Thermal and Textural Feedback for Telepresence

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Abstract

Tele-robotics - the remote control of robotic systems - can help in many situations; nuclear, space, undersea, and dangerous environments such as fire-fighting and rescue. At the moment, it is hampered by the poor quality and quantity of sensory feedback to the human operator and to supervisory control systems that reduce the work load on the operator. This lack of sensory feedback also affects people who have artificial limbs or have lost the sensory ability in a limb.

This project had the aim of improving two areas of sensory feedback; **Textural** feedback, which includes the sensations of slip, edge detection, and textural information of objects being manipulated, and **Thermal** feedback, which includes the thermal conductivity and temperature of an object being manipulated.

To this end a small, portable textural and thermal feedback system was designed and constructed, and system software developed for the microcontroller and PC. The system was tested, both for physical accuracy and speed, and for physiological accuracy of the sensations. In the case of thermal feedback, the system performed well, but in the case of textural feedback, some performance was below that expected.

The system was also used for real-time object material recognition by thermal characteristics, and virtual object sensation generation, producing highly accurate results.

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Definitions

Afferent - Conducting inwards or towards. Describes nerves which carry sensation to the brain.

Data Fusion - deals with the synergistic combination of information made available by various knowledge sources such as sensors, in order to provide a better understanding of a given scene. This requires methods by which redundant or conflicting information collected by various sensors can be combined.

Glabrous - (skin) free form hair.

Human Operator - this is the person doing the observing (monitoring) and the acting (controlling), whether in direct or supervisory control.

Innervate - Supply (an organ or receptor) with nerves.

Mechanoreceptor - The sensory receptors that respond to mechanical stimulation; pressure, touch, vibration, and tactile sensation.

Prosthetics - The making up of bodily deficiencies, by artificial limbs etc.

Peltier Effect - Defined as "When a direct current is passed through two dissimilar materials, heat will be absorbed or rejected at the junction"

Sensor Fusion - see Data Fusion.

Sensory Substitution - is the use of one human sense to receive information normally received by another sense. For the sense of touch, sensory substitution may also be the use of one area of skin to receive tactile information normally received at another location.

Supervisory Control - Where one or more human operators are intermittently programming and continually receiving information from a computer that itself closes an autonomous control loop through artificial effectors and sensors to the controlled process or task environment.

Teleoperator - a Teleoperator is a machine that extends a person's sensing and/or manipulation capability to a location remote from that person. A teleoperator necessarily includes artificial sensors of the environment, a vehicle for moving these in the remote environment, and communications channels to and from the human operator. In addition, a teleoperator may include artificial arms and hands or other devices to apply forces and perform mechanical work on the environment.

Telepresence - Consists primarily of visual, auditory, thermal, proprioceptive, and tactile feedback to a person from a remote location. Telepresence means that the operator receives sufficient information about the teleoperator and the task environment, displayed in a sufficiently natural way, that the operator feels physically present at the remote site.

Telepresence is sometimes used to mean virtual presence.

Thermoreceptors - The sensory receptors that respond to thermal stimulation.

Vibrotactile - Stimulation to evoke tactile sensations using mechanical vibration of the skin, typically at frequencies of 10 - 500 Hz.

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1. Introduction

The safe and economic exploitation of hazardous and remote environments such as those in the nuclear, explosive, chemical, and sub-sea industries or in space often requires the use of a tele-manipulator to undertake a task that might normally be performed by a human.

As remote manipulation and tele-operator systems become more complex, two main obstacles to their effective use remain. These are:

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

ii). the presentation of this information in a form that produces the appropriate response without a time lag.

It is important that this information be presented in a form that can be easily detected and processed by the brain as a reflex action, since an excessive need for thought could detract from the primary task.

These objectives can be achieved by directly mimicking three of the primary human senses, namely vision, hearing and touch. To a great extent the first two of these senses have been replicated using cameras/television and microphones/speakers respectively (although the actual interpretation of these parameters has not yet been solved). By contrast tactile and thermal sensing and feedback are primitive at best, and this severely hampers the manipulative dexterity of the operator. Any system for the feedback of tactile and thermal information is also of use in prosthetics research.

In both telepresence and prosthetics the problem can be divided into three main areas:-

a). The sensing (transduction) of the tactile and thermal information at the robot manipulator, or at the 'fingers' of the artificial limb.

b). The transfer of this information, whether over a few inches for prostheses, or over miles for undersea and space systems.

c). The regeneration of the information into a form such that the human operator would feel the correct sensations.

All three points are considered in detail in this thesis.

1.1 **Aims and Objectives**

The aim of the project was to design and build a Textural and Thermal feedback for Telepresence system, to improve the sensations felt either by the operator when using a telemanipulation system, or by a person who has lost a limb (or sensation in a limb), to a point where their subconscious reactions were correct for the situation.

In essence, the aim is to give the person the textural / thermal sensations of holding an object, even though the object is actually being held by a prosthesis, or robotic manipulator.

In order to set boundaries for this work, the following objectives were established:-

a). To design and build the system so that it would transfer temperature and thermal information from an object being manipulated, to the human operator, accurately and with no overt time delay.

b). To design and build the system so that it would transfer textural information from an object being manipulated, to the operator, to produce as realistic a sensation as possible, to those experienced if the operator were to touch the object with their own hands.

c). To produce a system that is light-weight, portable, small, and reprogrammable and allows both the operator, and the manipulator freedom of movement.

d). To produce a system that allows the integration of other sensors, as different as contact pressure, and radioactivity levels, into the same system; ie sensory substitution.

e). To investigate the use of an expert system to identify in real-time, the material being touched, using the data from the system.

f). To investigate the use of the system for sensation recording, virtual sensation production, interactive off-line planning.

2. Literature search

> "Living substance is not something which originated and exists distinct and separate from the non-living substance of the world. It has evolved through cosmic time out of the physical matter of the universe and for its continued growth and evolution requires not only a supply of the world's available energy but the ability to respond to a change in the environment, mechanical, chemical, thermal or electromagnetic. This adaptation to external conditions or irritability is a property common to all forms of life, animal or vegetable."

Wyburn, G M (1964)[1]

2.1 Introduction

As part of the objectives of this project was to impart thermal and textural information to the fingers of a human tele-operator, (or other skin locations, in the case of a limb-damaged person) the first half of this chapter gives an overview of current knowledge of the human's thermal and textural sense systems. This is followed by a review of the state of research on the detection, transmission and generation of the thermal and textural data.

2.2 The Skin and Cutaneous Senses

Our senses are a window on the outside world. Classically, the human being is listed as having five senses for the detection of external environmental changes, these being:-

- Vision (the eyes)
- Audition (the ears)
- Smell (the nose)
- Taste (the mouth)
- 'Touch' or 'feeling'

Touch / feeling is the most general of the five senses, as it applies to all organs of the body, both external and internal, as well as all tissues, and can be sub-divided as such, into:-

Visceral Sensibility - that of the organs

Deep Sensibility - that of skeletal muscles, tendons, joints.

Superficial Sensibility - that of the skin

In normal situations, only superficial sensibility is used in direct human interaction with the environment. The other sensibilities give an indication of the state of health of the body internally, and positional / force data of the body (proprioception).

The modalities associated with the skin (with superficial sensibility), are the senses of **touch** (Mechanoreception), of **temperature** (Thermoreception), and of **pain / damage** (Nociception) The first two are dealt with separately below, with pain mentioned in either when it is related to subject in question.

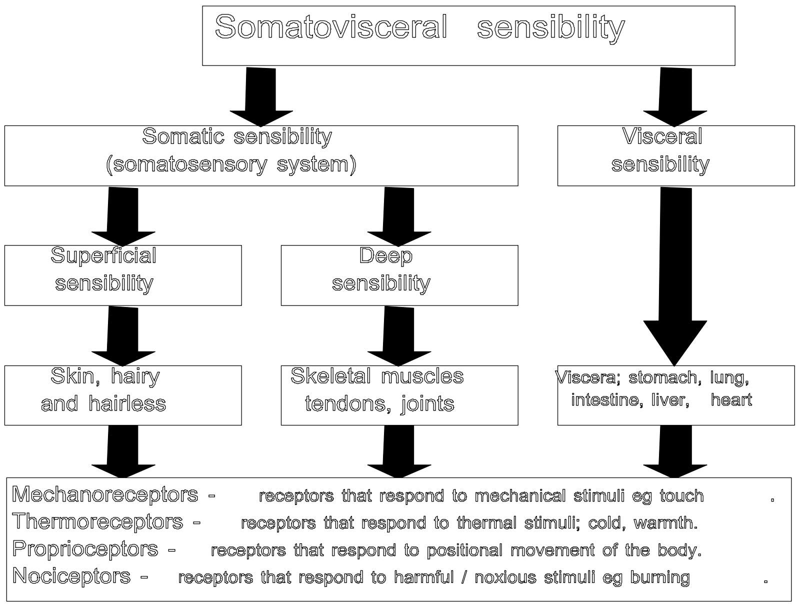

Fig. 2.1 - Graph of sub-division of feeling / touch, and associated receptors.

2.2.1 The Sense of Touch (Mechanoreception)

One of the earliest evolved sense organs were the Mechanoreceptors (tactile sensors), informing the organism about movement of parts, vibration, and skin contacts. The primary object of the tactile sense is to feel one's way about in the world and comprises four main qualities; these are the sensations of pressure, touch, vibration and tickle. The mechanoreceptors known, or assumed, to be concerned with the tactile sense are listed in 1.

Probable Receptor	Class (step indentation response)	Receptive field (mm²) (median)	Skin type	Frequency range (most sensitive)	Threshold skin deformation on hand (median)	Probable sensory correlate	Receptors /cm² fingertip (palm)
Pacinian Corpuscle	**PC / QA II**	10-1000 (101)	G,H	40-800 Hz (200-300 Hz)	3 - 20 ì m (9.2 ì m)	Vibration Tickle	21 (9)
Meissner's corpuscle	**QA I**	1-100 (12.6)	G	10-200 Hz (20-40 Hz)	4 - 500 ì m (13.8 ì m)	Touch Tickle Motion Vibr Flutter Tap	140 (25)
Hair follicle receptor	**QA**	Unknown	H	Unknown	Unknown	Touch Vibration	-
Ruffini ending	**SA II**	10-500 (59)	G,H	7 Hz	40-1500ì m (331ì m)	Stretch Shear Tension(?)	49 (15)
Merkel's cells	**SA I**	2-100 (11.0)	G	0.4-100 Hz (7 Hz)	7-600 ì m (56.5 ì m)	Edge (?) Pressure	70 (8)
Tactile disks	**SA**	3-50	H	Unknown	Unknown	Unknown	-
SA - Slow Adapting QA - Quick Adapting		I - Small, Distinct field II - Large, Diffuse Field			G - Glabrous Skin H - Hairy Skin		

Table 2.1 - Skin Tactile Receptors. '(?)' indicates 'possibly'. (from [4], [18], & [2])

They can be categorized into the following three groups, based upon which nerve fibres carry the signals to the brain, which are described in the following pages.

- Quickly Adapting Mechanoreceptive fibres. (QA I)
- Pacinian Afferent fibres. (PC)
- Slowly Adapting Mechanoreceptive fibres. (SA)

2.2.1.1 Quickly Adapting Mechanoreceptive Fibres

Quickly Adapting Mechanoreceptors (QA I) respond to a stepwise indentation of the skin, but do not respond to steady displacement of the skin; these fibres are velocity sensitive, being most sensitive in the velocity range 2-40 mm/s.[18] The QA I fibres have small, sharply bounded receptive fields, being smallest on the finger-pads, and somewhat larger on the palm; 9.4 mm² and 28.1 mm² respectively.[2]

QA I fibres respond to vibratory stimuli applied to the skin, having optimal sensitivity in the narrow range of 20-40Hz as in 2.

2.2.1.2 Pacinian Afferent Fibres (QA II / PC)

These fibres, so-called because of their proven identification as fibres innervating a Pacinian corpuscle,[18] are very sensitive to transient indentation of the skin over an extensive area, such as a whole digit or part of the palm. Pacinian afferents, like QA I fibres, respond to the initial indentation and withdrawal of a probe moving stepwise into the skin, but do not respond during steady pressure.

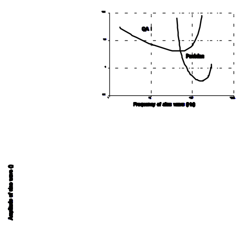

Fig. 2.2 - Threshold curves of **QA I** and **Pacinian** fibres, illustrating their responses to sinewave vibratory stimuli. (from [18])

PC fibres also respond vigorously to higher frequency vibratory stimuli, most readily in the stimulus frequency range 250-350Hz, as shown in 2. This diagram also shows the complementary nature of Pacinian and QA I fibres.

2.2.1.3 <u>Slowly Adapting (SA) Mechanoreceptive Fibres</u>

As well as responding to moving stimulus, these fibres also respond to periods of sustained indentation, even when the steady indentation is maintained for many seconds. For steady indentations, they give an impulse rate proportional to the amplitude of the indentation, and as such, are 'pressure' detectors.[3]

In humans, a small proportion of SA fibres have a larger, more diffuse receptive field,[18][4] and have been classified as SA II fibres, the main population being classified as SA I. SA II fibres are less responsive to indentation than SA I fibres, but are more responsive to lateral stretching of the skin, often showing a directional sensitivity to skin stretch and as such, are 'shear' detectors.

Both SA I and SA II fibres have some sensitivity to low frequency vibro-stimulus; both are most sensitive at about 7 Hz,[4] but require large amplitude vibrations.

2.2.1.4 <u>Detection and Neural Representation of Vibratory Stimuli</u>

Sensitivity to vibratory stimuli varies considerably over the body, the most sensitive area being the finger-pads and palms. With a small probe in contact with one of theses areas, the **threshold of detection** (minimum detectable) of vibratory movement varies with frequency. At frequencies of 100-300Hz, the peak to peak amplitude of the threshold stimulus is typically less than 1ì m, whereas at 5Hz the threshold increases to about 70ì m (3). At stimulus frequencies greater than 300Hz, the threshold rises rapidly,[18] with almost no stimulation above 500Hz.[5] According to Geldard,[15] these threshold values also vary with skin temperature, there being an optimal point about 4°C above normal skin temperature, as shown in 3.

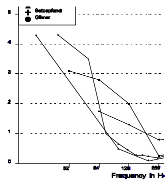

Fig. 2.3 - The frequency-intensity function for vibration at the fingertip. Results of four investigators combined. (from [15])

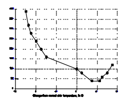

Fig. 2.4 - Vibratory sensitivity as a function of skin temperature. (from [15])

Qualitatively, the sensation evoked in humans by vibratory stimulus is 'flutter' at frequencies of 10-50Hz and distinctive 'buzz' at high frequencies (50-300Hz). Vibratory stimuli differs from other stimuli in that the skin is in continuous motion throughout the period of stimulation. Over a finite area beneath the vibratory probe, the skin moves in phase. Beyond this zone the stimulus spreads in the skin as a travelling wave.[18]

2.2.1.5 <u>Adaption to Vibrotactile Stimulus</u>

The threshold amplitude for vibrotactile stimulus also varies with the immediate history of the area being stimulated. If the area has recently - within the last few minutes - been subjected to large amplitude vibratory stimulus, the threshold is elevated; ie adaption has occurred. The amount of adaption depends on the amplitude and duration of the adapting stimulus, and the recovery time between the adapting stimulus and measurement of stimulus threshold.

Goble & Hollins[6] found that the threshold elevation, in decibel coordinates, approximates a linear function of adapting amplitude, with threshold rising 6 to 7 dB for every 10 dB of adapting amplitude, as in 5. Kaczmarek[4] gives a time of 2 minutes for full recovery from adaption.

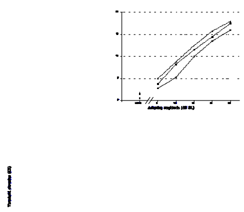

Fig. 2.5 - Graph of detection threshold elevation as a function of adapting frequency, for three subjects. (from [6])

2.2.1.6 <u>Reaction Time for Vibrotactile Stimulus</u>

Mountcastle et al[7] found reaction times of 400 - 500 ms at threshold stimulus, dropping exponentially to a minimum of 300 - 350 ms at stimulus strengths of 5 to 7 times threshold stimulus.

