Robotic Sensing Devices

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Abstract

Presented in this report is an overview of robotic sensors, many of which are in experimental stages. Two main sensor types are discussed: contact and noncontact. Descriptions of the physical measurements, how they are measured, and operating principles of specific devices are provided for both types of sensors. Contact, or tactile, sensors comprise three groups: touch, proximity, and slip sensors. Noncontacting sensors comprise six groups, according to principles of operation: optical, magnetic, capacitive, resistive, ultrasound, and air pressure, each of which can measure numerous physical properties.

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1. INTRODUCTION

The potential range of robotic applications requires different types of sensors to perform different kinds of sensing tasks. Specialized devices have been developed to meet various sensing needs such as orientation, displacement, velocity, acceleration, and force. Robots must also sense the characteristics of the tools and materials they work with. Though currently available sensors rely on different physical properties for their operation, they may be classified into two general types: contacting and non-contacting.

Since contacting sensors must touch their environment to operate, their use is limited to objects and conditions that can do no harm to the sensors. For instance, the elastic limit of a deformable sensor must not be exceeded; also, a material such as hot steel would be extremely difficult to measure using contact sensors. Contact devices vary in sensitivity and complexity. Some can only determine whether something is touching or not, while others accurately measure the pressure of the contact. The most simple contact sensor is merely a mechanical switch. The more sophisticated devices can produce a three dimensional profile of an object.

Noncontacting sensors gather information without touching an object. They can be used in environments where contact sensors would be damaged since they can sense most materials, including liquid, powder, and smoke; and they can measure many parameters, including velocity, position, and orientation. Simple noncontact sensors merely determine whether something is present or not. More complicated devices can be used to distinguish between objects and workpieces. Through special techniques, data for a three dimensional profile of an object can be obtained as with tactile sensing.

2. Contact, or Tactile, Sensors

Contact sensor operation is based on transducers. Whereas some use purely electrical transducers such as pressure variable resistances, others rely on mechanical processes that are changed into an electrical signal by various means such as strain gauges, optics, or potentiometers. Almost all contact sensors measure one of three different physical quantities: touch/force, proximity, and slip. Touch includes whether something is touching, the pressure of a touch, and weights and forces. Proximity sensors measure the nearness of objects and displacements of the robot or target. Slip refers to the motion of an object sliding out of a mechanical hand or gripper.

2.1 Touch and Force Sensing

Touch and force sensors determine whether the manipulator is touching something, the pressure of the touch, or how much of something is being touched. The simplest tactile sensor is a switch that either turns on or off when pressed. Simplicity and low cost are two of the benefits of switches, and they are a good investment for a system that only requires basic information such as whether an object is being touched. They have only two states, so they are ideal to interface with digital equipment. Most switches are mechanical, although one device uses a pneumatically operated switch. Switches may be used singularly or in large arrays to gain more information.

Tactile sensors that measure the touch pressure rely on strain gauges or pressure sensitive resistances. Variations of the pressure sensitive resistor principle include carbon fibers, conductive rubber, elastomers, piezoelectric crystals, and piezodiodes[7,8]. These resistances can operate in two different modes: The material itself may conduct better when placed under pressure, or the pressure may increase some area of electrical contact with the material, allowing increased current flow. Pressure sensitive resistors are usually connected in series with fixed resistances across a d.c. voltage supply to form a voltage divider. The fixed resistor limits the current through the circuit should the variable resistance become very small. The voltage across the pressure variable resistor is the output of the sensor and is proportional to the pressure on the resistor. The relationship is usually non-linear, except for the piezodiode[7,8], which has a linear output over a range of pressures. An analog to digital converter is necessary to interface these sensors with a computer. Many sensors can be used together to gain a larger sensitive area or to obtain a profile of the object being touched.

Pressure sensitive resistances are effective when used on the fingers of artificial hands or grippers to determine the force of the grip on objects. The pressure sensitive resistances on the inside of the gripper fingers can be monitored constantly to avoid damaging fragile objects. The pressure is compared to a maximum allowable pressure for each kind of material. If the task requires the handling of only one object material, this sensing method is advantageous. After completion of a specified task, the robot can be programmed to handle another material for the new task.

Other touch sensors use mechanical or semiconductor strain gauges to measure force, gripping pressure, or torque. Force sensors are used to determine loading on robotic arms or the weight of objects. Strain gauge torque sensors can detect loading on arms plus how tight a robot is turning a nut or a bolt. The force transducers for these sensors are often thin metal strips or wires that experience stresses due to an applied force or torque. The stresses cause elastic deformations which are measured by the strain gauges. The output of each strain gauge is converted into an electrical signal that can be used by the control system of the robot.

2.1.1 Mechanical Switches - The ACM [1]

The Active Cord Mechanism (ACM) [1] is a snake-like robot with 20 segments in its body. The robot can negotiate twisting mazes, wrap itself around objects to pull them along, and push off of objects when starting to move. The tactile sensors for the ACM consist of 40 on-off switches, one on either side of each segment of its body. The mechanical switches make contact when the active cord mechanism touches something. Mechanical switches are employed as sensors for many robotics applications, such as the ACM, where complex information is not required.

2.1.2 Pneumatic Switches

Pneumatic switches have been used as tactile sensors for a computer controlled gripper that has more than 100 switches on each finger. The gripper is used in a robotics experiment [2] to insert a peg into a hole. When the peg contacts the hole, a computer uses the force distribution on the sensors to calculate the approximate position of the hole. The path of the fingers is then adjusted so that the peg can be accurately inserted. (Figure 2-1 [2] shows an enlargement of the fingers.)

The sensors are covered with flexible sheets of insulating skin made of flexible rubber or polyurethane. The skin provides a high frictional force between the gripper fingers and the peg. A thin metal sheet is bonded to the rubber skin and connected to a voltage source. The thin metal sheet is also attached to reinforcement members to form pneumatic cells. Since all the cells are interconnected by holes, they are called plural pneumatic cells. Air or liquid pressure from a source tank maintains pneumatic pressure in all the cells, and a valve controlled by a computer adjusts the pressure to any desired amount. Figure 2-2 [2] is an enlargement of the sensors, and figure 2-3 [2] shows an enlargement of a switch.

A finger contacting the peg exerts pressure on the sensors. The rubber skin serves as a soft spring and

Figure 2-1: The fingers of the gripper.[2]

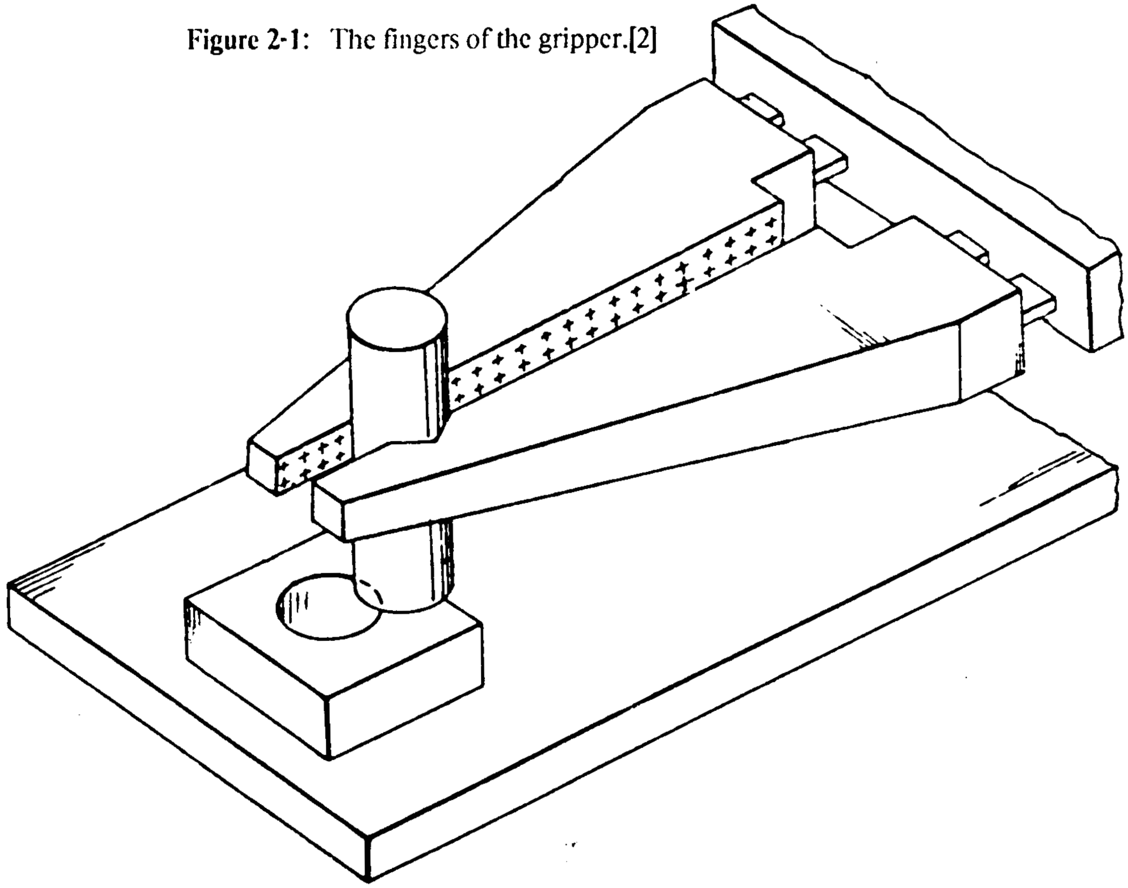
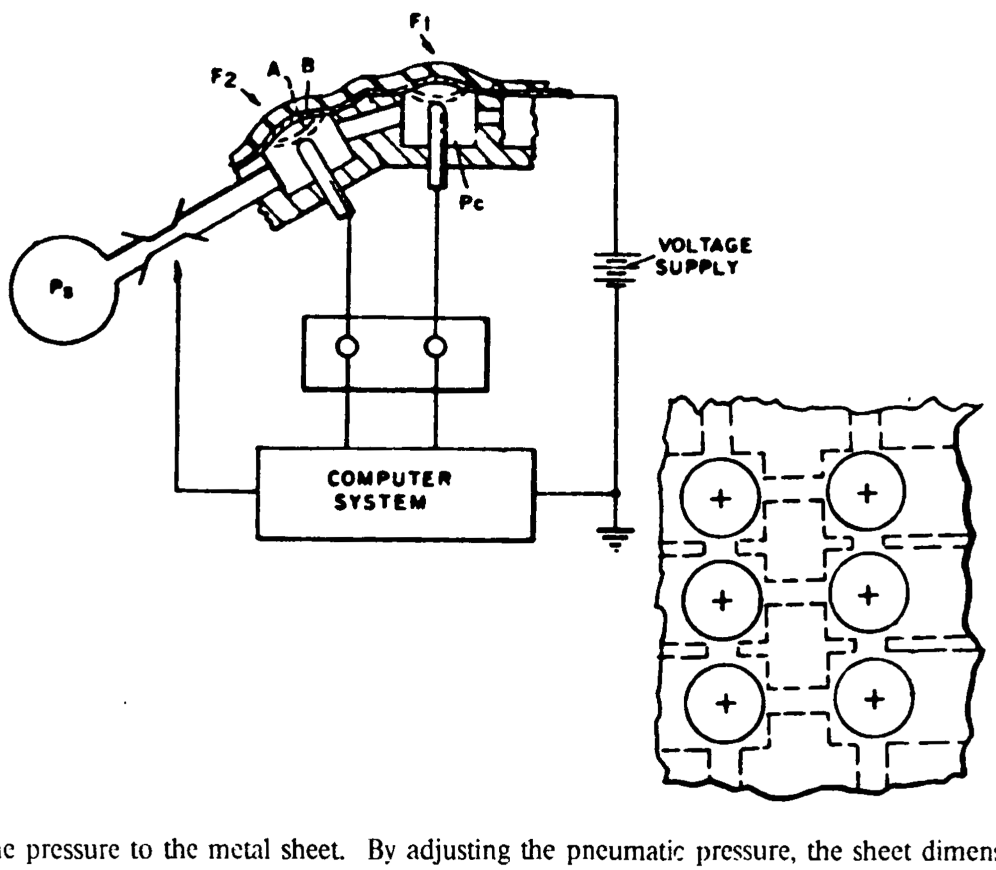
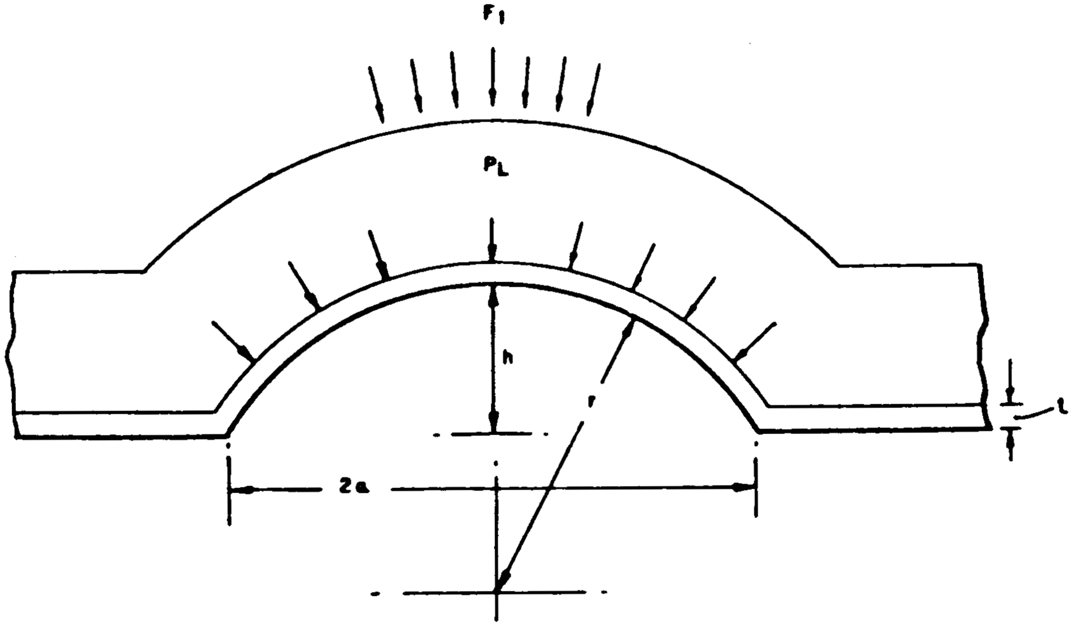


