A Survey of Perceptual Feedback Issues in Dexterous Telemanipulation: Part II. Finger Touch Feedback

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Abstract This paper (Part II of II) surveys the existing touch display technologies in the literature. This survey indicates 5 main approaches to touch feedback, involving *visual, pneumatic, vibro-tactile, electro-tactile* and *Neuromuscular stimulations.* A pneumatics approach could use air-jets, air pockets or inflatable bladders to provide touch feedback cues to the operator. Similarly, the vibro-tactile approach could use vibrating pins, voice coils, or piezoelectric crystals to provide *tickling* sensation to the human operator's skin to signal the touch. The electro-tactile stimulation method can provide electric pulses, of appropriate width and frequency, to the skin while the neuromuscular stimulation approach provides the signals directly to the primary cortex of the operator's brain. With regard to this, seventeen (17) devices, most of whom were built for sensory substitution purposes, have been examined and compared for their suitability as touch feedback devices for dexterous telemanipulation.

1 Why Touch Feedback?

The goal of this paper (Part II of II) is to evaluate the state-of-the-art technology available for designing and building a master glove capable of providing touch feedback to the human operator so that he can interact with the virtual and remote environments in a more realistic sense. In view of this, the paper identifies and analyzes specific concerns that must guide the design of touch feedback masters.

A central question to the present paper is: why do we need touch feedback to fingers in a dexterous telemanipulation context? Answer is quite simple and intuitive – how many object manipulation tasks could we successfully perform when our fingers are numb or when we are wearing thick gloves? – not many. The reason is, simply because we cannot know when the fingers are in touch with the object and when not. The further scientific evidence comes from the following:

- Lack of sensation due to wearing of work gloves prolonged a test task completion time by 10-75%, depending upon the thickness of the glove (See Sanders and McCormick, 1987).
- Lack of touch sensation due to wearing thick (space suit) gloves degraded the two-point discrimination ability of humans by 50% and prolonged the average task completion time by 80% (Chodack and Spampinato, 1991; see Figure 2 in Part I.).

Therefore, when using a multifingered robotic hand as the slave end effector, providing the human operator with a feedback sensation of touch from the slave fingers would positively enhance the operator's ability to judge the instance each finger touching something in its surroundings and to know if the grasped object is slipping. Then, the operator will be able to perform telemanipulation tasks in lesser duration of time and with fewer errors than before. Such an ability is not only desirable but it could be crucial to tasks involving grasping and manipulation of delicate objects.

2 Master Requirements in View of Touch Feedback

2.1 Existing Touch Feedback Methods

In principle, providing the touch feedback involves using the tactile sensor output from the remote slave fingers to trigger a stimulating device mounted on the human operators' hand. The stimulation to the human operator could be provided either in visual or in tactual form, although in any other form should also be possible. The approaches used thus far in the pertaining literature could be classified as follows: (a) Visual display (b) Pneumatic stimulation (Air jets, Air pockets, Air rings) (c) Vibrotactile stimulation (Vibrating Blunt pins, Vibrating Voice coils, Vibrating Piezoelectric Crystals) (d) Electrotactile stimulation (e) Functional Neuromuscular Stimulation (FNS).

In a visual display, the status of touch of the slave fingers is indicated by the appearance of an icon or via displaying the slave finger tip forces, digitally or graphically. When such a display indicate the possibility of loss of touch, the human operator moves his fingers or increases the forces appropriately so that the slave hand corrects itself. Providing a visual display as a substitute for touch feedback is not common and has a strong disadvantage in a telemanipulation situation particularly when the operator is provided with a visual feedback of the remote cite in addition to the visual display of the touch status.

As a pneumatic stimulation approach, micro air jets could be impinged on the ventral surfaces of the operator's fingers, Figure 1a. Alternatively, air pockets that could be placed below each finger digit, shown in Figure 1b, could be pressurized so that the pressing sensation on the fingers will be sensed by operator. The other approach involves placing inflatable air rings on the fingers of the human operator, as shown in Figure 1c. When the rings are pressurized the squeezing sensation on the fingers will be interpreted as the signal of touch.

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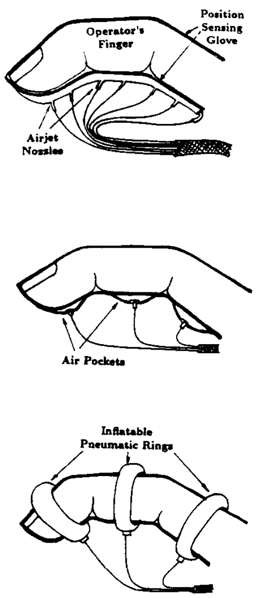

Figure 1: *Three (3) methods of providing touch feedback using pressurized air: (a) air-jet, (b) air-pocket, and (c) air-ring.*

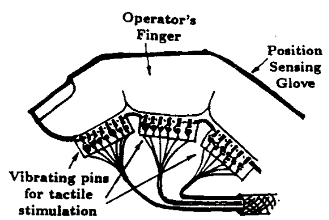

Figure 2: *Vibro-tactile stimulation as a means of providing touch feedback to the human operator during dexterous telemanipulation.*

An approach of vibro-tactile stimulation is by placing an array of thin blunt wires below each finger digit as shown in Figure 2 and make them vibrate with a desired frequency and amplitude using a battery of electric solenoids. The resulting *tickling* sensation on the fingers will be perceived by the operator as the touch feedback signal. The other approaches, using vibrating voice coils and piezoelectric actuators, work on principles similar to that of the vibrating pins. However, higher functional frequencies could be achieved while leading to reduced noise problem and increased portability.

In the electrotactile stimulation approach, mini electrodes are attached to the operator's fingers as shown in Figure 3. The electrodes are meant to provide electrical pulses of appropriate width and frequency to the operator's skin. The resulting tingling sensation will imply to the operator that the slave fingers are touching something (either intentionally or unintentionally).

