The Sense of Touch in Humans: Implications for designing haptic interfaces for teleoperation and virtual environments

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Abstract

In my talk I would like to offer a different perspective on teleoperator and virtual-environment systems from those of many attending ICAT '99. First, in my research program, I have chosen to focus on the human operator per se, rather than on either hardware or software systems. I am broadly interested in the capabilities and limitations of the human user with respect to sensing, perceiving, thinking and manipulation, and the reasons that underlie such performance constraints. Second, I have chosen to focus on the sense of touch, as it is used both on its own and in conjunction with other sensory systems (e.g., vision, audition). As a cognitive scientist, I have worked for many years now with engineers, computing scientists, and medical personnel. In that capacity, I have come across many user-controlled systems that appear to have been elegantly designed. Ultimately a number of them have failed, in part I believe, because the designs did not take into account the capabilities and limitations of the human user. I will argue that to design an effective teleoperator or virtual-environment system, it is as critical to understand the processing characteristics of the human user as it is the hardware and software.

Why would you want to know about the sense of touch? One obvious application domain that I will consider is medicine. Touch is one of the most critical sensory modalities used by a physician during patient examination. And many surgical procedures are frequently guided more by touch than by vision. In the future, such tactile information may prove critical for remote medical examination and surgery (both open and minimally-invasive). In performing such functions, there may be significant benefits from capitalising on the recent development of "haptic interfaces", one of the most exciting and promising new technologies for the medicine of the future (see e.g., [1] [2]). The haptic system is an information-processing system that uses inputs from receptors embedded in skin, muscles, tendons and joints to perceive and manipulate concrete worlds (real or simulated). A haptic interface is a system that senses forces applied by the human operator to a remote environment; it may also display them to the operator's hand [3]. In the medical examples above, the goal of such systems is to provide general practitioners and surgeons with a sense of touch while working remotely on natural or virtual bodies. Ultimately, the doctor should be able to feel as if he or she were palpating the tissue directly.

In my talk, I will provide an overview of some of the important things I have learned about human haptic processing. I will concentrate on three of the behavioural research programs that I have been conducting for many years now with my long-term collaborator, Dr. Roberta Klatzky (Carnegie Mellon University, USA), our students and staff. In each case, I will briefly present selected aspects of this work. I will then derive a number of general principles pertaining to constraints on human-operator performance for use in designing haptic interfaces for teleoperator- and virtual-environment systems.

We began to investigate haptic processing systematically as a result of a simple but informative study in which we demonstrated that, counter to the prevailing opinion of the time, human haptic processing can be both fast and very accurate [4]. Our early research program subsequently concentrated on the nature and significance of unconstrained purposive manual exploration for the haptic perception of real objects and their properties. Lederman & Klatzky [5] showed that people systematically engage in a variety of stereotypical hand-movement patterns, which we have called "exploratory procedures"; each of these manual patterns of exploration has been shown to be closely associated with one or more class of object property (texture, hardness, weight, shape, etc.). We offer two general principles for designing haptic interfaces based on the results of many experiments that have addressed the role of unconstrained, purposive manual exploration in haptic perception and cognition, with and without vision. First, how one manually explores the concrete world constrains not only the nature of, but also the level of precision, with which property information about that world may be haptically extracted. Second, in contrast to vision, the haptic system processes material properties more efficiently than it can geometric properties (e.g., [6] [7]).

More recently, we have begun to investigate the consequences for tactile and haptic sensing of either temporally or spatially constraining the nature of the haptic input(s) to the observer.

In the first of these research programs, we considered what information about objects and their properties can be derived from a single brief contact lasting only about a couple of hundred milliseconds ([8] [9]). Our results indicate that when inputs are temporally restricted, coarse variations in properties that are haptically coded intensively (e.g., roughness, compliance, thermal properties, presence/absence of edges) are processed more efficiently than those that are processed spatially (e.g., relative position, shape, and size). By intensive, we mean that the percept of the targeted property is processed and represented in terms of some uni-dimensional magnitude. By spatial, we mean that the targeted property is processed and represented with respect to some spatial reference system. We derive two general principles from this research program. First, material properties and edges are perceptually available from brief contact earlier than geometric properties. This leads to a second general principle -- when one wishes to haptically signal the operator quickly and/or when coded (as opposed to natural) inputs to the hand are desirable, the designer should use variations in material properties and edges.

In the second of our more recent research programs, we directly considered whether spatially distributed forces should be delivered to the hand of a human operator using a haptic interface. Currently, it is technologically very difficult to build tactile array force sensors and stimulators; however, there is little scientific evidence that directly addresses the consequences for perception and manipulation of limiting tactile feedback to only net forces. In this program [10], we psychophysically investigated the extent of sensory and perceptual impairment in performance when spatially distributed forces were either presented to the fingertip or eliminated. There was substantial impairment in the performance of a number of sensory and perceptual tasks, and moderate impairment in others. The results of this program suggest that there is potentially considerable value in presenting spatially distributed force-feedback to the hand, and thus, a need to develop complex array-force technologies.

In conclusion, our research findings argue strongly for a potentially significant role of haptic interfaces in exploring and manipulating remote environments. Ultimately, I believe the greatest promise for unimodal sensory interfaces lies in their being integrated into multimodal systems, which can offer both redundant and complementary feedback via several sensory modalities (e.g., vision, audition, haptics, olfaction).

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