The Robot's Sense of Touch: Some Lessons from Human Taction

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Abstract

A consideration of the logical functioning of human taction may suggest methods for solving problems of automated taction. The features of the human tactile system that may be relevant include its spatial resolution, mechanical modification of stimuli, temporal and spatial inhibition, adaptation characteristics, and exploration strategies. Artificial tactile systems would be least likely to gain from lower-level, physiology-coupled features of human taction, but might be significantly advanced if higher-level transformations of sensory input were implemented.

Introduction

There is a great deal of interest in developing tactile sensing for robots (Harmon, 1983). A consideration of the characteristics of human taction may provide some ideas that will help speed development of automated tactile systems. This paper reviews some functional characteristics of human taction that may interest computer scientists and engineers working in tactile pattern recognition. The emphasis is on function (logical transforms of data) and not on structure (anatomy). This focus derives, of course, from the fact that artificial systems will be implemented in media far different from those that appear in natural systems. The discussion then turns to implications for automated taction.

Most of the information about human taction presented here is from reviews by Geldard (1972, Chapters 9 and 10), Mountcastle (1980, Chapters 11 and 12), and Loomis and Lederman (in press). The reader interested in original reports of research on taction will find them cited in abundance in these reviews. The reader with interests in phenomenology or the history of science will enjoy the account by Boring (1942) of early work on tactile sensing, including the research of introspectionists.

Different tactile systems

Many people think only of cutaneous (skin) sensing when considering tactile sensing, but tactile sensing has another important component: kinesthesia, the sense of limb and digit position. Together, cutaneous and kinesthetic stimulation allow a person to perceive objects of three dimensions and events in three dimensional space. Cutaneous sensations allow the detection of texture and details of shape, while kinesthesia allows the detection of larger contours and enables a person to control exploratory movements. Cutaneous stimulation and kinesthesia must work together for an organism (or robot) to be able to actively explore and perceive its tactile environment.

One can also distinguish between an "old" and a "new" tactile system. The evolutionarily older system processes signals concerning extreme temperature and stimulation that is likely to cause tissue damage. This system does not provide very exact information about the location of stimulation, but rather signals with pain when escape is advisable. The newer touch system provides high resolution sensing and maps the body surface onto the cerebral cortex, i.e., associates neurons in the same cortical region with the same area of skin. It is primarily the newer system that we are concerned with here because it mediates the fine pattern discrimination necessary to carry out detailed tasks and perceive three-dimensional objects.

Receptors, end organs, and fibers

Estimates of the spatial resolution of the finger tips vary from 0.8 mm to about 3 mm. The traditional method of assessing resolution is to determine how well a person can tell whether one or two relatively sharp points are being pressed against the skin. The minimum separation required to be able to report with 75% accuracy that two points are being applied is called the two-point threshold. With this method, one gets estimates from about 2 mm to 3 mm. (Estimates for the tip of the tongue are smaller.) Other methods of assessing resolution include determining how well people can detect gaps in a surface applied to the finger, determine the orientation of a fine grating, and identify the forms of alphabetic characters. These latter methods yield resolution estimates near 0.8 mm, possibly because they involve more sensing surface, and hence increase redundancy.

The receptive fields of tactile sensory units overlap. A single neuron sends many fibers to the skin. Fibers from several different neurons may innervate the same area of skin. A relatively small stimulus activates a population of receptors, with the most central receptor showing the greatest activity. This arrangement creates redundancy, allowing detection in the absence of the central receptor. It also creates ambiguity, but, as discussed below, this is mitigated by lateral inhibition.

Nerve-fiber endings are often associated with non-nervous structures that filter or otherwise modify mechanical signals before they are transduced to electrical signals, thus influencing the sensitivity and dynamic range of nerve endings. A fairly well understood modification is carried out by the Pacinian corpuscle, a lamellar, turgid capsule that encloses a single, straight nerve ending. The Pacinian corpuscle acts as a high-pass mechanical filter and seems to aid in the detection of light contact and vibration. Another structure that modifies mechanical signals is the hair follicle, around which some nerve endings wind. Besides serving the obvious function of allowing detection of objects that are not in contact with the skin, hair follicles also provide a relatively firm substrate for nearby nerve endings when they are pushed against the hair, thus increasing neighboring fibers' sensitivity. Other mechanical modifications of tactile stimulation derive from other types of encapsulations and the location of endings at different depths in the skin.

The types of nerve fibers that carry signals away from endings are associated with different kinds of touch sensations. Nerve fibers are either large in diameter (quickly conducting) or small (slowly conducting). Some nerve fibers are surrounded by a discontinuous sheath of nonneural cells that speeds conduction of impulses. In general, fine, specific sensations (such as light contact and vibration) are associated with large fibers that have sheaths, and less specific sensations (such as tickle and pain) are associated with smaller fibers that do not have sheaths.

Coding of information

Nerve fibers discharge in an all-or-none fashion, but, before discharge, the most terminal parts of the fiber respond in an analog fashion to stimulation. Stimulation is encoded initially as continuously varying generator potentials, which are related linearly to stimulus intensity. When a threshold is crossed, a pulse is sent to the central nervous system. Generator potentials, which are analog in nature, can sum over space and time. That is, the final discharge of the fiber may be a function of subthreshold mechanical stimulation that was integrated over a period of time or summed over several branches of the same nerve ending.