The functional neuromuscular stimulation takes a totally different approach. Here, the stimulation is not provided to the operator's skin. Instead, the stimulation in

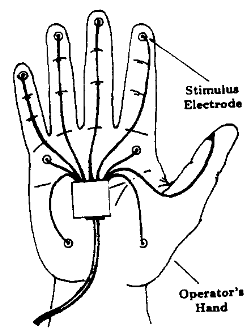

Figure 3: *The principle behind using electro-tactile stimulation as a means of providing touch feedback to the human operator's fingers in dexterous telemanipulation.*

the form of neurological signals is provided directly to the neuromuscular system. If appropriately done, the operator's brain will be able to perceive this as the touch of his/her own fingers. This approach, however, is debatable as it is invasive, hard to find subjects for experimentation and involves extremely high liability.

2.2 Constructional Requirements

The primary requirements of an instrumented glove or an exoskeleton meant for telemanipulation with touch feedback are the following. First, it must be light in weight to reduce user fatigue and to increase portability. Second, it must be compact and must not limit the natural motion rages of the human fingers. Third, it must be precise in its measurements and its perceptual feedback. Fourth, it must be inexpensive. Fifth, it must avoid the use of sensory substitution – the system should be such that the user does not have to think in order to understand the meaning of the signal. Further, the system should be safe to use for extended periods of time and be compatible with the dimensions and the motion ranges of the human hand.

Apart from these requirements, an important consideration in the design of a master device with touch feedback is: what areas of the human hand plays an important role in grasping and manipulation? Answer to this question is given in Figure 4 wherein, the important areas are shown to be the distal phalanges of the thumb and the fingers as well as the central palmer region on the ventral side of the hand (Tubiana, 1984). Further, the areas with large dots are more actively used than those with small dots. This is because of the way we grasp, hold and manipulate objects as well as the shape and size of the object in addition to the task requirement itself. What we learn from Figure 4 is that the touch feedback to the human operator is important in these shaded areas and hence the touch feedback device must be designed so as to just cover these areas alone.

2.3 Functional Requirements

A typical touch feedback system consists of a contactor (also called an effector) that transmits the touch information to the skin of the fingers and palm. In view of the

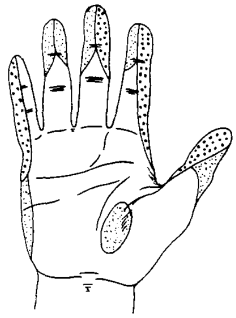

Figure 4: *The zones of the palm and fingers of the human hand that are functional during the grasping and manipulation tasks. The areas with large dots are more actively used than the areas with small dots. Undotted areas are used less frequently, depending upon the size and shape of the gripped object and the intended task. Adapted from Tubiana et al. (1984).*

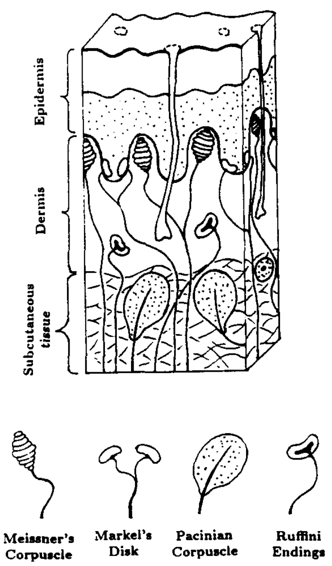

Figure 5: *The structure and position of the 4 types of touch receptors within the glabrous skin of a human hand. Adapted from Seow (1988).*

functional requirements, all devices that one could cite for use as touch feedback devices could be classified as non-vibrating type and vibrating type. The former include the displays using the visual, pneumatic stimulation, electrotactile, and functional neuromuscular stimulation approaches. The vibrating type include the vibro-tactile approaches. The design of any such system requires that the functional aspects be included such that the resulting device will have functional compatibility with the human hand.

• **Issues with Non-vibrating type devices:** As stated earlier, the use of visual display for touch feedback is uncommon though it is useful in its own right. Dealing with such visual displays in general is deemed beyond the scope of this paper. Nevertheless, it is useful to note that a large body of literature exists on the visual display of a variety of information (Sanders and McCormick, 1987).

When using a pneumatic stimulation devices — air jets, air pockets, or air rings, the issues are the magnitudes and the duration of times that the fingers are exposed to the jets, the pressure or the squeezing effect. It is known from the human factors research (Wiker et al, 1989) that when the human fingers are exposed to constant forces over sustained periods of time, the ability of the fingers to sense forces magnitudes and directions deteriorates temporarily. The other issues with pneumatic stimulation is that the human fingers cannot sense a pressure below 0.2 N/cm^2 (Grupen et al., 1989). On the other hand, sustaining large pressures for a prolonged periods induces muscular fatigue in the operator's fingers. Hence, the contact areas of the air pockets and air rings must be designed such that the nominal pressure on the skin must be just above the threshold pressure of 0.2 N/cm^2. Another concern with airjets is, a finger exposed to pressurized air jets for sustained periods becomes numb and temporarily looses its tactile abilities and will have inferior 2-point discrimination ability. Hence, the jet pressure must be determined taking this issue into consideration.

In the use of electrotactile stimulation or the functional neuromuscular stimulation, the pulse width and the frequency of the stimulation are very crucial. Reportedly, the sensibility thresholds in these cases are very close the thresholds of pains as well. However, the experimental subjects used by Steinmintz (1988) did not report any pain. Extreme care must be taken for choosing the locations for placing the extero-cutaneous electrodes in the case of electro-tactile stimulation and the locations for placing the intramuscular electrodes in the case of functional neuromuscular stimulation. Otherwise the response to a given stimulus input will be much inferior to the best.