Figure 2-2: An enlargement of the sensors.[2]



transmits the pressure to the metal sheet. By adjusting the pneumatic pressure, the sheet dimensions, and

Figure 2-3: An enlargement of one of the switches.[2]



using different sheet materials, the sheet can be made to snap to the inward position under a certain specified pressure and to snap back when the pressure is removed. When the metal sheet snaps inward, it touches another piece of metal to make electrical contact; when the metal sheet snaps back, the contact opens. Pneumatic switches are more expensive than mechanical switches, but they allow for an adjustable threshold pressure by changing the pneumatic pressure or the metal in the thin sheet.

2.1.3 Carbon Fiber Sensor

This sensor [3] is made of carbon (graphite) fibers 7 to 30 microns in diameter. When pressure is exerted on a single carbon fiber its resistance changes; but the resistance change over a useful range of pressures is not useful for sensing. The area of contact between two fibers is what is important for sensing. When two fibers come into contact the area of the junction is approximately .5 mm by .5mm, and its resistance is about 2 kilohms [3]. As pressure is applied, the fibers press together and the area of contact increases by elastic deformation. The conductivity of a junction increases with increasing area of contact. As increasing pressure is applied the resistance and the noise level of a junction both decrease (table 2-1).

Carbon fibers are produced in a flat ribbon approximately half a millimeter across and a tenth of a millimeter thick. Two of these ribbons placed across each other form the basic multifiber junction. An effective way to utilize carbon fibers is to make a matrix of many fibers; a multifiber junction makes an ideal matrix with a nominal thickness of about 1 mm. Researchers make sensor elements by forming a sandwich of one or more matrices between or across foil electrodes. A single 1 cm^2 matrix 1 mm thick has a resistance of about 200 ohms [3]. The matrix is flexible and can be custom shaped for any application.

Table 2-1: Resistance of Fibers under Pressure [3]

Pressure (force on .25 sq mm)	R(Ohms)	Noise level (Ohms)
*******************	*******	****************
0	2000	50
1g	1000	5
5Kg	200	distortion begins
1000Kg	0.1	-

The primary advantage of carbon fibers is the cost: One dollar will buy enough carbon fibers for over 500 sensors. The major problem with carbon fibers is how to establish an electrical connection to them. The current method is a mechanical crimp encapsulated in resin. For matrices, a foil electrode connected by point application of a light hardening adhesive is the accepted method for making contact.

Carbon fiber pressure transducers are being developed almost exclusively for robotics applications. One such application for carbon fibers is to place a matrix inside a washer of insulating material that can be used to measure the weight on the robot arm or to determine how tight the robot is turning a bolt or nut.

2.1.4 Conductive Silicon Rubber Sensors

The silicon rubber sensor consists of two electrodes, one or both made of electrically conductive silicone rubber in a convex shape resembling a rod. The rounded component can be the metal, the rubber, or both. When no pressure is exerted on the device the rubber-metal junction area is at a minimum corresponding to a maximum resistance. As the pressure is increased, the contact area increases, giving a current more parallel paths to flow through decreasing the resistance. The most common way to connect the sensor is in series with a fixed resistance as a voltage divider (figure 2-4). The output voltage (figure 2-5) varies rapidly for small pressures and then changes more slowly for higher pressures. The voltage shown in figure 2-5 is for a 1 kilohm series resistor. A series resistance higher than 1 kilohm would shift the whole curve downward and make the device very sensitive to very low pressures, eg.less than 50 grams per junction. Operation in the low pressure range is not always reliable because the metal electrode can slide off to one side instead of being grabbed by the rubber. Another problem with the rubber is that its voltage output changes slowly when a pressure is applied. The output is insensitive to the radius of the cylindrical electrode: Even a flat electrode shifts the output curve by only about .25 volts.

The experimental rubber cord is "D" shaped with the flat portion measuring 1/16 of an inch in width. Electrical contact to the cord is made with conductive adhesives or by inserting the edge of a thin metal sheet into a slit cut into the flat face of the cord. The thin sheet of metal method gives support as well as electrical

Figure 2-4: The sensing configuration and its circuit principle [4].

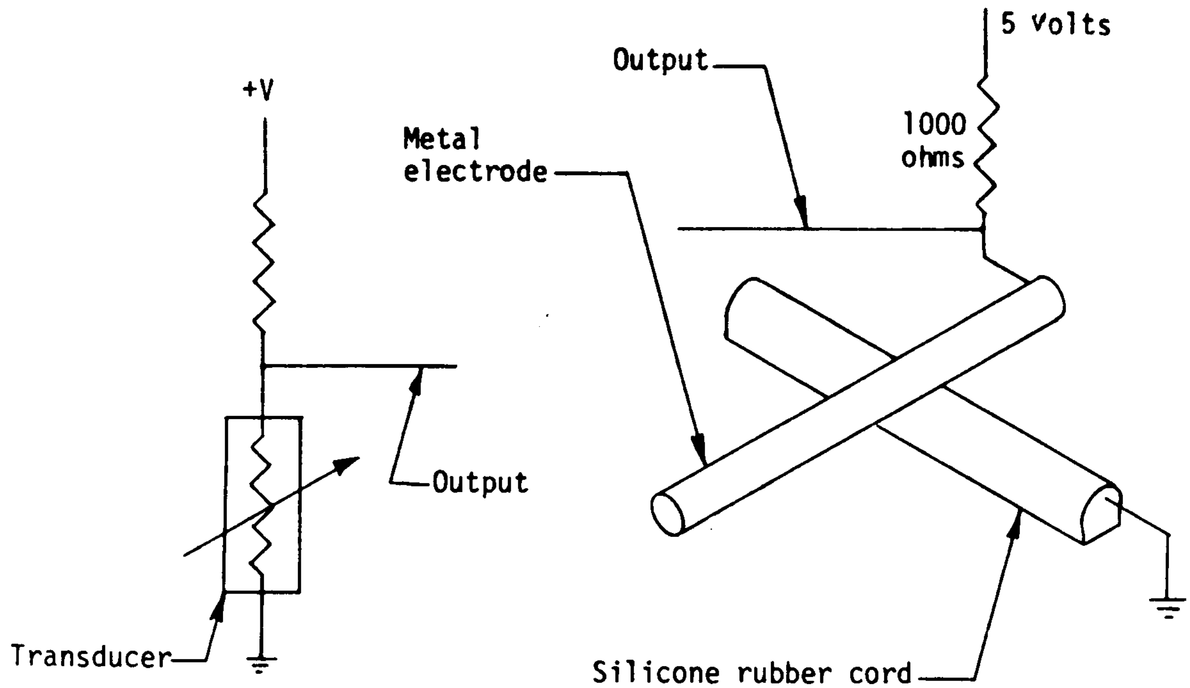
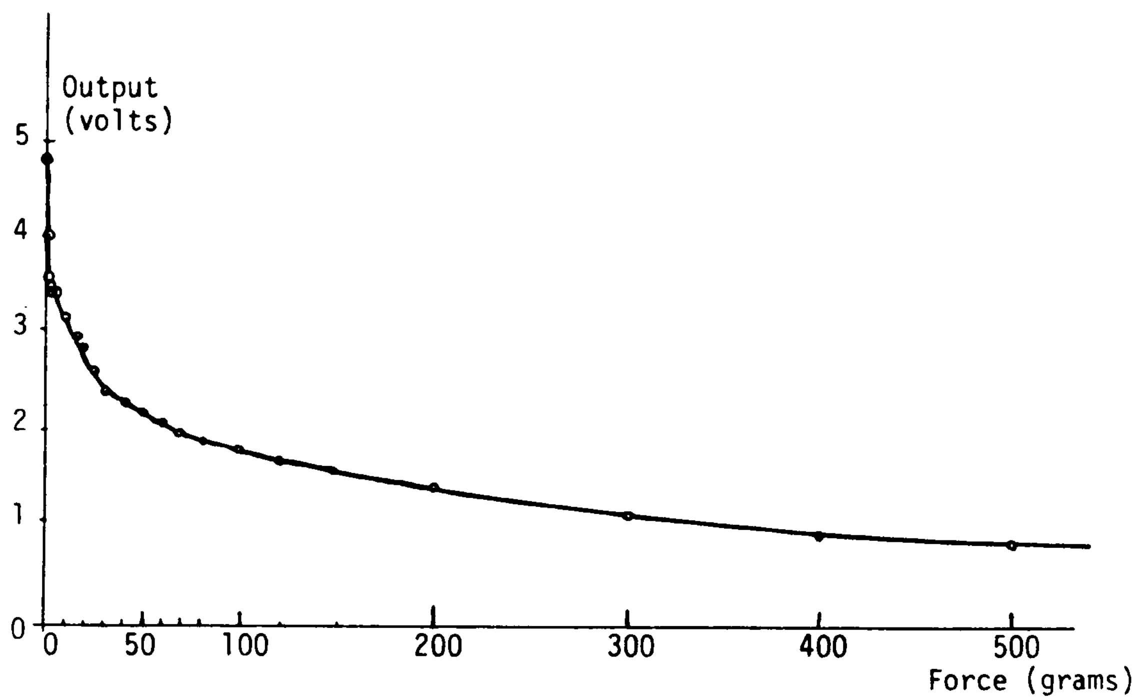