2.2.1.7 Spatial Resolution

Various measurements have been conducted to find the spatial resolution of parts of the body. The most commonly quoted is the two point discrimination threshold, which is the threshold distance at which it is possible to distinguish between two simultaneous stimuli. This varies from 2.3mm at the fingertip to 67mm on the thigh.[3]

2.2.1.8 Feeling Texture

Whereas very coarse textural features can be ascertained from a finger pad simply touching an object, the human's ability to discern finer textural features, and complex spatial microstructure, requires the finger to slide tangentially across the surface to be 'read'.[8] The more demanding the identification task, the more carefully the subject examines the object by moving the fingers to and fro, across the surface. This movement can improve textural resolution by a factor of a 1000, and allows, for example, smooth glass to be distinguished from lightly etched glass having eminences no higher than 0.001mm[15]

With familiar surfaces, the actual pattern of scanning movement and speed of the fingers are not critical since they may be substantially changed without degrading the subjects ability to identify the surface. Similarly, the contact force between the finger pads and surface may vary considerably without altering the subject's performance. Scanning speed is on average, 2 cm/sec with approximate range of 1 - 25cm/s.[9] Contact force is about 4oz (112g) with approximate range of 1 - 16 oz.[9](28-448g)

The structure of finger-tip skin, particularly the papillary ridges (The raised ridges on the fingertips that produce fingerprints), also contribute to textural sensing. During fine movements of the fingers, the ridges create vibratory effects that propagate through the various skin layers, adding to tactile recognition.[10]

2.2.1.9 Active Touch and Haptics

It is generally agreed that for the human textural sensing ability to function most accurately, 'Active touch' as opposed to 'passive touch' is required. The latter is where stimuli is caused by some outside agency (The finger is held stationary), whereas the former is where the stimuli is caused by the person's own motor activity. Active touch is an exploratory rather than a merely receptive sense and uses kinesthetic as well as cutaneous information.[11]

Active touch is the basis of Haptic exploration, which is the perception of information about objects, in three dimensions[12], as shown in 6.

Fig. 2.6 - Haptic exploratory procedures and the object attribute(s) with which each is associated. (from [**Error! Bookmark not defined.**])

2.2.1.10 Feeling Slip

Whereas texture is the detection of surface details as a finger moves relative to an object under actuator control, overt slip is the unexpected detection of surface details when the object moves relative to the finger's receptors.[33] The discharges from these receptors elicit an automatic adjustment of the finger tip forces to increase the safety margin against future slips.[13] The need to prevent slippage has to be balanced against the need to minimize grasp forces to conserve effort and to avoid damage to fragile objects. For this reason, a human chooses a grasp force that is near the minimum effective value required for the object weight and surface friction by using tactile sensory information, and then 'tunes' this force if any slippage, either incipient or overt, occurs.

2.2.1.11 <u>Tactile Sensing - in Summary.</u>

a) The Human touch sensing is thought to be the combination of four or more sub-systems, that work in parallel, but have different purposes.

b) The finger pads can detect vibratory movement of less than 1ì m in the range 100 - 300 Hz, about 70ì m at 5 Hz, and can feel vibratory movement up to about 500 Hz.

c) Two point minimum distances are about 2.3 mm on the finger pads.

d) To detect fine textural features, the finger has to be moved tangentially across the surface. The speed of this movement and the finger pressure applied is not critical.

e) Humans require active touch for optimum tactile ability, and for haptic exploration.

2.2.2 The Sense of Temperature (Thermoreception)

Man maintains a body temperature which varies within narrow limits around 37°C (98.4°F) and is regulated by a number of internal mechanisms including heat loss/gain though the body surface. At normal ambient temperature (25°C), there is a heat loss from the hands and feet of 47 to 80 Watts / m² (4.7 to 8mW / cm²) and a skin temperature of between 31 and 34°C.[14] These figures vary according to ambient temperature, a person's recent activity, the area of the body, and even the time since the person woke up, but are still useful as a 'ball-park' reference.

2.2.2.1 Dual Sensors

Thermoreception can be divided into two distinct systems, on the basis of both objective and subjective findings. These are the senses of Cold and Warm. Factors pointing to this dual sensor conclusion include;

* In the skin there are specific cold and warm points, at which only sensations of cold or warmth can be elicited
* Reaction-time measurements have indicated higher conduction velocities for sensations of cold, than for warmth
* By selective blocking of nerves, it is possible to prevent either the cold sensation alone or the warm sensation alone.[16]

There is however, a functional overlap in the temperature range of the separate warm and cold sensations, to give greater flexibility within a smaller temperature range. The distribution of these cold and warm spots varies over the body, but as a rule there tends to be more cold spots than warm spots in a given area, as shown in 2

	'Spots' /cm²			'Spots' / cm²	
	Cold	Warm		Cold	Warm
Forehead	8.0	0.6	Nose	8.0 - 13.0	1.0
Upper Lip	19.0	-	Chin	9.0	-
Upper Arm, volar side	5.7	0.3	Upper Arm, dorsal side	5.0	0.2
Chest	5.0	0.3	Bend of Elbow	6.5	0.7
Forearm, volar side	6.0	0.4	Forearm, dorsal side	7.5	0.3
Back of Hand	7.0	0.5	**Palm**	4.0	0.5
Fingers	2.0 - 9.0	1.6 - 2.0	Thigh	5.0	0.4
Lower Leg	4.0 - 6.0	-	Sole of Foot	3.0	-

Table 2.2 - Comparison of Warm- and Cold-spot concentrations. (from [15])

2.2.2.2 Depth of Hot and Cold Sense Receptors

Measurements have shown that the rate of heat penetration through the cutaneous tissues is in the range 0.5 to 1.0 mm / sec[15] depending on vascular conditions at the time.

Experiments to determine the depth of the thermal sense organs have determined the latency of the cold sensation is 0.3 - 0.5 secs. This places the cold sense receptor at about 0.15mm below the skin surface. Warm sensations are aroused more slowly, at 0.5-0.9 secs, placing the receptor at about 0.3mm below the skin surface. As with pressure and pain, there is no absolute certainty as to the identity of the end organ responsible for warm and cold sensations.

2.2.2.3 Stimulus and Adaption

The thermal stimulus is the temperature at the level of the receptors, and not the actual temperature on the surface of the skin. To be more precise, it is the rate of change in the temperature, except when the constant temperature is outside a certain normal range. It is possible to record temperature movements at a depth of up to 0.6mm below the skin and to show that, with constant skin temperatures below 20°C or above 40°C, sensations of cold, or warmth persist even after the rate of thermal change at the level of the receptors is zero.[1]

Within the range 20°C to 40°C, a thermal sensation requires a certain rate of thermal change and will tend to disappear (adapt) when, or shortly after, the temperature movement ceases. Adaption occurs for both warmth and cold. Prolonged stimulation with heat reduces warmth sensitivity (raises thresholds to heat), and prolonged cold stimulation reduces cold sensitivity (raises cold thresholds). What complicates the situation however, is that adaption to hot stimulus brings with it an actual lowering of the cold threshold, in that temperatures which would normally result in thermal indifference or even produce mild warmth now feel cool. Similarly, cold stimulation reduces the threshold for warmth; lower temperatures than normal arouse warmth.[15]

For a given area of skin, there is always some temperature representing thermal indifference. With a normal heat equilibrium with the surrounding air and no immediate history of unusual thermal stimulation, this corresponds to the skin temperature (about 32°C normally). This is 'physiological zero' until warm stimulation raises it, or cold lowers it. Then it migrates temporarily to a new level.

The nearer the skin temperature at the time of stimulation is to 20°C, or to 40°C, the smaller the rate of thermal change required to elicit a sensation. For example, +.001°C/sec and -.001°C/sec are only noticeable above 38°C, and below 25°C respectively.[1] Something like constancy of temperature increment/decrement is realized at rates of change of 0.1°C/sec (6°C/min) and above.[1516]

The total area of skin stimulated also influences its threshold values. If the whole body is exposed, the range of thermal indifference (ie when there is no thermal sensation with a constant temperature) is narrowed to between 32°C and 35°C.[1]

2.2.2.4 Paradoxical Cold

Stimulation of cold spots by heat above 45°C results in a sensation of cold. Since it seems paradoxical that a hot stimulus would yield impressions of cold, the phenomenon was named 'paradoxical cold' and there is some evidence[1] that the hot sensation felt at temperatures of 45 - 48°C, although introspectively a single subjective experience, is in fact a mixture of warmth and paradoxical cold.

2.2.2.5 Thermal Pain

The range of temperature adequate for the arousal of paradoxical cold is well above that necessary to arouse warm spots and only a little below that needed to produce thermal pain. This normally has a threshold of about 48°C, above which heat becomes a burning sensation. It has been shown that pain has its own receptors, nerve fibres, pathways within the central nervous system and final receiving centres in the cortex; these receptors are called nociceptors, and appear to respond only to any form of stimulus intense enough to cause tissue damage or be harmful.[1][18]

Intense cold can also be a painful sensation as anybody making snowballs, without gloves on, can testify. Literature has little mention of cold pain, though both Geldard[15] and Barlow[17] state that it occurs below 3°C. (Darian-Smith,[18] though, states it to occur at 15°C!)

2.2.2.6 Latency to Detection of High Temperatures

Campbell[19] found that for the finger tip, the median time to detection of temperature stimuli ranging from 39 to 51°C, dropped exponentially from 1100ms to 700ms. For the arm, the exponential drop was from 1100ms to 400ms. Both were measured from a steady, and adapted to, temperature of 38°C, and used a laser to warm the skin to the final temperature within 200ms.

2.2.2.7 Temperature - in Summary.

a) A healthy human has a body temperature of 37°C.

b) The surface of the human finger is at about 32°C in normal ambient conditions, but can vary over a large range.

c) The reaction time for cold sensations, with a temperature drop of greater than 0.1°C/sec, is 0.3 - 0.5 seconds.

d) The reaction time for hot sensations, with a temperature rise of greater than 0.1°C/sec, is 0.5 - 0.9 seconds.

e) Thermoreceptors can sense rates of change of temperature as small as 0.01°C/sec (0.6°C/min) ie. (relative) temperature change is accurately measured.

f) For small areas of skin, the range of temperatures that the skin can adapt to, is in the range 20 - 40°C ie. most of the range of absolute temperature is adapted to, and cannot be accurately gauged.

g) Below 20°C, there is a constant cold sensation (full adaption does not occur), which gives way to cold pain at below 3°C.

h) Above 40°C, there is a constant hot sensation, which gives ways to burning sensation/pain, and possible skin damage, at above 48°C.

i) (from texture section) Humans cannot recognise materials by temperature / thermal sensations alone, but used in conjunction with textural and other sensations in Haptic exploratory procedures, gives accurate object recognition.

2.3 Textural Sensing, and Vibrotactile Feedback

The electronic detection / transduction of object tactile features has been tried by a reasonable number of researchers, mainly for contact pressure and edge detection. These systems tend to have spatial resolution of about 2mm, giving only coarse textural features. Only a few researchers have looked at texture; it's transduction and regeneration.

2.3.1 Textural Sensing

For transducing texture, very few sensors are available. Pennywitt[10] does comment on textural sensing but references no actual sensors.

Patterson and Nevill[20] used a device that utilises the vibrations produced during sliding motion of the sensor to provide surface characterising information. Called the induced vibration touch sensor, it consists of a textural compliant artificial "skin" and a transduction element.

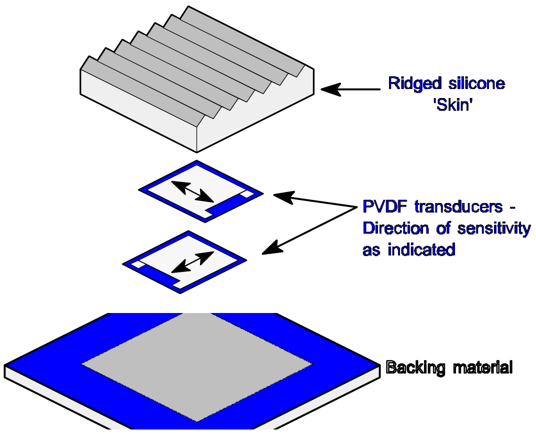

Fig. 2.7 - Inverted exploded view, Patterson & Nevill's induced vibration touch sensor. (from[20])

The prototype sensor skin, made from silicone rubber, has seven triangular prism ridges each 0.5" long x 0.04" high x 0.065" base, extending below a 1" x 1" x 0.06" base layer. The transduction element consists of two uniaxial metallized Polyvinylidene Fluoride

(PVDF) film transducers, one oriented orthogonally to the ridges, the other oriented parallel to the ridge, 7.

The output signals of the two transducers were used for pattern recognition, based on the spectral signatures for the bandwidth 0 to 800Hz. No speed of movement of the sensor is given. Results obtained show very high object recognition rates.

Cameron et al[21] suggest that their photoelastic tactile sensor can be used to get fine textural detail while moving across a surface, but only a mathematical model is given in the paper referenced.

Caldwell et al[33] have used an electro-magnetic sensor for measuring texture and slip. This consists of a detector probe connected to a soft iron core armature, mounted within a sensing coil.

Gosney[22] used a record stylus with the needle replaced with a piece of 2mm diameter wire, to produce a move study sensor. The sensor was found to be over sensitive and would be damaged by contact force overload.

Other tactile sensors, although promising, have only been tested whilst stationary on an object, giving coarse textural features, eg Begej's[23] finger-shaped optical sensor, and Dario's articulated finger.[2425]

2.3.2 Textural Sensation Feedback and Regeneration

Again, few researchers have tried to regenerate textural or other tactile sensations for a human operator. At present, tactile information cannot be directly transferred between the sensor and the part of the human central nervous system, such as the intact nerves of an amputee.[26]

The indirect means for transmitting tactile information to the brain, such as sound, light or vibrotactile stimulation have limited bandwidth. Electrotactile stimulation of the human finger is a possibility, but the difference between the threshold level and the pain level is very small, adaption occurs readily and electro-chemical reactions / electro-osmosis can occur, altering the sensation and damaging the skin in contact with the probe.[4]

In the main, vibrotactile stimuli is used, both in telepresence research and in sensory substitution research for the blind and people with sensory damage. An example of this is the commercially available 'Optacom' (optical to tactile converter). It converts text to a vibrotactile letter outline on the user's fingertip.

Caldwell[27] states that piezo-electric vibrotactile stimuli was the most successful of a number of techniques, although the transducer drive voltage required was 350V. Gosney[22] also used a piezo-electric sounder quite successfully with a drive voltage of 120V pk-pk, although with audible noise problems. Due to the capacitive nature of the piezo-electric sounders, static deformation of the sounder is not possible.

Other promising systems include "shape memory metals" using an alloy called 'Nitinol' produced by Tini, California. Nitinol cast in one shape, and then reshaped to another. Then while it is electrically stimulated, the alloy returns to its cast shape. It can be built into an array, as that tested by Rheingold;[5]

> "I touched my finger to the grid and felt something like a pencil lead underneath a piece of cloth, moving across my fingertip as the rows of pins were activated in the programmed sequence; I could feel the individual pins, but I detected the edge that their pulsed arrays created"

The array, however has limited frequency and spatial resolution at present.

2.4 Temperature/ Thermal Sensing, and Feedback

The idea of sensing thermal conductivity / temperature data, for instance of an object to be manipulated, is not new, but tends to be ignored, even though thermal properties help in the identification of an unknown object.

2.4.1 Thermal Detection

Most devices for measuring temperature and thermal conductivity are active, in that they consist of a heat source, and sensor. Russell[28][29] proposed a single sensor, using thermistors and a power transistor as a heater; 8. This was to replicate the human thermal sense system.

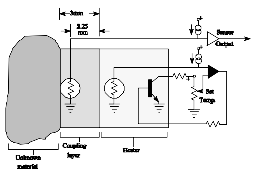

Fig. 2.8 - Schematic diagram of Russell's thermal sensor. (from [28])

He also constructed a 10 $\times$ 10 thermal sensor array,[30] using integral heating elements, which achieved a 90% response time of about 4 secs but required 20 secs to recover.

An extension to this is the 4 $\times$ 4 thermal array superimposed on an 8 $\times$ 8 array of force sensors, shown by Siegel et al,[31] which had a 90% response and 90% recovery time of about 18 seconds.

Caldwell et al[27] and Monkman & Taylor[32] have used Thermo-electric coolers (TECs) - also known as Peltier heat pumps - as temperature sensing elements. Thermo-electric coolers consist of a series of semiconductor couples connected electrically in series & thermally in parallel, which are attached between two electrically insulated ceramic faceplates. The TEC is designed to pump heat from one ceramic faceplate to the other, but if used in reverse, a temperature gradient across the device produces a proportional potential; a measure of the relative temperature change. Thermal sensing devices, built from thermo-electric coolers have 90% response and 90% recovery times of 1.8 secs & 7.8 secs respectively,[32] but the ceramic faceplates are too brittle to be useful on a robotic manipulator.

