Proceedings of the 1996 IEEE
International Conference on Robotics and Automation
Minneapolis, Minnesota - April 1996

Tactile Perception and its Application to the Design of Multi-modal Cutaneous Feedback Systems.

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Abstract

Applications in tele-presence, virtual reality and virtual environments have highlighted the need for an advanced realistic user interface to remote and virtual entities. Vision and audition have been well developed leaving touch as a key sensory parameter which is presently under-utilised.

In this paper a detailed study of the present knowledge of the human sensory nervous system relating to the 'sense of touch and feeling' is undertaken. Using this knowledge of the operation of tactile nerves a multi-modal cutaneous tactile feedback glove has been designed and tested. The construction of this system which feeds back data on texture/slip motion, edges/ridges and surface contours, contact force and thermal parameters is detailed with the test results and system assessment.

1. INTRODUCTION

Applications in tele-presence, virtual reality and virtual environments have highlighted the need for an advanced realistic user interface to remote and virtual entities. In humans this interface is provided by five key sensor elements; vision, audition, smell, taste and 'touch'. Of these elements vision and audition have been most used and most fully developed, while smell and taste have had few applications or indeed needs. This presently leaves touch as a key sense with potential for use in tele-presence/VR/robotics but with many problems relating to its implementation [1-2]. Three of the main sensory obstacles to effective widespread use are:

i). The detection of sensory signals

ii). The feedback of real-time sensory information to the operator

iii). The presentation of this information in a form that can be easily detected and processed by the brain as a reflex action.

Klatzky and Lederman [3] in their physiological studies have revealed that human touch is the active co-ordination and combination of cutaneous information (data from the nerves in the skin) and kinaesthetic information (data from the joints and muscles). These features have been defined as perceptual entities called haptics [3], where the haptic model identifies; material properties (texture, hardness, temperature and weight), structural properties (shape weight and volume) and functional properties.

Inspired by the recent demands of tele-presence and VR, and the longer standing demands for rehabilitation systems, a number of units have been developed aimed at simulating some aspect of human 'touch'. These include:

i). Air or water jet displays [4-5].

ii). Air or water bladder displays [6]. These generally have a low bandwidth.

iii). Mechanical tactor elements [7-9]. Two methods of actuation dominate these displays: solenoid activated pins and cantilevered piezoelectric bimorph reeds with a pin mounted to the tip. Recently there has been interest in the use of shape memory alloys (SMA) again operating on a cantilever system.

iv). Voice coil displays [10].

v). Electrotactile displays. Electrotactile displays elicit touch sensations by indiscriminately stimulating all the touch and pain sensors by passing a current through the skin [11].

vi). Thermal displays. Thermal systems simulate the cooling/heating effects of object contact [12].

The systems highlighted above have concentrated on cutaneous feedback (as this will be the theme of this paper), however, full 'touch' sensation will require the co-ordination of cutaneous data with kinaesthetic data. This kinaesthetic data can be derived in a number of ways:

i). Hand exoskeletons which prevent the fingers from closing. These systems are usually considered to have limited kinaesthetic abilities since they are only applied to the hand to give closure effects rather than mass, and inertia [13].

ii). Force reflecting devices. These can vary from powered full arm exoskeletons to external force reflectors that mainly constrain position. The fully powered exoskeleton is usually very heavy and generally supported by an external frame which is usually non-portable [14-15].

iii). Recently there has been a move to smaller force reflecting joystick devices which can combine many of the force reflecting traits of the full exoskeleton with the smaller compact design of the hand exoskeleton, eg PHANToM and the Immersion systems [16].

In this paper a detailed study of the human sensory nervous systems relating to 'sense of touch and feeling' is undertaken to provide an analysis of the nerves which will respond to inputs in a cutaneous tactile feedback system. Using this knowledge of the fibres in skin and how they respond to stimuli, a combined multi-modal mechanical and thermal output system has been designed and constructed which provides (to a remote operator working in a tele-presence environment) feedback data on textures/slip, edges/ridges/surface contours, contact force, and thermal conduction. The construction of this system is described, together with an analysis of the performance and user feedback on the implementation and quality of this system.

2. TOUCH SENSATION

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 the area over which the sensation is active. 'Touch/feeling' 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. It can be divided into three strands [17]:

i).Visceral Sensibility - sensation associated with the internal organs,

ii).Deep Sensibility - sensation associated with the skeletal muscles, tendons, and joints,

iii). Superficial Sensibility - sensation associated with the skin.

