Enhanced Tactile Feedback (Tele-Taction) using a Multi-Functional Sensory System

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Abstract

The safe and economic exploitation of remote manipulation techniques is dependent on accurate, responsive handling abilities. This usually means the use of tele-operation, however, the construction and control of effective general purpose end-effectors remains complex, and tactile data collection by, and feedback from these devices is at best primitive.

This work studies the development of an advanced instrumented finger with multi-modal tactile sensations ranging from contact pressure/force, to hardness, texture, temperature, slip, surface profile/shape, and thermal conductivity. This is integrated with a portable gloved tactile feedback unit providing the operator with directly stimulated feedback of tactile data (tele-taction) on the pressure, vibrational and thermal effects of the handling operation.

1: Introduction

Efficient tele-operation is vital to the safe and economic exploitation of hazardous and remote environments such as those in the nuclear, chemical, and sub-sea industries or in space [1]. In all these instances machines (robots) are required to function in environments that are too dangerous or expensive for direct human operation. Computer control and artificial intelligence are not, however, sufficiently developed to permit the robots to perform these advanced technical tasks under their own initiative, and there is always a human operator in the loop. This operative is responsible for monitoring and controlling the motions and action of the manipulator, and this ability depends on the user having adequate information fed back from the remote environment. Essentially, this means that the operator would wish to have visual, audio and tactile feedback of a quality and form comparable with that normally produced by the eyes, ears and skin [2,3].

With the application of electronic technology to this domain advanced tele-operated manipulators have been developed with visual and audio feedback to the operator, providing a general impression of the remote task environment. These abilities contribute to what is termed **Telepresence** [4].

Cameras/televisions and microphones/loudspeakers are well adapted to this function, with stereo imaging if required. However, there are many instances, particularly in handling operations, where this information is insufficient. In these circumstances the available information needs to be augmented by tactile data [5].

Unfortunately, tactile sensing and feedback (tele-taction) abilities cannot be compared with the performance of cameras/televisions and microphones/loudspeakers and this severely hampers the manipulative abilities of the operator. These limited tactile capabilities are due to a number of factors including:

i). the control he/she has over the end-effector and the ease of use,
ii). the lack of sensory information available from the gripper
iii). the lack of an effective method for transferring tactile data from the manipulator to the operator.

The control of these manipulators has received considerable attention and some progress has been made in recent years with the development of dedicated inputs devices such the Dataglove and Cyberglove [6]. However, the problems with tactile data collection and tactile feedback still remain very potent.

This study will first consider the tactile requirements needed to provide a robot or a human operator of a tele-manipulator with an artificial form of tactile perception. In most current applications the cutaneous tactile information feedback is limited to contact pressure/force, and little attempt has been made to apply multi-modal sensory feedback which could provide the operator with sensations comparable with the normal human perception of feel [7-8].

Using this basic need for humanised sensory feedback the development of a multi-sensor tactile digit will be described. This instrumented 'finger' has the ability to detect contact pressure/force, hardness, texture, temperature, slip, surface profile/shape, and thermal conductivity. This information is subsequently transferred directly from the robot to the skin of the remote operator using tactile feedback units based on piezo, vibro and thermal effects.

2: Sensory Qualities of Touch

Humans possess 5 primary senses for detection of external environmental changes. These are vision, hearing, touch, taste and smell, of which the most important in robotic applications are vision, hearing, and touch. Fortunately visual and audio sensing technology is well advanced and can provide very life-like representations. The same cannot, however, be said of touch [7].

Touch forms the most complex human sensory system and is capable of detecting a diverse range of parameters including: frequency and intensity changes (for pressure

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and texture/slip perception), thermal changes (for safety and in object identification) and pain sensors for system protection [9]. In the development of a multi-purpose tactile system for skin function replication it is imperative that the basic features in human perception of touch are identified. It is suggested that the minimum specification for a generalised tactile sensor should include [7-8]:

<u>Contact pressure/force</u>: to ensure that the end effector has a firm grip, but at the same time to prevent excessive force and damage.

<u>Object texture</u>: grip force is often regulated using knowledge of the surface nature and forms an aid in object identification.

