ABSTRACT: A major portion of tactile sensing research has emphasized the fabrication of small, sensitive transducer arrays rather than the development of complete touch sensing systems. This emphasis has resulted in a large number of "bench top" sensors, very few of which have seen actual use in real manipulation systems. This paper reviews preliminary work aimed at understanding the general issues and trade-offs governing the design of extended tactile sensing systems. Also, specific designs emphasizing practical necessities such as simplicity, reliability, and economy are discussed along with plans to incorporate a tactile system into the Utah/MIT Dextrous Hand.

Introduction

Research in robotics and automation is gradually revealing the importance of tactile information in the control of mechanical manipulation systems. Substantial research efforts have been devoted to the construction of compact, high-resolution force sensing arrays that employ sophisticated transduction and processing techniques. Researchers have experimentally investigated a variety of systems, and a widespread optimism exists regarding the potential usefulness of complex tactile sensing systems in robotic end-effectors. Unfortunately, relatively few multidector systems have seen actual use in real manipulation systems. Those designs that have been applied in automated environments have almost invariably been used in static circumstances for simple contact imaging rather than for active manipulation. Therefore, despite the dozens of tactile sensor designs that exist, it is becoming clear to researchers that much work remains to be done at the system level before machine touch can be understood.

The need for some kind of tactile sensing capability in robot manipulators has fostered the investigation of nearly every conceivable means of force transduction. These efforts have resulted in a diverse and impressive variety of tactile sensor arrays, some of which rival the spatial sensor densities of the human hand [1]. Among the phenomena that have been exploited as tactile sensors are: elastomeric piezoresistive, piezoelectricity, optical reflection and absorption, capacitance, inductance, magnetostriction, and many others. Surveys of tactile sensing research reflect the emphasis on transduction techniques and report the promise of sensing arrays with even higher densities and resolutions [2], [3].

Despite the progress in sensor fabrication, it, nevertheless, seems that researchers today have made only marginal progress toward a fundamental understanding of how machine manipulation systems can productively utilize tactile information to enhance grasp performance. Although mathematical devices such as the sampling theorem, Carson's rule, and Shannon's theorem provide some design guidelines, no single rigorous tactile sensing theory exists for explicitly specifying important system parameters such as sensor density, resolution, location, and bandwidth. In fact, despite the growing interest in array-based tactile sensors for industrial applications, robotic touch has seen limited use in all but the most rudimentary forms. Only a few substantial tactile systems are commercially available for research and industrial purposes, and these often suffer from being too cumbersome or fragile for practical use. Although it is true that better transducers are needed, the fundamental obstacle in tactile sensing seems to be one of fully understanding the relationships between the mechan-
ical, sensing, and control aspects of the manipulator, and the ways in which these aspects relate to the manipulation environment. In order to discuss such issues, it is useful to begin by considering the ingredients and mechanics of a mechanical manipulation system.

**Mechanical Manipulation Systems**

In general terms, machine manipulation involves the repeated execution of two actions: (1) the spatial positioning of an end-effector relative to an object or the environment, and (2) orienting movable elements of the end-effector (digits) so that they contact, move, or release the object in a desired way. What this desired way is and what strategies are required to achieve it are the fundamental questions in generalized machine manipulation.

Figure 1 schematically illustrates a general manipulation system consisting of six subsystems: (1) command source, (2) controller, (3) effector, (4) observers, (5) models, and (6) the physical environment.

The command source issues instructions of various levels of complexity. These instructions may be in the high-level form of complete and comprehensive tasks or in the primitive-level form of individual actions such as reach or grasp. Low-level instructions command individual joint angles from a teleoperation master. The controller is subdivided into three levels and can utilize information from the model for various purposes. The high-level controller formulates strategies for the execution of tasks. The middle-level controller, in response to action commands from the high-level controller, selects reasonable trajectories that are within the physical constraints of the manipulator. The low-level controller simply performs the function of servo control of the manipulator based on commands from the middle-level controller. The effector system physically interacts with the environment and includes structures, actuators, sensors, coverings, power systems, and the end-effector itself.

Important issues in the design of an end-effector and its sensor system include joint kinematics and system geometry, active properties such as the strength and speed of the system, and passive properties such as achieving minimum output impedance at maximum bandwidth. The model can be either a simple or a complex representation of the effector and its environment. Simple models can consist merely of a limited number of parameters or static gains in feedback loops. More comprehensive models can include dynamic adaptation, self-calibration, and other capabilities. Observers continuously supply information to the model and utilize internal sensors for the determination of the effector’s position, lead, and so forth.

External sensors determine environmental states based on vision, tactile, and proximity data. The observer’s information must be available at sufficient bandwidths and at a sufficient resolution to enable proper closed-loop control of the manipulator during task execution.