Monkman & Talyor have also produced thermal sensing devices using ferroelectric crystal pyrometers, as used in Infrared security detector systems. This is covered with a simple electrically resistive heater element etched in PCB copper on a thin layer of film mounted on an opaque, thermally conductive material, as in 9. The device gives 90% response & 90% recovery times of 600mS & 1.8 secs respectively, according to Monkman, but gives only a relative temperature change, as shown below, and again is brittle.

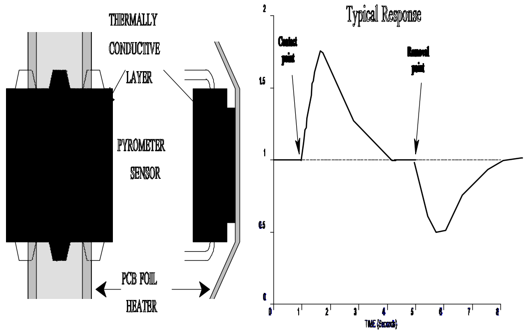

Fig. 2.9 - Monkman & Taylor's Pyrometer device (from [32])

2.4.2 Object Material Recognition using Thermal Data

Both Russell[28] and Caldwell[27] have used thermal detection in the recognition of object composition. Both used a version of the thermal sensor, 8, with the heater temperature 'turned up' to 40-50°C to give a greater temperature gradient when touching an object at room temperature. These gave accurate results with 3 and 7 materials respectively, but lose the 'human-ness ' of the sensor due to the increased temperature. Caldwell and Monkman & Taylor[32] also used the TEC sensor for material recognition.

2.4.3 Thermal Sensation Feedback and Regeneration

For tele-presence, the thermal data must be presented to the remote operator; Caldwell and Gosney are two of the few researchers to have thought about this. Both have used a Thermo-electric cooler, in its proper configuration of heat-pump, to produce a relative temperature on the back of the hand of the operator. Problems with the systems include 90% response time of about 20 secs, 90% recovery time of 30 - 60 sec,[33] and severe oscillation.[22]

A commercial system, the "Displaced Temperature Sensing System X/10" is available, produced by CM Research, League City, Texas. It includes "an assembly consisting of a thermoelectric heat pump, a temperature sensor and a heat sink."[34] No other details are known.

3. System Design

3.1 Introduction

The previous section has shown that despite a large base of research on tactile transduction and feedback, very little research has been conducted on thermal and textural sensation transduction and generation. This chapter describes the development of the thermal and textural feedback system to cover the aim and objectives stated in section 0.

3.2 System Basics

From the objectives, it was clear that the basic system required a unit at the tele-manipulator end, to detect temperature/thermal conductivity and texture of the object being manipulated, and a unit at the operator's end to regenerate these sensations.

The connection between the two ends needs to transmit the tactile data accurately and reliably, over long distance with a cable of as few cores as possible. For these reasons, a digital serial bus was chosen in preference to a multiplexed analogue connection.

In addition, the system required connection to a PC for use with software for an expert system, for off-line planning / virtual presence and for sensation recording. Connection was also required to a power supply. To reduce cabling and the number of connections, as few supply voltages as possible were used, with the aim of one power supply running all the circuitry, be it analogue, digital or power.

As most of the processing is required at the operator end of the system, the micro-controller to control the system and to oversee the swapping of data with the PC, was placed at the hand end. This gives a basic structure as shown in the block diagram, 1.

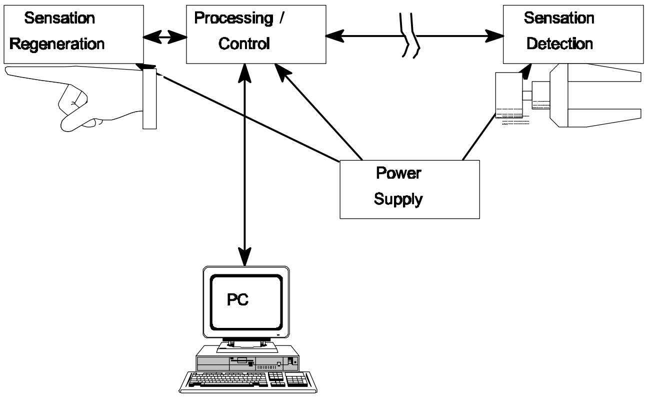

Fig. 3.1 - Basic Block Diagram of the overall system.

The basic ideas for each section were as follows.

3.3 Outline of the Textural System

From the objectives, there are three tasks the textural subsystem needs to cover:-

a). To detect texture at the manipulator and regenerate that texture for the human operator to feel.

b). To allow the PC access to the detected texture for recording, for sensor fusion, or for an expert system to process.

c). To allow the PC to provide data to the microcontroller to generate texture for the human operator, be it actual recorded texture, computer generated texture or other data for sensory substitution.

To fulfil these tasks, the texture of the object being manipulated is sensed, digitized and passed, in real time, across the serial bus cable to the microcontroller. This raw digitized texture data is made available to the PC by the microcontroller. At the same time, the microcontroller alters the raw data to include any information the PC has sent to it, and generates a representation of this textural data for the operator to feel.

The time delay from the manipulator feeling the texture, to the operator feeling the texture has to be as short as possible so that the sensation marries up with the motion that caused it, and the operator has a chance of reacting correctly to both expected and unexpected situations, such as object slip, edge detection or contact with an object.

3.3.1 Choice of Textural Sensor

Although both Patterson & Nevill's and Gosney's textural sensors (section 0) worked well, both had drawbacks. Gosney's sensor was over-sensitive and not overload proof but its single channel output was representative of the objects texture. Patterson and Nevill's sensor was more sturdy, but larger and with two channels to represent the texture, increasing complexity.

Therefore, it was decided to build a sensor that was a hybrid of the above two sensors, using a single PVDF film sensor in a similar design to Patterson and Nevill's sensor but smaller.

3.3.2 Choice of Texture Sensation Regenerator

The only safe, portable, hand-mounted system from section 0, is the vibrotactile system. As both Caldwell and Gosney used piezo-electric sounders as vibrotactile devices, it was chosen for this system.

3.4 Outline of the Thermal System

Humans need to feel temperature changes relative to skin temperature, with body temperature producing a temperature gradient, to acquire object thermal conductivity information as well as temperature information. This means that simply sensing the temperature of an object being manipulated and generating that same temperature at the operator's fingers will tell the operator only the ambient temperature where the manipulator is situated. (assuming that the object is at room temperature)

The way to give the human operator a realistic impression of the thermal conductivity of the manipulated object is to emulate the human sensing system at the manipulator, to get the relative temperature change that would be felt by a human and reproduce that temperature change for the operator. This is similar to that used by Russell and others; see Section 0

The PC, on the other hand, requires absolute temperature as well as relative temperature changes, for more accurate identification of material thermal conductivity, as well as for other material properties. For this reason, all temperatures in the system are measured absolutely, and the microcontroller calculated the relative temperature change to be presented to the operator. This is calculated by taking the difference between when the artificial skin sensor is not touching anything, and when it touches the object in question. This relative temperature is added to the skin temperature of the operator, to get the required temperature to present to the operator, ie.

$$T_x = T_{skin} + (T_{Mtouch} - T_{Msteady})$$

$$\text{where}$$

$$T_x = \text{Temperature to present to operator}$$

$$T_{skin} = \text{Temperature of o'perators skin}$$

$$T_{Mtouch} = \text{Temperature at manipulator / object interface}$$

$$T_{Msteady} = \text{Temperature at manipulator interface when touching nothing}$$

This is the general equation used for the thermal system. As $T_{Msteady}$ can only be measured when the manipulator is not touching anything, and should be steady, it is assumed to be a predetermined value, and the heater temperature preset to give the correct temperature. Any offset between the assumed value and the actual value of $T_{Msteady}$ is constant, and as long as it is small (±1°C max.), the hand does not notice the steady offset.

As well as producing thermal sensations for the operator, the microcontroller also sends the absolute temperature data for all of the sensors, to the PC for recording, expert systems or sensor fusion. The microcontroller also acts upon any data sent from the PC, altering the operator's sensations for special situations, for example, to give the operator an attention seeking step change in temperature, or a painful sensation if the PC determines the manipulator to be in danger of damage. (Cold pain is used in preference to hot pain, as there is less chance of damage to the operator's skin.)

3.4.1 Choice of Thermal Sensor

Section 0 gives a reasonable range of thermal sensors, but can be reduced as Monkman and Taylor Pyrometer device has no absolute temperature sensing, and the thermoelectric cooler used by both Caldwell and Monkman and Taylor is too fragile for a robot manipulator. This leaves the type of sensor used by Russell and others which while slow, can give absolute temperature and fulfils the requirement.

3.4.2 Choice of Thermal Sensation Regenerator

The only self-contained, solid-state electronic method of thermal generation (cooling as well as heating) is the thermoelectric cooler (also known as the Peltier heat pump), which fits the requirements, so it was chosen.

3.5 Detailed System Design

As the two sub-systems are part of the same overall circuit, and use mainly common elements, they will be detailed together.

3.5.1 The Serial Link

Although most systems will already have a manipulator to operator link for the teleoperator system, it was assumed for this project that no extra capacity is available, or that it is easier to use a separate serial bus for this system.

For a full system, the distance between the manipulator and the operator could be of the order of 1 metre for a prosthesis, 50 metres (eg for manipulating chemicals inside safety cells), 1 Mile (eg for work inside a contaminated nuclear power station), or even the distance from orbit to ground level for planetary tele-exploration from an orbiting space craft.

As any decision regarding the serial bus is totally dependant on this end-to-end distance, the media of the link (be it cable, fibre-optic or radio-link) and the requirements of the signalling standard (eg RS232,RS422,custom), this area was not investigated. Instead a simple, short-length serial bus, called the I²C bus, was used for the development of the system. The Philips I²C (Inter Integrated Circuit) standard mode serial bus has the following features[35]:-

- Only two bus lines are required; a serial data line (SDA) and a serial clock line (SCL).
- A complete range of microcontroller and peripheral chips with the bus interface on-chip, is available.
- Each device connected to the bus is software addressable by a unique address.
- It's a true multi-master bus including collision detection and arbitration.

- Serial, 8-bit oriented, bidirectional data transfers can be made at up to 100kbits/s.
- The length of the bus, and the number of IC's that can be connected to it limited only by the maximum bus capacitance of 400pF. (This can be increased to 4000pF with a pair of buffer driver chips)
- Chip count is reduced as the bus interface is already integrated on-chip.
- Package size is reduced as there are only two connections to the bus.

As the unbuffered I²C bus is limited to 400pF total capacitance, and assuming 50pF capacitance for connectors, PCB tracks and IC connections, this allows the cable to have a maximum capacitance of 350pF. Therefore 10 metres of 30pF/m ribbon cable was used for the serial bus as it is within the specified limit.

To reduce cross-talk between the serial bus clock and data lines, the ribbon cable cores were allocated so that the two were separated by power/ground connections, as shown in 2.

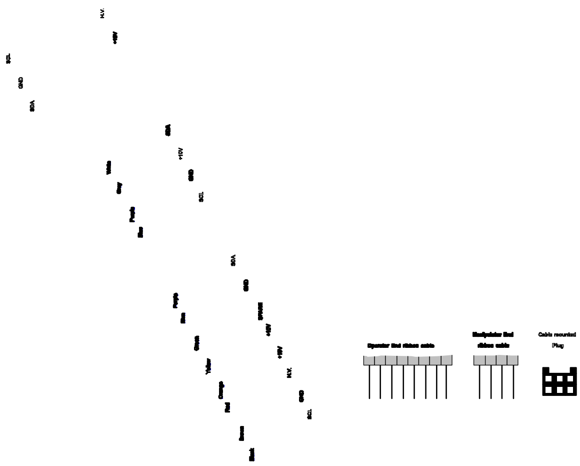

Fig. 3.2 - Allocation of Ribbon cable cores.

Note that for the operator end cable, two cores are paralleled for the +10V and Gnd supplies, because of the high current required.

3.5.2 The Manipulator End

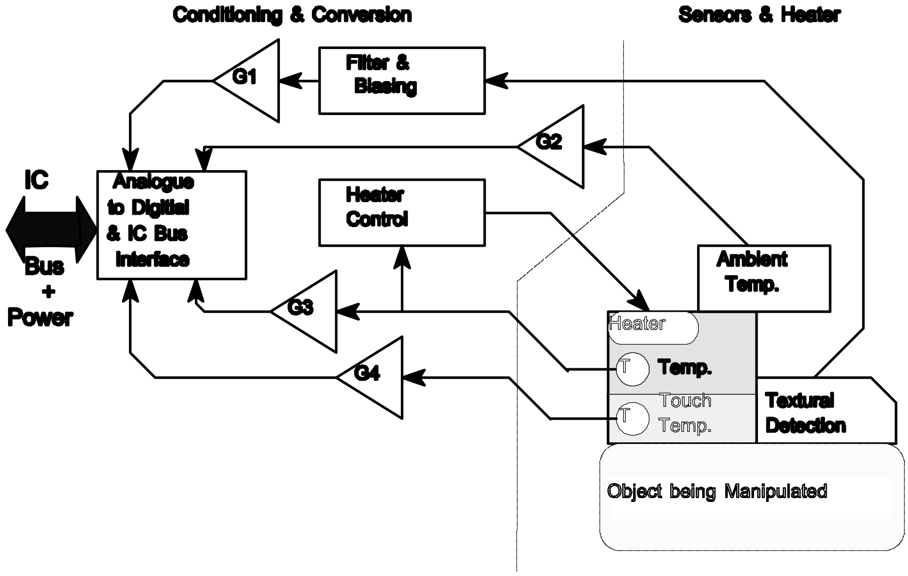

Fig. 3.3 - Block diagram of the manipulator circuit

It can be seen from the block diagram, that the manipulator circuit is split into two sections; the sensors and heater section, which is mounted on one of the manipulator's fingers, and the rest of the circuit, which is mounted on the manipulator's arms. This separation of the sections is to keep as much of the weight of the unit above the manipulator's wrist, to keep the manipulator's inertia low. The trade-off of this, though, is that the amplifiers are some distance (≈20cm) from the transducers, potentially giving increased noise pick-up.

3.5.2.1 The Manipulator's Thermal Sensors

From 3 it can be seen that there are three temperature sensors required. These sensors have different functions and thus require different characteristics:-

a). <u>The Touch Temperature Sensor, $\mathbf{T_{Mtouch}}$</u>

The touch temperature sensor requires a response time in the tens of milliseconds range, so that the sensor does not delay the pick-up of sensations. Intrinsically linked with the requirement for response time, is the requirement for small thermal mass, and therefore small dimensions (of about $1mm^3$), with a flat sense area so that the whole area is in contact with objects being manipulated. The sensor also requires linearity, absolute accuracy of the order of ±½C, and a range of 0 to 55°C

Platinum film detectors were rejected due to their large size and fragility. Semiconductor sensor ICs were rejected due to their large package size and slow response time (>0.5 seconds, even in flowing liquid[36]). Thermistors (as used by Russell[28]) were rejected due to larger than required size, and response time of 0.5 sec minimum.[37]

Although Thermocouples have major disadvantages (as noted below), a type T rapid response foil thermocouple was used (shown in 4). This met most of the criteria, having a 63% response time of 10ms(typ.), a temperature range of -160 to +370°C, a thickness of 0.05mm and is extremely robust.[38]

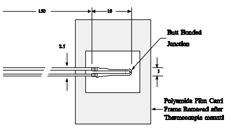

Fig. 3.4 - Dimensions of Type T rapid response Thermocouple. (from [38])

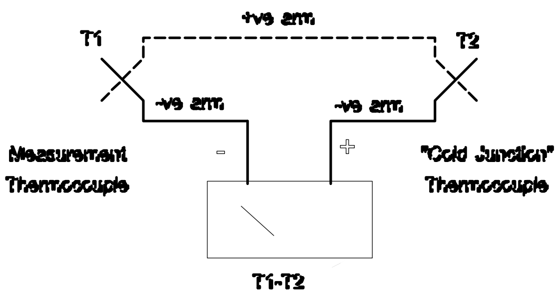

Fig. 3.5 - Basic diagram of thermocouple effect. (after [39])

The disadvantages of Thermocouples include:-

- a thermocouple gives a voltage proportional to the difference in temperature between two junctions rather than an absolute temperature, 4. Therefore, one of the junctions (the reference junction) has to be at a known temperature, to get the absolute temperature of the other junction. This is done either by physically keeping the junction at a known temperature (usually the ice point, 0°C), or by measuring the temperature at the junction with an absolute temperature detector, to compensate for changes in the reference junction temperature.[39]
- Thermocouple output is in the microvolt range; for a Type T thermocouple it approximates 40.25ì V/°C in the range 0°C to 50°C. This gives a requirement for a large gain in the any circuitry it drives.
- This output value is not linear, also varying with temperature; at -100°C it is 28.4ì V/°C and at +200°C it 53.2ì V/°C.[40] (Graph given in Appendix B2)

To compensate for the variation in cold junction temperature, to give an absolute temperature measurement, a Linear Technology LT1025 direct thermocouple cold junction compensator IC was used. This IC tracks the cold junction temperature and subtracts a voltage proportional to this temperature from the thermocouple voltage to give a voltage proportional to the measurement junction temperature in degrees Centigrade,[4142] giving the basic circuit, 6 below.