<u>Slip</u>: important in handling where it gives information on the stability of the grip.

<u>Hardness</u>: ensures soft objects are not excessively compressed and aids identification by touch.

<u>Profile</u>: provides detail on how flat an object is, or the extent of curvature, ie general shape data.

<u>Temperature</u>: prevents damage to the gripper from excessively high or low temperatures.

<u>Thermal Conductivity</u>: used to aid material identification by touch eg metals 'feel' cold.

It must be stressed that there is no need to limit robot sensory abilities to these human/animal faculties.

3: Multi-Functional Tactile Sensor

The diversity of the nerves in human skin and the functions they perform is in part due to the multiplicity of the functions that the hand must accomplish. The primary functions of a manipulator are grasping/handling and identification, with identification being further sub-divided to shape identification and material type identification.

The multi-functional sensory system, fig. 1, uses a variety of sensing mechanisms to replicate human abilities including: plastic optical fibres, electro-magnetic systems, potentiometers, thermocouples and peltier effect devices [7].

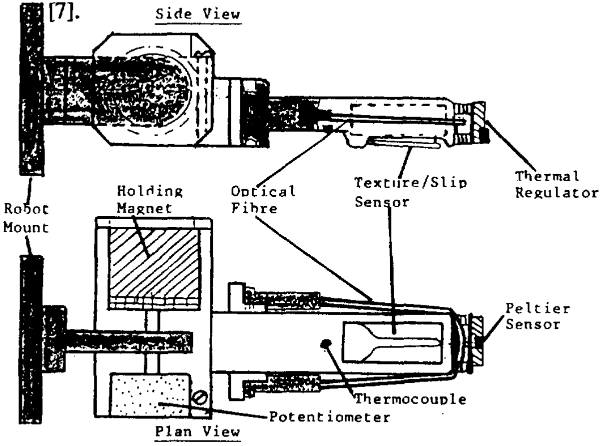

Fig. 1. Multi-Functional tactile Sensor Design

3.1: Pressure/hardness/profile sensor design

The primary characteristic of touch is the ability to detect contact. The multi-modal system achieves this objective using a plastic optical fibre arrangement (infra-red diode source, plastic fibre, infra-red photo detector) based on amplitude modulation induced by total internal reflection of light within the fibre [7,10].

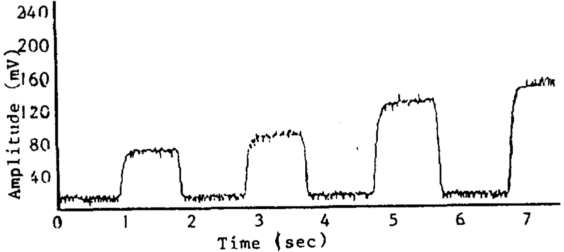

Figure 2. Performance of the Plastic Optical Fibre

A typical response plot for this system, figure 2, under increasing loading shows a very rapid response rising to a steady and maintainable level. This response stabilises within 0.25 sec. From previous analyzes of this system the key specifications are [10-11]:

- almost instantaneous unit-step response time
- no hysteresis.
- monotonic, logarithmic response.
- wide dynamic range (0.05N to 60 N).
- good repeatability for appropriate design.
- easy to design and to fix because of the cost of the device.
- Versatility: because of the wide dynamic range, the sensor can be used for different functions.

Although some performance criteria are below the levels specified by Harmon the system compares well with other tactile sensors and forms an acceptable base unit [10].

It has also been demonstrated that the use of haptic exploration techniques (combined pressure and motion data) provides information on the hardness and shape/profile of a grasped or touched object. This data is useful in both manipulative tasks and material type identification [7-8,12].

3.2: Thermal sensor design

The second tactile trait studied was the thermal sensing ability. This can be considered from two perspectives; absolute and relative (thermal conductivity) sensing.

A simple thermocouple was used to obtain the absolute temperature measurements, while the thermal conductivity data was provided by a Peltier effect sensor. These Peltier devices are ideal for this latter task since any temperature gradient creates an output voltage that is proportional to the gradient, and changes can be quickly and accurately detected [7,10]. The Peltier effect module was mounted on a thermally regulated plate attached to the end portion the finger, figure 1. The temperature of this element was maintained at 40°C +0.5°C.