**Utah/MIT Dextrous Hand**

Progress in machine manipulation research has been hindered by a lack of experimental machinery. This lack is largely due to the belief that definitive machinery cannot be designed until certain fundamental issues are better understood; however, in order to understand these issues, tools are needed. The development of experimental machinery is a complicated and expensive task, and should probably not be done by every laboratory desiring to do research in machine manipulation. Design of the end-effector is influenced by many interrelated factors arising from (1) the tasks to be performed, (2) the objects to be manipulated, and (3) the dynamic characteristics achievable by the mechanics of the system.

Our approach at the Center for Engineering Design at the University of Utah, in collaboration with the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology, has been to develop a comprehensive experimental tool, which has been designed so that basic issues can be studied without the hindrance of inadequate experimental apparatus. The result of our efforts is the Utah/MIT Dextrous Hand (Fig. 2). The details of hand design and control have been described in previous papers [4]-[6], and a number of production models have been made available to researchers in academia and industry.

The Dextrous Hand was not intended for immediate application in industrial environments, but rather as a research tool with sufficient functional richness to permit ex-

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**Fig. 1.** Six subsystems of a manipulator.

**Fig. 2.** Version IV Utah/MIT Dextrous Hand.
perimentation aimed at understanding fundamental issues. Specific performance targets included: (1) speed, (2) strength, (3) range of motion, (4) the capability for graceful behavior, (5) reliability, (6) the possibility of including a comprehensive tactile sensing system, and (7) economy. The hand can be reconfigured as theories regarding machine manipulation evolve.

Present efforts are now focused on the development of a comprehensive tactile sensing system for inclusion into the Dextrous Hand. The conceptual basis governing the design will be described next.

**Tactile Sensing Systems**

**General Requirements**

A number of system issues must be comprehensively addressed in the design of a usable tactile sensing system. System parameters such as the number of sensors, the number of electrical conductors, and the data bandwidth are strongly interdependent, and the implementation of a high-performance tactile sensing system must be a complex optimization exercise requiring the trade-off of one feature at the expense of others. System performance is dictated not only by the isolated quality of the individual system elements but also by how system elements interact to produce overall system behavior.

If an ideal tactile sensing system satisfying desired performance criteria could easily be built, it would already have been done, and researchers would now be focusing in earnest on the deeper issues of how tactile data should be used in active machine manipulation. Unfortunately, only partial systems exist, often consisting only of cleverly designed transducer arrays with little potential for immediate application in research because of their low reliability, lack of interfacing hardware, or bulky geometry.

Therefore, we began the design process with the formulation of a conceptual model that includes the essential ingredients of a general tactile sensing system. This model has been used to explore various system designs and relevant trade-offs.

**General System Model**

A conceptual model of a complete tactile sensing system is schematically illustrated in Fig. 3. The functional divisions fall into a pyramidal form, with the more computationally intensive processes occurring at the upper end of the pyramid and the more functionally rigid processes residing near the bottom. The vertical connections between elements are bidirectional, permitting data flow downwards for addressing purposes and upwards for signal use by higher subsystems. This sensing structure fits easily into established paradigms for manipulator control, which are also typically hierarchical in nature [7]. This architecture is by no means unique to tactile sensing or manipulator control systems. Researchers have presented similar models for multisensor integration [8], human cerebellar function [9], automated production [10], and many other applications. The advantage of using a hierarchical structure is that complex processes can be systematically decomposed into subprocesses, which can then be implemented at desired levels of complexity.

**Transduction** of contact data constitutes the lowest level of the system model and may involve complex measurements, such as the detection of normal force, shear, and their spatial derivatives at the contact surface. Conversely, very simple transducers, such as switches, can be used to merely indicate contact with an object. Obviously, individual transducers must be sufficient in number and density to permit an accurate reconstruction of contact details. Much of the previous interest in tactile sensing has been focused on transduction, and past development efforts provide a rich foundation from which to draw potential transducer designs.

The second level, **preprocessing**, is strongly dependent on the type of transduction array used and can range from a simple scaling of the data for transmission to elaborate preprocessing schemes for detecting geometrical features such as edges or holes. The selection of a particular transduction and preprocessing scheme strongly influences the reliability, size, and mechanical behavior of a tactile sensing array. Initial choices are important since they will later impose bandwidth constraints on data access by the higher levels of the system.

The third level, **multiplexing and transmission** of tactile data, involves the interrogation of sensors and the preparation of collected information for transmission. Critical trade-offs exist between the operating speed and the number of electrical wires in a con-
duce the amount of data that must be transmitted from the hand by selecting which sensors or sensor patches should be interrogated. In very simple tactile systems with relatively few transducers, compromises may not be necessary, and all sensors can be scanned repetitively. In more extensive systems, sensor selection will be a necessity and may be predetermined (thus becoming automatically responsive to contact events) or may be modularized, in anticipation of upcoming interactions planned by the controller.