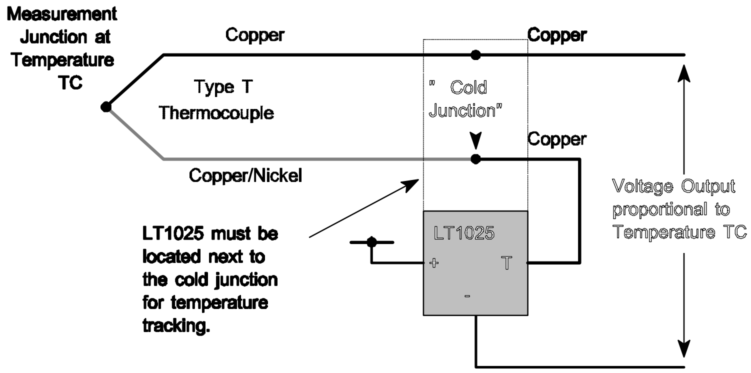

Fig. 3.6 - Basic diagram of Thermocouple compensation.

Although it was planned to correct the thermocouple non-linearity in software, this did not occur, giving a 2°C absolute temperature error at 50°C.

b). Heater Temperature Sensor, $\mathbf{T}_{Mheater}$, and Ambient Temperature Sensor, $\mathbf{T}_{Mambient}$

As there was only a requirement for accurate measurement, the heater temperature sensor, and the ambient temperature sensor, were implemented using an IC temperature sensor, the LM35DZ.[43] The LM35 is mounted in a TO92 package and gives a 10mV/°C output, accurate to ±0.6°C

3.5.2.2 The Heater and Control Circuit

The heater circuit is based upon the heat dissipation in a power transistor, as used by Russell.[28] The advantages of this method are:-

a). Only a low current drive is required to drive the transistor.

b). The underside of the power transistor provides a conveniently sized thermally conductive flat surface, to build the manipulator sensors on.

c). The power transistor is robust enough to use as part of the manipulator.

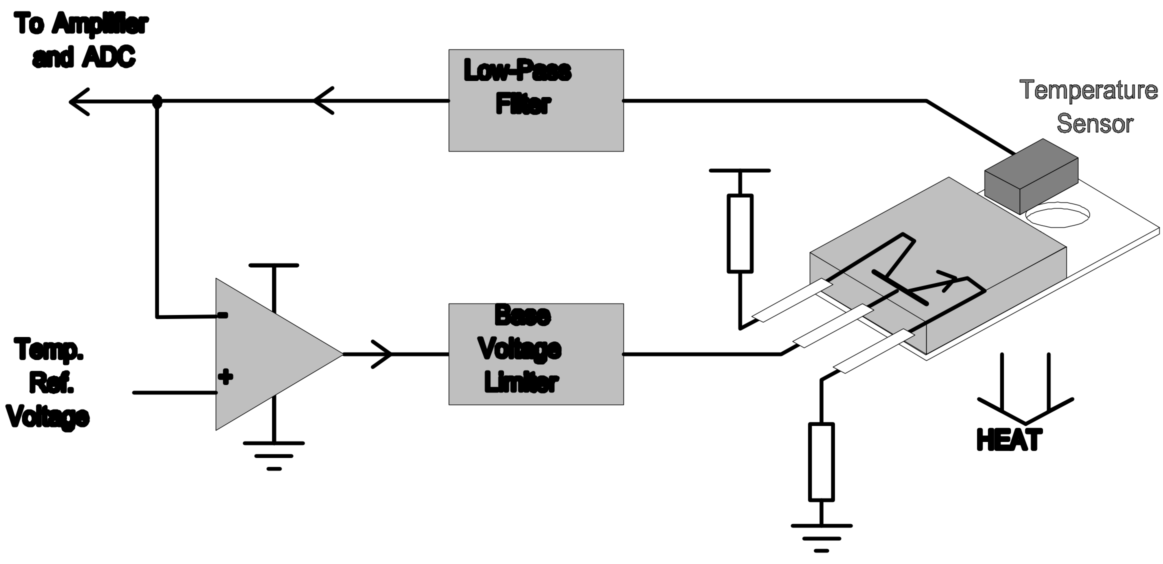

Fig. 3.7 - Block diagram of heater drive circuit.

Although PWM drive of the transistor was envisaged, the circuit used in testing was a simple on-off comparator circuit, as shown in block diagram, and in the heater circuit diagram, 25.

No hysteresis was built in, as the thermal time lags inherent in the system, together with the noise reducing low pass filter, produce a steadily increasing temperature signal for a few seconds after switching off.

The base voltage limiter circuit is included to limit the 'on' base voltage to just below that which gives maximum power dissipation in the transistor, and low power dissipation in the collector and emitter resistors, as shown in 8.

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BGI Graphics
Creator:
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Preview:
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with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

Fig. 3.8 - Graph of power dissipation in the transistor, and the collector & emitter resistors.

As noted in the results section, this on-off method of heater temperature control was barely adequate, and future designs should PWM drive the transistor for stability.

3.5.2.3 Thermal Data Conditioning and Conversion

As shown in 3 (the block diagram of the manipulator circuit), the three thermal signals used by the microcontroller are first amplified, so that the signal range required covers the voltage range 0 to 5V. The Heater temperature and Ambient temperature signals were given ranges of 0°C to 54°C and 0°C to 40°C respectively. To get these ranges with a sensor output level of 10mV/°C, only low gains of 9.2 and 12.5 respectively were required. (Associated calculations shown in Appendix B1.)

For the Touch temperature, which is at a thermocouple level of 40.25ì V/°C, given a required range of 0°C to 59°C, a gain of 2106 was required. Another requirement was that the amplifier input offset voltage was proportional to less than ¼°C, which for the Heater and Ambient sensors is an easily met amplifier input offset voltage of 2.5mV or less. For the touch thermocouple amplifier, this required an amplifier input offset voltage of less than 10ì V, requiring a special operational amplifier. In this situation, one half of a dual Precision CMOS Chopper Stabilized amplifier, the LTC1051 was used as it has a maximum input offset voltage of ±5ì V maximum, and has rail-to-rail outputs with a single 5V supply.[44] All signals were amplified using single stage amplification.

These amplified signals are then digitized, and sent across the I^{2}C serial bus when requested by the microcontroller, both tasks integrated into the PCF8591 serial Analogue-to-Digital IC. This IC is a 4 channel, 8 bit I^{2}C Serial Analogue to Digital Converter, with a single 8 bit Digital to Analogue converter (unused in this design).

At preliminary testing, the amplifier outputs of the sensors gave an accurate result on a DC volt meter, but the oscilloscope showed rail-to-rail (ie 5v pk-pk) 50Hz oscillation on the DC level of the thermocouple signal.

Active notch reject and low pass filters, such as the Linear Technology LTC1062 5th Order Low Pass filter, were evaluated and rejected. This was because they could not be used at the amplifier input, as their offsets swamped the thermocouple temperature voltage. Due to using single stage amplification, no intermediate points were available, and they could not be used at the amplifier output as the oscillations were rail-to-rail at this point.

The Analogue Devices AD595 Monolithic Thermocouple Amp, with cold junction compensation[45] was also trailed, as it's differential inputs reject common mode noise, giving a stable output, but the device was found to be slow to react to temperature changes ($t_{90\%}$ > 5 seconds). Instead, a simple passive low pass filter (G_{-3dB} = 3Hz) was built onto the input of each thermal sensor amplifier (not just the thermocouple amplifier). Together with shielding of the sensor wiring and the circuit boards, this gave an acceptable noise reduction, to approximately 1LSB of the digitised signal level. This was at the expense of some increase in response time, due to the reduced bandwidth.

3.5.2.4 Textural Sensor and Filter Circuit

A PVDF film sensor, 42 x 16mm x 80Ì m was used in the design. As it is an active sensor, generating its own output signal, no supply is required to the sensor. An output range of ±2.5 volts maximum was found for coarse textural features, in preliminary testing. This meant that no amplification, and only a +2.5 volt biasing circuit was required to get a 0 to +5 volt output signal. The +2.5 biasing voltage was supplied by a Texas Instruments TLE2425C[46] +2.5V precision virtual ground, in TO92 package, which "splits" the +5V / Gnd rails to give +2.5V.

The textural signal is then clamped to prevent sensor overload causing signals to go more than 0.3V outside the 0 to +5V range, using Schottky diodes to the supply rails. After this the textural signal is filtered, with a 4th order 2dB Chebyshev low pass filter,[47] to below

475Hz before driving the Analogue to Digital Convertor. The filtering removes frequencies above 475Hz which are outside the human vibrotactile stimuli range, and allows analogue to digital conversion rates from 950 Sps(Nyquist limit).

As op-amps with a rail-to-rail range were not available, a dual op-amp with an input range down to the negative rail (0V) was used, powered from the 10V rail, instead of the 5V rail. This introduced some extra noise, and necessitated an extra Schottky clamp diode and resistor, to guard against the op-amp output being higher than +5v.

Again testing showed pick-up of 50Hz mains noise. As this was within the frequencies of interest, no filtering was possible. Instead the cable from the PVDF sensor to the circuit was shielded, reducing the noise to 1 L.S.B.

3.5.2.5 Assembly of the Manipulator's Thermal Sensor

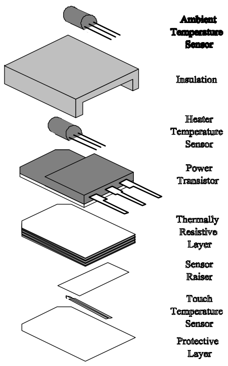


Fig. 3.9 - Exploded view of manipulator's thermal sensor

As shown above, the heater temperature sensor is mounted on the upper surface of the power transistor tab, using thermally conductive epoxy to give both strength and thermal bonding. The thermally resistive layer, in this case 12 layers of black electrical insulation tape are stuck on the underside of the tab. The advantages of electrical tape are that it is slightly compliant, requires no glue and the thermal resistance can be varied by varying the number of layers.

Onto this a 5mm squared piece of insulation tape is added to raise the thermocouple slightly above the rest of the surface, to give improved contact with rough or curved object surfaces. The thermocouple tip is placed onto this square, and covered by a single layer of insulation tape. This both holds the thermocouple in place, and insulates and protects it from the outside world. The upper surface of the assembly is covered by a thermally insulating foam layer and a layer of adhesive aluminium tape, to keep the transistor temperature as stable as possible.

The connections to the assembly are brought out to the conditioning and conversion circuitry (≈40cm), with the thermocouple connections extended by type T thermocouple extension cable and sheathed in shielding braid.

3.5.2.6 Assembly of the manipulator's textural sensor

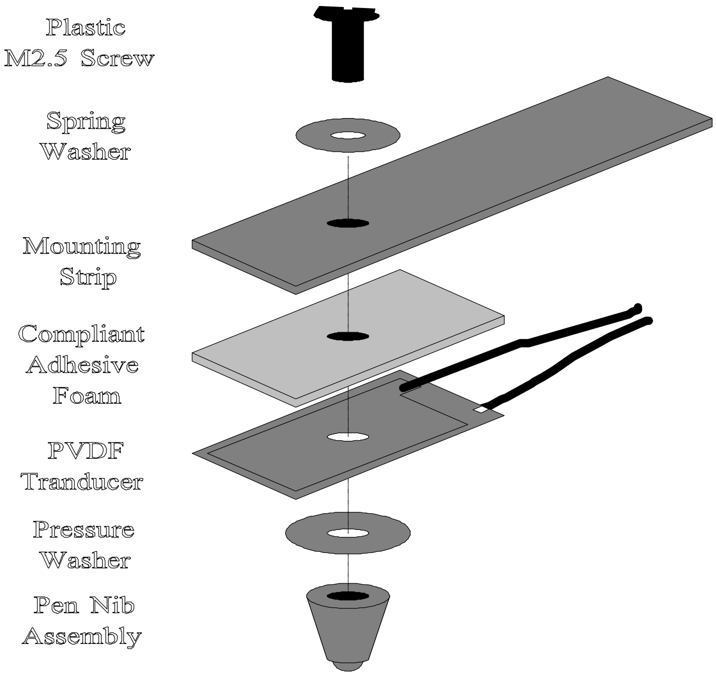


Fig. 3.10 - Exploded view of manipulator's thermal sensor

As shown above, the textural assembly was mounted on an 80 x 12.5mm strip of 2mm thick steel. The PVDF film transducer was mounted on this, using a compliant base of double-sided sticky foam pads. The connections to the two silvered plates of the transducer were made using gold-plated wire-wrap pins clamped to the silvering, as the transducer could not stand soldering. The assembly was then insulated using a layer of insulating tape before a clearance hole for a 2.5mm screw is drilled. The ball-point assembly is fitted using a 2.5mm plastic screw and spring washer above, and a flat washer below, pressing onto the PVDF very slightly.

3.5.3 The Power / Display Module

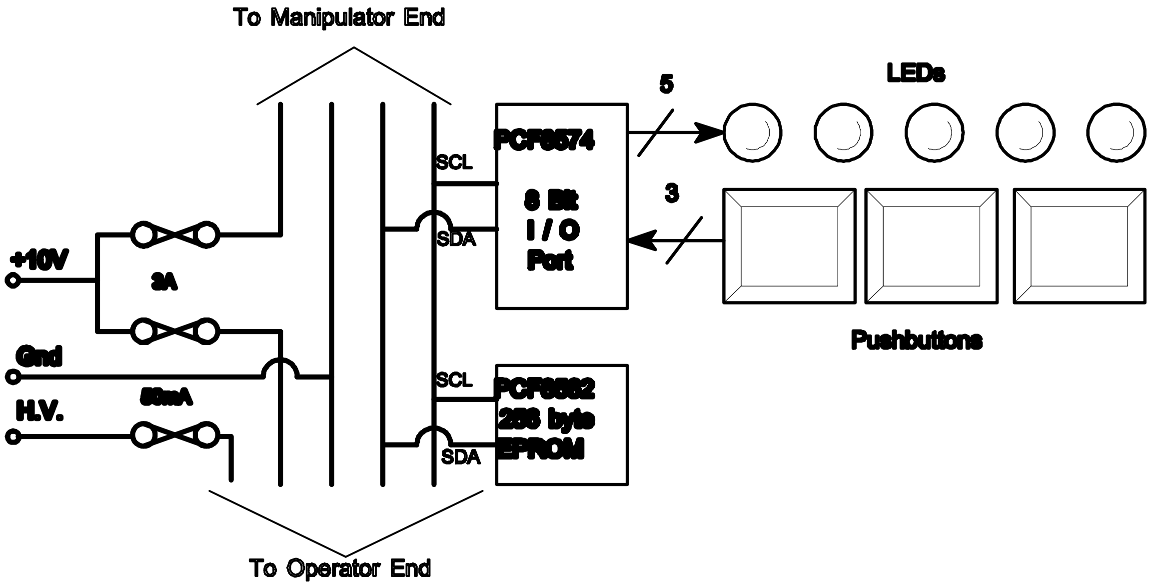


Fig. 3.11 - Block diagram of the power and display module.

This module serves three functions, as shown in 11:-

a). It connects the power supplies to the manipulator and operator ends, through the serial bus cabling. Each end's 10 Volt supply is fused separately, at 3 Amps each, and the high voltage supply fused by a single 50mA fuse.

b). It displays system status on 5 LEDs and provides a 3 button keypad, both connected through the I²C bus, to provide user input/output when the system is not connected to the PC nor to the LCD display. This function uses the PCF8274 Remote 8-bit I/O expander for I²C bus.[48] 5 bit are used as outputs, to directly drive the LEDs, and the other 3 bits used as input for the 3 pushbuttons.

With the present software, 4 of the 5 LEDs (coloured red, orange, green, blue) are used to indicate power levels into the thermoelectric heat-pump (from 'too hot' through to 'too cold'), and the other to show a software 'heartbeat' (yellow). Of the pushbuttons, only the red central one is used in software, as a shutdown switch.

c). A 256byte I²C E²PROM is also mounted off this board to store parameters, but was not used in software.