Some tactile sensory units adapt slowly and some quickly. Adaptation refers to how a unit's responses vary with continued stimulation. Some units send a burst of impulses at the onset of stimulation, some at offset, and some throughout stimulation. A nerve ending in a Pacinian corpuscle is an example of a unit that responds at onset and offset. An example of a unit that responds continuously is the muscle spindle, which sends information about muscle fiber length and, hence, limb position.

Receptors that respond continuously during stimulation (or adapt slowly), encode stimulus magnitude as discharge frequency. A linear function usually relates stimulation to response. For example, a slowly adapting skin receptor signals skin indentation as discharge frequency and frequency is related linearly to indentation. The muscle spindle relates degree of muscle fiber stretch linearly to discharge frequency. For receptors that adapt quickly, stimulus intensity can be encoded as number of units active.

Inhibition

Inhibition plays an important part in tactile sensing, as it does in other senses. The functions of inhibition include sharpening boundaries and allowing the perceptual integration of successively presented stimuli. Spatial inhibition refers to the raising of some sensory units' thresholds as a result of the activation of a unit innervating a neighboring region of skin. (The inhibitory area can be relatively large. In the monkey, for example, the inhibitory area for a small area of the forearm is the rest of the forearm.) This has the effect of exaggerating differences in stimulation, a procedure familiar to researchers in pattern recognition. In vision, spatial inhibition is due at least in part to relatively periheral connections between sensory units, while in touch it appears to be due to more central processing.

Temporal inhibition, also known as masking, refers to the disruption of a sensory impression by succeeding stimulation, usually following the first impression by less than 1 sec. This occurs in other senses; in general, it seems to help the perceiver sense a fragmented series of stimuli as a meaningful, smooth flow of events (Neisser, 1967).

In touch there is anatomical evidence (in the form of connections between different parts of the central nervous system) that higher-level centers modify the functioning of more peripheral parts of the system, probably in part through inhibition. This may be related to the hypothesis-driven nature of perception, which is discussed below.

Exploratory behavior

Behavior that allows the acquisition of information about an object is just as important as lower-level properties of taction. Studies of the methods that people use to explore objects manually reveal that identifications can be made on the basis of very fragmentary explorations. Zinchenko and Lomov (1960) showed that people first find a reference point on the object (called a reckoning-off point) that is usually near the top of the object. They then carry out a series of explorations of the object, rarely visiting two adjacent parts successively and rarely following contours. Gurfinkel et al. (1974) presented traces of single finger explorations of some simple shapes. One subject identified a cube by feeling only some of its edges. Another subject identified a cone without feeling the bottom half of the object at all. Apparently, people know what they are looking for when they explore an object. Their exploration is guided by hypotheses about what the object could be. Current hypotheses could even affect the operation of peripheral sensory units, as evidenced by the nervous system connections running from higher to lower centers.

Implications for robotics

If the designer of an automated tactile system were going to use human taction as a model (that this may be a mistake is discussed below), then the automated system would have certain characteristics. "Skin" receptors would have overlapping sensory fields and provide resolution of 1 to 3 mm. Position and movement information would be integrated with cutaneous information. Spatial inhibition would be used to sharpen boundaries. Signals would sum over space and time. Temporal inhibition would result from a sensory buffer that is rewritten with each stimulation. Mechanical signals that arrive at receptors would be mechanically conditioned to provide varying sensitivities and dynamic ranges. Surface receptors would respond primarily when stimulation changed, while joint receptors would signal position continuously. Linear functions would relate surface indentation to receptor response, and change in actuator length to actuator receptor response. Stimulation would be encoded as discrete pulses and stimulus magnitude as frequency of pulses or number of units active. A danger-signalling system would interrupt general system functioning and trigger escape routines if extreme temperature or equipment damage were sensed. Exploration of objects would be driven by hypotheses and would allow identification on the basis of contact with a very small sample of object parts.

Given present technology, it might not make sense to copy slavishly the human's tactile system. The human's and robot's media of implementation are, of course, very different, each having its own advantages and disadvantages. The human has parallel processing to the cortical level (although some higher levels of deciding and perceiving are sequential), complex cooperation between different senses, large memory, mechanically complex skin that employs microscopic mechanical filters, signalling that is based on the electrostatics of cell membranes, and so on. Artificial systems are by most, but not all, measures inferior. To their credit, artificial systems can conduct signals more quickly than can biological systems, can make more precise and reliable quantitative measures (such as length, angle, weight, etc.), can adhere more rigorously to rules of logic, can better remember simple quantitative data, and can receive other than mechanical input (e.g., magnetic). It may be neither possible nor necessary to build many characteristics of human taction into artificial systems at this time.

The features of human taction that would be least likely to be of value in artificial systems are those most stongly coupled to peripheral physiology, e.g., features related to mechanical properties of skin, summation at nerve endings, and types of peripheral encoding. The features related to logical processing of information acquired through taction are most likely to be "machine" independent, e.g., inhibition, the hypothesis-driven nature of exploration, and the functions that relate stimulus magnitude to response. These features of the tactile system should at least be considered as design possibilities by the roboticist. Given that there are some higher-level characteristics of human taction that would be desirable to implement, there is still the question of whether our technology is sophisticated enough to do so. The differences in processing capabilities between machine and human should not, however, cause us to throw up our hands in frustration. By systematically considering physiologic accomplishments and translating them into logical accomplishments we can move closer to developing intelligent machines.

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