The fifth level, tactile data interpretation, forms a dynamic tactile "map" of contact interactions and might also perform computations that enhance or identify contact features. Fifth-level data must be placed in a format that is useful to the next level of the system.

At the sixth level, multisensor fusion, the tactile data is blended with the output of other sensory systems. Tactile data is fused with other sensory data fields, such as the manipulator joint angles, joint velocities, and joint torques, as well as proximity or visual information.

World model construction takes place at the seventh level of the system. A multidimensional image is constructed of the manipulator, its environment, and the nature of the object contacted.

At the eighth level, control, the algorithms for grasp and manipulation are implemented. At this level, tactile system parameters such as sensor density, resolution, and location are particularly important, since information must be sufficient to allow reliable control of complex tasks.

Many of the functions to be performed by the system shown in Fig. 3 are poorly understood. While technologies certainly exist to implement the low end of the model, the nature and mechanics of the higher functions, such as sensory data interpretation, integration, and manipulator control, remain vague.

The logical approach to a solution is to proceed from the lower, more hardware-intensive levels upward to the conceptually more difficult and poorly defined areas. The following sections review the four lowest levels of the system and then present some specific approaches to their design.

**Low-Level Elements of a Tactile Sensing System**

In the design of the tactile sensing system, we have emphasized the sequential development of system elements rather than the fabrication of a single transducer array. First efforts are being focused on the four lowest levels: transduction, preprocessing, multiplexing and transmission, and tactile data selection. The end product will be a high-performance tactile sensing system that will, in the same way as the Utah/MIT Dextrous Hand, provide researchers with a general tool for the study of machine manipulation.

**Transduction and preprocessing** The simplest tactile sensing element is a binary switch, which determines the locations at which an object touches the gripper. A more comprehensive tactile sensor measures the six degrees of freedom of the point of contact: three orthogonal contact forces and three moments. Force and moment measurements are usually made by detecting the displacement between a base and a moving armature whose movement is partially restrained by an elastic structure. Sensor armatures possessing from one to six degrees of freedom are typically covered by, or imbedded in, a compliant protective cover, which functions as the outer surface of the end-effector. By using information from groups of adjacent sensors, gradient information can be calculated and, ultimately, a surface map of the contact state can be constructed.

Many phenomena have been investigated for use as tactile transducers, and the experience that researchers have gained with these devices provides a rich knowledge base from which to begin the design of the transduction mechanism. Selection of the appropriate transduction method will be based on the evaluation of specific constraints as they relate to the overall system. Some specific examples of tactile transducers include:

- binary membrane switches
- silicon micromechanical structures
- conductive elastomers
- strain gages
- piezoelectric devices
- magnetostrictive devices
- magnets that move relative to Hall-effect sensors
- electrometers that move relative to field-effect transistors
- inductive coupling devices
- capacitive coupling devices
- reflected intensity optical devices
- strain-induced birefringence devices

The respective qualities of each methodology have been reviewed by a number of investigators [21, 11, 12], and no attempt will be made here to duplicate their efforts. It is important to note that some methods are considerably more developed than others, even to the point of commercial availability [13]-[15].

The selection of a specific transducer must be based on the required characteristics of the overall sensing system, including performance, configuration, robustness, reliability, and economy. Desirable features for tactile sensors are summarized below and have been reviewed by researchers studying machine manipulation [16]-[18].

An advanced tactile transducer should provide the information needed to achieve a stable grasp. The exact nature of this information is, however, presently unknown. Individual detectors must produce repeatable signals with the sensitivity to resolve relatively small forces over a reasonable dynamic range, though precise range and resolution requirements have yet to be rigorously specified (an industry survey has indicated that a resolution of one part in one thousand, or roughly 10 bits of force data, is desirable [16]. The Version IV Utah/MIT Dextrous Hand utilizes 12 bits of joint angle data and 12 bits of joint force data.) Sensors should be immune to electrical noise, drift, and hysteresis. The chosen transducer must employ a technology that allows it to be fabricated on a scale corresponding to a few millimeters of center-to-center spacing and permits mounting on a compliant convex base. Connections to the sensor should be minimized to reduce the probability of site failure due to wire breakage, and conductors must exhibit reasonable lifetimes under conditions of constant flexing. The entire system must be robust enough to withstand the shocks and vibrations that are unavoidable in research and industrial environments.