• **The touch receptors in human hand:** From this subsection onwards, the vibrating type devices will be dealt with. In a typical vibrating type device for touch feedback, vibrations produced via mechanical, electric, electro magnetic or piezo-electric approaches is presented to the skin which is perceived by the human operator as tickling sensation and interpreted as the signal to mean that the slave fingers are touching something in their environment. In the design of such devices, the issues are: (i) how many contactors must be placed over a unit area of the palm? (ii) what should be the cross-sectional area of each contactor? (iii) what should be the amplitude and frequency with which the contactor must be vibrated? In order to answer these questions, it is essential to first know the different types of touch receptors present in human hand and their functional characteristics. So that, the functional characteristics of a hand master's touch feedback system could be designed to be compatible with those of the human hand.

Briefly, there are 4 types of touch receptors (also called the mechanoreceptors) present within the glabrous (hairless) skin of a human hand, Figure 5. They are (i) Meissner's Corpuscles, (ii) Markel's Disks, (iii) Pacinian Corpuscles, and (iv) Ruffini Endings. The spatial distributions of these 4 types are as shown in Figure 6. Quantitatively, as Westling shows they constitute 43%, 25%, 13% and 19% respectively (Seow, 1988). For a

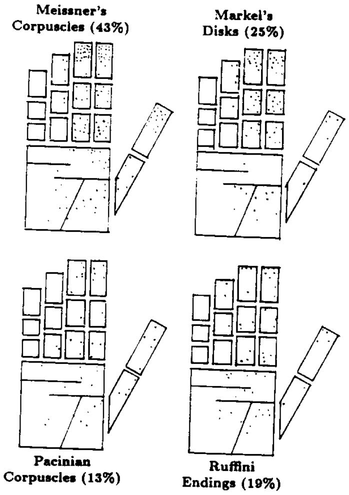

Figure 6: *The distribution of the 4 types of touch receptors on the human hand. Note the density variations over the fingers and on the palm. The required areas of touch feedback are indicated by the density of the touch receptors. Different receptors sense tactual informations of different frequencies. Adapted from Johansson and Vallbo (1979).*

given input stimulus, the output response of each receptor decreases over time and this is called the **stimulatory adaptation** (Langley et al., 1974). The meissner's corpuscles and the Pacinian corpuscles are of the rapidly adapting (RA) type while the Markel's disks and the Ruffini endings are of the slowly adapting (SA) type. Hence, the 4 receptors are often referred to as RA-I, RA-II, SA-I, and SA-II type respectively, Table 1[1]. Also detailed in Table 1 are such details as the location of the receptors within the skin, their mean receptive areas, spatial resolution, responsive frequency range and the frequency for maximum sensitivity. These details, among others, form a crucial input data to the design of touch feedback devices.

• **Contactors per unit area:** This pertains to the number of contactors that must be placed over a unit area so that the human operator's fingers get adequate sensation of touch. As the number of contactors per unit area decreases, so does the effectiveness of touch feedback. At the other extreme, as the number of contactors/unit area increases beyond a point, it will not yield any improved performance. This threshold point is where the spacing between two contacts will be equal to the minimum distance between two points that the human skin can discriminate at that location. It is also referred to as the 2-point discrimination ability of the human hand. The quantitative data on this at several important regions on the hand are collectively presented in Figure 7. As is seen, the index finger pulp can sense all points that are over 2 mm apart while the center of the palm cannot discriminate if the two points are less than 11 mm apart (Tubiana, 1984). What we learn from this is, the optimum number of contactors per unit area at a given location on the hand must be such that the distance between two adjuscent effectors must be equal to the 2-point discriminating ability of the skin at that location.

[1] All tables are on the next page.

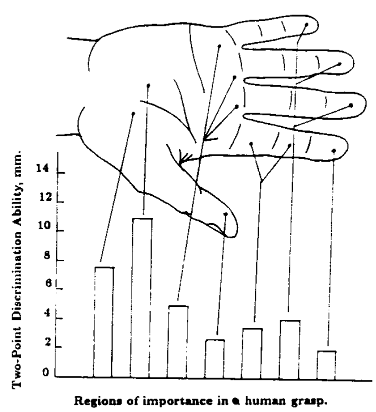

Figure 7: *The minimum distance between two adjuscent points that can be discriminated by the skin on the human hand (two point discrimination test). Data from Tubiana et al. (1984) and, Sanders and McCormick (1987). This data is useful in determining the required minimum clearance between any two touch feedback effectors in a dexterous master for telemanipulation purpose.*

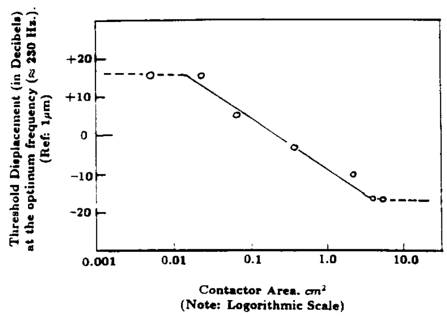

Figure 8: *The effect of the cross-sectional area of the touch effector on the minimum sensible displacement when using vibro-tactile stimulation (at 200 Hz) as a means of touch feedback. Adapted from Verrillo (1963).*

• **Cross-section area of each contactor:** The cross sectional area of each contactor or the contact has an important role (Verrillo, 1963). As seen from Figure 8, at a given functional frequency, the minimum amplitude of vibration that the fingers can sense increases with a decrease in the cross sectional area of the contactor. A decrease in the contact area by about 1000 times (from $5.1 cm^2$ to $0.005 cm^2$) increased the minimum sensible amplitude by 30 times (from −15 db to +15 db). However, the experimental results in Figure 8 also show that the displacement versus area curve seems to level-off below $0.02\ cm^2$ and above $8\ cm^2$ of contactor area. This means that there is no advantage in increasing the contactor area above $8\ cm^2$ or decreasing it below $0.02 cm^2$. Optimally, the contactor area must be between these limits. Within these limits, the variation in displacement is of the order

Table 1: A comparison of the functional features of the 4-types of cutaneous mechanoreceptors found below the skin of the human hand. Adapted from Iggo (1988), Lederman and Browse (1988), and Westling (see Seow (1988)).

