin. The thermal feedback module is fitted within the glove index finger on the back surface of the first (proximal) joint where the density of thermal sensors is high and the skin is thinner. An upper temperature limit of 45°C was set to prevent injury, while the lower limit was -5° C. Temperatures as low as 0°C have been continuously maintained on the cool face for over 10 mins. without any rise in the module. There appears to be no thermal limitation on the period that this design can be kept cool.

3.3 Kinaesthetic Stimulation

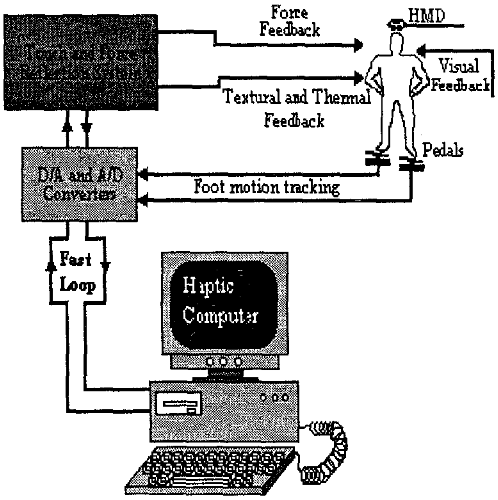

Figure 4. Schematic of System Configuration

3.3.1 Proprioceptor Feedback: A force reflecting joystick developed by the Immersion corporation (IMPULSE ENGINE) was used to simulate kinaesthetic information by exerting an external force on the user hand. The impulse engine has a position resolution of 0.0009mm, a workspace of 13 x 23 x 23cm, backdrive friction <0.14N and can exert a maximum force of 8.9N.

In this instance the Impulse engine and the tactile glove are connected to the main control PC (Haptic PC). This is a Pentium (133MHz) with 8MB RAM and 4MB VRAM This PC also monitors inputs from motion control foot pedals as hand motions cannot be used effectively in a haptic world. The figure also shows system inputs from external visual displays and control mechanisms if required. This permits utilisation of the interface with VR or telepresence robotic controls. A Schematic of the system is shown in figure 4.

Fig. 5. Operation of Impulse Engine while wearing the Tactile Glove

4. Haptic Rendering using Integrated Feedback

As the study of the nerves in the hand has revealed that there is no single sensing element which can be equated with the sensation of touch, the formation of a realistic feedback mechanism will require the combination of tactile elements in a manner that will stimulate the appropriate nerve and fool the finger into believing that a particular object manipulation or identification procedure is in progress. The following model has been used to provide a feeling for the forces, displacement, velocities, acceleration and associated response that form a base for representation of haptic sensation. This model clearly has many limitations, however, it does form a initial starting point for the generation of the mechano, proprio and thermo stimuli needed to 'fool' the body into a belief in artificial taction and to be used with the integrated haptic interface (IHI).

Somatic Sensibility = Proprioception + Mechanoception +
Thermoreception

Proprioception = Position detectors + Motion Detectors + force detectors
= Rigid body contact force ($F_{contact}$)+ Coulomb friction ($F_{coulomb}$) +Texture ($F_{friction}$) + limb position(D_{joints})

Mechano reception =Vibration(acceleration) receptors + Pressure receptors +Touch (velocity) receptors + Lateral Stretch receptors

= Texture ($D_{texture}$) + Contact ($D_{contact}$) + Skin stretch (F_{static}) + slip (F_{static} + $D_{texture}$)

Thermoreception = Cold Sensation (T_{cold}) + Hot Sensation (T_{hot})
Somatic Sensibility = $F_{contact}$+ $F_{coulomb}$ + $F_{friction}$ + D_{joints} +$D_{texture}$ + $D_{contact}$ + F_{static} + T_{cold}+ T_{hot}

where F is a force output, D is a displacement output and T is a thermal output . In this design forces are provided by the Impulse engine with displacement and thermal contributions from the TactileGlove. In its present format the TactileGlove cannot impart force (of significance) and therefore mechanoreceptor force F_{static} cannot be simulated.

Based on this model a series of tactile conditions can be defined which start to replicate in a global sense tactile perception. The tactile stimulants transmitted to the hand by TactileGlove and the Impulse Engine are now considered.

Free space movement is achieved through the use of a input/feedback system with low friction, inertia and vibration. These requirements must be satisfied by the design of the force reflecting joystick. The mass of the components in the TactileGlove are kept to a minium so that this factor cannot unduely affect the sensation of free motion.

Contact transients On contact forces must increase rapidly. This requires good bandwidth and stiffness in the interface and for the joystick is modelled as a one-sided spring function [21]. The magnitude of the perpendicular force is given by: $F = K * d$. Where K is a positive number depending on the hardness of the object (stiffness) and d is the penetration depth. In addition to the forces imparted by the joystick the TactileGlove makes a contribution in two forms. At contact and break of contact skin sensations are generated by a high frequency spike. Longer term stimulation is also simulated by inflation of the relevant air pockets. FSR elements within the pockets form a closed loop to regulate skin contact pressure.