3.5.4 The Operator's End

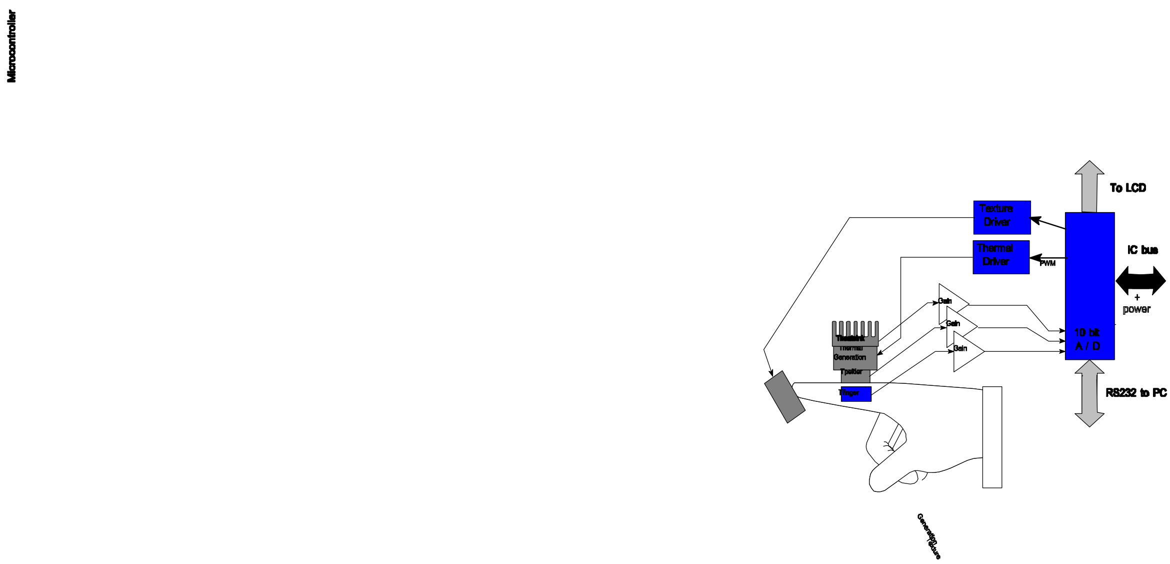


Fig. 3.12 - Basic block diagram of operator end of system.

It can be seen from the block diagram above, that the operator end of the system is split into two sections - the sensation generation section mounted on the operator's index or middle finger, and the processing & drivers section, mounted on the operators lower arm. As with the similar setup on the manipulator end, this is to keep as much weight as possible above the wrist.

3.5.4.1 Thermal Generation

The only self-contained, solid-state electronic method of thermal generation (cooling as well as heating) is the thermoelectric cooler (TEC); also known as the Peltier heat pump. This is a series of p-type and n-type semiconductor junctions thermally in parallel, bonded between 2 thermal ceramic faceplates - 13. When a current flows though the device from one terminal to the other, heat is pumped from one face to the other. When the direction of this current flow is reversed, so the direction of heat pumping is also reversed.

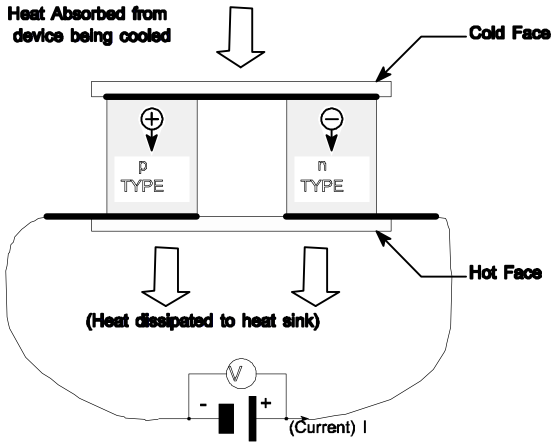


Fig. 3.13 - Basic Diagram of a Peltier Thermoelectric Couple

When a positive DC voltage is applied to the n-type thermoelement, electrons pass from the p- to the n-type thermoelement and the cold side temperature will decrease as heat is absorbed.

The heat absorption (cooling) is proportional to the current and the number of thermoelectric couples, and occurs when electrons pass from a low energy level in the p-type thermoelement, to a higher energy level in the n-type thermoelement. The heat is then conducted through the thermoelement to the hot side, and liberated as the electrons return to a lower energy level in the p-type thermoelement[49].

The Thermoelectric cooler used, was determined by 4 criteria;

- Cooler **Wattage** requirements - The human heat loss is approximately 8mW / cm² at room temperature. Gosney[22] had used an 15.3 Watt cooler, which was more than adequate, with static results of 30°C drop across the cooler whilst on the skin.
- **Size** - the human finger is only so big; for the fingertip pads, the area is approximately 1.5cm square for a flat contact surface. On the back of the finger, between the knuckle and first joint, the area is larger at about 2.5cm by 1.2cm wide. Only flat TECs are available at present, but TECs curved to fit the finger back, or tip, could be made, at a price. (about £100 each, plus £10K-£100K of non-recurring engineering charge, for large quantities.[50])
- **Voltage / Current** requirements - This is linked to point a) above, in that the electrical power required is a function of the heat pumped. In general, to fulfil the requirement for only having one supply voltage for both the cooler drive and for the digital and analogue processing (Section 0) requires a cooler maximum voltage of above 7 Volts. (5v for digital circuit plus regulator overhead.) The current was to be as low as possible, so that the driver circuit size and heat dissipation are as small as possible.
- **Speed** of temperature change - the ceramic faceplate, on the finger side of the cooler, must be thin, so as to store as little heat as possible, giving a fast response.

These four factors narrow down the range of coolers to approximately a dozen, of which the MI1023T[51], manufactured by Marlow Industries, was chosen as be most suitable cooler. The dimensions and performance curves of the MI1023T are given in 14. The maximum operating temperature of this TEC is 85°C.

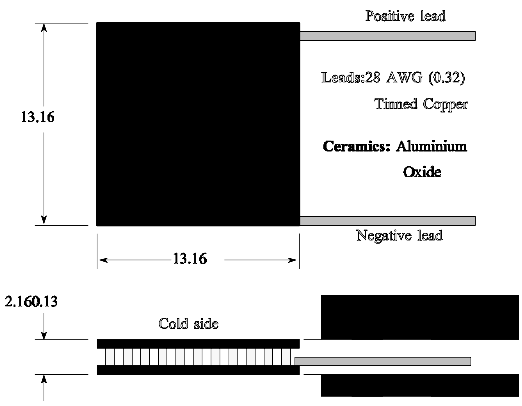


Fig. 3.14 - Mechanical details and performance curve of the MI1023T Thermoelectric device (from [51])

3.5.4.2 The TEC Drive Circuit

The TEC requires a reversible supply of up to 2 Amps at 8 Volts. To drive it with linear amplifiers would require driver dissipation of up to 20 Watts and a bridge configuration for reversing the current flow, to heat as well as cool. It would also require an analogue drive signal from the microcontroller.

A much more efficient way of driving the TEC is to use Pulse Width Modulation (PWM) drive, which is a train of pulses of fixed frequency, with width proportional to the power required. The only proviso is that the PWM frequency is high enough that the solder at the thermoelectric cooler junctions is not thermally cycled,[52] the figure of 20kHz being given by the makers as acceptable. For the testing of the system, the MI1023T was driven by a slightly lower PWM frequency of 16kHz, without any noticeable effects.

To drive the TEC using PWM the driver can be a simple H - bridge. This would require 2 PWM signals or a small amount of logic to use a single PWM signal and a direction signal. An integrated solution, the Sprague UDN2954W Full-Bridge PWM Motor Driver, has a 2 Amp continuous output H-bridge and driver logic together with crossover protection and current limiting, in a 12 pin single in-line power tab package.[53] It requires only PWM and direction input signals, at TTL levels.

3.5.4.3 The Thermal Sensors and Conditioning Circuit

From 12 it can be seen that there are three temperature sensors required. These sensors have different functions and thus require different characteristics:-

a). The TEC / finger interface temperature sensor, $\mathbf{T_{peltier}}$

The TEC / finger temperature sensor requires a response time of tens of milliseconds, so that the TEC temperature control loop response times are small. Intrinsically linked with the requirement for response time, is the requirement for small thermal mass, and therefore small dimensions (of about $1mm^3$), with a very thin flat sense area so as not to affect the finger to TEC contact. The sensor also requires linearity, absolute accuracy of the order of ±½C, and a range of 0 to 50°C. As with the manipulator's T_{Mtouch} sensor, a type T rapid response foil thermocouple was used.

b). The TEC heater temperature sensor, $\mathbf{T_{heatsink}}$

The TEC heater temperature sensor requires a small sensor so as to get as close as possible to the heatsink face of the TEC, for early warning of overheating. The sensor also requires, absolute accuracy of the order of ±2°C, and a range of 0 to 80°C. For this sensor a type T welded tip, PTFE insulated thermocouple was used. (RS part no. 158-907[38]) c). The operator's finger temperature sensor, $\mathbf{T_{finger}}$

The finger temperature sensor requires a small sensor which, when in contact with the finger, would give the finger's skin temperature accurately; absolute accuracy of the order of ±2°C, and a range of 20 to 40°C. As with the manipulator's $T_{Mheater}$ and $T_{Mambient}$ sensors, an IC temperature sensor, the LM35DZ was used.

Again, all signals from the sensors to the amplifiers were shielded and low pass filtered to remove any mains noise. Both thermocouples were amplified using a dual precision CMOS chopper stabilized amplifier, as shown in Fig. 3.19.

3.5.4.4 Textural Generation

As noted in section 0, the main way of producing textural & vibrational information is a piezo-vibrator. No better way of reproduction was available, so piezo was used. The smallest available piezo sounder was 27mm dia., which is slightly large, with a resonant frequency of 1.8kHz and capacitance of 25nF.

3.5.4.5 Textural Driver

Piezo vibrators require an AC voltage potential across the two faceplates, to vibrate, the amplitude of which is proportional to the amplitude of the AC voltage. Therefore, as high a voltage as possible within the constraints of space, was required. As this amplitude has to be controllable, and the drive circuitry small, the best solution was bridge drive circuit using op-amps in a DIP or other small PCB mounted package. At the time of designing, the highest voltage op-amp available were the Burr-Brown OPA445 High Voltage FET-input Op-Amp,[54] with a maximum supply voltage of 90 Volts. This limited the maximum bridge output voltage to 150V pk-pk, which although lower than hoped, was thought to be useable.

One side of the op-amp bridge is driven by a digital to analogue converter, the ZN426 8-bit monolithic D-A converter[55], through a buffer amplifier. The other side is driven by an unit gain op-amp inversion of the buffered DAC output. The DAC receives a 6 bit value from the microcontroller (the 2 Least significant bits of the DAC are unused). This gives the circuit shown in Fig. 3.23.

3.5.4.6 Assembly of the Operator' Thermal Feedback Unit

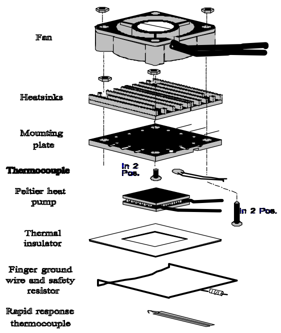


Fig. 3.15 - Exploded assembly diagram of thermal feedback unit

The operator's thermal feedback unit is assembled as shown above. The TEC is cemented to the mounting plate, and the two thermocouples are cemented to the assembly with thermal epoxy, which is also used to insulate to rapid response thermocouple from the operator's finger.

3.5.4.7 Requirements for the Micro-Controller

The minimum requirements for the micro-controller which runs the thermal and textural systems were as follows:-

a) **8 bit processing** - a 4 bit micro-controller would require approximately 20% more instructions and double the data memory, due to the need to handle 8 bit data to / from the various Analogue to Digital Converters, the serial link to the PC, and the LCD. 16 bit processing was thought to be an advantage only in a few calculations.

b) On chip peripherals - as the overall requirements were for a system that is as small as possible, the choice of a micro-controller with at least **four 8bit ADC's** (for temperature measurement), a **hardware PWM output** (to drive the Heat Pump Circuit), an **I²C serial bus** (to communicate with the rest of system), and a **serial port** (to communication with a PC) built into the micro-controller gives a large reduction in board space and quantity of components required.

c) **2Kbytes of program memory**, on chip, as a minimum.

d) **Small Package size** - again for a smaller Circuit board.

e) A reasonably fast instruction set.

f) A micro-controller from a common 'family' with easy to use assembly language.

The 87C752 from Philips, was chosen as the micro-controller best suited for the final system, but is difficult to use while developing the system, due to its inability to use external EPROM, difficulty in finding a programmer to program the internal EPROM, and absolutely minimum memory. For this reason the 80C552,[59] and an external EPROM were used for developing the system, as it overcomes these problems, but requires more board space as the 80C552 is a 68 pin PLCC package and the EPROM is a 24 pin DIL.

3.5.5 RS232 Link to PC

The microcontroller has a full duplex asynchronous serial port that provides data in the correct serial format for the PC, except that the voltage levels are 0v and 5v, instead of the ±10v RS232 minimum requirement for the PC's serial port. Therefore only a level shifter IC is needed for the connection. The disadvantage of this is the injection of noise, both high and low frequency, from the PC into the system and the possibility of ground loops.

For these reasons, an enhanced level shifter circuit was built, with opto-isolation of the transmitted and received signals, and transformer isolation of the level shifting power supply; 16 shows the block diagram. As chips for this type of circuit are readily available, a 2 chip set, the Maxim MAX250 and MAX251, were used, together with two 4N26 opto-isolators, and a small pulse transformer. The full circuit, shown in 24, has a maximum data rate of 19.2kbaud[56] (Replacement of the opto-isolators with 6N136 devices would give 90kbaud) and a isolation voltage greater than 500V. This circuit was built on a separate, small PCB (shown in Appendix D4) with a 3 metre connection to the microcontroller, and a 10 metre connection to the PC.

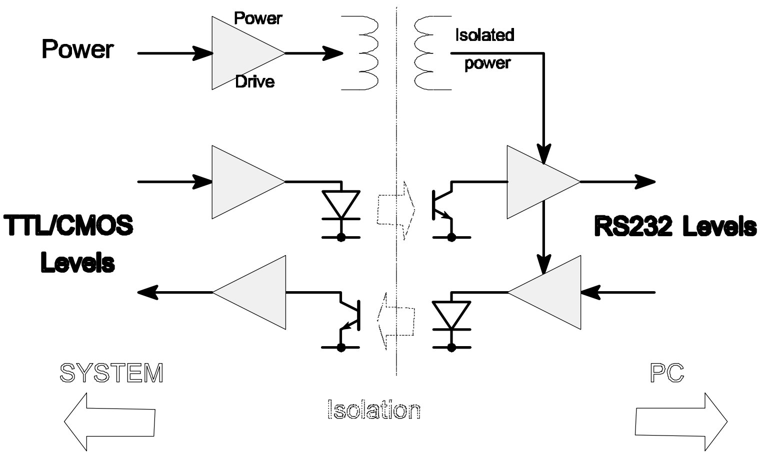


Fig. 3.16 - Block diagram of the serial connection between the system and the PC

3.5.6 LCD Display

For system development, an LCD display was used to display sensor temperature readings, power levels, status, and any error messages. The LCD chosen, the Philips LTN211 5 x 7 dot, 16 character, 2 line matrix module that requires only a contrast adjust preset resistor, and connection to power and data lines.[57] The display can be driven by 3 control lines, and either 4 or 8 data lines. So that only one port (8 bits) of the microcontroller was used (Port 4), the 4 bit data mode was used. Build details are given in appendix D8.

The display has a character ROM with 160 characters, and allows 8 extra characters to be user defined, seven of which are defined by the software. These are:-

1 - ■1   2 - ■2   3 - ■3   4 - ■4   5 - ■5   6 - ■6   7 - ■7

3.5.7 Circuit Diagrams

The following pages show the circuit diagrams for the whole of the system, divided into actual PCBs, as shown in 17. (PCB layouts, bill-of-materials, and other information on the circuits are given in Appendix B.) Note that where a +12V power connection is referenced, this is actually the +10V supply.

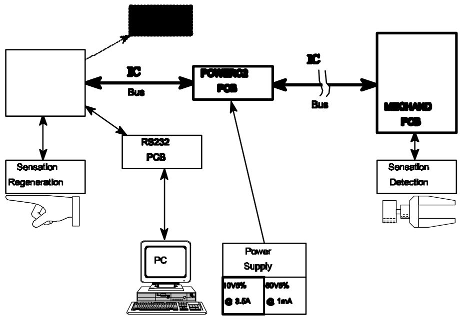


Fig. 3.17 - Block diagram of full system separated by circuit board (above) and picture of main elements (below) cross-referred.