		Cutaneous Mechanoreceptors			
	Features	**Meissner Corpuscles**	**Pacinian Corpuscles**	**Merkel's Disks**	**Ruffini Corpuscles**
1.	Rate of adaptation	rapid	rapid	slow	slow
2.	Name based on adaptation	RA-I	RA-II	SA-I	SA-II
3.	Location	Superficial Dermis (Shallow)	Dermis and Subcutaneous (Deep)	Basal Epidermis (Shallow)	Dermis and Subcutaneous (Deep)
4.	Mean Receptive Area	13 mm^2	101 mm^2	11 mm^2	59 mm^2
5.	Spatial Resolution	poor	very poor	good	fair
6.	Sensory Units	43 %	13 %	25 %	19 %
7.	Frequency range of response	10–200 Hz.	70–1000 Hz.	1–200 Hz (?)	1–200 Hz (?)
8.	Frequency of Min. Threshold	40 Hz.	200–250 Hz.	50 Hz.	50 Hz.

Table 2: An overview of the tactile feedback devices built thus far either for sensory substitution, dexterous telemanipulation or for virtual reality applications.

		Tactile Display Technology Used								
			Pneumatic			Vibrotactile				
Year	**Researchers**	**Visual**	**Air jets**	**Air pockets**	**Air rings**	**Blunt pins**	**Voice coils**	**Piezo -electric**	**Electro -tactile**	**FNS**
		1	2	3	4	5	6	7	8	9
1969	Leighton and Wormley (see Sheridan and Ferrel, 1981)		•							
1971	Bliss et al. (see Johnsen and Corliss, 1971)		•					•		
1983	Calder			•		•		•		
1985	Blamey and Clark								•	
1985	Leysieffer (see Patrick, 1990)							•		
1986	Linvill (see Patrick, 1990)							•		
1987	Zimmerman et al.							•		
1987	Foley					•	•	•		
1988	Silvermintz									•
1988	Tan								•	
1988	Zhou								•	
1988	Oomichi et al.		•					•	•	
1990	Patrick	•					•			
1991	Stone			•						
1991	Sato et al.				•					
1992	Howe	•								
—	Optacon (see Kantovitz and Sorkin, 1988)					•				

Note: FNS – Functional Neurmuscular Stimulation (Silvermintz, 1988).

Table 3: A comparative evaluation of the available tactile display technologies in view of their suitability for dexterous telemanipulation.

		Available Tactile Display Technologies								
			Pneumatic			Vibrotactile				
	Features	**Visual**	**Air jets**	**Air pockets**	**Air rings**	**Blunt pins**	**Voice coils**	**Piezo -electric**	**Electro -tactile**	**FNS**
		1	2	3	4	5	6	7	8	9
1.	*Cost*	high	low	low	low	med	med	med	high	high
2.	*Complexity*	low	low	low	low	med	med	med	med	high
3.	*Heaviness*	med	high	high	high	high	med	med	low	low
4.	*Comfort*	good	fair	fair	fiar	good	good	good	fair	poor
5.	*Suitability for more dofs.*	good	poor	fair	fair	poor	fair	fair	good	?
6.	*Noise*	none	high	med	med	high	med	med	no	no
7.	*Power Requirement*	low	med	med	med	high	low	high	high	high
8.	*Induction of Numbness*	no	low	low	low	med	med	med	high	?
9.	*Pain*	no	no	no	no	some	no	no	yes	yes
10.	*Liability*	nil	low	low	low	med	med	med	med	high
11.	*Invasiveness*	nil	low	low	low	med	med	med	high	v.high
12.	*Sensory Substitution*	yes	no	no	no	no	no	no	no	no

Note: FNS – Functional Neurmuscular Stimulation (Silvermintz, 1988); med – medium; v.high – very high.

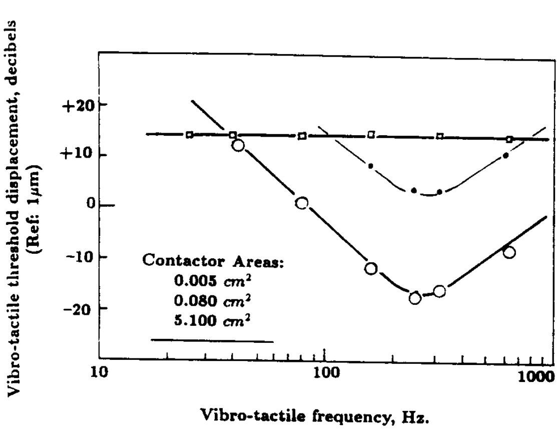

Figure 9: *The effect of the functional frequency on the minimum sensible displacement when using a vibro-tactile stimulation as a means of touch feedback. Adapted from Verrillo (1963).*

of microns only and hence choosing the cross-sectional area must be constrained by the necessary displacement.
• **Amplitude and frequency of contactor:** As seen earlier from Figure 8, the minimum amplitude sensible is a function of the contactor's cross sectional area. Further, it also depends upon the chosen functional frequency (Verrillo, 1963), Figure 9. To have a smaller amplitude, larger cross-sectional areas are preferred. however, the 2-point discrimination ability of the fingers places an upper limit on the contactor's area. Once the cross-section area is chosen, the amplitude is now a function only of the frequency of vibration. From Figure 9, the amplitude for a given area has a minimum between 200 Hz and 300 Hz (approximately 230 Hz). Thus, operating around 230 Hz would require minimum displacement (or amplitude of vibration) in order to provide the necessary stimulation to the skin of the human fingers.