Figure 2-5: Output voltage verses applied pressure/force [4].



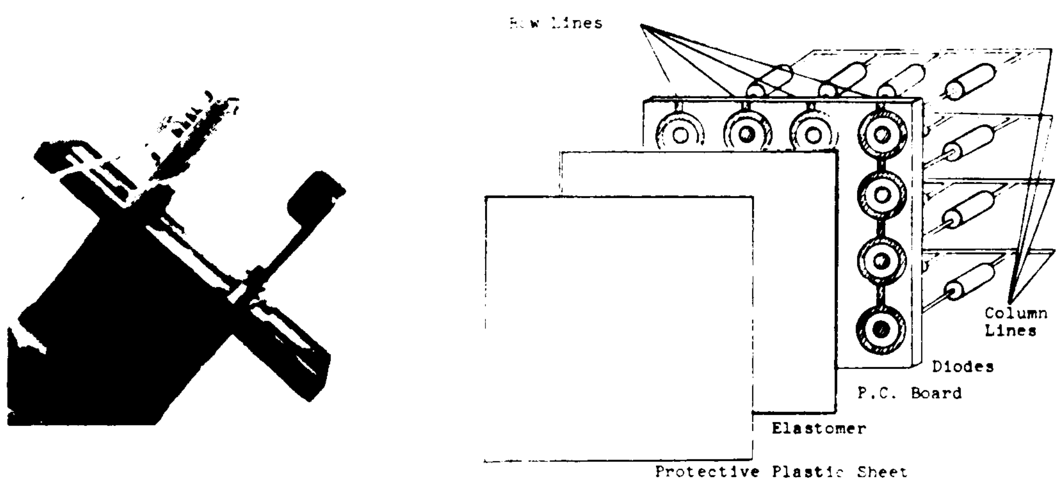
contact. The resistance of the rubber cord is about 500 Ohms per centimeter so contact must be made at frequent intervals along its length. The rubber cord isn't overloaded or damaged easily: it was subjected to a force of 10 Kg per cm of length without incurring any damage or change in operation [4].

The inventor suggests laying several metal wires across the rubber cord or making a matrix of wires and cords to form a sensor pad. A pad made only of rubber cords is attractive because it would be flexible as well as sensitive to pressure. Each point where two cords cross forms a tactile sensing element that can be tested by connecting the row cord to ground and the column cord to +5 volts via a fixed resistance. A computer can scan an array of almost any size automatically. For robotics use, the top cords of the sensing matrix are attached to a flexible nonconducting skin, while the bottom cords are bonded to some fixed surface.

2.1.5 Conductive Elastomer Sensors

The elastomer sensor (figure 2-6) consists of a sheet of elastomer placed over a printed circuit board etched with 16 pairs of concentric rings: Each pair of rings forms a sensing element. The outer rings are connected together to make four rows, and each inner ring is contacted through the printed circuit board and connected to the cathode (-) of a diode. The anodes (+) of the diodes are connected into four columns of four diodes apiece and each diode column is connected through a fixed resistor to +5 volts. The sheet of elastomer is attached to the printed circuit board with plastic tape.

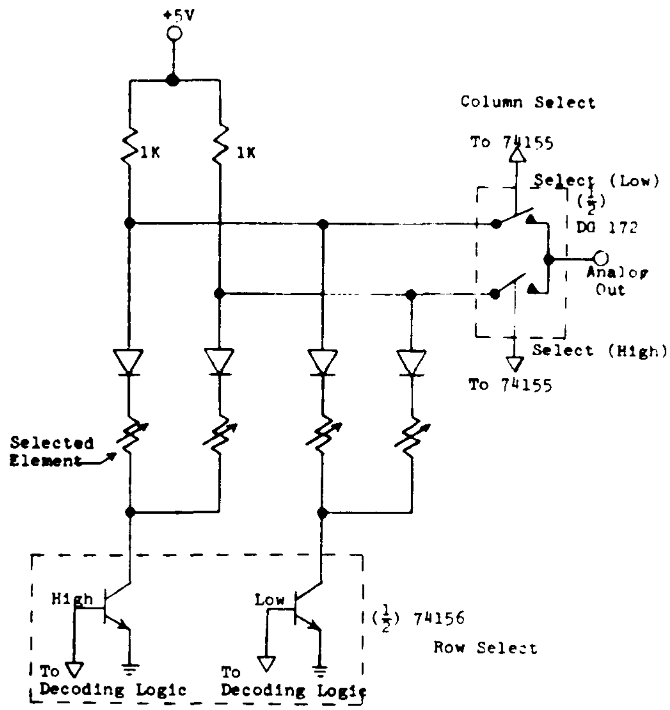
Figure 2-6: Elastomer sensor [5] copyright 1978 IEEE.



The device functions as follows: A row is chosen by grounding one of the sets of outer rings and leaving the other three rows floating. Current flows from the +5 volt Vcc through the four fixed resistors into the grounded outer rings. The elastomer forms a pressure variable resistor between the inner and outer rings of each element in series with the fixed resistor from Vcc. Together, the series resistors make a voltage divider whose output varies with the pressure on the elastomer. The column is selected by connecting the output of one of the elements to an analog to digital converter through a multiplexor driver (figure 2-7).

The inventor tested four different elastomers in the robot sensor: Dynacon A,B,C and MOS packing foam. Dynacon A, B, and C were made by Dynacon Industries [6] from metallic compounds mixed with silicon

Figure 2-7: The sensor circuit [5] copyright 1978 IEEE.



rubber. The fourth elastomer tested was conductive foam used to pack MOS components. MOS packing foam's resistance changes little with pressure, but it is still useful as a sensor because pressure brings the foam into better contact with the rings on the printed circuit board to make it conduct better.

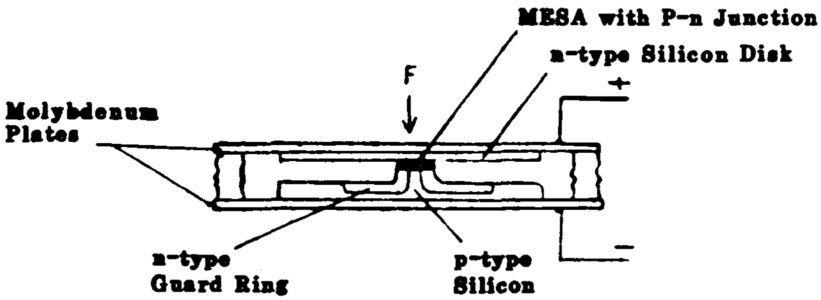
The biggest problem associated with elastomer sensors is that after several hundred operations the elastomer wears out. Every time the sensor is used, the elastomer presses against the printed circuit board, and sharp objects tend to cut the elastomer. After several hundred operations, cracks develop in the elastomer that cause its conductivity to fall to a level useless for pressure sensing. The sensor will not fail suddenly because the sensitivity of the elastomer declines slowly. The elastomer sheet is cheap and easy to replace, but checking the sensor and replacing the sheet periodically can be an annoyance. Scientists need tougher rubbers that can withstand many more operations.

2.1.6 The Piezodiode [7,8]

The piezodiode is a special p-n junction whose output is a linear function of the applied pressure. Pressure applied axial to the junction changes the reverse bias v-i characteristics of the diode.

The pressure sensing element consists of a piece of p-type silicon sandwiched between two molybdenum plates (figure 2-8). The transducer is a mesa diode mounted on the bottom plate and surrounded by an n-type silicon guard ring. A disk of n-type silicon bonded to the upper molybdenum plate acts as an ohmic contact for the n-type region of a shallow p-n junction on the upper surface of the mesa. The bottom molybdenum plate is the electrical contact for the p-type region. The p-type and n-type materials could be switched without radically changing the design, but the device would have to be operated with the opposite polarity to keep the junction reverse biased. The diode should be operated under reverse bias with a small constant current (approximately 100 microamps). The voltage across the diode is then a linear function of the pressure applied to the junction over a certain pressure range.

Figure 2-8: Close up of the piezodiode [7].



The piezodiode was patented in 1967 [7] and in 1970 the same inventor patented [8] a mechanical hand that used piezodiodes as tactile sensing elements. The hand was meant for prosthetic and robotic use and could grasp odd shaped articles of varying fragility. Neither the hand nor the piezodiode have been used much for robotics since no information except the patent is available on them. Such a linear output pressure sensor has a high potential for meeting many robotic sensing needs.