Only Superficial and Deep sensibility contribute to the interaction with the environment, as the Visceral senses deal primarily with the state of health of the body. In robotic applications these Superficial and Deep sensations 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 cutaneous sense mediates awareness of stimulation at the skin, while kinaesthesia provides information on body posture as well as positions and movements of body parts. Conscious experience of mechanical cutaneous stimulation is known as 'tactile perception' [18].

The neurophysiological and psychophysical mechanisms that underlie tactile perception have been a subject of much research [19-20] and the structure and function of the low-level fibres innervating the skin is reasonably well understood, however the high-level mechanisms are still an area of speculation [21]. 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). Only the mechano and thermo receptors will be dealt with directly in this study. Pain perception will only be considered by association.

2.1 Mechanoreception

Different parts of the body clearly have different sensitivities to mechanical stimulation of the skin, with experiments showing that the face and fingertips possess the most sensitive skin, while the legs and torso are much less sensitive. Since tactile exploration is usually done with the hand and fingers it is this sensing modality that will be studied. However there are also significant differences in the nerve densities even within the hand/fingers, table 1. It is immediately obvious that the fingertip (glabrous skin beyond a transverse line through cortex of skin ridges dividing fingerpad into two parts), being most richly innervated, is the most sensitive part of the hand [21].

	Region of Hand			
Fibre Type	Palm	Proximal & Middle	Distal Phalanx	Finger tip
RA	25	70	77	140
SA I	8	30	42	70
SA II	16	14	28	49
PC	9	10	15	21

Table 1. Mechanoreceptive fibre innervation density

The human fingertips are covered with ridged glabrous skin, innervated by 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 disc-like 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.

Probable Receptor	Class (step indentation response	Receptive Field (mm^2) (median)	Skin type	Frequency range(most sensitive)	Threshold skin deformation on hand(median)	Probable Sensory correlation	Receptors $/cm^2$ fingertip (palm)
Pacinian Copuscles	PC	10-1000 (100)	G,H	40-800Hz (200-300Hz)	3-20μm (9.2μm)	Vibration Tickle	21 (9)
Meissner's Corpuscles	RA	1-100 (12.6)	G	10-200Hz (20-40Hz)	4-500μm (13.8)μm	Touch tickle Motion Vibr	140 (25)
Hair follicle Receptor	RA	?	H	?	?	Touch Vibration	
Ruffini ending	SA II	10-500 (60)	G,H	7 Hz	40-1500μm (331μm)	Stretch Shear Tension(?)	49 (16)
Merkel's Cells	SA I	2-100 11.0	G	0.4-100Hz (7Hz)	7-600μm (58.5μm)	Edge(?) Pressure	70 (8)
Tactile disks	SA	3-50	H	?	?	?	?

G-Glabrous Skin
H-Hairy Skin

Table 2. Skin Tactile Receptors

Physiologic research has identified four functionally distinctive groups of mechanoreceptive afferent nerve fibres in this type of skin. They include rapidly adapting afferents (RA or QE), slowly adapting mechanoreceptive afferents (SA I), slowly adapting afferents type II (SA II) and Pacinian afferents (PC). Based on morphological observation, 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. To date only the Pacinian system has been experimentally verified.

2.2 Functional Characteristics of the Afferents

The four afferents were identified on the basis of receptive field characteristics, adaptive properties of the fibres to stepwise indentation and frequency response to sinusoidal vibration and these characteristics have been shown in table 2 together with the probable correlation between the receptor and the sensory input.

2.2.1 Receptive Field characteristics

RA fibres have small, sharply bounded receptive fields of the order of 3-4 mm in diameter. Sensitivity remains more or less constant within the field and drops with a steep gradient outside the field. SA I fibres have slightly larger receptive fields (of the order of 5-6 mm in diameter) with a similarly steep sensitivity gradient at the border. SA II and PC fibres both have relatively large receptive fields with a gentle gradient and poorly defined boundaries. The shape of the receptive fields suggest that RA and SA I fibres may contribute to the spatial acuity of human skin, while SA II and PC are more responsive to indentation over larger areas.

2.2.2 *Response to stepwise indentation*

RA fibres respond vigorously at the onset and withdrawal of a stepwise indentation but remain inactive during steady displacement of the skin. The response of the PC fibres is similar to that of the RA afferents with activation over an extensive area (such as an entire finger). SA I and II fibres, by contrast display both a transient and a steady state response to stepwise indentation. SA I is more responsive to step indentation, while SA II is more responsive to lateral stretching of the skin. Both fibres display an edge enhancement effect to probe stimuli during sustained indentation.