3 Touch Feedback Devices

In what follows, several touch feedback devices built by earlier researchers for teleoperational purpose as well as for sensory substitution are described, and evaluated with respect to their constructional and functional features. These details have been compactly presented in Table 2.

3.1 Visual display approach

Patrick (1990) built two types of visual displays (in addition to his main concern of building a vibro-tactile display). Both these displays were meant for a pinch grasp task involving the thumb and the index fingers. In one type of display, the locations of the two fingers and the boundaries of the object were displayed on a CRT screen as separate icons. The operator could, therefore, know how far his fingers are relative to the object surface. In the second type of display, the object boundary icons were displayed all times while the finger tip icons appeared only when the fingers touched the object. In this case, the operator cannot know how far his fingers are from the object and hence the former display is better in view of this.

In the system built by Howe (1992), the CRT screen showed the plot of each finger force of the slave system versus time. As soon as the object gripped by the slave fingers slips, the acceleration sensors on the slave fingers sense the slip and trigger "blips" in the force plot displayed on the CRT. The human operator interprets the blips as the indicators of slip and hence increases the finger forces so that the slave fingers also do so and hence avoid the possible loss of touch.

3.2 pneumatic stimulation approach

• **Air jets:** Bliss and his coworkers were perhaps the first ones to use airjet stimulation for visual sensory substitution to enable blinds read (see Johnsen and Corliss, 1971). The device consisted of a 12×12 array of mini air jets placed in contact with the pulp of the index finger as in Figure 1a. The shape of a character or a letter was displayed to the finger using the jets of air. Similar device could be used in order to provide touch feedback to the operator in a teleoperational setup. A similar but a smaller device consisting of a 3×3 array of jets was used by Leighton and Wormley (see Patrick (1990), p. 27 for details) for touch display to enable human subjects recognize changing patterns. Recently, Oomichi et al. (1988) studied the effectiveness of using similar array of jets for a touch feedback hand master, however, no technical details on the device presented.
• **Air pockets:** Placing minute air pockets facing the finger tip pulps and pressurizing them to signal the touch of the remote finger is another elegant approach (Calder, 1983). Here, the touch sensor signal from the remote slave activates a pressure regulator that increases the air pressure within the mini pockets as in Figure 1b. Recently, the **Teletact** glove, designed and fabricated by Stone (1991a) and his coworkers, uses similar approach while the glove is meant to be used with a position sensing device such as a dataglove. The notable limitation of a pneumatic system is its highest achievable bandwidth. Aimed towards the same goal, Calder (1983) also conceptualized an electrostatic actuator to apply pressure on the operator's finger. The device however was not built due its impracticably high voltage requirements.
• **Air rings:** Ring-like inflatable pneumatic balloon actuators, as shown in Figure 1c, were used for a teleoperator touch feedback by Sato et al. (1991). The principle of operation is similar to that previous two pneumatic approaches. An interesting finding in this study was that the functional bandwidth of the balloon actuator was dependent upon the stiffness of the operator's fingers. The highest bandwidth of 10 Hz was obtained when the balloon actuator was fitted on to a metallic finger while on a human finger the bandwidth dropped by 50% to just 5 Hz.

3.3 Vibro-tactile stimulation

The vibrotactile displays have been the most popular at least in sensory substitution applications. In teleoperation, however, no such use have been reported yet. In general, there are 3 types of displays and the same are described below.
• **Blunt pins:** An array of blunt pins placed against the pulps of the fingers of the human operator, when vibrated with specific frequencies, cause tickling sensation to the fingers as shown in Figure 2. This sensation is interpreted by the human operator as the touch feedback from the slave fingers. Once again, no evidence of using

such devices in a teleoperational context exists to-date, however, the approach is very popular in sensory substitution (Johsen and Corliss, 1971). Recently, Foley (1987) reported attempts to equip the VPL-DataGlove with such a touch feedback device for virtual reality applications, but no further progress has yet been reported.

• **Vibrating Voice coils:** The vibrating voice coils placed below each digits of the fingers could transmit low amplitude high frequency vibrations onto the skin of the operator. The advantages of these over the vibrating pins (that typically use solenoids) is the reduced mechanical complexity, noise, and the consumption of power. Also, they are relatively small and hence easily portable and do not obstruct the normal motion ranges of the fingers. Patrick (1990) built such a device to work with a hand exoskeleton (Exos, 1992). The chosen functional frequency was 250 Hz, which was the optimum frequency at which the skin of the human fingers is highly sensitive (Verrillo, 1963). Patrick's experiments showed improvement in mean task error over that of the visual feedback alone within the context of teleoperation and interaction with virtual worlds. On similar lines, high frequency and low amplitude vibrations were hoped to be achieved with the shape memory alloys (SMA) (Foley, 1987). However, the current state-of-the art SMAs just cannot provide the expected nominal bandwidth of 200-300 Hz.

• **Piezoelectric crystals:** Using an array of vibrating piezoelectric crystals is an alternative approach to provide vibro-tactile stimulation to the human fingers. Bliss et al (see Johnsen and Corliss, 1971) also used this approach for touch feedback. But no technical details on this system are available to the author at this time.

Zimmerman et al. (1987) used piezoresistive benders for the same purpose. The functional frequency used was 20-40 Hz sine wave which was almost one tenth of the optimal frequency of about 250 Hz. This means the amplitude of vibration resulted in this touch feedback device was much larger than what it could have been if a frequency around 250 Hz was used. Foley (1987) reported on the attempts of using piezoelectric crystals to provide similar touch feedback with the dataglove, but no physical implementations have yet been reported either by VPL or by Foley himself. Recently, Oomichi et al. (1988) examined the possibility of using the same approach for their teleoperator master device with touch feedback, however, again no technical details presented in their report.