2.1.7 Strain Gauge Force and Torque Sensor

Two metal rings connected by several thin strips of metal or wire form this force sensor. The rings and wires are made of Aluminum to avoid a force hysteresis problem. Strain gauges mounted on the thin metal strips serve as the force transducers for the device. When the sensor experiences a force or torque, the thin pieces of metal deform and the strain gauges detect the change in dimension. A mechanical strain gauge must be connected to a potentiometer to obtain an electrical output signal, but a semiconductor strain gauge requires no potentiometer and may be connected directly to the sensing circuit.

The sensor's base ring is connected to a core with four thin Aluminum strips that resemble the spokes of a wheel. Four metal supports connect the core to an upper ring. A pair of strain gauges is mounted on each of the eight sensing elements: four spokes and four supports. Almost any range of force measurement can be realized by changing the dimensions of the sensor. Sensors capable of measuring pressures in the range of 0.1 - 10 kilopascal and 1 - 200 kp are currently being tested with a robot [9].

A robot can use the sensors two ways: They can be mounted in each finger of a gripper or between the robot arm and the hand/gripper at the "wrist" of the robot. Finger mounted sensors usually measure the force with which a robot hand is gripping an object. Wrist mounted sensors measure all forces present except the gripping strength: The weight of the robot hand is included in all measurements and must be subtracted by the computer. An industrial robot that assembles simple oil pumps uses a wrist mounted force and torque sensor [9]. For this task the torque sensing function was crucial because the robot had to screw parts together.

2.2 Proximity or Displacement Sensing

Contact proximity sensors function as follows: A rod protrudes from the sensor, and motion of the robot toward a target object pushes the rod back inside its housing. The distance to the object in question is the amount that the rod is pushed back inside subtracted from the length of the rod. Displacement sensors operate by registering the final position of the rod after motion in either direction. The displacement can be from the rod moving relative to a fixed robot or from the robot moving along a stationary rod. The average velocity of this motion may also be determined by dividing the displacement by the elapsed time. Many different techniques exist for detecting the position of the rod after it moves relative to the robot or the sensor. Potentiometers will be discussed in section 2.2.2 and optical and magnetic means will be discussed in the noncontact section.

Rods can be used to measure more than just a single distance. A three dimensional profile of specific objects can be produced with rods in two ways: an array of many rods can be placed on the target surface or a single rod can be moved about on the target surface. Robotic sensors have been built that use both methods.

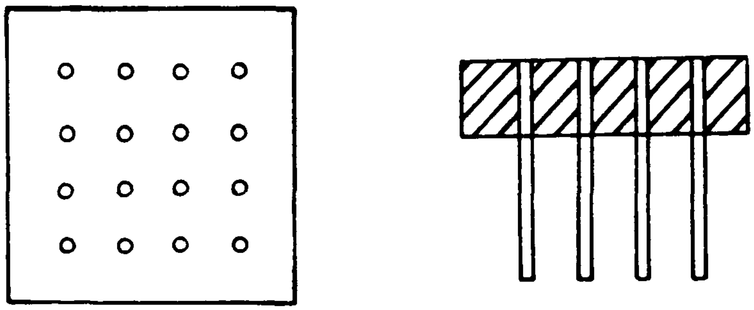
Potentiometers can measure the angular displacement of a rotating shaft and also the linear displacement of a rod. Almost any output function of displacement can be realized as result of custom design and fabrication.

The following sections describe actual robotic sensing devices.

2.2.1 3-D Tactile Sensor

This robotic sensor consists of a rigid mount with a square matrix of holes drilled in it perpendicular to the plain of the mount (figure 2-9). A thin ferrous rod is inserted into each hole with its top flush with the upper surface of the mount. The rods fit snug enough so that they can't slide out without an applied force, but not so snug that they won't slide easily when pushed upon. During sensing operations, the sensor assembly is lowered onto an object with the plane of the mount kept parallel to the plane of the working area. The rods move upward through their respective holes according to the contours of the specimen. The amount that each rod sticks out above the upper surface of the mount provides a measure of the relative heights of the contours of the object in question.

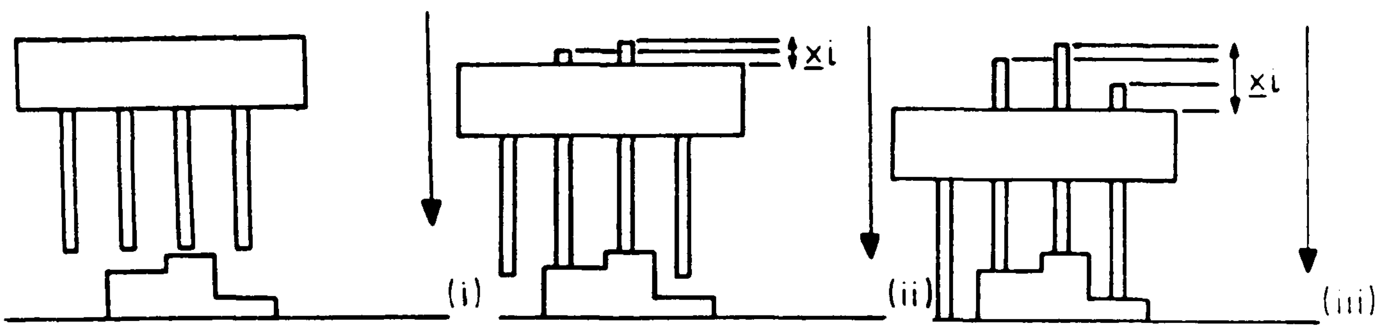
Figure 2-9: Construction of the 3-D Tactile Sensor [10].



The height of the bottom of the sensor mount is constantly measured as the whole device is lowered onto an object. The height registered when each probe first moves by more than a tiny amount from flush with the mount's upper surface defines the height of that portion of the object which happens to be under a particular rod of the device. This simplifies the displacement sensing of each rod to a binary function: movement or no movement.

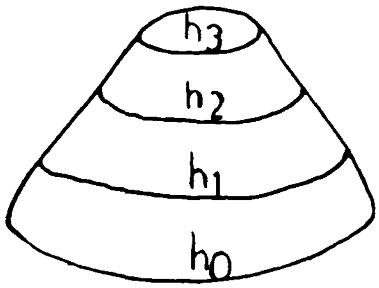
The operation of the sensor takes place in three parts: First is the lowering of the whole assembly while constantly monitoring its height (figure 2-10). Second is the sampling of the probe states: displacement or no displacement. Third is the correlation of the data into a table of the object's profile. Figure 2-11 [10] illustrates the correlation between contour lines and tactile sensor data.

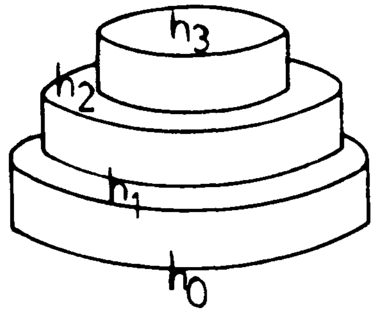
Figure 2-10: Sensor as it is lowered onto a target [10].



The inventors of the 3-D tactile device later suggest detecting any displacement of the rods with a coupled magnetic field [11]. This detection scheme limits the metal rods to only ferrous materials. The coupled field detection scheme will be discussed in section 3.3.5. Another group has developed a similar device that uses a potentiometer to determine the amount that each rod has been displaced (figure 2-12). Since the position of each rod is measured, monitoring the height of the assembly above the working surface is no longer necessary.

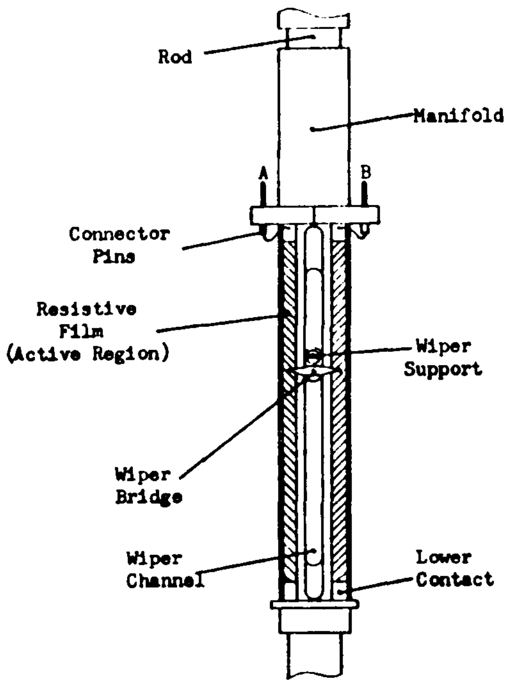
Figure 2-11: A - Object contour lines [10]. B - Tactile sensor data [10].

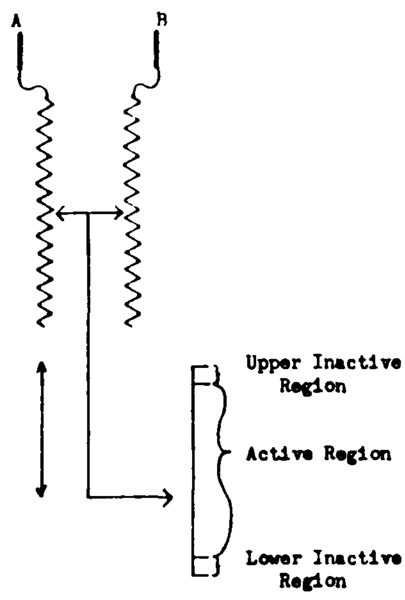




Each of the rods moves upward inside a tube when it is displaced by an object. Two linear resistive strips of film are attached to the inner surface of each tube. A conducting wiper connected to each rod with a nonconducting support forms an electrical connection between the two resistive films. As the rod pushes the wiper upward in the tube, less and less of the resistive film is in the sensing circuit. The variable resistance formed by the two films is connected in series with a fixed resistor to form a voltage divider, and the sensor forms an array of these dividers. The output of each divider is linearly proportional to the position of each rod within its respective tube. The device has an output voltage of 0 to 8 volts d.c. for each rod [12].

Figure 2-12: The potentiometer detection system [12].