Because of size limitations, many of the detectors that have been developed sense only forces that are normal to the contact surface. Nevertheless, attempts should be made to design sensors that determine all six components of the contact forces and moments in order to develop a general and versatile tactile sensing tool. Surveys of industrial manipulation tasks have also suggested the importance of slip and shear sensing [11], [16]. Some investigators have devised means of inferring these forces from tactile arrays [19], while others are able to measure...
these forces directly via finger-mounted multidirectional load transducers [20], [21]. Unfortunately, as yet, no general criteria exist for the exact specification of sensor deployment and the relationships between particular manipulation tasks and required sensory data. It has been shown that certain array properties, such as sensor area and density, are critical to the recognition of contacted surfaces [22], and it is likely that such relationships will be clarified via experiments with manipulators that incorporate advanced tactile sensing systems.

The need to preprocess tactile data at or near the transducer is currently a controversial issue in tactile sensing research. Many researchers believe that it is essential to incorporate extensive data preprocessing at the transduction site in order to eliminate the large data transfers that can affect operating speed and system complexity. There is also some evidence to suggest that similar processes may take place within the human hand [23]. However, to avoid inflexible hardware, early research systems should probably avoid preprocessing subsystems until the needs and requirements are more fully understood.

**Multiplexing and transmission** The transmission of the output of multiple detectors over a limited number of wires in a conduit requires a temporal sharing of the conductors. Of specific importance to tactile sensing is the relationship between the number of sensing sites monitored and the bandwidth of the total system.

The means for serially transmitting data have been extensively explored in applications ranging from telephone communications to satellite telemetry. Time-division multiplexing is a technique commonly used for transmitting both analog and digital information in commercial systems, where each time interval of the transmitted signal corresponds to a particular data source. The multiplexed data may be either bit interleaved (for pulse amplitude, width, and delay modulation) or word interleaved (for pulse code modulation) [24].

Digital pulse modulation techniques show particular promise for tactile sensing applications due to the discrete nature of the data and the high signal-to-noise ratios that are possible. For analog data, pulse amplitude, width, or delay modulation can be used, and analog-to-digital conversion can take place at or near the controller. If the conversion is performed prior to transmission, then pulse code modulation schemes can be used, employing amplitude, frequency, or phase-shift keying to transmit the data.

Addressed multiplexing systems can be subdivided into two distinct stages: the query stage and the access stage. In the query stage, the controller specifies the specific sensory data required for an immediate task and correlates the selected data with its known address. This address, or series of addresses, is transmitted across some channel to a number of receivers that respond to their corresponding address by enabling the sensory data for output. Residing at each address may be a single sensor or a family of sensors, the output of which has been pre-conditioned for optimal transmission. After the data sequences have been properly queued, they are transmitted to a receiver at the controller and routed to the desired destination within the computational structure. Although the two stages are used for different purposes, the methods available for data transmission in each case are similar.

The impact of the multiplexing method chosen on the overall performance of a tactile sensing system has been recognized by other investigators. Operating speeds for sensing arrays using parallel, serial, and matrix addressing have been estimated in a general way [25], [26]. However, some confusion still seems to exist between predicting the performance of a tactile system and the content of the data carried by the system (spatial density of tactile sensors and cycle rates of data). Strictly speaking, the number of sensors, the number of conductors, and the data bandwidth are independent of the parameters that the system is measuring. In subsequent sections, some performance calculations will be made for a variety of tactile systems based purely on considerations of speed, and independently of the data content.

**Tactile data selection** During a manipulation sequence, the controller must make use of tactile data in a variety of forms, and it must be available at data rates that allow for accurate manipulation. As with visual data, not all of the tactile data will be meaningful, and processing time can be greatly reduced by internally updating only the data elements that have changed or only the sites of interest. Methods of data management that permit the system user to specify (in software) the nature of tactile data selection and to influence the speed at which data processing can be performed have been identified.

**Full scan** Many of the tactile sensing systems that have been previously implemented have been hard-wired to scan the entire sensing array during each cycle of data acquisition. For relatively small sensing arrays or for low operating speeds, this method is sufficient for the execution of simple handling tasks. This method, also useful for the acquisition of high-resolution tactile images, will be used during the first stages of the tactile sensing system development. In later versions, which will incorporate a large number of high-resolution sensors, the need for high-speed updates will prohibit the luxury of polling each site individually. On a much larger scale, the sensory system of a production process or even of an entire factory can easily have a size that prohibits the use of a full scan of all sensor elements within the necessary time interval. In these cases, another method of accessing data is imperative.

**Reactive scan** In many cases, the manipulation algorithms may only require information that has changed since the last sensor system scan, for example, when detecting slip during an object transport sequence or in the early stages of object acquisition. In order to facilitate this process, only the sets of sensory patches having elements that have changed since the last update cycle are refreshed in the sensor state table. The monitoring of each sensor patch can be performed continuously by a local processor. Although this approach does not completely eliminate the possibility that the data from an inactivated sensor will be processed, it will increase the speed at which the sensor state table may be updated and, hence, will improve the bandwidth of useful information transmission.