2.2.3 *Frequency response to Sinusoidal Vibration*

The response of the four afferents to sinusoidal vibration is strongly dependent on frequency. SA I and SA II fibres respond only to very low frequency vibrations, RA fibres are most sensitive in the range of 20-40 Hz, and PC fibres are most sensitive in the range of 200-300 Hz.

2.2.4 *The Roles of the Afferents in Tactile Perception*

The behaviour of the mechanoreceptive fibres may be summarised as follows:

i). When a step indention is applied the RA and PC fibres only respond to the application and the withdrawal of the force (they are rate sensitive) while the SA I and SA II fibres respond throughout the indentation and are displacement sensitive.

ii). When a vibratory stimulus is applied, the SA I and II nerves are most sensitive to low frequencies, RA fibres are most sensitive in the range 20-40Hz and the PC nerves respond best at frequencies around 250hz.

iii). SA I is primarily responsible for form perception and has the greatest spatial acuity.

iv). RA and PC systems are responsible for sensing vibrations and small surface variations that can register as local vibrations.

v). SA II fibres sense lateral stretch.

vi). Although there may be one dominant sensing mechanism for any particular situation neurophysiology suggests that the human sensations described as touch are the complementary combination of some or all of these nerve impulses.

Full haptic sensation will of course involve the contribution of the cutaneous sensation explored here with kinaesthetic inputs from joint position and torque.

2.3 Thermal Sensation

As with mechanoreception, thermoreception is not believed to be due to inputs from one type of nerve. Thermoreceptors have in fact been divided into 2 separate systems; warm and cold, based on both objective and subjective findings. Factors pointing to this dual sensor system include [22]:

i).The skin has specific cold and warm points at which only sensations of cold or warmth can be elicited.

ii). Reaction time measurements have indicated higher conduction velocities for sensations of cold than for warmth. Experiments on the rate of heat penetration in cutaneous skin have provided values of 0.5-1mm/s, and with latency to cold in the order of 0.3-0.5s it has been estimated that these receptors are 0.15mm below the skin surface. For warm sensations the latency is greater and it is estimated that heat receptors are at a depth of 0.3mm.

iii). By selective blocking of nerves it is possible to prevent either the cold sensation alone or the warm sensation alone.

There is, however, a functional overlay in the temperature range of the separate cold and warm sensations to give greater flexibility within a smaller temperature range. The distribution of these cold and warms spots varies as shown in table 3, but there in general appear to be more cold than warm spots. 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.

	Spots/cm^2			Spots/cm^2	
	Cold	Warm		Cold	Warm
Forehead	8.0	0.6	Nose	8.0-13.0	1.0
Upper Lip	12.0	-	Chin	9.0	-
Upper Arm Inner	5.7	0.3	Upper Arm(Outer)	5.0	0.2
Chest	5.0	0.3	Elbow	5.5	0.2
Forearm Inner	5.0	0.4	Forearm Outer	7.5	0.3
Back of Hand	7.0	0.5	Palm	4.0	0.6
Fingers	2.0-9.0	1.5-2.0	Thigh	5.0	0.4
Lower Leg	4.0-6.0	-	Sole of Foot	3.0	-

Table 3. Cold and Warm Spots Concentrations

2.3.1 *Thermal Response Mechanism*

As with many natural sensing mechanisms thermosensitive nerves are not absolute measures of temperature but can more generally be regarded as detectors of the rate of change of temperature, with a 'normal' working field of 20°-40°C. Within this temperature range a certain constant rate of change must be generated to elicit a feeling of warmth/cold. If the rate is too low no sensation will be detected. The closer the skin temperature at the time of stimulation to 20°C or 40°C the smaller the rate of thermal change required to elicit a sensation. For example ±0.001°C/s changes are only noticeable above 38° and below 25°C. Constancy of temperature change is noticed at rates of change of 0.1°C/sec (6°C/min) and above.

Within this 20°-40°C thermal range there is for any portion of skin some temperature representing thermal indifference (feeling of neither warmth nor chill). Under normal equilibrium conditions with no immediately preceding unusual thermal stimulation this corresponds to a skin temperature of about 32°C. This is 'physiological zero' until thermal stimulation raises or lowers it, causing it to migrate temporarily to a new level. In addition within the basic thermal detection sequence there is also rapid adaptation to the presence of heat or chill which is further complicated by the fact that stimulation by heat desensitises the skin to cold. This means that temperatures that might normally have resulted in thermal indifference or even slight warmth will feel cold. A similar reversal is observe when initially stimulated by cold. With these factors in mind it can be seen that what one individual may find hot, another will not and indeed repeated thermal stimuli could vary significantly with only one individual. Thermal pain is produced at a threshold of about 48°C for heat and 3°C for cold although some researchers have put the cold pain threshold as high as 15°C.