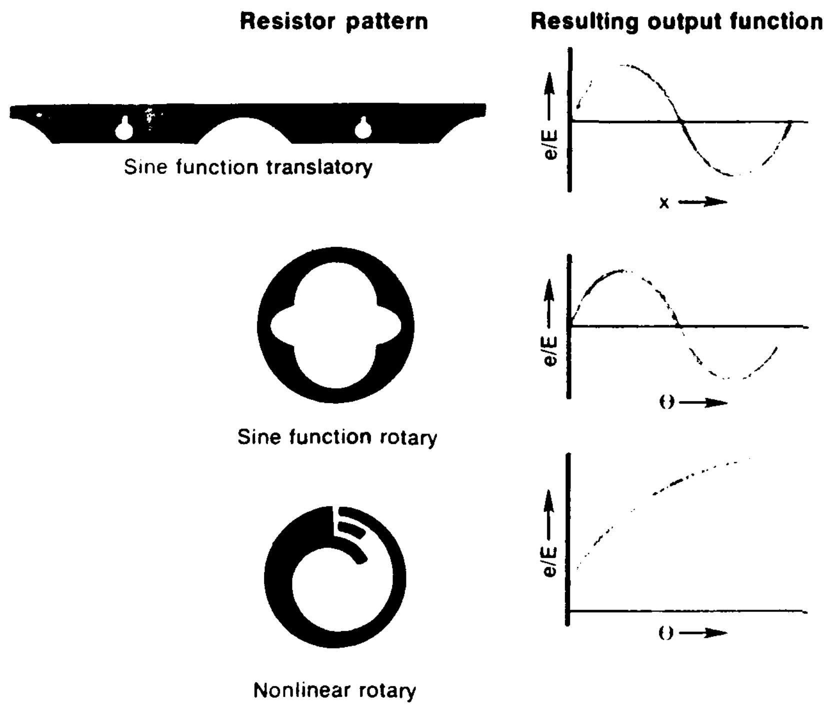


2.2.2 Potentiometers as Sensors

In a potentiometer position sensor, a conductive slide moves back and forth over resistive material, and the slide position determines the output voltage. Displacements are registered by the motion of a slide over a straight track for linear motion and over a circular track for rotary motion. Some newer devices use conductive plastic resistors because they cure at high temperatures and are more temperature stable than carbon resistors. Plastic resistors produce little wear on metal slides compared to the ceramic and metal resistors once used.

Some position sensors rely on carbon film resistances to produce sinusoidal, logarithmic, and other signals through changes in the width of the resistive material. The output changes because resistance is proportional to the dimensions of the material. Modified secants, modified tangents, and many arbitrary functions have been produced by specially made potentiometers (figure 2-13).

Figure 2-13: Some common output functions and their resistance patterns [13].



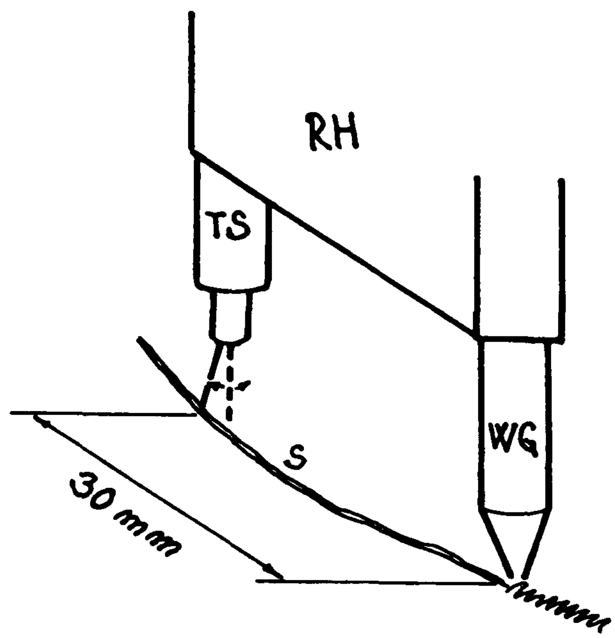
Potentiometers have potential use in robotic displacement sensing of rods and the like. A version of the 3-D sensor in section 2.2.1 relies on potentiometers for displacement measurement. Angular displacement potentiometers could be useful in monitoring the rotation of a robot or its arm.

2.2.3 Tactile Welding Seam Trackers

The four tactile devices described here use a single tactile finger or needle to detect the weld seam for an arc welding robot. Three of the devices are active and one is passive: Active devices move and monitor the needle constantly while passive ones allow the needle to be guided by the weld seam.

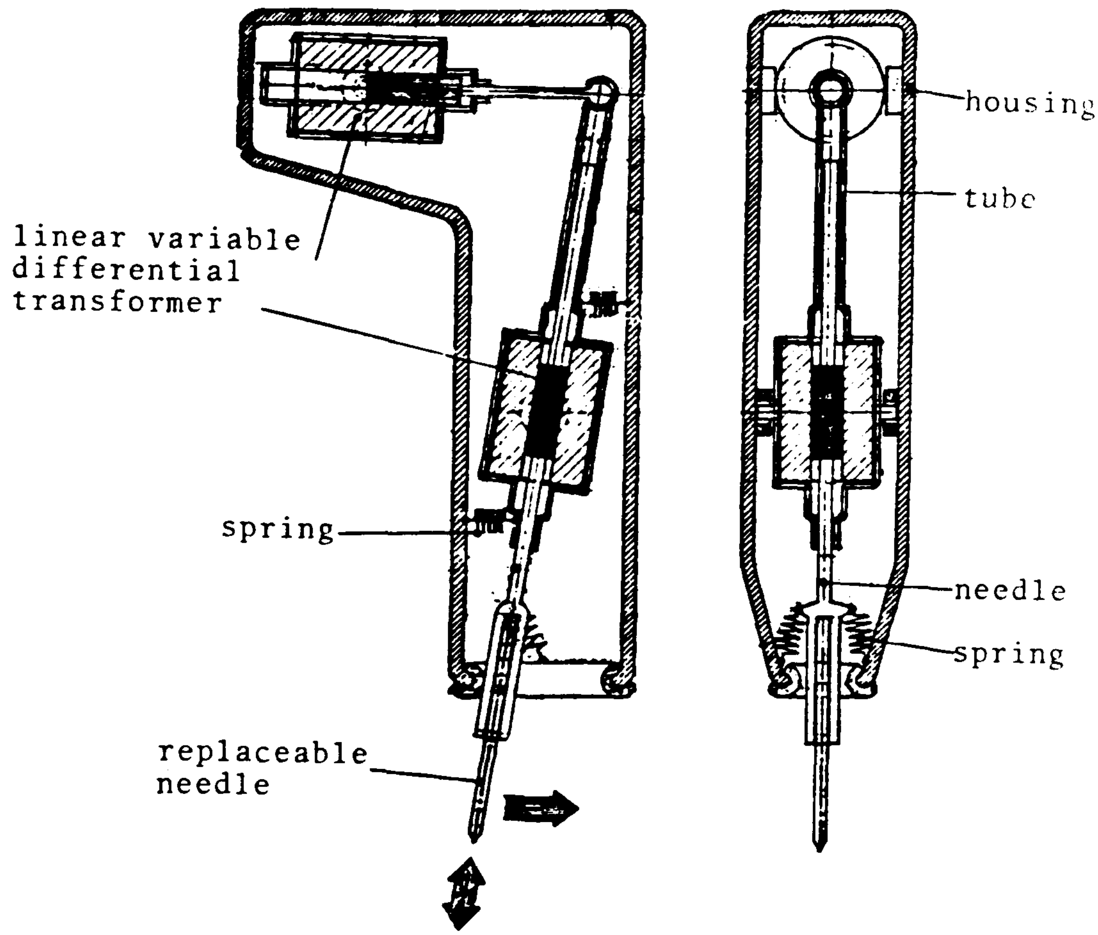
The first sensor (figure 2-14) consists of a needle rested on the welding surface three centimeters in front of the welding gun that is dragged from side to side across the weld seam. When the needle hits the weld seam it is pushed up or allowed to fall down depending on the seam. Optical sensors (section 3.1) detect the orientation and position of the needle at all times.

Figure 2-14: Simple active tactile seam tracker [14].



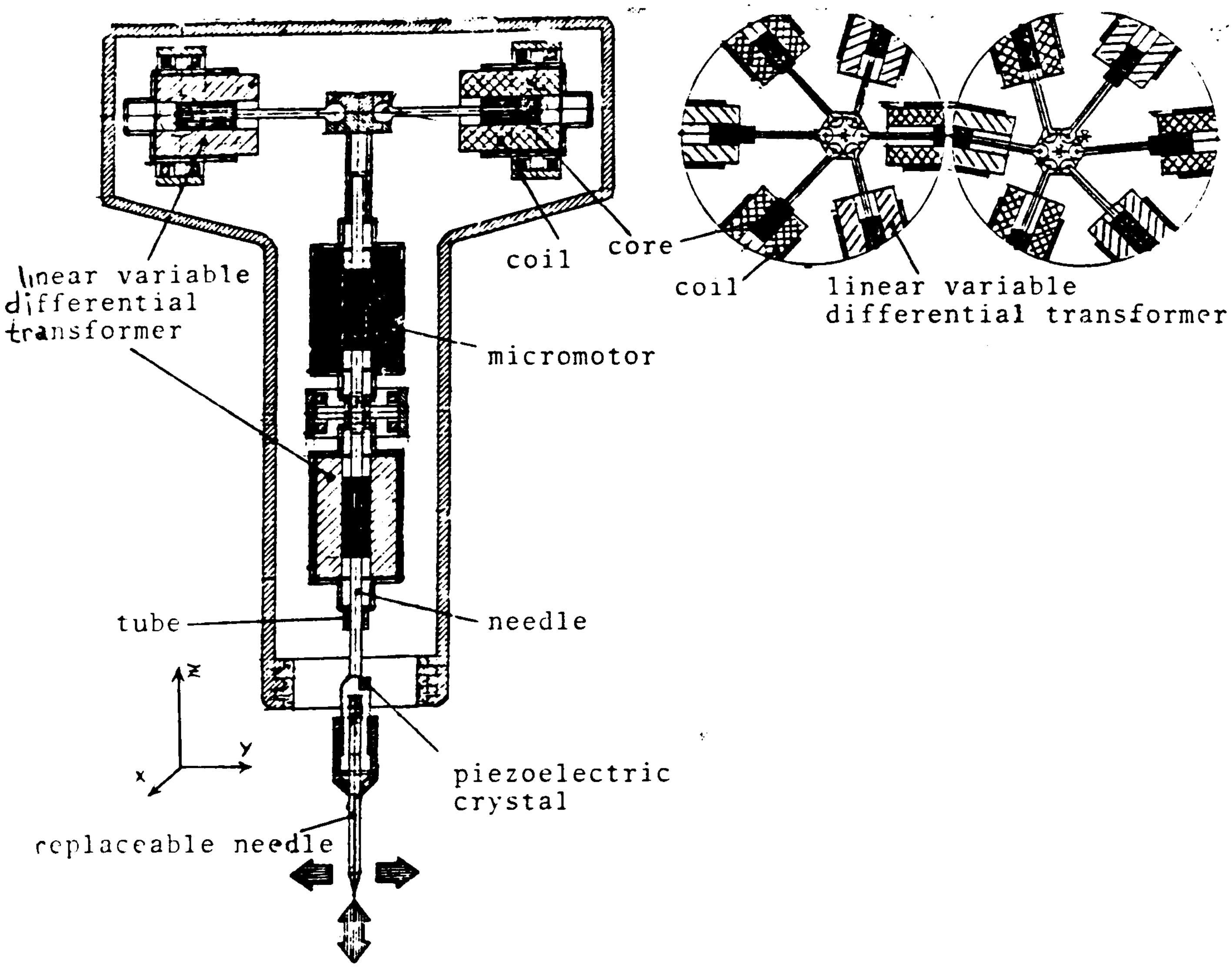
The next sensor is a passive device that has two passive degrees of freedom (figure 2-15) As the robot moves its arm along the trajectory of the seam, the measuring needle is pulled along the actual seam and guided by it. Springs inside the sensor serve for passive positioning of the needle into the seam, and linear variable differential transformers (section 3.2.10) measure the needle's displacement at equal time intervals as it moves along. The advantages of this passive sensor are its speed, robustness, accuracy, and simplicity. This model also has problems: The sensor is one sided so it must be rotated 180 degrees to make measurements on the opposite side. The device has difficulties with rough seam surfaces because it must be dragged in the seam, but the problem can be solved by mounting a small wheel or ball on the end of the needle.