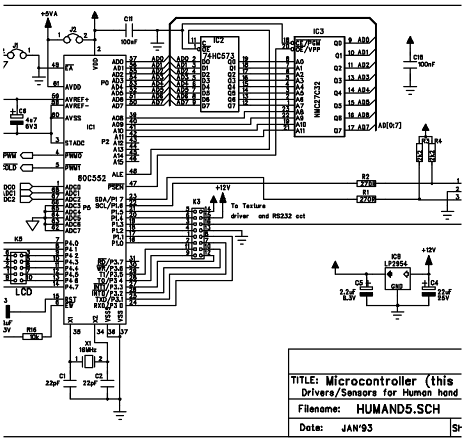


Fig. 3.18 - Circuit Diagram of the Humand PCB (Microcontroller)

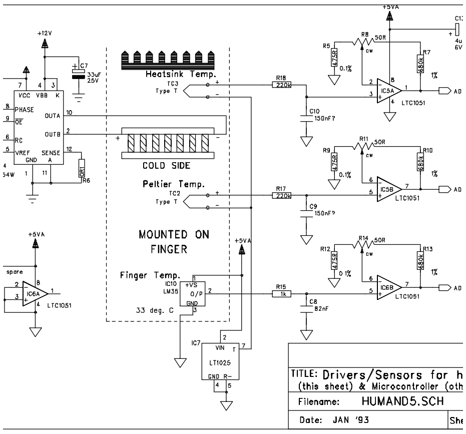


Fig. 3.19 - Circuit Diagram of the Humand PCB (drivers)

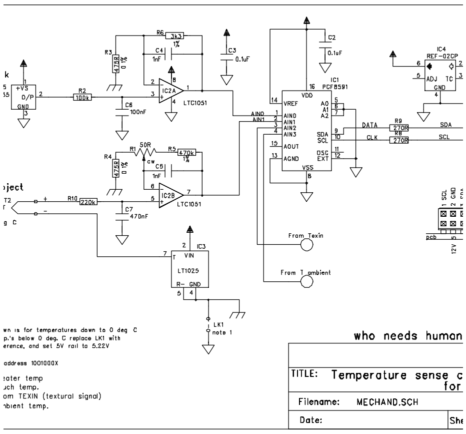


Fig. 3.20 - Circuit Diagram of the Mechand Board

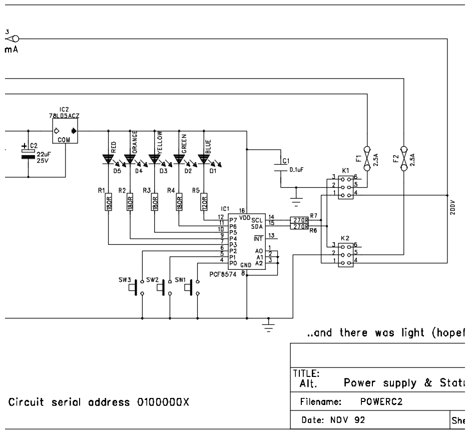


Fig. 3.21 - Circuit Diagram of the Powerc2 board

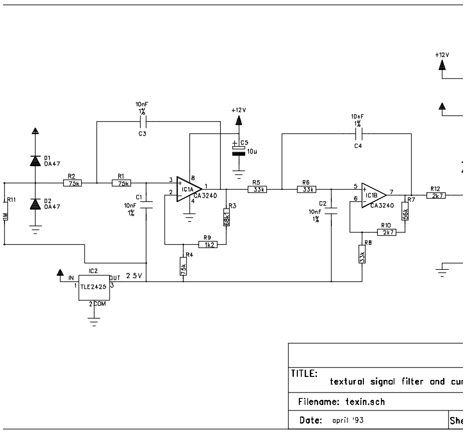


Fig. 3.22 - Circuit Diagram of the Texin board.

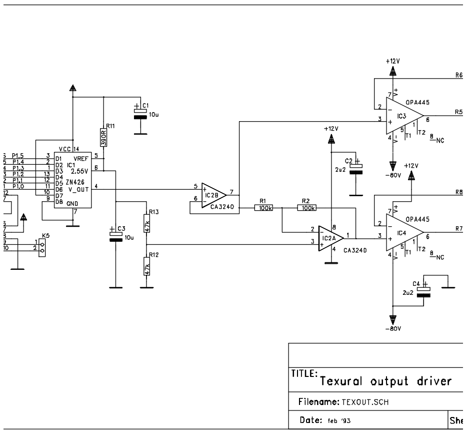


Fig. 3.23 - Circuit Diagram of the Texout board.

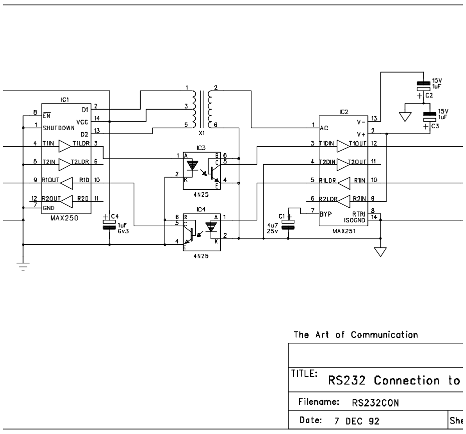


Fig. 3.24 - Circuit Diagram of the RS232 isolation board

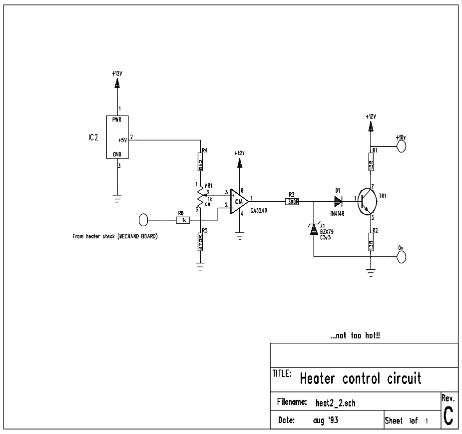


Fig. 3.25 - Circuit Diagram of the Heater Circuit

3.6 System Software Design

The microcontroller's software to run the system is completely interrupt driven, with only the system setup and the spare time counter not on a interrupt. Software listings are given in Appendices C1 to C9. The control algorithms for the two sections are as follows:-

3.6.1 Textural System Software Control Algorithm

The textural software used the following control algorithm:-

Inputs:-

Digitized signals	- from Manipulator (Texin)	0-255 (8 bit integer)
	from PC	0-255 (8 bit integer)

Control values:-	- Manipulator (Texin) multiplier	0-255 (8 bit integer)
'volume controls'	- PC multiplier	0-255 (8 bit integer)

Output:-

Digitized signal	-to Texout	0-63 (6 bit integer)

Control equation:-

(((Texin I/P x Texin Multiplier)/ 256 + (PC I/P x PC Multiplier)/ 256) / 4) % 64

If the sum of the PC and texin multiplier is greater than 256, an overflow is possible, but is ignored. The control equation allows full control of the proportions of both the PC generated texture signal and the manipulator texture signal which are mixed to form the output signal. For instance, with the Texin multiplier set to 255 and the PC multiplier set to 0, the textural output will follow the data from Texin. With Texin multiplier set to 0 and PC multiplier set to 255 the textural output will follow the data from the PC. If both multipliers are set to 64 the output will be an equal mixture of PC and Texin data but the output signal will be half its maximum.

3.6.2 Thermal System Software Control Algorithm

The thermal software used the following control algorithm:-

Inputs:-

Digitized Temperatures -$T_{peltier}$ - 0.00 to 255.99°C (16bit fixed point)

(values of 45°C and above shutdown system)

-T_{finger} - 0.00 to 255.99°C (16bit fixed point)

(values of 40°C and above shutdown system)

-$T_{heatsink}$ - 0.00 to 255.99°C (16bit fixed point)

(values of 64°C and above shutdown system)

-$T_{Msteady}$ - 0.00 to 255.99°C (16bit fixed point)

(set to 31.0°C on power up.

Can be altered by PC ('Tx' command))

-Offset T - -128 to 127.99°C (16bit fixedpoint)

(set to 0.0°C on power up.

Can be altered by PC ('Ox' command))

-T_{Mtouch} - 0.00 to 255.99°C (16bit fixed point)

(values of 64°C and above shutdown system)

can be set by PC to a held value ('Ax'command)

Control values:- 'maximum power limits'	- Maximum Proportional Power level	0-255 (8 bit integer)
	- Maximum Bang-Bang Power level	0-255 (8 bit integer)

Output:-

PWM power level and power direction	-to TEC via power drive	0-255 (8 bit integer) + sign (1 bit)

Control equation:-

Required TEC temperature = ((T_{finger} + T_{Mtouch}) - $T_{Msteady}$) + OffsetT (15bit fixed point +sign)
(if less than 0°C set to 1°C)

Error = Required TEC temperature - $T_{peltier}$

If (-2.00°C < Error < +2.00°C)

PWM Power level = (Error / 2.00 x Max. Proportional) + power adjust

(-ve = cool)

If Error >= 2.00°C

PWM Power level = + Max. Bang-Bang (ie heat)

If Error <= -2.00°C

PWM Power level = -Max. Bang-Bang (ie cool)

Power adjust is an approximate compensation for the difference in temperature between the two faces of the TEC and is included to improve accuracy with large TEC _'s.

$=fn\ (\ int\ (T_{peltier} - T_{heatsink}))$

3.7 System Safety

In developing the system, operator safety was considered in both the hardware and the software. For the textural feedback, the 150V pk-pk piezo drive voltage is a danger, so the piezo sounder was insulated with a layer of insulating tape.

For the thermal system, the danger is of burns. The software guards against this by checking all critical temperature readings against safe limits. If any are outside these limits, the system shuts down, and displays an error message. Shutting the system down can itself cause danger if the heatsink temperature is above 55°C, as the TEC power is keeping the finger cool against this temperature. Within a second of shut-down the temperatures either side of the TEC equalise, to almost the heatsink temperature (due to it's greater mass). To guard against this, and component failure, the assembly was mounted on the finger with velcro, rather than an elastic loop, for quick removal.

The PC software also had an alarm built in, to warn of shutdown and approach of shutdown limits.

3.8 PC software design

The PC software (TGRAPHS) is basically a data acquisition and graphing program, written especially for this project. This meant that the 'C' source code was available to be altered and recompiled, to add extra functions and special tests when required, for example to add real-time object material recognition. The 'C' code, history and usage instructions are given in appendix E. The results section gives examples of the thermal, textural and timing data acquired by, and graphs drawn by the program.

Due to the high speed communications and different graphs required for the textural tests, the TGRAPHS program was altered, including the removal of all thermal PC routines. This program was named XGRAPH, and although faster, still required a 486DX2 PC, to keep up with the communications queue. The XGRAPH 'C' source code is not given in the appendices, as it is only 15% different to the TGRAPHS code.

4. System Testing and Results

Due to lack of facilities, no tests were carried out with the manipulator assembly mounted on a robot arm. Instead the manipulator assembly was moved by hand.

4.0.1 Weight and size of system components

Weight on operator's finger (thermal) = 20g
plus (textural) = 5g total = 25g

Weight on operator's lower arm = 180g

Weight on manipulator's gripper (thermal) = 25g
plus (textural) = 15g total = 40g

Weight on manipulator's lower arm = 140g

Weights of all system components are given in Appendix G4. As shown in 1, the operator's end of the system fits neatly onto the operator finger and lower arm.

Fig. 4.1 - Operator's end of system mounted on an operator's arm

4.0.2 Size of software Routine

The system software object code was 2558 bytes, which equals 63% of maximum memory space.

4.0.3 Spare Processing Time available

```
LOOPY:   INC     (IDLETIME + 1)     1
         MOV     A,(IDLETIME + 1)   1
         JZ      IDLE_OV            2 >
         NOP                        1
         NOP                        1
         SJMP    LOOPY              2
                                    =8

IDLE_OV: INC     IDLETIME           1 <
         NOP                        1
         SJMP    LOOPY              2
                                    =8
```

As mentioned in the system software section, the software for the microcontroller included an idle time counter, the result of which is displayed on the LCD every 0.39 seconds, which equals 524288 cycles. The average idletime value displayed was BAAx hex, which equals the range 48032 to 48047 loops, each of 8 cycles. This gives a 73% idle time. (48032 x 8 / 524288). (ì C s/w ver 8.3 4800 baud)

4.0.4 Data transfer to and from the PC

The test results later in this section show the quality of the data transfer to, and instruction transfer from the PC. The textural tests were conducted with the RS232 link transferring data at 16,600 baud without error, giving approximately 650 sets of readings per second, eg 1. The thermal tests were conducted at a more leisurely 4800 or 2400 baud giving 20 or 10 sets of readings per second respectively. 6 shows the quality of the data transfer to and instruction transfer from the PC.

It should be noted that for all of the thermal tests, the baud rates were slightly slowed to give an exact number of data reading sets per second. 2400 baud was actually

2315 bps to give 10 sets per second. 4800 baud rate was 4630 to give 20 sets / second.

4.1 Textural System Testing and Results

This section describes the tests undertaken on, and results obtained from, the textural sub-system, first for the manipulator end, then for the operator end.

4.1.1 Manipulator end tests

Tests using the manipulator textural sensor, with a very light pressure, gave very clear data for coarse textural features. As an example, a plot of the manipulator textural sensor moving across a 20 Way 0.05" pitch ribbon cable is shown in 1, overpage. The pulses resulting from each of the 20 cores can be clearly seen.

The amplitude of each pulse is a product of the sensor pressure and the shape of each textural feature. The period of each pulse is a product of the pitch of the textural features, and the speed that the sensor moves across these features. For example, in 1, the pitch of the individual ribbon cable cores is 0.05" (1.27mm), and by the middle of the cable, the period of each cycle is 31ms. Therefore the speed at which the sensor moved across the ribbon cable was $1.27 \div 0.031 = 41$mm/s.

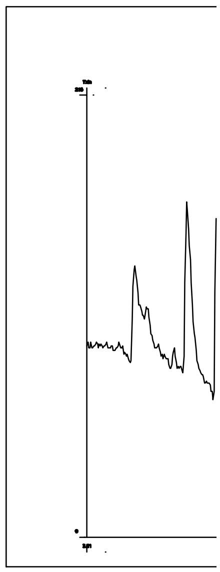


Fig. 4.2 - Graph of Manipulator's texture sensor moving across a 20 Way,0.05" pitch ribbon cable.

This can be used 'in reverse' to find the period of regular texture features, if the speed at which the sensor moves is known, say if it is being moved by a robot arm. As no robotic manipulator facilities were available, no object texture recognition tests of this type could be carried out.

Sadly, tests on the finest textural features have very little amplitude resolution, due mainly to the manipulator end Analogue-to-Digital Converter being 8 bit, giving a restricted dynamic range.

4.1.2 Operator end tests

Initial testing of the texture generator circuit showed it to be 'all sound and no feel' as one test subject put it. With industrial ear plugs to mask the sound, very little could be felt. With a PC generated sinewave at maximum PC amplitude and no Texin amplitude (ie commands %255,M0) the vibrotactile sensations dropped below threshold at about 25Hz. (20 to 32Hz depending on the operator wearing the device.) With a PC generated squarewave at maximum PC amplitude and no Texin amplitude, the sensations were felt down to 1Hz (the minimum value allowed in the XGRAPH software). This is assumed to be due to the higher frequency component being felt be the operator.

4.1.3 Full Textural system tests

Preliminary testing of the full textural system, showed that no definite sensations could be felt, even when the textural sensor was moved across a coarse textural surface. Because no solution could be found to up the power of the piezo, within the time limits, no other tests could be conducted on the full textural system.

4.2 Thermal System Testing and Results

This section describes the tests undertaken on, and results obtained from, the thermal sub-system, first for the manipulator and operator ends separately, then for the combined system.

4.2.1 Manipulator end tests

4.2.1.1 Heater stability and sensor accuracy check

The heater for the thermal sub-system at the manipulator end, had a temperature, measured at the output pin of the temperature IC (IC5, Mechand PCB), of 32.3°C (323mV), cycling ±0.2°C. Cycle time was approximately 16 seconds when the manipulator was in free air, dropping to less than 8 seconds when the manipulator was touching a thermally conductive object.

These values were closely matched by the processed values, indicating that the Gain, Analogue to Digital Conversion, and Software processes do not introduce significant errors to $T_{Mheater}$. The actual value for $T_{Mheater}$, downloaded to the PC over the serial link, was 32.03°C, which cycled + 0.26°C. This value is +1 least significant bit of the 8 bit A/D converter, for this signal.

Despite this temperature variation, the heater was used for the following tests, although it was barely adequate, and did introduce errors, which are noted.