3.4 Electrotactile Stimulation

Introducing electrical pulses to the skin of the human operator to signal the remote touch is another popular approach, see Figure 3. This has been extensively used in sensory substitution (Zhu, 1988). There have also been some attempts to use the principle within a telemanipulation frame work as well.

Blamey and Clark (1985) used a battery powered device for representing speech to individuals with hearing impairment, through electrical current pulses via the electrodes placed on the fingers and the wrist. Tan (1988) and Zhu (1988) used similar approach to provide sensation to astronauts wearing thick gloves. Their experiments show that the astronaut subjects quickly learnt to interpret the stimulus and did not report any irritation, discomfort or pain.

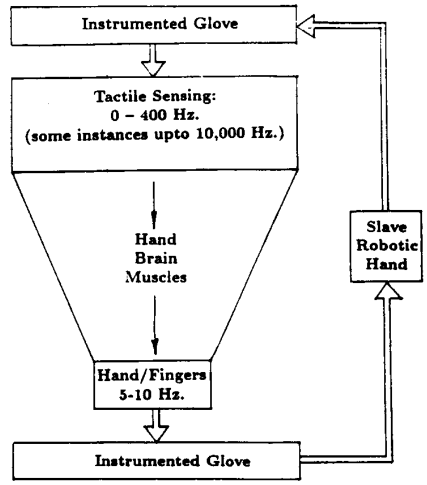

Figure 10: *Asymmetric input/output tactile capabilities of the human fingers. Adapted from Brooks (1990).*

Recently, Oomichi et al. (1988) reportedly considered the approach as one of the alternatives for their touch feedback master for telemanipulation. No technical details are available however.

3.5 Neuromuscular Stimulation

In this revolutionary approach, the electrical stimulation is provided directly to the somatosensory cortex and hence make the human operator feel illusively as if he is touching something (Silvermintz, 1988). The approach has been used to activate paralyzed limbs – hands and legs, but it has not caught the attention of the telemanipulation research. The approach varies in sophistication. In a simplistic approach, the stimulus electrodes could be placed on the operator's fingertips and palm. In a more advanced approach, the electrodes must be placed in touch the neuromuscular system below the skin. Because the system is invasive and involves extremely high liability in case of damage to the neuromuscular system, the approach is not seen as an attractive alternative for touch (or force) feedback by the teleoperations community.

4 Conclusion

The central issue in this two-part survey is of making the human operator feel the grasping and manipulating forces exerted by a multifingered slave robotic hand and the associated tactual sensations in a telemanipulation environment. In this context, this part (Part II) identified and analyzed some specific requirements on the design of the dexterous hand masters that incorporate touch feedback to the human master. The main conclusions of this paper are:

- 5 possible approaches are available for providing touch feedback to the human operator. They involve visual, pneumatic pressure, vibro-tactile, electro-tactile, and neuromuscular stimulations.

- The structural and the functional characteristics of the human hand provides guide lines for the design of touch feedback masters. The important regions on the hand, the type and the location of the sensors, the spacing, the cross-section, and the amplitude and frequency of vibration could all be chosen based on fairly clearcut guide lines so as to be structurally and functionally compatible to the human hand. Functional asymmetry (Figure 10) and bandwidth requirements (Figure 11) of the human hand must be given due care in this process.
- 17 touch feedback devices have been examined and compared. Most of them were built for sensory substitution while only a few were built for teleoperation purpose. No successful use of touch feedback has yet been reported in teleoperation using a multifingered hand as the slave.
- The choice of the technology for touch feedback master must be guided by such factors as the cost, complexity, weight, comfort, noise, power requirement, effect on psychometric stability of natural sensing, sensory substitution, invasiveness and the extent of liability.

The design of a touch feedback glove must consider all these issues. The choice of the technology itself, however, must be guided as per the criteria such as the cost, complexity, weight, portability, noise, power consumption, pain involved , the liability, sensory substitution, invasiveness, and so on. A comparative evaluation of the available tactile display technologies based on these criteria is presented in Table 3.

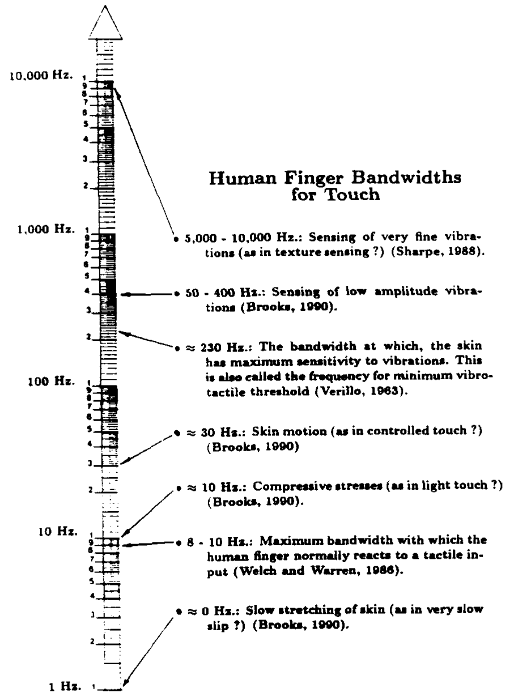

Figure 11: *Human finger bandwidths (Touch).*

References

[1] Bejczy A.K., 1977, "Effect of hand-based sensors on manipulator control performance," *Mechanisms and Machine Theory*, vol 12, pp. 547-567, 1977.

[2] Bejczy A.K., Kim W.S., and Venema S.C., 1990, "The phantom robot: predictive displays for teleoperation with time-delay," *Proc. of 1990 IEEE Int. Conf. on Robotics and Automation*, Cincinnati, OH, May, pp. 546-551.