Contact persistence To push into a contacted object requires an interface that can exert sufficient forces to make the object feel solid without actuator saturation or instability [21]. This contact push is again generated by the joystick in combination with the low frequency pneumatic pockets.

Surface friction

There are several methods of simulating friction (static and dynamic) [21]. **Static friction** is produced by applying surface tangential forces resisting motion and trying to restore the user back to the initial point of contact.

$$F_{fr} = n_s * F_{normal}$$

where n_s is the coefficient of static friction. If the force required exceeds the tangential forces then the user point starts sliding along the surface, moving to a dynamic friction condition. Imparted **Dynamic friction** is simulated by applying tangential forces in the direction opposite to the direction of motion. The magnitude of these forces can be computed using either:

i). The magnitude of the tangential friction forces is only a function of the friction coefficient and normal force.

$$F_{fr} = n_d * F_{normal}$$

ii) The magnitude of the tangential friction forces is a function of the velocity of the user point.

$$F_{fr} = B * V$$

Friction effects are imparted primarily by the force reflecting device, with this system using the second formulation.

Surface curvature discontinuities at edges and corners are replicated by control of the normal vectors, with users perceiving a surface norm discontinuity as an edge/corner. Objects can be made to feel smooth by varying the direction of the force vector continuously. Actions of this type are joystick based. These sensations are augmented by high frequency pulses at the edge transitions, with edge stimulation by the mid range bimorphs and loss or restoration of contact pressure in the pneumatic pockets. Only the force reflector can effectively generate a direction profile for the edge/corner.

Surface texture The impression of haptic roughness can be produced by applying force pulses to the hand. The nature of these pulses (magnitude, frequency) is determined by the physical characteristics of the surface. A number of researchers have developed techniques for texture generation [22]. For this system the surface textures are produced by combining textural forces generated by the Impulse Engine and following the tangential force method [1] and superimposing on this micro vibrations produced by the high frequency modules in the TactileGlove. The surface details are generated by the simulated contour method [22]. The magnitude of this component will be given by:

$$F_{texture} = B_{texture} * V + D_{texture}$$

Where $B_{texture}$ and $D_{texture}$ are factors that depend on the surface geometry at a given point and V is the sliding velocity. These factors can be read as a texture map while the virtual finger is moving along the surface.

The forces generated during a haptic motion and imparted by the Impulse Engine, for a single axis system are a combination of the forces outlined above :

$$F_{total} = K * d + V * (B + B_{Texture})$$

Thermal Effects: Contacts with most objects produce some form of heating or cooling effect, although the object itself need not be a heat source or sink. These effects are due to the ranging thermal conductivity properties of materials -a key identification marker. Heating/cooling effects are generated by the TactileGlove mounted Peltier module in response to all contacts. In this virtual world every object is modelled with a temperature and thermal profile characteristic.

5. Qualitative System Testing

Testing is at present very subjective. Artificial walls, tables, surfaces, hot/cold objects have been generated and subjects asked to describe the sensations associated with touching these objects. Comments from these initial tests can be summarised as:

i). Recognition of surface texture was relatively simple, and felt 'fairly' human. The combined textural effects were more realistic than the component parts.

Improvements were suggested by increasing the number of active sites to give more of a spatial impression.

ii). Operators easily detected slippages of 0.5mm or more, but with very small motions (0.1mm) it was difficult to distinguish slip stimuli from a vibration spike.

iii). It was easy to distinguish contact points at different points (lateral and palmar surfaces) on the fingers. The use of relatively high pressures meant that contacts could feel firm but not hard.

iv). Thermal changes at rate of change of temperature up to 20°C/s were possible permitting hot and cold sensation detection. Thermal lag was acceptable.

v). Contact with objects of varying stiffness was realistic provided high input forces were not used which overcame the resistance of the motors.

vi). Object shapes/edges/corners were effectively modelled and could easily be determined. With no friction edge tracking was difficult but with friction this improved substantially and became more realistic.

vii). Friction effects improved realism.

viii). For small masses inertial effects helped to improve sensation.

ix). Edge transitions, switch detents, and contact were very easily detected and realistic.

Based on their experiences the subjects suggested that the major deficiencies of the test system were:

i). relatively poor spatial perception of transition of surfaces across the finger pad,

ii). no tangential forces for lateral shear prior to slip.

iii). 'Hard' contacts with surfaces are not truly hard

iv) The exploration workspace was too small for effective easy exploration.

v). Forces can only be experienced in 3 axes.

6. Future Developments/Conclusions

The study of the human tactile sense undertaken in this work has revealed the complexity of the system and the difficulties that will be encountered when trying to deceive the nervous system and brain. In trying to facilitiate these response an integrated haptic feedback system has been developed combining mechano, thermo and proprio stimulation in a touch and force reflecting system.

The performance of these units was qualitatively tested and subjects reported good level of simulation using the individual units but enhanced performance when the system was integrated. Future work in this area will attempt to develop a full cutaneous array permitting improved spatial perception. In terms of the force reflection future requirements will include: larger work volumes and more degrees of freedom.

By combining the presently available tactile effects with the enhancements suggested a truly realistic haptic interface for use in tele-presence, teleoperation, VR and rehabilitation applications will become feasible.

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