The $T_{Mambient}$ sensor was found to be too closely coupled to the heater, giving high readings. Because of this, all measurements of ambient/room temperature were taken using a digital battery operated room temperature meter (Maplin ref FE33L[58]) accurate to ±1.0°C and resolved to 0.1°C.

4.2.1.2 Manipulator thermal response times when touching object

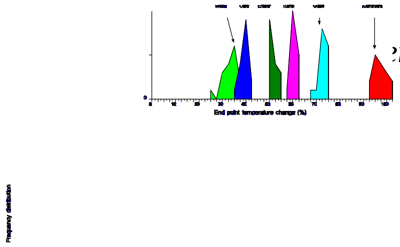
These tests checked the response times of the manipulator end of the thermal sub-system when reacting to, and when recovering from, touching objects with a medium pressure. This involved measuring the time to 10%, 63%, 90% and 100% change of temperature, both reacting and recovering. 1 below shows the mean results from tests on 6 materials.

Material	Reaction time (secs)				End point T_{cf}	Recovery time (secs)			
	To 10%	To 63%	To 90%	To 100%		To 10%	To 63%	To 90%	To 100%
Aluminium Block	0.174 (ó=0.058)	0.646 (ó=0.051)	2.93 (ó=0.434)	10.8 (ó=2.97)	.96	0.433 $ (ó=0.074)	7.60 $ (ó=0.406)	21.7 $ (ó=1.96)	39.0 $ (ó=3.66)
Card	0.143 (ó=0.051)	0.454 (ó=0.051)	1.341 (ó=0.514)	3.94 (ó=0.98)	.38	0.448 (ó=0.185)	6.453 (ó=0.846)	20.7 (ó=4.45)	30.2 (ó=5.68)
Glass	0.174 (ó=0.058)	0.739 (ó=0.192)	2.498 (ó=0.521)	7.53 (ó=1.94)	.72	0.317 (ó=0.074)	6.597 (ó=0.659)	20.8 (ó=1.70)	39.8 (ó=4.97)
Plastic Eraser	0.124 (ó=0.044)	0.460 (ó=0.062)	1.814 (ó=0.585)	4.62 (ó=1.34)	.50	0.379 (ó=0.122)	7.853 (ó=0.881)	21.3 (ó=2.73)	30.0 (ó=4.29)
Tufnol™ Block	0.124 (ó=0.026)	0.488 (ó=0.033)	1.706 (ó=0.262)	6.74 (ó=1.24)	.59	0.376 (ó=0.060)	6.436 (ó=0.702)	18.8 (ó=1.79)	29.7 (ó=3.06)
Wood	0.149 (ó=0.063)	0.547 (ó=0.121)	2.253 (ó=0.249)	3.42 (ó=1.57)	.32	0.139 # (ó=0.111)	7.086# (ó=1.668)	22.0 # (ó=4.56)	24.2 # (ó=3.79)

Notes:- Readings taken 7/12/94 - 21/12/94 PC s/w ver 7/12/94 ì C s/w ver 8.2, except tufnol, ver 8.3
All readings taken at 2400 Baud ∴ ≈100msec accuracy, except Tufnol taken at 4800 Baud ∴ ≈50msec accuracy

Table 4.1 - 10,63,90 and 100% response and recovery times, and end points for 6 objects of differing material. ç=16 except marked #=15, $=14. ó = s.d. (Raw data presented in Appendix G.1)

The final settling temperature was dependant upon the material being touched and the heater and object temperatures. Using the following temperature drop factor equation, the test results from tests on the 6 materials give the graph shown in 3.



$$\textit{...rature change factor}\ T_{cf} = \frac{T_{Mnot\ touching} - T_{Mtouch}}{T_{Mnot\ touching} - T_{object}}$$

Fig. 4.3 - Frequency distribution graph for 6 materials. (from results given in appendix G1)

In these and all following results, the room temperature in the vicinity of the object was measured, and assumed to be the actual object temperature, T_{object}. This assumption holds true as long as the object is not self-heating/cooling, has been in the room long enough to acclimatise, and the room temperature is not changing significantly. This gives the equation below.

$$\textit{End point temperature change factor} = \frac{T_{Mheater} - T_{Mtouch}}{T_{Mheater} - T_{room}}$$

4.2.1.3 <u>Object Material Recognition by computer</u>

When touched by the manipulator, object of different materials and thermal conductivities produce different 'touch' temperatures and different end point temp. change factors, as shown in 3. This 'touch temperature', together with the object temperature, can be used by PC based 'expert system' software to guess the material of the object being grasped, but the time required for the touch temperature to settle to this temperature can be up to 11 seconds, as shown in 1.

To reduce the time required before a material's identity can be established, the characteristics of the temperature change curve were investigated. 4 gives a **simplified** thermal diagram of the manipulator sensor, together with the electronic analogy for ease of comprehension. This diagram gives an equation for the change in temperature T_{Mtouch} over time after touching an object.

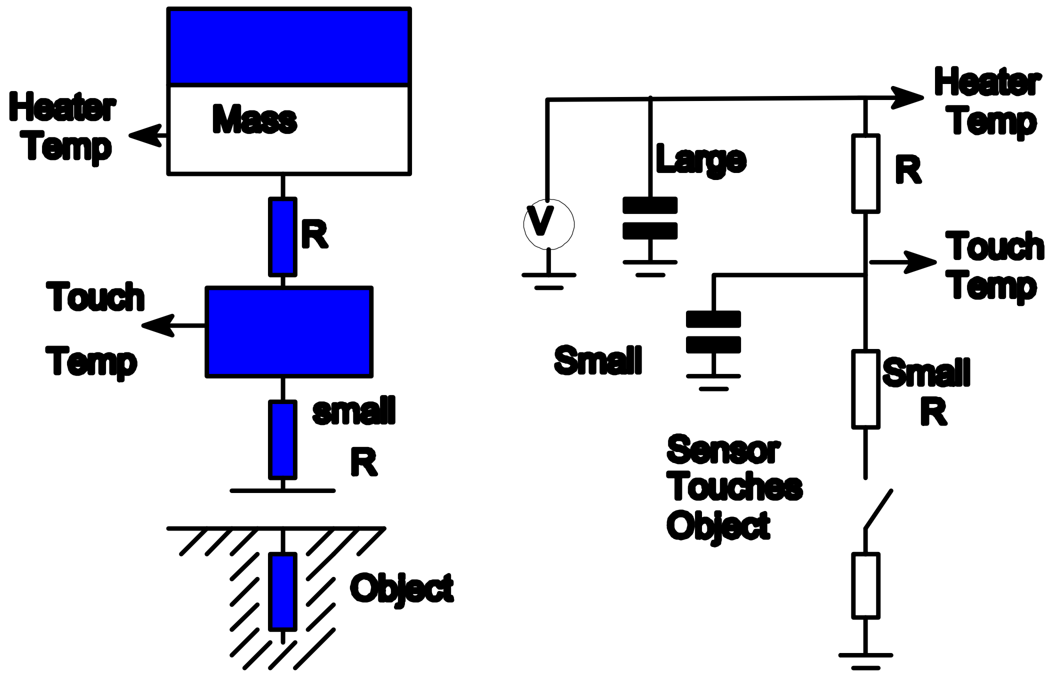


Fig. 4.4 - Simplified thermal diagram of manipulator sensor, with electronic analogy.

The equation can be rearranged to give an equation that predicts the end value of the exponential decay curve, from the T_{Mtouch} value at a time 't' seconds, as shown below.

$$Estimated\ end\ point\ change\ factor = \frac{T_{heater} - \left(\dfrac{T_{Mtouch(time\ t)} - T_{heater}\,\mathrm{EXP}^{-\frac{time}{t63\%}}}{1 - \mathrm{EXP}^{-\frac{time}{t63\%}}} \right)}{T_{heater} - T_{room}}$$

As this equation requires to know when the object is touched, a T_{Mtouch} temperature drop of 2LSB within 200ms (for 2400baud) or 150ms (for 4800baud) was used as the trigger for the material guessing equation. This trigger was used to calculate the starting time t_0, as shown in 5.

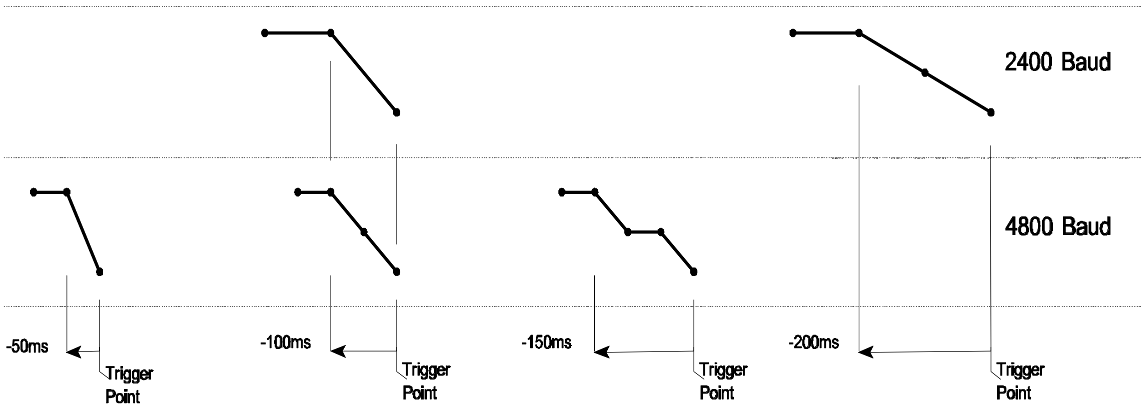


Fig. 4.5 - Time back-track from trigger condition.

Using this equation, with $t_{63\%}$ set to .375 seconds (an average of the various values of the materials in the following test, when the manipulator's thermal sensor is pressed hard onto the material.) and the means and standard deviations given in 6(top), real-time material recognition was incorporated in the PC software.

The software, when acquiring data, waited for a trigger as shown in 5. It then back-tracks to give the time since the object was touched. This time, together with the value T_{Mtouch}, was used to calculate an estimated end-point temperature change factor, using the equation given on the previous page. Each of the object were then given a score as follows;

9 for an estimated end-point temp. factor within 1 S.D of mean for that material.

8 for an estimated end-point temp. factor within 2 S.D of mean for that material.

5 for an estimated end-point temp. factor within 3 S.D of mean for that material.

0 for an estimated end-point temp. factor outside 3 S.D of mean for that material.

This was repeated for each data set (ie every 50ms for 4800 baud), with the scoring values doubled after 1 second, when the end-point estimate is more accurate. After 2 seconds, the material with the largest total score was deemed to be the object material.

A series of 234 tests were conducted on the 13 'materials' (a loose term due to the inclusion of hot and cold), giving 90.6% material recognition accuracy results. As can be seen in 6 (bottom) in only 22 of the 234 tests were materials mis-classified. One of the 22 misclassifications was due to a mis-trigger when testing ice, about 1.5 sec before the actual trigger condition, as can be seen from the raw data in Appx G2; in the first second the average predicted end point temp-factor is 0.065, in the second, average is 0.959 with the reference mean and standard deviation values being 2.0 and 0.25 respectively.

For the other 21 misclassifications, the test material was classified into an adjacent group, eg Black Foam classified as expanded polystyrene or white foam. This was felt to be partly due to the heater temperature cycling and partly due to the 8 bit ADC giving a resolution (LSB step) of 0.23°C for T_{Mtouch}. At a heater temperature of 32°C and a room temperature of 22°C, the difference between end point temperatures for Black and White foam is only 0.3°C.

Grouping all the foams, and grouping Wood and Card, removes 14 of these 21 misclassifications as shown in the combined materials result table, to give a 96.6% accuracy for 10 'materials'.

It should also be noted that 12 tests on the expanded polystyrene did not trigger due to the trigger conditions, 5, not being met. Therefore only 8 test results are given for expanded polystyrene.

Fig. 4.6 - Top **-** Mean & Standard deviation values used in testing, giving assumed frequency distribution shown in graph.
Bottom **-** Material recognition results from 234 tests.(Raw data given in Appx G2)

4.2.2 Operator end tests

These tests, with the exception of TEC control loop test, were conducted with various volunteers wearing the thermal feedback assembly. All testing was conducted at normal room temperatures (about 22°C), and all operators were warm, giving finger temperature (T_{finger}) measurements of 29 to 33°C. Preliminary testing on the author had shown that a person feeling cold, gave a very low T_{finger} readings (25 to 28°C).

4.2.2.1 System checks on TEC control loop

Attempts were made to cause instability and oscillation in the TEC temperature control loop. Using the standard microcontroller software (actually ì C ver 8.3), with proportional maximum power and bang-bang maximum power set to 255 (the maximum) and a +10°C change to try to induce instability, produced only a 2½C maximum overshoot which settled within 200ms, with no oscillation. No operator was wearing the feedback assembly during this test for safety reasons, and it was assumed that with the feedback assembly on a finger, the overshoot would be damped further, giving less chance of instability.

4.2.2.2 Software induced step change test

This test involves a PC induced step change of either +10°C or -10° in T_{Mtouch}, with the full system working normally, and the operator end of the system mounted on the operator's middle or index finger. This step change in T_{Mtouch} causes an error of 10°C in $T_{peltier}$, which the microcontroller attempts to correct by pumping heat in the required direction. 6 shows the speed at which the system follows the induced input step change. 2

gives the average times for start of reaction, mean time to 63% of change, and mean time to 90% of change, for both negative and positive steps.

Step change of -10°C		
	response times	recovery times
10% of change ie dead-time	0.114ms (ó=0.025)	0.142ms (ó=0.061)
63% of change	0.383ms (ó=0.038)	0.809ms (ó=0.055)
90% of change	0.546ms (ó=0.040)	0.980ms (ó=0.085)
Step change of +10°C		
	response times	recovery times
10% of change ie dead-time	0.121ms (ó=0.039)	0.099ms (ó=0.001)
63% of change	0.355ms (ó=0.018)	0.348ms (ó=0.001)
90% of change	0.475ms (ó=0.039)	0.469ms (ó=0.027)

Table 4.2 - Response times for step change of +/- 10°C. Figures are an average of 6 runs. Each run consisted of -10°C, clr, +10°C, clr.(PC ver25/1/95 ì C ver8.3 raw data in Appx G3)

Fig. 4.7 - graph showing response of the system to software induced step changes

4.2.2.3 Human reaction time to step change in temperature

For this test a momentary pushbutton was connected to the PC via pins 13 & 18 (paper out signal & gnd) of the parallel (printer) port. The TGRAPHS software had instructions added so that the 'F1' key caused an instruction to the microcontroller to be sent after a random amount of time, between 0 & 25 seconds. The s/w also had a line added to 'bookmark' the graph when the pushbutton was pressed. The operator was instructed to place their finger on the pushbutton, and when, after a random time, they felt the TEC change temperature, to press the pushbutton which was logged by the PC.

Tests were conducted for a 10°C, 5°C, and 2°C drop and a 5°C rise. The results of these tests, given in 3, show that reaction times to temperature drop were sub-second, even for a drop as small as 2°C. The 5°C rise correlated well with the reaction time given in 0. These results show that shock temperatures are not necessary to alert the operator to a situation quickly.

	10°C drop	5°C drop	2°C drop	5°C rise
Operator 1	398ms	397ms	685ms	1063ms
Operator 2	546ms	547ms	577ms	1312ms
Operator 3	518ms	546ms	646ms	1054ms

Table 4.3 - Response times for 3 subjects, for randomly timed temperature changes. Each result is an average of 5 tests. (raw data given in Appx G5)

4.2.2.4 Software generated virtual thermal sensations

Using the material recognition algorithm 'in reverse', a PC generated representation of a material's thermal sensations can be sent over the serial link to the operator, in real-time, to give the thermal sensations of touching the material in question. The equation used was :-

$$Virtual\ T_{Mtouch} = (Tf_{material}\,\mathrm{EXP}^{(-\frac{time\ elapsed}{375ms})} + (1 - Tf_{material}))x(T_{finger} - T_{roomtemp}) + T_{roomtemp}$$

$$where\ Tf_{material} = end\ \ point\ temperature\ \ factor\ of\ \ the\ material$$

This produces a virtual absolute T_{Mtouch}, which is calculated 20 times per second, and sent across the RS232 serial bus (in the form 'A',nnnnnnpp binary, where number = n.p°C). The microcontroller then uses this value to calculate the correct temperature $T_{peltier}$, as if the T_{Mtouch} value had come from the manipulator end.

4.2.3 Full Thermal system tests

As noted in the literature search (0) humans have poor absolute temperature sensing ability and cannot reliably recognise all the thirteen test objects from thermal data only. Because of this no object recognition tests as such were conducted. Instead, the following two tests were conducted :-

1) Differentiating pairs of objects - to check relative temperature realism of the system
2) Object thermal conductivity - to check absolute temperature realism of the system.