[3] Blamey P.J. and Clark G.M., 1985, A wearable multiple electrode electrotactile speech processor for the profoundly deaf, *J. of the Acoustical Society of America*, vol. 77(4), April, pp. 1619-1620.

[4] Brooks T.L., 1990, Telerobotic response requirements, *Proc. IEEE Int. Conf. on Systems, Man, and Cybernetics*, Los Angeles, CA, November, pp. 113-120.

[5] Brooks F.P., Ming O.-Y., Batter J.J. and Kilpatrick P.J., 1990, "Project GROPE — Haptic displays for scientific visualization," *ACM Computer Graphics*, vol. 24, no. 4, August, pp. 177-185.

[6] Burdea G.C., 1989, Human/machine interaction in telerobotic dextrous feedback, *ASME WAM: Issues in Modeling and Control of Biomechanical Systems*, Stein J.L., Aston-Miller J.A. and Pandy M.G. (Eds), DSC-Vol. 17, Dec., pp. 65-69.

[7] Burdea G., Zhuang J., Roskos E., Silver D., and Langrana N., 1992, A portable dexterous master with force feedback, *Presence: Teleoperators and Virtual Environments*, June, In Press.

[8] Burdea G.C., and Speeter T.H., 1989, Portable dexterous force feedback master for robot telemanipulation, *Proc. NASA Conf. on Space Telerobotics*, Pasadena, CA, Jan/Feb, vol. II, pp. 153-161.

[9] Calder B.E., 1983, *Design of a force feedback touch inducing actuator for teleoperator robot control*, B.S. Thesis, Departments of Mechanical and Electrical Engineering, Massachussetts Institute of Technology, Cambridge, MA.

[10] Chodack J. and Spampinato P., 1991, Spacesuit glove thermal micrometeoroid garment protection versus human factors design parameters, *Proc. SAE Conf. on Space Station and Advanced EVA*, Society of Automotive Engineers, Publication No. SP-872 (ISBN 1-56091-152-2), July, pp. 67-83.

[11] Clark D., Demmel J., Hong J., Lafferriere G., Salkind L., and Tan X., 1989, Teleoperation experiments with a Utah/MIT hand and a Dataglove, *Proc. NASA Conf. on Space Telerobotics*, Pasadena, CA, Jan/Feb., vol. V, pp. 81-89.

[12] Crane III C.D., Duffy J., Vora R., and Chiang S.-C., 1989, "Telepresence system development for application to the control of remote robotic system," *Proc. NASA Conf. on Space Telerobotics*, Pasadena, CA, Jan/Feb, vol. 3, pp. 201-210.

[13] Exos, 1991, Product Literature on Dexterous Hand Master and Grip Master, Exos Inc., Lexington, MA.

[14] Fisher S.S., 1986, Telepresence master glove controller for dexterous robotic end-effectors, *Intelligent Robots and Computer Vision*, SPIE Vol. 726 (Fifth in a Series), pp. 396-401.

[15] Fisher S., McGreevy M., Humphries J., and Robinett W., 1987, "Virtual interface environment for telepresence application," *Proceedings of the International Topical Conference on Remote Systems and Robotics in Hostile Environments*, Pasco, WA, March/April, pp. 71-77.

[16] Foley J.D., 1987, "Interfaces for advanced computing," *Scientific American*, October, pp. 127-135.

[17] Funda J. and Paul R.P., 1991, "Efficient control of a robotic system for time-delayed environments", *Proc. 1991 Int. Conf. Advanced Robotics*, Pisa, Italy, June, pp. 219-224. Also in Funda J., 1991, *Teleprogramming: Towards dealy invariant remote manipulation*, Ph.D. Dissertation, Dept. of Computer and Information Sciences, Univ. of Pennsylvania, Philadelphia, PA.

[18] Grupen R.A., Henderson T.C. and McCammon I.D., 1989, "A survey of general purpose manipulators," *Int. J. Robotics Research*, vol. 8, no. 1, pp. 38-62.

[19] Hightower J.D., Spain E.H. and Bowles R.W., 1987, "Telepresence: A hybrid approach to high-performance robots," *Proceedings of the ICAR*, Versailles, France, October, pp. 563-573.

[20] IEEE, 1970, Special issue on Tactile Displays, *IEEE Trans. on Man Machine Systems*, vol. MMS-11, 1970.

[21] Iggo A., 1988, "Cutaneous sensory mechanisms", in H.B. Barlow and J.D. Mollon (Eds), *The Senses*, Cambridge University Press, Cambridge, UK., pp. 369-408.

[22] Iwata H., 1990, Artificial reality with force-feedback: Development of desktop virtual space with compact master manipulator, *ACM Computer Graphics*, vol. 24, no. 4, August, pp. 165-170.

[23] Johansson R.S. and Vallbo A.B., 1979, "Tactile sensibility in the human hand: Relative and absolute densities of four types of mechanoreceptive units in glabrous skin," *J. of Physiology* vol. 286, pp. 283-300.

[24] Johnsen E.G. and Corliss W.R., 1971, *Human factors applications in teleoperator design and operation*, Wiley-Interscience, New York, NY. (see page 169-171).

[25] Kantowitz B.H. and Sorkin R.D., 1988, *Human factors: Understanding people system relationships*, John-Wiley and Sons, New York, NY., (pages 251-271).

[26] Langley L.L., Telford I.R., and Christensen J.B., 1974, *Dynamic anatomy and physiology*, New York: McGraw-Hill Pub. Co.

[27] Lederman S.J. and Browse R.A., 1988, "The physiology and psychophysics of touch", *Sensors and sensory subsystems for advanced robots* NATO ASI Series vol. F43, Springer-Verlag, Berlin, pp. 71-89.

[28] Ling D.T., 1991, "Virtual Worlds and Teleoperations," *Proc. ICAR*, Pisa, Italy, June, pp. 174-179.