**Anticipatory scan** In the time interval immediately prior to the acquisition of an object of known geometry and location, it may be desirable to monitor specific sensor patches (for example, at the fingertips) at very high speeds in order to determine the exact instant of rendezvous. In this case, only the sensor patches of interest are monitored, regardless of whether or not sensor activation has taken place. Again, if only some of the sensory patches have been selected, sensor data update times will decrease in a manner proportional to the number of patches selected, permitting very high operating bandwidths. Later versions of the sensory system, which will integrate the joint angle and joint torque sensors as well, will permit more rapid updating of these sensors at the expense of tactile sensors. It is also possible to combine reactive and anticipatory scanning and update only those sensory patches that have been selected and have changed since the last update cycle. Such an approach would result in the highest possible operating bandwidth.
Tactile System Examples

In order to clarify the relationships between operating speed, the number of sensors, and the number of data lines, two general sensor network configurations will be presented and their performance analytically characterized. Although these two systems are fairly representative of most of the tactile networks that have been developed, it should be noted that many other configurations are possible and have been implemented by investigators.

Site-addressable sensing systems Suppose we are considering a tactile system design for a robotic hand in which all of the sensors are connected to a common address/data bus. Each sensor can be individually addressed via the bus, and responds by sending tactile data to a data register, for use by high-level algorithms. Figure 4 shows such a system. In this arrangement, a number of sensors (Ns) are addressed by a Sensory Data Register, which receives requests for tactile data from a central controller. Addressing of the individual sensors takes place via a number of address lines (Na_a) that run throughout the system. The time interval between successive addresses is \( \tau_a \), a limit imposed by the hardware comprising the Sensory Data Register. Each sensor has associated with it a response time (\( \tau_r \)) between the time that it is prompted by its address and the time it responds with the measured data. Note that the response time may also include some preprocessing of data at the transducer. The data itself consist of a number of data bits \( (N_d) \) that are transmitted across \( N_{dl} \) data lines, where the time interval between successive data transfers is \( \tau_d \). Note that one address ‘word’ consists of \( N_{aw} \) parallel bits, and that one address word is sent every \( \tau_a \) interval. Address and data transfers may require more than one (parallel) word, and so the number of words transmitted per address or data set is denoted by \( N_{aw} \) and \( N_{dw} \), respectively.

We begin by assuming that the total time for a full scan of all the sensors (a single tactile “image”) is equal to the number of sensors multiplied by the total access time of a single sensor \( \tau_a \). In other words, the number of times per second that the entire tactile contact “image” can be scanned (the image frequency, denoted by \( f_i \)), is

\[
 f_i = \{ N_{aw} \tau_a \}^{-1} 
\]

The access time for a single sensor, \( \tau_a \), is made up of three phases: (1) an address transmission phase, (2) a delay phase, and (3) a data transmission phase. The address transmission phase for any sensor is the time that it takes for that sensor’s address to be sent and received and is equal to the minimum address word transmission time \( \tau_a \) multiplied by the number of parallel words \( (N_{aw}) \). The delay phase is simply the response time of the sensor \( \tau_r \), and the data transmission phase is the minimum data word transmission time \( \tau_d \) multiplied by the number of parallel data words \( (N_{dw}) \). Substituting expressions for these phases into the preceding equation gives

\[
 f_i = \{ N_{aw} \tau_a + \tau_r + N_{dw} \tau_d \}^{-1} 
\]

Note that this formula assumes that all addresses and data are individually sequenced at their highest possible bandwidth, but it does not take into account methods of interleaving data, such as sending a new address before the data from the previous address has been returned. The formula gives only a general estimate of how the system will perform if it is configured in the manner described here.

All that remains now is to establish the exact method of addressing the sensors and the method of transmitting tactile data. If pulse code modulation is used, it is common to employ a binary scheme in which the number of address lines, the number of address words, and the number of sensors are related by

\[
 N_s = 2^{(N_{aw} \times N_{dl})} 
\]

As an example, if four parallel lines are available \( (N_{dl} = 4) \), a designer will typically choose to transmit four bits \( (N_{aw} = 1 \text{ word}) \), eight bits \( (N_{aw} = 2 \text{ words}) \), and so on. This is one reason for the predominance of sensing arrays consisting of \( 2^n \) sensors \( (N_s = 4, 8, 16, 32, 64, \ldots) \).