4.2.3.1 Differentiating pairs of objects (relative temperature change)

In this test the manipulator end thermal sensor was held on one of the test objects for five seconds then swapped onto another test object. The operator was then informed of the objects under test and asked as to which was tested first, and which was tested second.

The operators correctly determined the order of the objects consistently, as long as the manipulator sensor was swapped to the second object without excessive delay, and the 2 objects were not of similar materials.

4.2.3.2 Object Thermal Conductivity (Absolute temperature change)

The aim of this test was to see if the operator's feeling of thermal conductivity married up with the position of the material under test, in the end-point temperature factor graph, 6. In this test the manipulator end thermal sensor was held on one of the test objects until the operator described the temperature they were feeling, from the list below:-

Hot

Warm

Neutral

Slightly Cool

Cool

Cold

Ice

Due to lack of time, no results were taken for this test, but preliminary testing indicated that there was a good correlation between the feeling stated, and the end-point temperature change factor.

4.3 Operator Safety during testing

During three months of testing, only one accident occurred. This was when an operator, on the human reaction time tests, received a slight burn that was sore for a few hours. This occurred when one of the leads connecting the $T_{peltier}$ Thermocouple broke, causing the A/D input pin to float and causing control loop failure. The pin floated low over time (due to the discharge of the low-pass filter capacitor), as if the TEC was too cool whereupon the microcontroller compensated by full powering the TEC causing the burn.

After this the Humand PCB was altered to include 1MÙ pullup resistors in front of the low-pass filter on each analogue input. Any break in a thermocouple will cause the amplified analogue input to the microcontroller to be pulled to 5 volts, within a millisecond. This will be seen by the microcontroller as an out-of-limits value, shutting down the system.

5. Conclusions

The full thermal and textural feedback system was designed and built. Software was written for both the system and the PC, and the system tested. Most of the system worked well, with the exception of the operator's piezo texture generator, which was found to be seriously under-powered, giving maximum sensation levels barely above the threshold value. The manipulator's textural sensor and associated circuitry, performed well, despite the limited dynamic range of the 8bit ADC's, and the end-to-end performance was marred only be the limitations of the piezo texture generator.

The thermal system as a whole worked impeccably, giving precise end-to-end performance, at speeds such that no noticeable time lag occurred. The 'expert system' material recognition worked almost perfectly, giving better than 90% correct results even with very similar materials. The material recognition algorithm was also used in reverse to give computer generated virtual sensations.

Overall, the textural system requires a redesign to use a different sensation generator that would produce more powerful sensations, before it could be used in practical situations. The thermal system, on the other hand, demonstrates itself to be usable in practical situations, with very little modification.

5.1 Applications

The thermal system has demonstrated itself suitable for use in practical situations. In particular, with the addition of a hardware fail-safe mechanism, the system is ready to be used in prostheses and other medical systems, or similar situations with short end-to-end distances.

The operator end of the thermal system, has the potential for use in Virtual Reality and Training, again with only the addition of fail-safe mechanism. The thermal sensor has shown itself as a quick and accurate method of material recognition.

Other areas that may benefit from incorporation of the thermal system include Nuclear, Space, Hazardous chemicals, Explosives and Sub-sea, where direct human action is ideal but the environment is usually too dangerous, expensive or both.

5.2 Comparison of Objectives and Results

The following is a comparison of initial objectives and final results:-

a). *To design and build the system so that it would transfer temperature and thermal information from an object being manipulated, to the human operator, accurately and with no overt time delay.*

The thermal system was built, and worked very accurately, with no noticeable time delays. Results of testing show the system has quick response and accuracy.

b). *To design and build the system so that it would transfer textural information from an object being manipulated, to the operator, to produce as realistic a sensation as possible, to those experienced if the operator were to touch the object with their own hands.*

The textural system was built, and tested but part was found to perform inadequately. The textural sensor worked well, though would have been improved by an analogue to digital converter with greater resolution. The textural generator did not meet expectations, being seriously underpowered.

c). *To produce a system that is light-weight, portable, small, and reprogrammable and* *allows both the operator, and the manipulator freedom of movement.*

The results show that the system designed is lightweight, portable and small, with both the operator's end and the manipulator's end being totally arm-mounted. This gave both the operator and the manipulator freedom of movement limited only by the power/serial cable's length. As it stands, the system is reprogrammable by replacing the PROM chip.

d). *To produce a system that allows the integration of other sensors, as different as contact pressure, and radioactivity levels, into the same system; ie sensory substitution.*

Although no actual tests were conducted to show this objective was achieved, it was shown that the system can be driven by the PC, and it can be seen that this allows any sensors connected to the PC to be integrated for sensor substitution.

e). *To investigate the use of an expert system to 'guess' in real-time, the material being touched, using the data from the system.*

A simple expert system was developed on PC that could recognise materials in real-time using thermal data from the system. This gave better than 90% success at recognising 13 different materials, and gives an idea of the potential of the thermal sensor for material recognition.

f). *To investigate the use of the system for sensation recording, virtual sensation production, interactive off-line planning.*

Using the material recognition equations 'in reverse' virtual sensations of the 13 materials were produced on the operator's finger, with realism equal to those from the manipulator thermal sensor.

5.3 Future Work

This section is in point form, giving avenues of future work to improve the system, both specific and general. Some points assume the system will stay as a stand-alone, although most are relevant to the system incorporated within an overall tele-presence system.

- The manipulator end of the system requires a microcontroller, with at least 6 channels of 10 bit A/D, so that some local processing can take place, for example heater control, and possibly even material recognition.

- The thermally resistive layer requires redesign, to give a stable specific thermal resistance, and still keep the slightly compliant properties of the current design.

- The microcontrollers at both the operator and manipulator ends, should calculate heat loss / gain, or alternatively use a PID algorithm, so that both the peltier heat pump, and the heater can react faster and more accurately to changes.

- Integrate fuzzy logic into the 'expert system' material recognition system.

- Use either a faster 80C552 (either 24 or 30 MHz instead of 16MHz[59]) and larger EPROM (possibly on-chip; the 87C552), or a 16 bit embedded microcontroller, to allow faster / more precise operation and extra functions, and to allow programming in a high level language such as 'C', using a real time operating system kernel.

- Redesign the textural driver circuit to give 660 Volts pk-pk into the piezo, using 2 Apex

AP42s[60] in bridge configuration, a 10 Volts to ±175 Volt DC-DC step-up convertor (eg the Maxim MAX774 & similar), and an 12 bit or better audio DAC to give a large dynamic range above the finger's vibration threshold. Safety aspects of this higher voltage require scrutiny.

• Investigate more extensively, alternatives to piezo, to impart textural information to the human finger.

• Design and build a thermal subsystem that uses an array of thermal detectors coupled with an array of small Thermoelectric heat pumps, shaped to fit the finger tip or back of finger, to give the operator a sense of edges of objects and dissimilar material.

• Use I²C buffer ICs at both ends to increase I²C serial bus length up to approx. 400 Metres of ribbon cable[61], and investigate other manipulator / operator data busses eg RS485, Fibre optics and modem links.

• Redesign the analogue circuitry especially the thermocouple circuitry, to increase accuracy and noise rejection, with emphasis on 50/100Hz mains-induced noise rejection. Incorporate active low pass filtering of the mains noise, use correct pcb layout techniques, eg amp input guard rings, balancing of parasitic thermocouples and ground planes, and surface mount components.

• Trial the system with a robot arm, operator glove etc.

• A more detailed investigation of the human finger's temperature at the thermoreceptors, and at the skin's surface, when touching objects, is required so that a mathematical model can be constructed.

- Use a more efficient pin heatsink for any new design of heat pump, with the aim of eliminating the need for the fan.

- Design an object temperature sensing thermocouple into the manipulator assembly, to help the material recognition.

- Trial the system in a prosthesis.

- Build both hardware and software safety interlocks into the thermal system including a second (supervisory) microcontroller, to assure operator safety, when the thermal system is worn as part of a glove that takes seconds to remove.

References

.M Wyburn (ed), *Human Senses and Perception*, Oliver & Boyd, 1964, (src-MMU)

.S Johansson, Å.B Vallbo, *"Spatial Properties of the Population of Mechanoreceptive Units in the Glabrous Ski Human Hand"*, in Brain Research, Vol 184, pp353-366, 1980 (src-UMIST)

.G. Webster (ed), *Tactile Sensors for Robotics and Medicine*, John Wiley & Sons, New York, Chap 1,2, pp1 - 8

.A Kaczmarek, J.G Webster, P Bach-y-Rita, W.J Tompkins, *Electrotactile and Vibrotactile Displays for Sens bstitution Systems*, in IEEE Trans. Biomed. Eng.,vol 38, No 1, pp 1-16, Jan 1991 (src-LU)

I. Rheingold, *Virtual Reality*, Mandarin Paperbacks, London, 1992

.K Goble & M Hollins, *Vibrotactile adaption enhances amplitude discrimination*, in J. Acoust. Soc. Am., vol 93 418-424, 1993 (src UMIST)

.B.Mountcastle, R.H LaMotte & G Carli, *Detection Thresholds for Stimuli in Humans and Monkeys...*, ir urophysiol. Vol 35, pp 122-136, 1972 (src UMIST)

Darian-Smith, A Goodwin, M Sugitani, & J Heywood, *Scanning a Textured Surface with the Fingers: Event nsorimotor Cortex*, in Exp. Brain Research, Suppl 10, 1985

S.J Lederman, *Tactile Roughness of Grooved Surfaces: The touching process and effects of macro- rosurface structure*, in Perception & Psychophysics, Vol 16 (2), pp385-395, 1974

K.E Pennywitt, *Robotic Tactile Sensing*, in Byte, Jan 1986, pp177-200

J.J Gibson, *Observations on Active Touch*, in Psychological Review, Vol 69, No 6, Nov. 1962, pp477-491 we)

R.L Klatzky & S Lederman, *Intelligent Exploration by the Human Hand*, in Dextrous robot hands, nkataraman & T Iberall eds, Springer-Verlag, 1990, pp66-82

B.B Edin, R Howe, G Westling & M Cutkosky, *A Physiological Method for Relaying Frictional Information t man Teleoperator*, in IEEE Trans. Sys, Man, Cyber, Vol 23, No 2, pp427-432, March/April 1993

Monteith & Mount, *"Heat Loss from Animals and Man"*, London Butterworths, p167, 1974

F.A. Geldard, *The Human Senses*, 2nd ed. John Wiley & Sons, 1972, Chap.9 - 12 (pp 258 - 375) (src MMU)

R.F Schmidt (ed),*Fundamentals of Sensory Physiology*,Springer-Verlag, 1986, chap 1-4, pp 1 - 143 (src-SU)

H.B Barlow & J.D Mollon (eds), *The Senses*, Cambridge Uni. Press, p385, 1982 (src-UMIST)

Darian-Smith, *Handbook of Physiology*, American Physiological Soc., 1984, Section 1:The Nervous System, ensory Processes, Part 2, Chapters 17-20 (src-UMIST)

J.N Campbell & R.H LaMotte, *Latency to Detection of First Pain*, in Brain Research, vol 266, pp203-208, 1983 T)

R.W Patterson & G.E Nevill Jr, *The Induced Vibration Touch Sensor - a new dynamic touch sensing concep* ootica, Vol 4, 1986, pp27-31

A Cameron, R Daniel & H. Durrant-Whyte, *Touch and Motion*, in Proc. IEEE Int. Conf. Robotics Automat., Vo 38, pp1062-1067

C Gosney, B.Eng. Final Year Project report, University of Salford, 1992

S Begej, *Planar and Finger-Shaped Optical Tactile Sensors for Robotic Applications*, in IEEE Jour. Robo om., Vol 4, No 5, Oct 1988, pp472-484

P Dario, A Bicchi, A Fiorillo, G Buttazzo & R Francesconi, *A Sensorised Scenario for Basic Investigation ive Touch*, in Robot Sensors, Vol 2:Tactile and non-vision (ed I Pugh), Springer-Verlag, 1986, pp235-245

P Dario, M Bergamasco, A Femi, A Fiorillo & A Vaccarelli, *Tactile Perception in Unstructured Environments se Study for Rehabilitive Robotics Applications*, in IEEE Procs. Int. Conf. Robotics Autom., Vol 3, 1987, pp20 54

P Dario & D De Rossi, *Tactile Sensors and the Gripping Challenge*, in IEEE Spectrum, Aug 1985, pp 46-52

D.G Caldwell & C Gosney, *Enhanced Tactile Feedback (Tele-taction) using a Multi-Functional sensory Syst* cle for publication, 1992

R.A Russell, *A Robot Sensor for Measuring Thermal Properties of Gripped Objects*, in IEEE Trans. Instr. Me IM-34, No 3, Sept. 1985, pp 458-460 (src-SU)

R.A Russell,*Tactile Sensing of 3-Dimensional Surface Features*, in Robotica, Vol 8, pp 111-115, 1990 (src-SU)

R.A Russell, *Thermal Sensor for Object Shape and Material Constitution*,in Robotica, Vol 6, pp 31-34, 1988,(src

D. Siegel, I. Garabieta, J.M Hollerbach, *An integrated tactile and thermal sensor*, in Proc. IEEE Int. Conf. Robo omat., 1986, (src-A1)

G.J Monkman, P.M Taylor, *Thermal Tactile Sensing*, in IEEE Trans. Rob. Automat, vol 9, no 3, June 1993, 3 - 318, (src-LU)

D.G Caldwell, A Buysse, Z Weizhan, *Multi-sensor Tactile Perception for Object Manipulation / Identificat* E/RSJ Int. Conf. Intelligent Robots and Systems, Raleigh, NC, July 7-10, 1992, pp 1904 - 1911 (src-SU)

Displaced Temperature Sensing System, in Compuserve forum 'Cyberspace', Section 'VR Tech Watch', F

SS.TXT' and 'DTSS.SEA', CM Research, Texas, Sept 1992

The I²C-bus and how to use it, Philips Semiconductors, The Netherlands, Jan 1992

Semiconductor Sensors data handbook, Book SC17, Philips Semiconductors, 1993

NTC Temperature Sensors brochure, Philips Semiconductors, 1994

RS Catalogue, Section 26, p1.765, 1994

Thermocouples, RS Data Library data sheet 10322, March 1990, pp1-4

Temperature sensing with Thermocouples and RTs, 2nd ed., Labfacility Ltd

LT1025 Micropower Thermocouple Cold Junction Compensator, Linear Technology Data sheet, 1990

Thermocouple Measurement, Linear Technology Application Note AN28, Feb 1988

Temperature sensor IC, LM35CZ & LM35DZ, RS Data Sheet 8307, Nov. 1987

LTC1051/LTC1053 Dual/Quad Precision Chopper Stabilized Op-Amps With Internal Capacitors, Lin chnology Data Sheet, 1990

AD594/AD595 Monolithic Thermocouple Amplifiers with Cold Junction Compensation, Signal condition nponents & subsystems data, pp13-9 - 13-17

TLE2425C,I,M,Y Precision Virtual Ground, Texas Instruments Data sheet D3824, June 1991

P Horowitz & W Hill, *The Art of Electronics*, 2nd ed, Cambridge Uni. Press, 1989, pp273-276

PCF8574 Remote 8-bit I/O Expander for I²C bus, Philips I²C data book, May 1989, pp347-357

Thermoelectric products catalogue, Marlow Industries, inc., 1992, pp4 - 6

Fax communication, S. Lawther / Denise Parker, Marlow Industries Europe, 8th. April 1994

MI1023T Thermoelectric Cooler, Data sheet 802A, Marlow Industries Europe, England, April 1990

Thermoelectric Cooler Control : Pulse Width Modulation, Application Note 1.921111, Marlow Industries, (90

UDN2953B and UDN2954W Full-Bridge PWM Motor Drivers, Sprague integrated circuits data book WR-504, 0 - 4-74

OPA445 High Voltage FET-Input Op-Amp, Burr-Brown Data Sheet PDS-754A, June 1989

ZN426E-8 8-Bit Monolithic D-A Converter, GEC-Plessey Semiconductors data book, 1992, pp1-21 - 1-26

Maxim 1992 New Releases Data Book, Maxim Integrated Products (UK) Ltd, pp2.57-2.67

LTN211 Liquid crystal display, Philips components data sheet, July 1990, pp219-228

Maplin Catalogue, Section 14, p218, 1995

80C552 Single-chip 8-bit microcontroller, Philips Semiconductors Data sheet, Nov 25 1992

AP41/42, AP41A/42A High Voltage Power Operational Amplifiers, Apex Microtechnology Corp. Data Book Vo
)5, pp E89-E94.

Using the P82B715 I²C extender on long cables, Application note AN444, Philips semiconductors, June 1993,
71 to 1-193

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