During testing the tip of the finger probed the test object and the change in gradient caused by heat loss (or gain) was measured via a PC. The time required for each successful reading was 3-5 sec. An extensive range of materials have been tested including; metals (aluminium, brass and steel), paper, polystyrene, cotton, wood, formica and PVC. Typical thermal responses are shown in fig. 3.

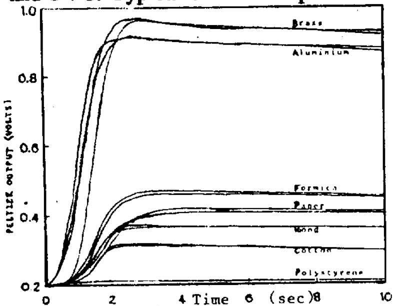

Fig. 3. Thermal Responses

3.3: Texture/slip sensor design

Texture and slip are complimentary tactile features and with this multi-modal system they are detected by a high sensitivity device driven by the interaction of electrical and magnetic fields [7]. Vibrations caused by relative motion of the surfaces, are transmitted to the detector by a sensing probe coupled to a rubber membrane which forms a protective non-restricting skin, fig. 1. During operation the robot mounted finger is scanned (20mm/s) across the object measuring the surface texture details. As the detector tracks across the surface movements of the membrane/probe induce motion in an armature, disturbing the magnetic field and producing a measurable response.

When the object moves relative to the sensor/finger assembly slip is detected as a series of spikes of varying frequency and amplitude.

Tests were conducted using four different types of material; a machined block of aluminium, a block of perspex, a block of wood, and rough metallic casing, figure 4a-d.

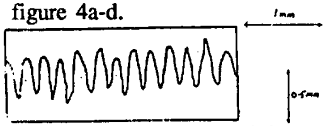

Fig. 4a. Machined Aluminium

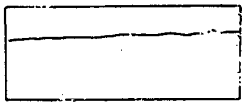

Fig. 4b.Perspex

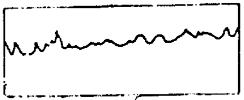

Fig. 4c. Wood

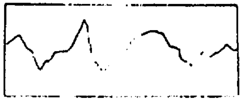

Fig. 4d. Metal Casing

The identification of the texture is based on the measurement of two parameters; the frequency (spatial separation of texture points) and the amplitude.

These results reveal;

1). That the movement of a sensor can vastly increase the detail that can be obtained from a surface [12].

2). There are distinct easily distinguishable differences between the object surfaces ranging from the almost flat smooth output for perspex, to the rough irregular surface of the casing.

4: Tactile Representation (Tele-taction)

Tactile feedback (tele-taction) of cutaneous data is a concept of growing importance in Virtual Reality and tele-manipulation applications [13]. The multi-modal sensor provides the fundamental front end data needed for effective safe manipulation and tactile recognition. During tele-manipulation this information can be fed back in two forms.

First, there is visual feedback were the system response to the range of pressure, vibrational and thermal stimuli is displayed on a computer. This can be augmented by use of a simple expert system to assist with material identification procedures [14]. Use of this technique is simple and effective but it does distract the operator. The second option is the use of direct tactile feedback to stimulate the skin in a manner that replicates true tactile sensation. As a further enhancement this direct feedback can be augment by visual data as required and the assistance of the expert identifier. This second option for direct feedback will be explored.

4.1: Texture/slip sensation feedback

The first tactile feedback parameter considered is texture/slip. These are characteristics vital for identification and grasp stability control. The nerves in skin detect texture/slip as a series of pressure changes when the object moves relative to the finger. This is particularly noted by vibration sensitive nerves: Meissner Corpuscles [9]. To replicate this feeling it is necessary to reproduce a vibratory mechanism, and a number of techniques have been tried including: direct electrical stimulation, electro-mechanical, hydraulic and pneumatic devices. The most successful of these based on a piezo-electric design converts electrical signals from the texture sensor into mechanical motion according to the reciprocal piezo-electric effect [15]:

$$\{D\} = [\epsilon^T]\{E\} + [d]\{T\} \qquad \{1\}$$

where $\{D\}$ is the electric displacement vector; $\{E\}$ is the electric field vector; $[d]$ is the piezo-electric constant matrix; $\{T\}$ is the stress vector and $[\epsilon^T]$ is the dielectric matrix evaluated at a constant strain.