Figure 2-15: Passive seam tracker with two degrees of freedom [15].



An improvement over the passive sensor is an active device with three degrees of freedom that uses the discrete seam tracking method (figure 2-16). In discrete tracking, the needle moves up and down, hitting the welding surface. A robot using the sensor moves its welding arm and the device together along the seam. Each time the needle hits the welding surface, its position is recorded. A piezoelectric crystal sensitive to the shock caused by the needle hitting something activates the reading of the needle's position. A 9.8 watt micromotor weighing 180 grams moves the needle about the z axis, and electromagnetic force from three iron cores connected to the needle move it in the x-y plane. Displacement in all directions is measured with linear variable differential transformers (section 3.2.10). This sensor has several advantages over the passive device: It is more flexible and has three degrees of freedom. The sensor is not sensitive to rough surfaces because it uses the discrete tracking method. The device also has many problems: The sensor is not robust, and its iron cores constitute a large mass to be moved. A great deal of energy is required to move the needle because the additional force of friction between the coils and the cores must be overcome. If the sensor moves too close to the welding surface, the needle will not have enough room to move; and if the sensor moves too far from the surface, the needle may not hit the target. When welding curved objects, both of these can be a problem.

Figure 2-16: Active seam tracker with 3 degrees of freedom [15].



An active sensor that has a small servomotor to adjust the distance between itself and the welding surface is an improvement over the last two devices (figure 2-17). Welding curved surfaces is not a problem because the sensor is kept a constant distance from the target object. The time between when measurements are activated and when the needle touches the object is measured and kept constant by moving the sensor toward or away from the target. Displacement in the z direction is measured with a linear variable differential transformer fixed to the tube that contains the needle. A micromotor such as the one in the previous device moves the needle in the z direction, and movement in the x-y plane is controlled by a less frictional positioning of coils. Capacitor plates (section 3.3) mounted inside the sensor measure displacement in the x-y plane. The capacitance change is nonlinear with displacement, but if a microprocessor is used with the sensor this is not a problem. This sensor has all the advantages of the last one, plus two more: The needle moves faster and requires less energy because the coils have less mass. The capacitive displacement sensor involves no friction, but it is sensitive to a polluted industrial environment. The capacitor plates must be shielded or cleaned frequently because films building up on the plates change their capacitance.

The first two sensors in this section are continuous seam trackers that drag the needle along the welding surface. The last two sensors are discrete seam trackers, in which the needle moves out of the sensor box toward the seam at a frequency of about 10 Hz. In discrete tracking, the needle is guided to the surface in a zig-zag trajectory and the needle's exact position is measured every time it hits the surface. By analyzing the collected data a microprocessor can calculate the seam trajectory. Rough surfaces and seams present no problems for discrete seam trackers and they can detect large seam gaps easily. In places where large seam gaps are thought to occur, the density of measurements is increased to obtain a two dimensional picture of the seam. The gap width can be calculated from the two dimensional data, and the speed and amplitude of zig-zag welding can be automatically calculated from the gap width.

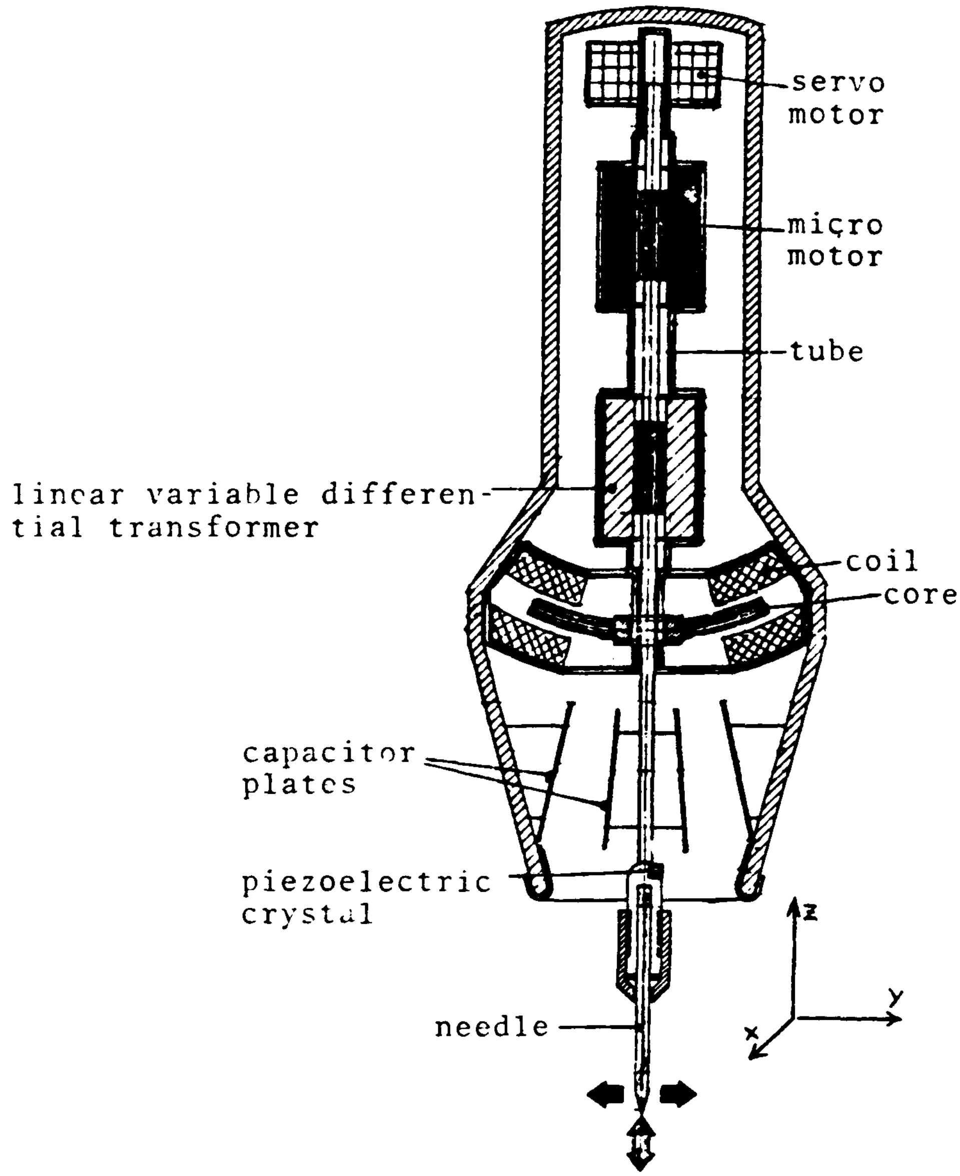
2.3 Slip Sensing

The function of slip sensing is to determine whether an object is sliding out of an artificial hand or robot gripper. If an object starts to slide out of a pair of grippers, the gripping force is not strong enough. A robot can be prevented from dropping an object if the pressure of its grip is increased until all slipping stops.

Slip sensors are used as follows: The robot grips an object lightly, and when the object begins to slip out of the grippers, its movement is registered and the gripping pressure is increased until all movement stops. Any time slippage is detected again during the operation, the pressure is increased again: The robot has little chance of dropping even slippery items. This technique is also good for fragile items because the robot uses only the minimum pressure required to hold them.

Slip sensing is based on detecting the first minute movement of the object held in the grippers. Three methods are currently available to detect movement: The first is to press a needle against an object that oscillates when the object moves. The second method is to translate the object's motion into another form of

Figure 2-17: Improved active seam tracker [15].

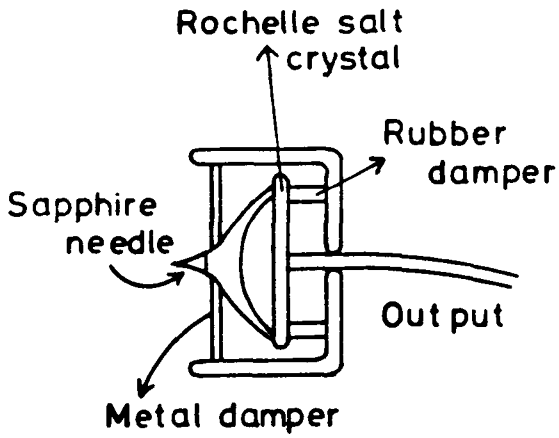


displacement with a cylindrical roller or a sphere. The third method is to detect changes in the grasping pressure distribution of the fingers with pressure sensors. See section 2.1 for a discussion of pressure sensors.

2.3.1 Tactile Slip Sensors for Industrial Robots

Slip sensing by detecting a forced oscillation due to the roughness of the surface of a moving object is in principle analogous to a record player: The needle-like part of the sensor oscillates in analogy to a phonograph needle. One such forced oscillation sensor (figure 2-18) consists of a sapphire needle attached to the front of a rochelle salt crystal mounted on a rubber damper. The rubber eliminates noise and the sapphire needle detects the surface roughness of the object when it moves. A slipping object causes the sensor to generate a voltage spike (figure 2-19) that is amplified and then used to trigger a flip-flop that controls the robot's finger motors. This sensor is simple and inexpensive, but the sapphire needle is fragile. A steel ball replaces the sapphire needle in an improved version of the sensor (figure 2-20). An oil damper increases the strength further and eliminates more noise. The inventors suggest that operational vibrations be kept to a minimum when using forced oscillation slip sensors because at times they cannot determine the difference between slippage and operational vibration.