2.3.2 *Characteristics of Thermal Fibres*

The basic behaviour of thermal sensors can be summarised as:

i). 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.

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.

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.

3. VIRTUAL TACTILE REPRESENTATION

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 sensor and fool the finger into the believing that a particular object manipulation or identification procedure is in progress. At the same time for use in tele-taction for tele-presence or VR applications the system must be light and compact. The system developed in this work which will be described in the following sections has been designed to fit inside a glove which can be worn by the operator without restricting motion or comfort, figure 1a and b. The sensory elements combined in this unit are shown below:

3.1 Data Glove Input System

The Data Glove Input System (DGIS) used in this work consists of a 'data glove' sensory system, conditioning electronics and a computer interface for the data glove [23].

The glove used in the input system is an ATB (cycling) glove and has the advantage of a smooth strong leather palm, robust construction materials and a rigid (plastic) surface over the knuckles, which makes attachment of the sensors easier. The position of each joint is measured using Hall Effect sensors and magnets on each link. Tests on the repeatability of the system [23] indicate that the input glove can be used by users with a large range of hand sizes (hand lengths from 19-22cm and metacarpal widths of 8.75-10cm) with no re-calibration and typically have finger errors less than 2°. For better accuracy calibration is required.

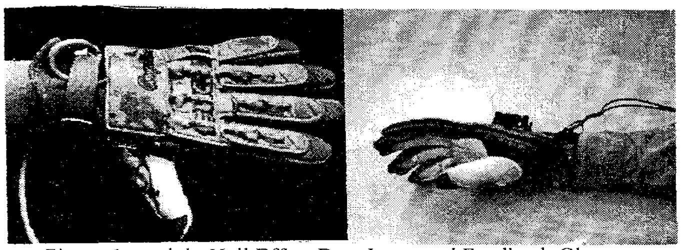

Figure 1a and b. Hall Effect Data Input and Feedback Gloves

3.2 High Frequency Mechanoreceptor Feedback

As indicated in the sensor study the sensations of texture and slip tend to be identified with high frequency vibrations in the frequency range from 50-300Hz. To achieve this output in a light compact and portable system a piezo-electric pulse unit was constructed from a PZT (lead zirconate titanate) ceramic disc 10mm in diameter and 1mm thick, mounted on a 1mm metal plate of diameter 15mm for added robustness. The weight of this unit is less than 2g and is driven from a high voltage (160-300V) source converting the electrical signals from the texture sensor on the multi-functional digit into mechanical motion.

For safety and to prevent contamination from dust or moisture, the transducer has been enclosed in a PVC film. The drive electronics are removed from the hand/arm to reduce the mass.

The piezo-electric module is attached to the inner index finger lining of the sensory glove under the distal pad of the finger, figure 1b.

3.3 Medium Frequency Mechanoreceptor Feedback

The medium frequency feedback system was designed to simulate the actual contact surface of an object in terms of details such as edges and ridges which could be detected when the finger is static or during slow motion as opposed to the high frequency texture data considered above. To achieve this a piezo electric bi-morph was used.

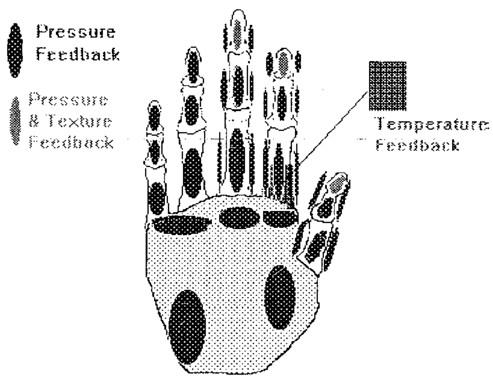

Figure 2. Location of Feedback Modules

This type of technique resembles the Braille type readers. However, these systems are too bulky for effective use in a freely moving system or to be mounted on a glove. To overcome this difficulty they have been constructed as individual cells containing only the bimorph connected to external drive circuitry mounted remotely from the hand to reduce mass. These bimorph strips are 25mm in length but only 1mm in depth and 2.5mm wide. 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. The displacement and force generated are dependent on the input voltage which can range from 50V to 250v depending on the motion required. These units are mounted at the fingertip where the sensory capacity is greatest.