The feedback module is constructed from a PZT (lead zirconate titanate) ceramic disc 10mm in diameter and 1mm thick. As this structure is brittle it has been mounted on a 1mm metal plate of diameter 15mm. The weight of this combined unit is less than 2g. The disc is driven from a high voltage source that transforms the texture sensor inputs into motion of the ceramic detectable by the fingertip. To prevent contamination from dust or moisture and to act as an electrical insulator the transducer has been enclosed in a PVC film. Although relatively high voltages (up to 350V) are used to drive the ceramic the insulation combined with the low current required to drive the piezo-electric module preclude any danger. Full system texture/slips feedback tests will be studied later.

4.2: Thermal sensation feedback

The second module considered was for thermal feedback which is of importance for safety and in material/object identification. Although absolute and relative thermal sensors were incorporated into the instrumented digit, skin is basically a relative mode sensor and the feedback module was designed to make use of this ability.

A Peltier Effect Heat Pump similar to that used as the thermal conductivity sensor formed the feedback unit. When used in this heat pump mode current flow generates a rise or fall in temperature depending on the energy input.

The Peltier system used weighs less than 10g with overall dimensions of 15mm x 15mm x 3mm. The power output of 15W provides very rapid cooling and heating of the operator's finger in response to stimuli. Initially this unit was operated open loop, but enhanced sensation discrimination was achieved when a rapid response thermo-couple (response 10mS) was mounted on the face of the Peltier module in contact with the operator's skin. This provides feedback on the operator's skin temperature, and the rate of cooling or heating was then regulated providing a more realistic sensation [16].

The heat pump can transfer relatively large quantities of heat, and temperature differences of up to 65°C between the warm and cold faces are possible. However, for optimum operation this gradient should be minimized. To ensure this, a small aluminum plate (10mm x 25mm x 2mm) was fixed to the exterior surface of the heat pump to act as a heat sink. This thermal regulator is only required when there is rapid temperature cycling (rises or falls of over 20°C in periods of less than 20 sec). Full system tests will be covered in detail in 6.2.

4.3: Pressure sensation

Pressure/force detection is used to regulate manipulative actions, and when combined with knowledge of the manipulator's vertical and lateral motions hardness and profile/shape data is possible. Pneumatic techniques have previously been applied to this domain and although the sensation is not natural, due to the compliance of the air, the overall impression is fairly realistic [17]. An unfavourable side-effect of this design is the need for a pneumatic power pack, valves and piping which can be cumbersome.

An alternative approach is the use of the piezo-electric module, described previously, combined with the extraordinary learning and adaptive abilities of the human brain. Using this approach forces detected by the artificial skin are transferred to the finger as a series of pulses of increasing frequency and/or amplitude. This design has the advantage that no new feedback modules need to be incorporated into the glove, but it is certainly not a natural human pressure based response. The ability of the operator to use this pulse based approach will be explored later.

4.4: Pain sensation

The final characteristic of touch detected by nerves in the skin is pain, both in response to pressure and temperature. No dedicated pain feedback module was developed, but dangerous inputs were reflected to the operator using thermal stimuli. The results of testing of this effect will be considered in 6.4.

5: Construction of the Feedback Mechanism

As these tactile feedback devices are to be used by operatives during normal motion, they are required to be small and compact. The elements are designed to fit into a glove and are located at sites where their dimensions would not cause them to protrude beyond the limits of the hand. In addition the system will be used for extensive periods and the weight must be kept to a minimum to limit operator fatigue. Limits of a few ten's of grammes were set for all the feedback modules. The circuitry associated with the system was also kept to a minimum to prevent obstruction of movement and to keep the weight as low as possible.