Figure 2-18: Sapphire needle slip sensor [16].



Another slip sensor translates the slip motion into an angular displacement with a cylindrical roller. The roller should be covered by an elastic coating with a large coefficient of friction so that it rolls with the motion of the object. Many different motion transducers and analog to digital converters may be used with roller type sensors. Two sensors are specified here: The first uses magnetic head such as one in a tape recorder as a transducer (figure 2-21). The roller has a permanent magnet embedded in it in one spot. In its reset position, the magnet is directly over the magnetic head, but when a slip occurs, the roller rotates the magnet away from the head. Unfortunately, if a second slip occurs before the sensor is reset it will go undetected. The second roller type slip sensor (figure 2-22) has an optical transducer. A slit made in the roller allows light from a lamp or an LED to pass through the roller to a photodiode. A slipping item rotates the slit away from the lamp and photodetector blocking the detector from the light source. Multiple slips also trouble this sensor, but the problem can be solved by cutting multiple slits in the roller.

Figure 2-19: Sapphire needle sensor output [16].

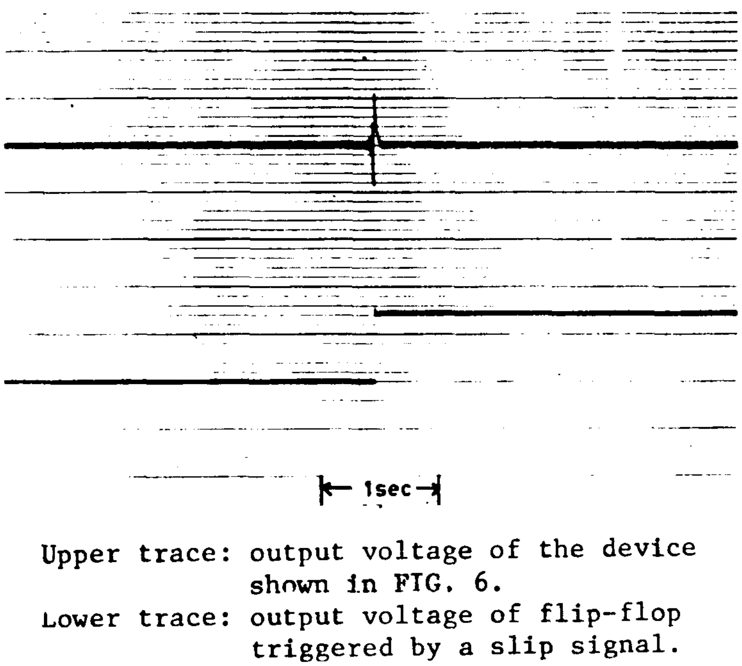
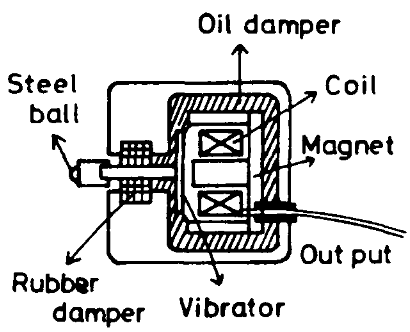


Figure 2-20: Improved forced oscillation slip sensor [16].



2.3.2 Slip Sensors from the Belgrade Hand

The Belgrade hand is a prosthetic device developed to enable handicapped people to grasp a variety of objects. It physically resembles a human hand and has a slip sensor on each thumb. Both forced oscillation and roller type sensors have been tested in the hand.

The first sensor tested in the hand (figure 2-23) has a vibrating needle and a roller. A slipping object rotates

Figure 2-21: Roller type slip sensor with magnetic transducer [16].

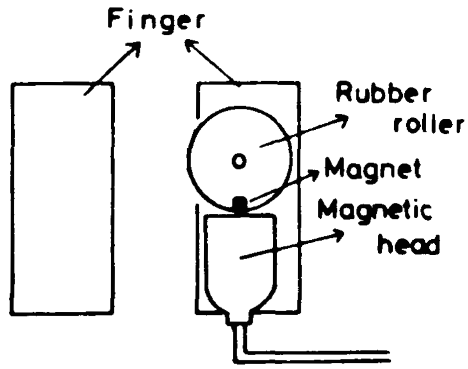
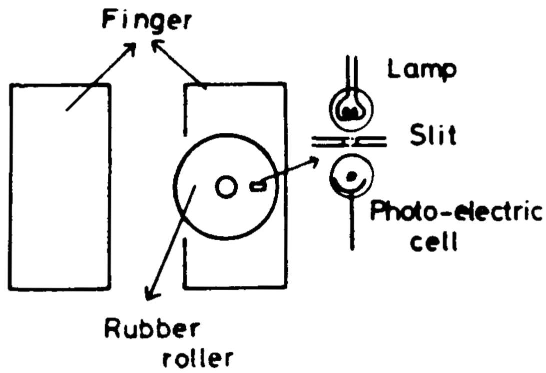


Figure 2-22: Roller type slip sensor with optical transducer [16].



a small rough roller sticking out of the contact surface. A needle pressed against the roller oscillates when the roller rotates. The needle and the sensing circuit produce frequency modulated output signals that provide information about the slippage. This device is hard to miniaturize and will not function unless the slippage force act in the plane of the roller.

The second sensor tested in the hand (figure 2-24) is similar to the forced oscillation sensors in the last section. It consists of a small needle sticking out of the contact surface that is driven into oscillations by the roughness of the slipping object's surface. The stiffness of the needle and the diameter of the hole it sticks out of determine the device's signal to noise ratio. The sensor is easy to miniaturize but it can only operate under slight pressures because the needle will not oscillate if subjected to a strong tangential force in one direction.

The main part of the final sensor developed for the hand is a small conducting ball partially covered with

Figure 2-23: First developed Belgrade Hand slip sensor [17].

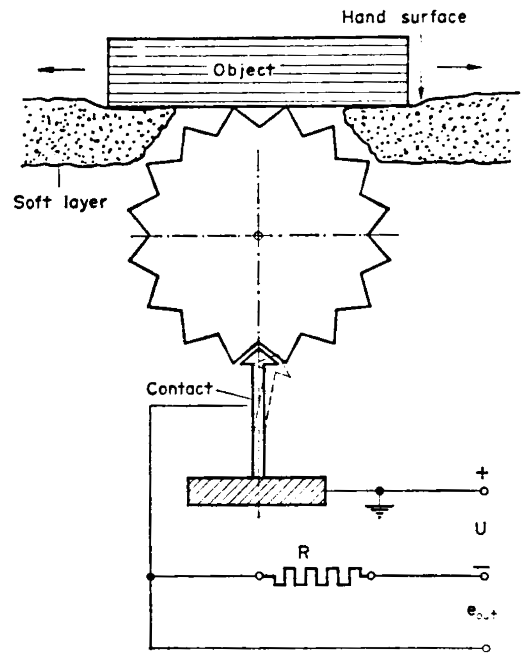
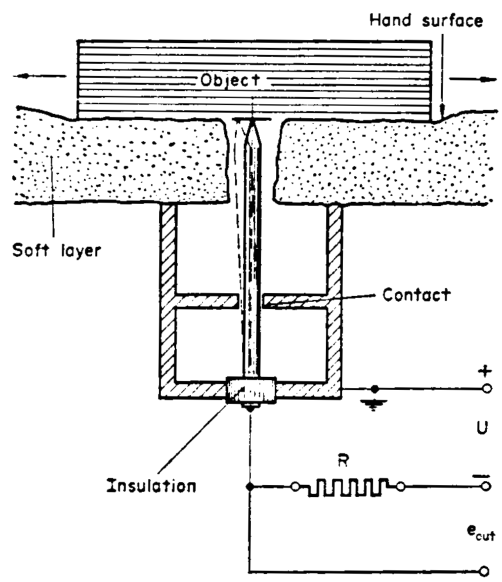
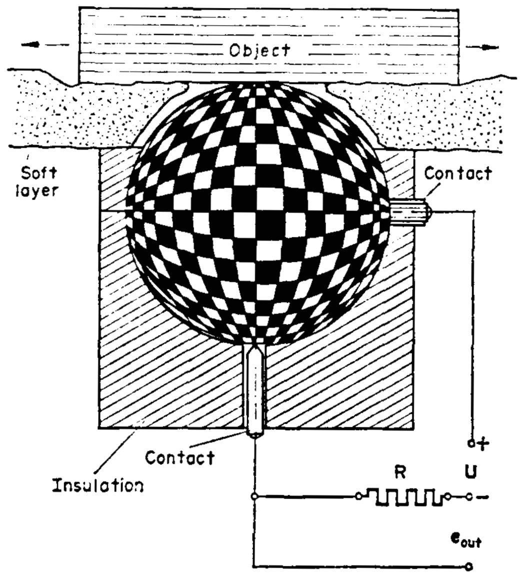


Figure 2-24: Second Belgrade Hand slip sensor [17].



non-conducting fields like a chess board (figure 2-25). Two contacts with areas smaller than the basic field are applied at arbitrary points on the ball. If the ball is set into motion in any direction between zero degrees and 360 degrees, the transducer produces frequency modulated pulses. The sensor can be easily miniaturized and can detect slip in any direction. The ball is not very sensitive to mechanical noise because it cannot be set into motion by vibration or shocks. The device becomes more sensitive with decreasing ball size and decreasing field area.

Figure 2-25: Slip sensor used in the Belgrade Hand [17].



3. Noncontact Sensors

Since almost every type of noncontact sensor can measure many different physical quantities, they are divided into groups according to their principles of operation. Six types of noncontact sensors according to operating principles are: visual, magnetic or inductive, capacitive, resistive, ultrasound, and air pressure, as described in separate sections below.

3.1 Visual and Optical Sensors

Visual and optical sensors operate by transforming light into an electrical signal. The photodetectors can be as simple as a single photodiode or as complex as a television camera. With stereo cameras, a robotic vision systems are analogous to the human sense of sight.

The simplest optical sensor consists of a single source and a single detector. Much like a mechanical switch, it only detects whether something is blocking the source or not. When an object moves between the detector and the light source, the sensor registers an item present. This type of sensor is not good for transparent items, because as long as the detector receives light from the source it will register nothing present. Single source/detector systems can function as detectors for contacting sensors with rods: When a rod moves, it can be made to block the light between source and detector. Optical encoders use the blocked light principle to measure linear and angular displacement and average velocity. Specialized detectors which detect infrared light can sense the temperature of hot objects. The benefits of single source/detector sensors are low cost and simplicity.

