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# SMART SENSORS AVAILABLE IN AN INDUSTRIAL ROBOT

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## ABSTRACT

This section outlines five main types of sensors: proprioceptive, kinematic, force, dynamic tactile, and array tactile sensors. A basic review of the first three of these is provided along with contact sensors that provide thermal or material composition data. However, greater emphasis is placed on tactile sensors that provide mechano reception. When considering tactile sensors, it is useful to begin by considering the fundamental physical quantities that can only be sensed through contact with the environment. The most important quantities measured with touch sensors are shape and force. Each of these may be measured either as an average quantity for some part of the robot or as a spatially resolved, distributed quantity across a contact area. In this chapter we follow the convention of studies of the human sense of touch and use the term touch sensing to refer to the combination of these two modes. Devices that measure an average or resultant quantity are sometimes referred to as internal or intrinsic sensors. The basis for these sensors is force sensing, which precedes the discussion of tactile array sensors.

## PROPRIOCEPTIVE AND PROXIMITY SENSING

Proprioceptive sensing refers to sensors that provide information about the net force or motion of an appendage, analogous to receptors that provide information in humans about tendon tensions or joint movements. Generally speaking the primary source for spatial proprioceptive information on a robot is provided by joint angle and force-torque sensors. Since joint angle sensors such as potentiometers, encoders, and resolvers are well established technologies, they do not warrant discussion here.

### Normal pressure

#### Piezoresistive array

• Array of piezoresistive junctions • Simple signal conditioning • Temperature sensitive • Embedded in an elastomeric skin • Simple design • Frail • Cast or screen printed

#### Capacitive array

• Array of capacitive junctions • Good sensitivity • Complex circuitry • Row and column electrodes separated by elastomeric dielectric • Moderate hysteresis, depending on construction

#### Piezoresistive MEMS array

• Silicon micromachined array with doped silicon strain-gauged flexures • Suitable for mass production • Frail

#### Optical

• Combined tracking of optical markers with a constitutive model • No interconnects to break • Requires PC for computing applied forces

**Skin deformation**

**Optical**

• Fluid-filled elastomeric membrane • Compliant membrane • Complex computations • Tracking of optical markers inscribed on membrane coupled with energy minimization algorithm • No electrical interconnects to be damaged

**Magnetic**

• Array of Hall-effect sensors • Complex computations • Hard to customize sensor

**Resistive tomography**

• Array of conductive rubber traces as electrodes • Robust construction • Ill-posed inverse problems

**Piezoresistive (curvature)**

• Employs an array of strain gauges • Directly measure curvature • Frailty of electrical interconnects • Hysteresis

**Dynamic tactile sensing**

**Piezoelectric (stress rate)**

• PVDF (polyvinylidene difluoride) embedded in elastomeric skin • High bandwidth • Frailty of electrical junctions

**Skin acceleration**

• Commercial accelerometer affixed to robot skin • Simple • No spatially distributed content
• Sensed vibrations tend to be dominated by structural resonant frequency

## WHISKER AND ANTENNA SENSORS

Whisker or antenna sensors are in essence a hybrid of proprioceptive and tactile information. This form of sensing was first explored in the early 1990s, for example, Researchers developed a whisker sensor with a base angle sensor and tip contact sensor that was attached to a robot arm to explore its environment. Another example by Kaneko et al. is one of the earliest examples of active antenna sensing. Kaneko et al. affixed a rigid spring steel antenna to a one-degree-of-freedom (1-DOF) rotating axis used to sweep the antenna from side to side similar to the method an insect would employ. The sweeping motion, in combination with a joint angle sensor and torque sensor, was used to assess encountered contacts. Clements and Rahn took a similar approach to Kaneko, but added an extra degree of freedom to the sweeping pattern of their whisker. Clements and Rahn used a motor-driven gimbal to drive their spring steel whisker in two DOFs to explore objects. Cowan et al. used a multi segmented piezoresistive antenna to aid a bio-inspired insect hexapod robot in a wall-following control task. For many animals, whiskers or antennae provide an extremely accurate combination of contact sensing and proprioceptive information.