The piezo-electric module (texture and pressure feedback) was attached to the inner lining of a thin cotton glove, in contact with the distal pad of the index finger (the most sensitive pressure and texture sensing site), while the thermal feedback module also fitted on the index finger was mounted on the back surface of the first (proximal) joint. This latter site was used partially because of space restrictions at the fingertip but primarily because the back of the finger has better thermal sensitivity. As the thermal comfort zone (outside which pain is experienced) is from 17°C to 43°C, an upper temperature limit of 50°C was set to prevent injury [9]. The lower limit of -5°C was set because skin is often in contact with temperatures down to freezing for short periods. As already mentioned pain (if required) will be generated using the thermal feedback stimulus.

6: Feedback System Testing

The instrumented finger sensor was mounted on a robot (Puma 560) for testing. Outputs from various sensory modules were transmitted from the digit to the feedback glove and the appropriate feedback transducer through conditioning electronics, and a PC to monitor the effects and display visual data.

As the testing of any form of feedback is a subjective experience the experiments were conducted by 10 operators. The results for the various feedback techniques are explored in the following sections.

6.1: Texture/slip feedback testing

Tests on the ability of the system to feedback texture and slippage sensations were conducted using four metal plates with different surface texture characteristics.

The texture of these surfaces can be described in terms of the spatial separation between features (frequency) and the depth/height of the feature (amplitude). The marks/scratches can also be described as random or regular. For these tests, low frequency is considered to be a spatial separation of 5mm or more, and high frequency is a separation of less than 1mm. A high amplitude scratch is greater than 1.5mm in depth/height, while low amplitude is less than 0.2mm.

The surface of the first plate was smooth to human touch (zero frequency, zero amplitude). The second plate had many light, random surface scratches (high frequency and low amplitude). The third plate was prepared with random low frequency, low amplitude scratches and the final plate had regular low frequency, very high amplitude scratch marks.

To control the motion of the robot a linear potentiometer with 10cm travel was connected to the robot controller. While wearing the feedback glove the operator could, without restriction, move this crude joystick and the robot would scan horizontally across the object. This gave the operator control over the velocity and position of the robot and provided arm movement and cutaneous data for improved feedback.

Each of the 10 test subjects was given 5 mins. to become acquainted with the use of this input scanner and the texture feedback sensations. Unseen they were then asked to identify the material 'touched' by the robot. This was repeated 50 times for each operator using random object selection.

Sample No.	Correct Identifications
1	94%
2	92%
3	91%
4	97%

Table 1. Texture Recognition Tests

From these tests, table 1, with only very short training periods the discrimination is excellent in all categories. The operators reported that recognition of surface texture was relatively simple, and felt 'fairly' human. The difference between natural texture sensations and the feedback effect were felt to be due to:

i) the high sensitivity of the texture sensor relative to the human finger.

ii) the whole finger tip acting as one lumped sensing area rather than many 10's or 100's of sensing points distributed over the skin.

The use of joystick control of the robot arm motion meant that the spatial separation between points was detectable, although estimates of the ability were not obtained.

In similar tests for slippage the operator was asked to indicate when the object moved. Motions of 0.5mm or more were easily recognisable, while very small movements (0.1mm) were detected, but it was difficult to distinguish slip motion from a vibration spike. Since there is only one sensing point it was not possible for the operator to say how far the object had moved.

6.2: Thermal feedback testing

As with the texture test the thermal feedback tests were conducted using 10 test subjects with a training period of 5 mins. Wearing the feedback glove the feedback temperature was adjusted until the operator felt it was at room temperature. This temperature varied by less than 1°C for the subjects. Five tests objects of different temperature or thermal conductivity were selected; a cube of ice, a soldering iron, insulating foam, a block of aluminium, and room condition (no change). In this instance the robot was pre-programmed to move to the test object and apply a contact force of 5N. The robot remained in contact with the object for 20 sec. before returning to its set position.

Sample	Correct Identifications
Ice	98%
S. Iron	98%
Foam	84%
Aluminium	93%
No Change	87%

Table 2. Thermal Recognition Tests

From table 2 it is clear that there is again good discrimination. The reduced although still acceptable identification rates (>80%) for 'no change' and the insulating foam are due to the relatively small thermal variations, which make discrimination difficult. Under normal conditions humans would have pressure data to augment the thermal data and assist with identification.