3.4 Low Frequency Mechanoreceptor Feedback

The previous sensors have dealt primarily with the higher frequency components of touch but have not really considered the contact forces. To achieve the higher force sensations needed an adapted form of the air bladder system based on a TELETACT system has been used. The following moifications have been made:

i). The original lycra glove has been replaced by a leather glove. This provides a much more stretch resistant medium and forces the expanding bladders to push on the skin rather than expending outwards.

ii). The number of active points has been increased to 30. This provided sensation on all the palmar surface of the fingers, as before, but also pockets have been added to 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).

As the system uses micro bore capillary tubing the flow rate is relatively slow and the response rate never exceeds 1Hz. However, this is not a drawback at the texture and edge sensors compliment this system.

3.5 Thermoreceptor Feedback

The thermal feedback unit used in the feedback system has been constructed using as a basis a Peltier Effect heat pump which weighs less than 10g with overall dimensions of 15mm x 15mm x 3mm. The power output of 15W allows very rapid cooling and heating (20°C/sec) of the operator's finger in response to stimuli from the sensor while enhanced sensation discrimination is achieved by mounting a rapid response thermocouple (response 10mSec) on the face of the Peltier module in contact with the operator's skin [24].

Early trials with this system revealed that performance was satisfactory if there was little thermal cycling (touch hot object, cool object, hot object etc) but when this was not the case the temperature of the device started to rise as the energy released in the cycles could not be dissipated quickly enough. This problem was solved by placing a heat sink on the Peltier device with a miniature fan. The added mass was less than 20g. Thermal cycling could now continue indefinitely.

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.

4. TACTILE SENSING SYSTEMS

A multi-modal tactile system has been constructed for use on a dexterous hand of a robot [25], to replicate the four basic human cutaneous nerve sensations: pressure, vibration, temperature, and pain. Using these parameters Contact pressure/force, Object texture, Slip, Hardness, Profile/shape, Absolute Temperature, and Thermal conductivity can be measured. This tactile sensor system has been used as the input system for direct feed and data collection for simulated trials.

4.1 Feedback System Testing

Clearly any testing of operator performance and the use of tactile feedback systems will be very subjective. Tests have been conducted for the various feedback systems and numerical data and operator system assessment was noted. As a major objective of this development was to produce a system which the operator felt was natural to use and produced a realistic simulated output, significant importance was placed on their qualitative assessment.

4.1.1 Edge/Pattern Recognition Tests: Mid Freq. Feedback

The performance of the medium frequency system was tested using the pattern shown below, figure 4. The operators were given an initial learning period of up to 1 hour and asked then to move around the test area identifying the region in which they were and trying to follow the outer contour lines around the grid.

From these initial results it was determined that the operators could recognise different areas (accuracy of over 90%) and follow straight edges fairly effectively. However, the operators found difficulty with tracking changing edges and tended to overshoot the corners. The test subjects observed that;

i) Individual regions were relatively simple to determine, however, the sensations were most emphasised by the apparent transition of a ridge or edge across the skin surface rather than static (no lateral motion) contact. This is in line with expectations from the nervous system analysis where the adaption of the nerves mean that with no motion, signals cannot be detected.

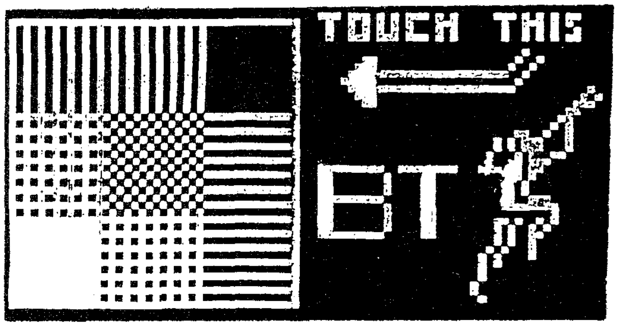

Figure 4. Test Pattern for Mid-Frequency Test

ii). Where the direction of an edge changed it was easy to detect the removal of the edge, however, it was more difficult to determine the direction of the new edge.

iii). The operators felt that the tracking was made more difficult due to the absence of frictional effects which tend to cause resistance at an edge and prevent slipping from that edge.

4.1.2 Texture/slip Recognition Tests: High Freq. Feedback

Tests on the ability of operators to recognise a number of materials were conducted using the high frequency piezo-electric feedback module. These included materials of different types and different surface characteristics on the same materials. The materials used were: Ribbon cable, a fine file, tissue paper , writing paper, cloth and steel plate.