## PROXIMITY

While proximity sensing does not strictly fall under the category of tactile sensing, a number of researchers have employed various proximity sensors for the application of collision detection between a robot arm and the environment and thus we briefly review these technologies here. Three primary sensor technologies which include capaciflective, infrared (IR) optical, and ultrasonic sensors have been used in this application. Vranish et al. developed an early capaciflective sensor for collision avoidance between the environment and a grounded robot arm. Examples of distributed IR emitter–detector pairs utilized within artificial skin for the purposes of proximity sensing have been presented by Lumelsky’s research group.

A more recent design using optical fibers is reported in. Other researchers have developed robot skins that include both distributed ultrasonic and IR optical sensors for the purposes of collision avoidance. Wegerif and Rosinski provide a comparison of the performance of all three of these proximity sensing technologies.

## OTHER CONTACT SENSORS

There are a variety of other contact-based sensors that are capable of discerning object properties such as electromagnetic characteristics, density (via ultrasound), or chemical composition (cf. animals, senses of taste and smell). For completeness, thermal sensors and material composition sensors are also briefly discussed below.

### Thermal Sensors

Thermal sensing can be used to determine the material composition of an object as well as to measure surface temperatures. Since most objects in the environment are at about the same (room) temperature, a temperature sensor that contains a heat source can detect the rate at which heat is absorbed by an object. This provides information about the heat capacity of the object and the thermal conductivity of the material from which it is made, making it easy, for example, to distinguish metals from plastics. Buttazzo et al. note that the piezoelectric polymer used in their tactile sensing system is also strongly pyroelectric, and use a superficial layer as a thermal sensor. Other sensors use thermistors as transducers, with Siegel et al. reporting a 4×4 array and Russell a 2 × 10 array. Some systems purposely provide an internal temperature reference and use the temperature differential from the environment as a means of finding contacts However, objects with a temperature the same as the reference will not be detected. Most of these sensors have a relatively thick outer skin covering the heat-sensitive elements, thus protecting delicate components and providing a conformal surface at the expense of slower response time. A more recent example of thermal sensing can be found in the work of Engel et al., who present a flexible tactile sensor design that includes integrated gold film heaters and RTDs on a polymer micromachined substrate.

### Material Composition Sensors

There has been a little work on sensors for material composition. In analogy with the human senses of taste and smell, liquid- and vapor-phase chemical sensors could potentially determine the chemical composition of a surface. Another sensing modality which provides information about material properties is electromagnetic field sensing, using devices such as eddy-current or Hall-effect probes to measure ferromagnetism or conductivity.

## KINEMATIC SENSORS

Although they are not generally thought of as tactile sensors, sensors that detect the position of a limb can provide the robot with geometric information for manipulation and exploration, particularly when the limb also includes sensors that register contact events. Examples of such sensors include the ubiquitous joint angle encoders found in virtually all robots as well as potentiometers, resolvers, and other joint angle measuring devices. For limbs that do not undergo large rotations one can also embed flexible structures such as elements composed of piezoresistive ink, e.g., as used by Cowan et al. Examples of combining information about joint angles with contact status sensors for manipulation include Kaneko’s work on the posture changeability of fingers.

## FORCE AND LOAD SENSING

### Actuator Effort Sensors

For some actuators such as electric servomotors, a measure of the actuator effort can be obtained directly by measuring the motor current (typically using a sensing resistor in series with the motor and measuring the voltage drop across the sense resistor). However, because motors are typically connected to robot limbs via gearboxes with output/input efficiencies of 60% or less, it is usually much more accurate to measure the torque at the output of the gearbox. Solutions to this problem include shaft torque load cells (typically using strain gages) and mechanical structures at the robot joints whose deflections can be measured using electromagnetic or optical sensors. For cable- or tendon-driven arms and hands it is useful to measure the cable tension – both for purposes of compensating for friction in the drive-train and as a way of measuring the loads upon the appendage.