The number of words required to transmit the tactile data is simply the number of data bits produced by each sensor divided by the number of data transmission lines, or

\[
 N_{dw} = N_{aw}/N_{dl}. 
\]

By substituting the last two equations into the expression for the image frequency, the result is an estimate of the bandwidth of the general system of Fig. 4. Note that the analysis is not limited to purely parallel binary systems, since by setting \( N_{dl}, N_{aw}, \text{and } N_s \) equal to 1, the system becomes a serial analog sensing network. If we consider, instead, a parallel, pulse code modulated system, and substitute the following typical values:

\[
 N_s = 256 \text{ sensors} \\
 N_{aw} = N_{dw} = 8 \text{ lines} \\
 N_{dl} = 8 \text{ bits/sensor} \\
 \tau_r = \tau_d = 50 \mu\text{sec} \\
 \tau_a = 10 \mu\text{sec} 
\]

then

\[
 N_{aw} = N_{dw} = 1 \text{ word} 
\]

so that a full scan of all the sensors can theoretically be accomplished at a rate of

\[
 f_i = 35.5 \text{ Hz} 
\]

Line-addressable sensing systems Line addressing (or matrix multiplexing—as it is sometimes called) is a common method of addressing tactile sensing arrays and has been successfully applied to both large and small sensing networks. Figure 5 illustrates a line-addressable configuration, which may be familiar as a keyboard or switchpad arrangement. In this configuration, every sensor finds itself at the intersection of two data pathways, one of which typically carries an enable bit, the other acting as a data output line for the sensor. As shown by the arrows in the figure, the horizontal lines \( (N_s) \) are enable lines, and the vertical lines \( (N_{aw}) \) are
Fig. 5. Generalized line-addressable system. Sensors are addressed according to the row (A) and the column (B) in which they reside.

The Sensory Data Register performs a similar function to that described in the previous section; however, now it generates two addresses: (1) a row (enable) address and (2) a column (read) address. These addresses are sent along (NAL1) lines and (NAL2) lines, respectively. The sensor data, delivered to the demultiplexer via the vertical columns, is transmitted across the data lines (NDL) back to the Sensory Data Register. The number of words per transmission can be found as in the previous section, using slightly different notation to account for the presence of the second addressing conduit:

- \( N_A = N_{AL1}N_{AL2} \)
- \( N_B = N_{AL1}N_{AL2} \)
- \( N_{AL1} = N_{AL2} = 1 \text{ word} \)
- \( N_{BL} = 8 \text{ lines} \)

The quantity \( r_R \) remains the response time of each sensor, and \( r_{AI} \) and \( r_{A2} \) denote the address spacing on the lines \( N_{AL1} \) and \( N_{AL2} \), respectively. \( r_D \) again denotes the spacing between successive data transfers. Employing a similar procedure to establish the speed of the system, we now get

\[
f_i = \left\{ N_A\left[N_{w1}r_{AI} + N_D(N_{w2}r_{A2} + \tau_R + N_{w3}r_D)\right]\right\}^{-1}
\]

Substituting similar values as before,

- \( N_A = 256 \) sensors
- \( N_{AL1} = N_{AL2} = 16 \)
- \( N_D = 8 \text{ bits/sensor} \)
- \( r_{AI} = r_{A2} = r_D = 50 \mu\text{sec} \)
- \( \tau_R = 10 \mu\text{sec} \)

then

- \( N_{w1} = N_{w2} = 1 \text{ word} \)
- \( N_{w3} = 1 \text{ word} \)

and a full scan of all the sensors can ideally be accomplished at a rate of

\[ F_i = 34.5 \text{ Hz} \]

Note that, for this particular sensing network, the convenience of fabricating the sensors in a cross-multiplexed array has a slight penalty in operating bandwidth. Using this method of analysis, sensing systems can be estimated for a particular number of sensors and a desired number of transmission lines. Based on this procedure, an efficient design for a tactile sensing system is proposed in the following section.