[29] Minsky M.R., 1984, "Manipulating simulated objects with real-world gestures using a force and position sensitive screen", *ACM Computer Graphics*, vol. 18, no. 3, July, pp. 195-203.

[30] Minsky M.R., Ming O.-Y., Stele, O., Brooks Jr., F.P. and Behensky M., 1990, "Feeling and seeing : issues in force display", *ACM Computer Graphics*, vol. 24, no. 2, March, pp. 177-185.

[31] Oomichi T., Miyatake T., Mekawa A. and Hayashi T., 1988, Mechanics and multiple sensory bilateral control of a fingered manipulator, *Proc. Int. Symp. on Robotics Research*, Bolles R. and Roth B. (Eds), Cambridge: MIT Press, pp. 145-153.

[32] Patrick N.J.M., 1990, *Design, construction, and testing of a fingertip tactile display for interaction with virtual and remote environments*, SM Thesis, Department of Mechanical Engineering, Massachussets Institute of Technolgoy, Cambridge, MA.

[33] Pepper R.L. and Kaomea P.K., 1988, "Teleoperation: Telepresence and performance assessment," *Proceedings of the International Symposium on Teleoperation and Control*, Bristol, U.K., July, pp. 227-234.

[34] Puttre M., 1991, "Virtual reality comes into focus", *Mechanical Engineering*, April, pp. 56-59.

[35] Quek F., Jain R. and Mitchell B., 1988, "Tele-perception," SPIE vol. 1006: Space Station Automation IV, pp. 152-162.

[36] Sanders M.S. and McCormick E.J., 1987, *Human Factors in Engineering and Design*, McGraw-Hill Book Co., New York, NY.

[37] Sato K., Igarashi E., and Kimura M., 1991, Development of a non-constrained master-arm with tactile feedback device, *Proc. International Conference on Advanced Robotics*, Pisa, Italy, June, pp. 334-338.

[38] Seow K.C., 1988, "Physiology of touch, grip, and gait", in J.G. Webster (Ed), *Tactile sensors for robotics and medicine*, John Wiley and Sons, New York, NY., pp. 13-40.

[39] Sharpe J.E.E.,1988, Technical and human operational requirements for skill transfer in teleoperation, *Proc. Int. Symp. on Teleoperation and Control*, Bristol, England, July, pp. 175-187.

[40] Sheridan T.B. and Ferrel W.R., 1981, *Man-Machine systems*, MIT Press, Cambridge, MA,

[41] Silvermintz L., 1988, "Sensor application to functional neuromuscular stimulation", in J.G. Webster (Ed), *Tactile sensors for robotics and medicine*, John Wiley and Sons, New York, NY., pp. 309-330.

[42] Stone R.J., 1991, "Advanced human-system interfaces for telerobotics using virtual reality and telepresence technologies," *Proceedings of the ICAR*, Pisa, Italy, June, pp. 168-173.

[43] Stone R.J., 1991a, Private Communications, Advanced Robotics Research Laboratory (ARRL), United Kingdom, November.

[44] Tachi S. and Arai H., 1985, "Study on tele-existence (II): Three-dimensional color display with sensation of presence," *Proceedings of ICAR*, Tokyo, Japan, September, pp. 345-352.

[45] Tachi S., Arai H. and Maeda T., 1989, "Robotic tele-existence," *Proc. NASA Conf. on Space Telerobotics*, Pasadena, CA, Jan/Feb, vol. 3, pp. 171-180.

[46] Tachi S., Arai H., Maeda T. and Oyama E., 1991, "Tele-existence in real world and virtual world," *Proceedings of the International Conference on Advanced Robotics*, Pisa, Italy, June, pp. 193-198.

[47] Tachi S., Arai H., Marimoto I. and Seet G., 1988, "Feasibility experiments on a mobile tele-existence system," *Proceedings of the International Symposium and Exposition on Robots (19th ISIR)*, Sydney, Australia, November, pp. 625-637.

[48] Tachi S., Kanie T., Komoriya K. and Kaneko M., 1984, "Tele-existence (I): Design and evaluation of a visual display with sensation of presence," *Proc. of RoManSy*, Warsaw, Poland, pp. 245-254.

[49] Tan B.T., 1988, "Sensor application to space-suit glove", in J.G. Webster (Ed), *Tactile sensors for robotics and medicine*, John Wiley and Sons, New York, NY. pp. 331-340.

[50] Tubiana R., 1984, "Architecture and functions of the hand" in R. Tubiana, J. M. Tomine and E. Mackin (Eds), *Examination of the hand and upper limb*, W.B. Saunders Co., Philadelphia, PA.

[51] Verrillo R.T., 1963, "Effect of contactor area on the vibrotactile threshold", *The J. of the Acoustical Society of America*, vol. 35, no. 12, pp. 1962-1966.

[52] VPL, 1991, Product literature on DataGlove Mark II, VPL Res. Inc., Redwood City, CA.

[53] Welch R.B. and Warren D.H., 1986, *Intersensory Interactions: The handbook of perception and human performance*, John Wiley and Sons, New York, NY.

[54] Wiker S.F., Hershkowitz E. and Zik J., 1989, Teleoperator comfort and psychometric stability: Criteria for limiting master-controller forces of operation and feedback during telemanipulation, *Proc. NASA Conf. on Space Telerobotics*, Pasadena, CA, Jan/Feb., vol I, pp. 99-107.

[55] Zimmerman T.G., Lanier J., Blanchard C., Bryson S. and R Harvill Y., 1987, A hand gesture interface device, *Proc. Conf. on Human Factors in Computing Systems and Graphics Interface (CHI + GI '87)*, Toronto, Canada, April, pp. 189-192.

[56] Zhu H., 1988, "Electrotactile Stimulation", in J.G. Webster (Ed), *Tactile sensors for robotics and medicine*, John Wiley and Sons, New York, NY., pp. 341-354.

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