On the metal plate the texture characteristics were distinguished in terms of the spatial separation between features (frequency), the depth/height of the feature (amplitude) and the randomness or regularity of the surface marks [12].

The operators reported, [9], that recognition of surface texture was relatively simple, and felt 'fairly' human. Improvements were suggested by increasing the number of active sites to give more of a spatial impression.

In tests for slippage, the operators easily detected motions of 0.5mm or more, but with very small motions (0.1mm) it was difficult to distinguish slip stimuli from a vibration spike [24].

Material	% Correct	Comments
Cable	97%	
Fine File	77%	Confused with steel plate
Tissue Paper	73%	Confused with Writing paper
Writ. Paper	80%	
Cloth	90%	
Steel Plate 1	94%	
Steel Plate 2	92%	
Steel Plate 3	97%	
Steel Plate 4	91%	

Table 4. Texture Recognition Results

4.1.3 Contact Shape Testing: Low Frequency Testing

The tests with the air bladder based system involved detection of contact points across all of the finger and palm contact regions.

The subjects reported:

i). that it was easy to distinguish contact points and no false indications were recorded during the tests.

ii). that it was equally possible to recognise contact on both the sides and the inner surface of the fingers without false readings. The greater number of sensory points meant contacts on the side of the fingers were clearly detected. This combined with more feedback points on the palm improved the 'clarity of the image'.

iii). that the use of the more resistant leather glove enhanced the force reflection into the hand and hence improved performance.

iv). that the higher pressure meant that the contacts were much firmer and gave a sensation of greater pressure in the contact and improved firmness however, with a pneumatic system hardness cannot be duplicated fully.

4.1.4 Thermal Sensation

Initial testing of the thermal system involved measurement of the ability of the system to generate rapid thermal sensation changes that can be imparted to the operator. In the first sequence of tests the feedback unit was driven through ±10°C cycles with the response rates and the recovery times being measured. These results, table 5 show that the rate of change of temperature is exceptionally high (>20°C/s) and allowing for the latency in the human finger can provide an excellent thermal stimulus of a form that could 'fool' the thermally sensitive nerves.

	Step change of -10°C		Step change of +10°C	
	response times	recovery times	response times	recovery times
10% of change ie dead-time	0.066ms (σ=0.026)	0.082ms (σ=0.041)	0.248ms (σ=0.100)	0.083ms (σ=0.026)
63% of change	0.372ms (σ=0.028)	0.712ms (σ=0.169)	0.720ms (σ=0.142)	0.364ms (σ=0.025)
90% of change	0.604ms (σ=0.058)	1.482ms (σ=0.821)	0.811ms (σ=0.163)	0.546ms (σ=0.083)

Table 5. Thermal Response Tests

The thermal feedback tests were conducted with objects at temperatures ranging from $0^{o}C$ to more than $45^{o}C$. When the temperature difference between objects was more than $3\text{-}4^{o}C$, accurate discrimination was possible, but with smaller changes the recognition ability based purely on thermal parameters was not reliable. These limits are due to the thermal resolution of the human finger. Operators reported that the feedback sensation was lifelike with little thermal lag.

Material	%Correct
Ice	99%
Boiling Kettle	100%
Foam	84%
Aluminium	87%

Table 6. Thermal Recognition Results

5. 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 skin into believing that a particular type of contact has occurred.

Despite these complexities it has been shown that the combination of a series of different types of feedback (mechanical and thermal) can be achieved and subsequently data can be imparted on aspects of touch such as slip, edges/ridges, contact force and hot/cold.

The test subjects in most instances reported that each of the sensations for each of the feedback modules was good on an individual basis, however, the key to effectively simulating 'touch' is in the combining of the sensation to generate the sequence of actions which stimulate the skin and cause a sensation. This work goes some way to addressing these issues however further developments will be required and are being considered for the next stage of this project. These include:

i). better spatial resolution,

ii). the introduction of tangential forces for lateral shear.

iii). simulation of frictional forces.

iii) and particularly the combination of the cutaneous sensations triggered in this present system with kinaesthetic sensation derived from joint and muscle position and force inputs. By combining these effects the development of a truly realistic haptic interface for use in tele-presence, teleoperation, VR and rehabilitation applications becomes feasible.

6. ACKNOWLEDGEMENTS

The authors wish to thank the EPSRC for their support of this work under contracts GR/H83058 and GR/J92637 and BT labs at Marlesham Heath, Suffolk.

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