**Toward an Implementation**

Like many researchers, our early efforts at implementing a tactile sensing scheme for the Utah/MIT Dextrous Hand were focused primarily on transducer issues. Sensor size, resolution, and durability defined the fundamental constraints of the development effort, and it was these parameters that were emphasized in the design of the initial tactile sensing system [4]. During subsequent experimentation, however, it was soon recognized that many of the desirable qualities of an experimental tactile system extend beyond the sensors themselves and are, in fact, embodied in the arrangement of the elements within the total sensing system. Viewed as a whole, these desirable qualities define system requirements for tactile sensing in machine manipulation research: (1) Sensors—a tactile system must be capable of managing not just a single array of a few dozen high-resolution transducers but also large numbers of sensors distributed across the surface of the manipulator. Each sensor must conform to practical requirements of size and sensitivity. (2) Speed—tactile data must be provided at rates that are well within the sensory feedback requirements for stable grasp and manipulation. Servo loop rates may equal or exceed 500 Hz in order to avoid sacrificing hand performance, as in the Utah/MIT Dextrous Hand [6], [27]. (3) Reliability—a tactile system must be reliable in order to be useful in a research environment. In addition to sensor durability, reliability also includes the reduction of system failures due to hardware damage, a problem that is largely avoided by reducing the number of data lines running from the hand to the controller and by minimizing the amount of electronic hardware that exists en route. (4) Modularity—ideally, tactile sensing should exist as a subsystem within a larger manipulator sensing network, including joint angle sensing, joint torque sensing, and perhaps others. In this way, modularized sensors can be substituted or added to the manipulation system as needed by researchers. It is intended that all sensors of the Utah/MIT Dextrous Hand will eventually exist within such an expandable and rational framework.
The development of a tactile sensing system for the Utah/MIT Dextrous Hand has been divided into three general phases. The Phase I system is a simple arrangement of binary switches and transmission lines aimed at sensing basic data for early experiments. Although such a system does not incorporate the high-resolution transducers that many investigators have emphasized, it, nevertheless, represents an early, practical compromise between desired performance and implementability. Experiments will be performed with this system to assess significant design constraints and the feasibility of future systems. The Phase II Tactile Sensing System will incorporate proportional contact transducers while maintaining roughly the same number of sensors on the hand. Initial work has been performed on proportional sensors based on both electrical and magnetic transduction techniques. The Phase III system will include the other transducers within the Utah/MIT Dextrous Hand, such as the joint position and joint torque sensors. The following sections describe the development of this expandable tactile system as it progresses from Phase I through Phase III.

Phase I Design: A Binary Sensing Network

Arrays of simple switches exhibit a number of features that make them desirable tactile transducers for the early stages of the project. Firstly, the mechanical simplicity of binary contact switches enhances reliability at this level, since the problem of force overloads is largely avoided. Second, their electrical simplicity reduces the susceptibility of the system to external noise, and no analog conversion is required. Third, transmission of contact data can be virtually instantaneous, with no delay due to the formatting of signals for transmission. When these data are combined with proportional joint angle and torque data by high-level sensory processing algorithms, the actual magnitude of the force across the contact area can, under certain conditions, be accurately deduced, providing proportional contact information without the associated electronic complexity. Such an operation, of course, comes at computational expense. Through the use of time-division multiplexing techniques, binary data can be transmitted at high speeds over a minimum number of conductors to a central controller. This is a significant practical consideration, since elements of the hand will be tightly packaged and in continual motion. Existing technologies permit fabrication of the dense, flexible arrays of switches that will be required.

In order for the Utah/MIT Dextrous Hand to grasp and manipulate objects in a stable fashion, the controller must be updated by sensory data at a conservative rate of approximately 500 Hz [6]. Based on the somewhat arbitrary sensor spacing criteria of 2 mm between sensing sites, the number of sensors required for the minimal contact surface of the Utah/MIT Dextrous Hand have been projected to be approximately 2000 sensors. For this number of sensors, the bandwidth over a single data line for all of the tactile switches must be approximately 1 MHz if switch response time is neglected. In the early stages of the Phase I effort, a full scan of all the sensors will be supported. Later modifications of the Phase I system to include a greater number of sensors and higher update speeds will render a full scan approach impractical. A more feasible solution to the problem of accessing a large number of sensors with a minimal number of wires is to use some method for addressing sensors, and, in effect, select the amount of data to be transmitted. However, each individual sensor need not be specifically addressed; neighborhoods of sensors occupying similar locations on the hand, such as on each finger link, can be grouped together for spontaneous transmission when the sensor group receives its particular address. Using such geographical divisions, the sensing surface of the hand has been divided into 20 regions or "patches" of approximately 100 sensors each.

Figure 6 illustrates the method by which sensors are addressed in patches. Each patch has associated with it an Array Scanning Stage, a Pulse Gating Stage, and a Patch Identification Register. Large amplitude signals on the serial input line are compared to each Patch ID Register, and, when a match occurs, the Pulse Gating Stage passes the low-level pulses that follow the serial address to the Array Scanning Stage. This stage sequentially scans all the sensors within the patch and shifts the state of each sensor onto the output line, which carries the serial data
back to the controller where a sensor state map is reconstructed. Note that the sensor query commands still originate at the controller, which cannot now address any single sensor but only the patch in which that sensor resides. For the binary sensors of the proposed Phase I system, full scan rates of 2000 sensors can be achieved at a rate of 500 Hz, with the options of higher bandwidth and more sensors available at the expense of some contact data.