For a enhanced feedback system, the force data can either be derived as direct tactile stimulation as described in the next section or it can be displayed visually together with the thermal response profiles. Tests with the visual technique raised the percentage correct identification of no change and insulating foam to 97% and 98% respectively.

Operators reported that the feedback sensation was lifelike but tended to the slightly slower than would be expected under normal circumstances. This is due to the finite heating/cooling rate of the heat pump, and can be improved through the use of a higher powered unit.

6.3: Force/pressure feedback

Tests of the pressure feedback mechanism were conducted with forces of 2N (0.5Hz), 10N (2Hz), 30N (6Hz), and 60N (10Hz). This represents graded changes from the minimum to the maximum detectable forces. The frequencies of the feedback pulses corresponding to these forces are shown in brackets and range from 0.5Hz to 10Hz.

Wearing the feedback glove the 10 operators were asked to identify the applied force as the pre-programmed robot finger made contact with a solid surface. The results for 50 test runs for each subject, table 3, indicate that operator force discrimination abilities are good, despite the rather unnatural form of the feedback.

Force	Correct Identifications
2N	91%
10N	94%
30N	95%
60N	97%

Table 3. Force Recognition Tests

With the robot free to apply any test force it was found that the operator could recognise the applied force on a gross scale ie low pressure, medium pressure, high pressure, and changes in pressure could also be detected, but the users were not able to give exact force estimates accurately (eg the force is 32N), although this ability did appear to improve with familiarization. This is in line with normal human abilities to estimate applied forces. The operators also reported that although the sensation was totally different from normal tactile perception of force, the signal was easy to use and to adapt to.

When the pulse measurements were combined with texture or thermal signals there was no measurable deterioration in performance. To discriminate the operator simply concentrated on the data required, as occurs in normal usage.

As an additional aid to the estimation of the force the computer generated values have been displayed for the operator. These displays were not used during the initial 'blind' tests as they would have had an unfair effect on the operators' performance.

6.4: Pain feedback

The feedback of pain (danger) signals used only the thermal system to simulate both force and thermal danger. The sensation was produced by very rapidly increasing the temperature to 50°C.

Simulated danger (overload) signals were transmitted to the operators at random periods during normal testing. At this point the operator would shut down the system. The average reaction time for these overload conditions was 0.9sec.. This was a fairly rapid response and the operators reported that the pain sensation although thermally generated initially felt 'sharp' like a pressure stimulus. This pain feedback can obviously be augmented with visual and audio feedback of danger signals, if required.

7: Conclusion

The human hand with its complex anatomical structure and network of tactile sensing and proprioceptor elements forms the most versatile end-effector known. Generally, however, the complexity of the design, sensing, feedback and control has mitigated against the widespread use of mechanisms which mimic hand operations, preventing truly efficient tele-manipulator operation.

These short-comings highlighted the need for an advanced instrumented manipulator, comparable in function with the human hand, integrated into a sophisticated tele-tactile system to provide the operator with a full range of sensory feedback data.

To satisfy these needs a multi-functional tactile sensor system was developed drawing upon modules based on plastic optical fibres, thermocouples, electro-magnetism, Peltier effect and potentiometers. Combining these units with a vital factor supplied by the robot; motion, it was possible to produce a instrumented finger capable of detecting sensations ranging from contact pressure/force, to hardness, texture, temperature, slip, surface profile/shape, and thermal conductivity.

The signals from these sensors can be fed to the operator as direct tactile stimuli, comparable in many instances with normal touch sensation. The feedback modules are light and compact enough to be incorporated into a glove worn by the operator, without restricting motion or comfort. The feedback modules provide the operator with pressure, texture, slip, and thermal data. The testing of this system revealed that the ability of the operator to recognise tactile features was high, and this can be further augmented with visual display data and expert system analysis.

Further system enhancements could include the ability to detect and feedback sensory data not normally available from skin, or at limits beyond the tolerance of skin (feedback scaling would be used).

Key areas which may benefit from enhanced tele-operator feedback are: **Nuclear, Space, hazardous chemicals, explosives, Sub-sea, Virtual Reality** and **Medicine.**

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