### Force Sensors

When actuator effort sensors are not sufficient to measure the forces exerted by or on a robot appendage, discrete force sensors are typically utilized. These sensors are found most often at the base joint or wrist of a robot, but could be distributed throughout the links of a robot. In principle, any type of multiaxis load cell could be used for manipulator force-torque sensing. However, the need for small, lightweight units with good static response eliminates many commercial sensors. The design of force sensors for mounting above the gripper at the wrist has received the most attention, but fingertip sensors for dextrous hands have also been devised. Often these sensors are based on strain gauges mounted on a metal flexure, which can be fairly stiff and robust. Sinden and Boie propose a planar six-axis force-torque sensor based on capacitive measurements with an elastomer dielectric. Design considerations for force sensors include stiffness, hysteresis, calibration, amplification, robustness, and mounting. Dario et al. present an integrated fingertip for robotic hands: an integrated force sensing resistor (FSR) pressure array, piezo ceramic bimorph dynamic sensor, and force-torque sensor. More recently Edin et al. have developed a miniature multiaxis fingertip force sensor. For applications where immunity to electromagnetic noise is desirable, Park presents a design for a robot fingertip with embedded fiber optic Bragg gratings, used as optical strain gages. Bicchi and Uchiyama et al. consider the optimal design of multiaxis force sensors in general. It is interesting to note that more than just force information can be gained by the use of fingertip load sensors. Information from the force sensors can be combined with knowledge of fingertip geometry to estimate contact location. This method of contact sensing is referred to as intrinsic tactile sensing, and was first presented by Bicchi et al. A comparison between intrinsic and extrinsic contact sensing (i. e., using distributed contact sensors) is presented by Son et al.

## DYNAMIC TACTILE SENSORS

Early special-purpose slip sensors based on displacement detected the motion of a moving element such as a roller or needle in the gripper surface (e.g., Ueda et al.). A more recent approach uses a thermal sensor and a heat source: when the grasped object begins to slip, the previously warmed surface under the sensor moves away, causing a drop in surface temperature beneath the sensor. A noncontact optical approach uses correlation to reveal motion of the object surface. A number of researchers have suggested using conventional arrays for slip detection, but the array resolution must be good and the scanning rate high to detect themotion of object features soon enough to prevent dropping the grasped object. In a systematic investigation of the feasibility of using vibration to detect slip, Rebman and Kallhammer used single elements from an array sensor to detect normal vibrations at the contact surface. Dario and DeRossi and Cutkosky and Howe note that piezoelectric polymer transducers located near the contact surface are very sensitive to vibrations and may be used for slip detection. Howe and Cutkosky show that using a small accelerometer to sense minute vibrations of a compliant sensor skin is an effective means of detecting slip at its earliest stages. For hard objects held in metal grippers, acoustic emissions may reveal incipient slip. Mor- rell and Tremblay investigated the use of slip sensors in grasp force control. Buttazzo et al. have built a texture-sensing fingernail as part of their anthropomorphic tactile sensing system. A piezoelectric element at the base of the rigid plastic nail produces a large signal as it is dragged over a textured surface. The stress rate sensor, the skin acceleration sensor, and the induced vibration sensor described above in the context of shape or slip sensing also respond to the small vibrations produced by sliding over fine surface textures. More recent adaptations of these sensors include piezoceramic bimorph dynamic sensors, with integrated FSR pressure array, and force-torque sensor.

## COCNCLUSION

In comparison to computer vision, tactile sensing always seems to be a few years away from widespread adoption. As explained in this chapter, the reasons include physical problems (placement and robustness of sensors, wiring challenges) and the diversity of sensor types for detecting forces, pressures, local geometries, vibrations, etc. As we have seen, the transduction and interpretation methods are typically different for each of these tactile quantities. However, there are some basic issues that apply to tactile sensing in general; for example, sensors are generally located within or beneath a compliant skin, which affects the quantities that they sense in comparison to pressures, stresses, thermal gradients or displacements applied to the skin surface.

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