Phase II Design: A Proportional Contact Sensing Network

Despite the simplicity of binary tactile sensing, simple switches do not completely provide the detailed local contact force information that seems to be needed for human manipulation. Transduction for the Phase II tactile sensing system will, therefore, employ a proportional sensing technique at approximately the spatial densities of the early switch arrays. Efforts at the Artificial Intelligence Laboratory at MIT to develop a capacitive tactile sensing array for use on the Utah/MIT Dextrous Hand have met with success [28] and show promise for applications in the near future. Another method that shows particular promise for proportional contact sensing is based on the field emitter/detector structure shown in Fig. 7. Here, a field detector placed in proximity to a field-emitting element experiences a change in field flux density when the emitter element is displaced. Magnets and Hall-effect sensors, or electrets and field-effect transistors, can be used as field-based strain sensors. The electrical output of the detector, which is proportional to the field flux change at its surface, indicates movement of the emitting element. Figure 7 shows a row of such sensors connected to a common addressing and data conduit. Such a transduction scheme has the advantage that the emitter elements can be embedded in a compliant layer, which acts both as a displacement medium and isolates the sensing structure from the external environment.

Project personnel have already had experience with field emitter/detector sensors employing electric, magnetic, and optical effects [5], [29]. More sophisticated forms of this transducer can determine up to six degrees of freedom, as shown in Fig. 8. When embedded in a compliant medium, as in Fig. 9, such devices can be expected to reduce the density of more conventional normal force sensors by detecting spatial variations in forces and torques directly. Accessing the data from a large number of these sensors requires careful consideration of the trade-offs between the number of wires, the addressability of each sensor, the nature of the data signals, and the speed at which the data can be transmitted.

A transmission scheme for the Phase II tactile sensing system, using proportional field-based emitter/detector transducers, is shown schematically in Fig. 10. Field detectors and emitters are arranged in groups or patches and are accessed via a common data and address conduit. Note that each emitter may have more than one detector corresponding to the measurement of more than one degree of freedom. As in the Phase I system, some data-selection technique must be employed to ensure that the required tactile information is made available to the controller at update rates sufficient for stable grasp and manipulation. The use of reactive scanning, as described earlier, will accomplish the required transmission speed of data from the hand. When even higher speeds are required, as, for example, during object acquisition, anticipatory scanning may be used.

Phase III Design: A Multiparameter Sensing System

The objective of the Phase III sensing system effort will be to incorporate the other sensory systems of the Utah/MIT Dextrous...
Transmission scheme for the Phase I1 tactile sensing system. Joint angle, joint force, and tactile data all exist within the sensory network. Fig. 10. Schematic representation of the transmission scheme for the Phase I1 tactile sensing system. Multiple field detectors are connected to a common addressing/data conduit.

As schematically represents the arrangement of the Phase I11 system. Obviously, the exact structure of the system depends on the insights gained during the first two phases of tactile system development, but some bandwidth constraints can be identified: (1) Joint angles must be monitored at a high speed. Under the current controller for the Utah/MIT Dextrous Hand, these update rates must be 500 Hz or greater. The joint angle data/bandwidth requirements will not be expected to vary greatly during object acquisition and manipulation sequences, favoring a more rigid, high-speed addressing. (2) Data from the joint torque sensors need not be updated at the constant speed of the joint angles, but rather varies from low sampling bandwidths (prior to object contact) to high bandwidths (during manipulation). In the higher levels of sensory data management, this may require computational emphasis at the expense of other sensory data. (3) As in joint torque sensing, bandwidth requirements for tactile sensing will vary greatly. As previously described, full scanning, reactive scanning, and anticipatory scanning will provide a means by which tactile data can be accessed at high speeds over a manageable number of wires.

Summary

A review of the current state of the art in tactile sensing indicates that a substantial effort has been directed toward the development of high-density sensor arrays. While this emphasis has brought about advancements in transducer technology, the research community has not come appreciably closer to a fundamental understanding of machine dexterity. Some success has been obtained with tactile imaging techniques using planar arrays, however, manipulation with end-effectors of all but the most minimal complexity remains poorly understood. The Utah/MIT Dextrous Hand, initially developed to address the need for a reliable, high-performance research tool in the area of machine manipulation, will be modified by the addition of an experimental tactile sensing system. By taking a comprehensive approach to the design of the system, interdependent constraints such as sensor density, resolution, and system bandwidth have been explored. General methods for estimating the bandwidths of line-addressed and matrix-addressed systems have been presented. The proposed tactile sensing system incorporates four subsystems that permit the high-speed access of tactile data: (1) a transduction scheme, which initially will provide binary contact force and location information, but which later will be updated to yield graded force vector data; (2) a preprocessing scheme, which will prepare the data for transmission; (3) a multiplexing and transmission subsystem, which is designed to access the sensory data at speeds proportional to a specified number of sensors; and (4) tactile data selection techniques, which increase the system bandwidth by using a number of user-specified scanning methods. Designs for implementation at each of these levels have been presented.

References


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