Optical proximity sensors use reflected light from lasers and other specialized light sources to measure the distance to objects. Proximity may be determined by triangulation, or if a laser is used, by the phase difference between the incoming and outgoing light. Sources and detectors set at certain angles from the plane normal to the object measure proximity via the amount of reflected light received, and the entire surface of the target object may be scanned by light reflected from special rotating mirrors. Solid state devices, called planar diodes, can determine the position of a spot of light on their surface. Researchers have obtained a two dimensional image of a target object from a planar diode using a very complicated algorithm. Light may be conducted from source to detector via lenses, mirrors, or fiber optics.

The most complex optical sensors are image sensors that allow robots to see their environment and recognize items. With multiple cameras and computer algorithms, data for three dimensional profiles of objects can be obtained. Both vacuum tube (television camera) and solid state imaging devices are available. The most common components of solid state imagers are linear and two dimensional arrays of photodiodes, charge injection devices, and charge coupled devices. Lighting techniques and material properties must be taken into account when using image sensors: Substances such as hot metal require no external lighting source. Specialized imagers that detect infrared light provide temperature profiles of hot items.

3.1.1 Closed Circuit Television Sensors

The sensing element of the camera is a vacuum tube, called a vidicon, with a thin target plate coated with photoconductive material at the front. An electron beam deflected by a magnetic field, just as in a television picture tube, scans the rear of the target plate. The scanning builds up a charge on the back of the plate. Any light entering the front of the vidicon tube and striking the front of the target plate causes some of the built up charge to leak away. The amount of beam current needed to replace the lost charge is proportional to the amount of light striking a particular section of the target screen. Changes in the beam current as the beam scans the target plate are amplified and transformed into a changing voltage that represents the image. The image can be displayed on a conventional television monitor.

Vidicons are currently made with two types of target plate materials: Antimony trisulfide (Sb_2S_3) and silicon; the standard material is Antimony trisulfide. A standard vidicon is sensitive over the entire visual range of light, and the sensitivity can be changed by varying the target plate voltage in the tube. Some vidicon cameras have feedback circuits that automatically adjust the vidicon's sensitivity to accommodate different background lighting. Antimony trisulfide vidicons do not react instantly to changes in the image of received light: They have a lag time of about .2 seconds [18]. The newer silicon target plate vidicons react faster. Lag time is important because it limits the speed of moving objects sensed by a vidicon. The target speed can be increased by using a strobe light along with a vidicon camera.

A raster is the name for the scanning pattern one sees on a closed circuit television monitor. Scanning is done left to right at 15 kHz and top to bottom at 50 kHz, and a television field is made up of a single scan of 312.5 lines. The maximum frame speed is around .05 seconds per frame because the electron beam requires .05 (1/20) seconds to cover the whole monitor screen [18].

Closed circuit television cameras have advantages such as cost and ease of use but there are some problems: The electronic scanning has linearity errors up to 2 percent so the position of the detected image can be off by that much. Shading occurs when the edges of the image are darker than its center, but it is not a major problem with more expensive cameras. Vidicon closed circuit television cameras are limited to applications where very high quality measurements are not crucial, and this is the case for most robotics applications.

3.1.2 Solid State Imagers - Photodiode Arrays

Silicon photodiodes convert light energy into a photocurrent within the surface of the silicon. Photons of light striking the surface of the silicon generate electron hole pairs that collect at the p-n junctions of the photodiodes. The junctions can be represented as capacitors discharged by the collection of electron hole pairs. The diodes in an array have overlapping sensitivities so any image can be represented in an electrical form without discontinuities. Large two dimensional arrays and linear arrays of photodiodes are available with up to 2048 diodes in a single line for imaging[19].

A robot sensor [19] has an ordinary camera with a two dimensional array of photodiodes or PIN diodes put in place of the film plane. The array is square with 256 diodes on a side and is manufactured with a clock all on one integrated circuit chip. The entire array is scanned every clock cycle, and when each diode is in turn connected to the video line its capacitance charges to the potential of the video line. The diodes are then left open circuited until the next scan and during this time they collect light. Each diode capacitor is discharged by the recombination of the optically generated minority carriers with the charge initially put on the diode by the video line. Every time the diode is sampled, the lost charge due to the received light must be replaced with current from the video line. The resulting video line current is a signal consisting of a train of charge pulses, proportional in magnitude to the light received by a corresponding photodiode.

The charge pulses are changed into a series of voltage pulses that can be used to form an image two ways: They can be put into a comparator or a digital to analog converter. The comparator determines which bits are light or dark and its output is made into a binary image. The digital to analog converter produces several bits that indicate the brightness of each spot: The image is constructed from various shades of gray. Arrays of photodiodes that are sensitive to infrared light can give a temperature profile of hot objects. Several lighting schemes are are used with the camera: Light may be shined directly on the object and reflected into the camera, or shined from behind the object, making the target's shadow the image. For hot metal no lighting source is required.

3.1.3 Solid State Imagers - Charge Injection Devices

Cameras may use arrays of charge injection devices (CID'S) instead of p-n junctions. A CID is a metal-oxide-semiconductor (MOS) device with multiple gates similar to a charge-coupled device. A negative gate voltage applied to each CID in an array creates a surface potential well. When photons of light are absorbed, minority charge carriers collect in the nearest potential well, and the configuration of the charge in all the wells is a point by point sampling of the light from the image. Removing the negative gate voltage from each device in the array injects the minority carriers generated by the light into the bulk of the semiconductor where they recombine with majority carriers at the substrate contact (figure 3-1): Hence the name charge injection device. The video signal is a current pulse in the external circuit caused by the recombination of carriers at the substrate contact. Each device in a two dimensional array requires two separate metal electrodes: One connected to a vertical access line and the other to a horizontal one. To discharge each CID, the horizontal and vertical gate voltages, must be set to zero. The CID image may be scanned (figure 3-2) or read out in parallel (figure 3-3).

Figure 3-1: Charge injection in the CID.

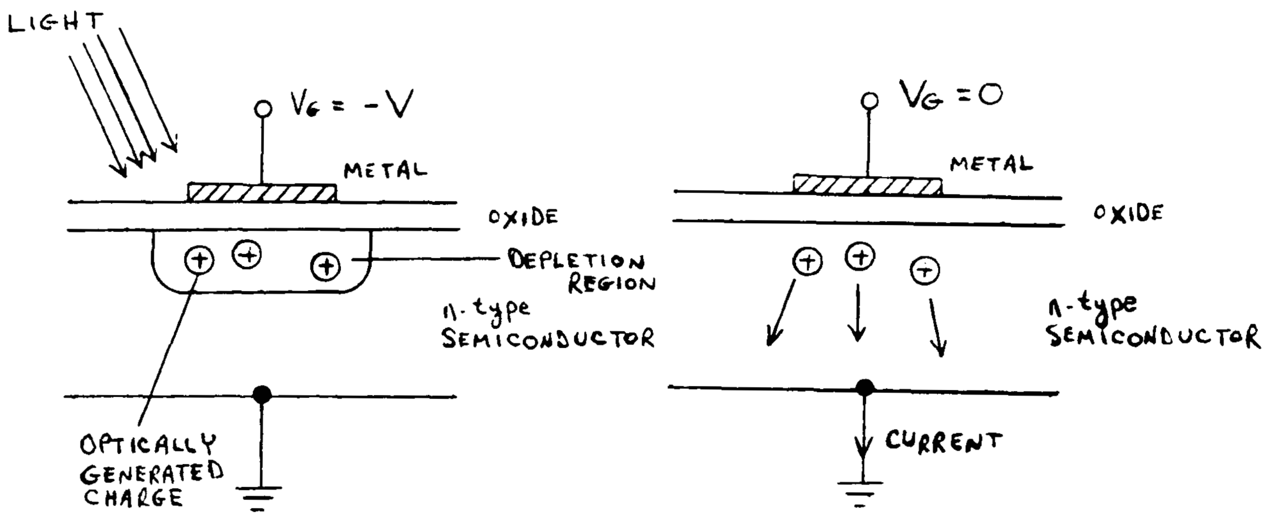


Figure 3-2: X-Y accessing scheme for a CID array [20].

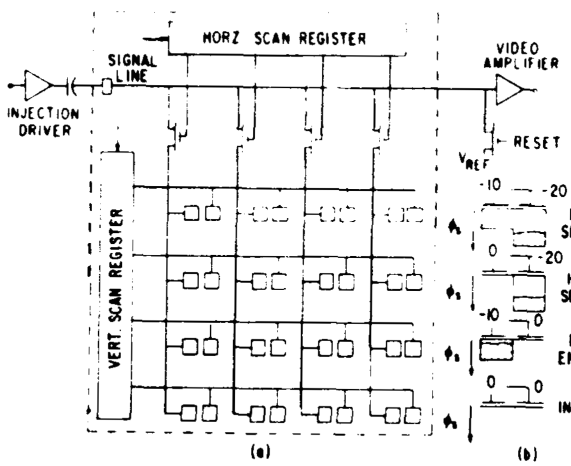
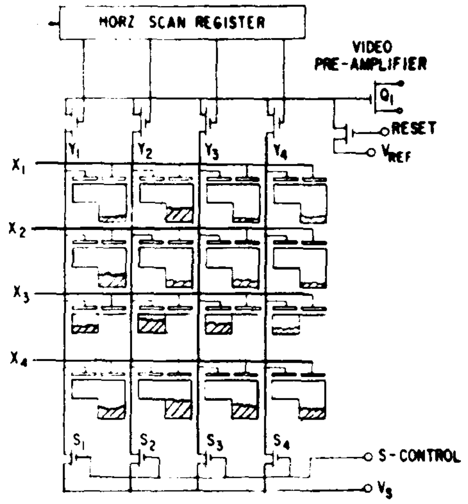


Diagram of basic *X-Y* accessing scheme for a CID imager. (a) Schematic diagram of a 4 × 4 array. (b) Sensing site cross section showing silicon surface potentials and location of stored charge for various operating conditions.

Figure 3-3: Parallel injection readout for a CID array [20] copyright 1977 IEEE.



Schematic diagram of a 4 × 4 CID array designed for parallel-injection readout. Silicon surface potentials and signal charge locations are included.

General Electric makes a television compatible charge injection device camera (Z7892 CID camera [21]) that has 244 rows with 188 charge injection elements per row. It produces a television image that provides a video signal for all raster lines of a 525-line, 30 frame per second television monitor.

3.1.4 Solid State Imagers - Charge-Coupled Devices

A charge-coupled device (CCD) is a MOS device similar to the charge injection device (figure 3-4), and it also collects optically generated charge in potential wells created by gate voltages. The difference between a CCD array and a CID array is the way in which the video signal is created: In a CID array, the charge is injected into the bulk of the semiconductor to create a current, but in a CCD array the optically generated charge itself forms the video signal. A charge-coupled device functions as an analog shift register: After charge is generated, it is shifted out through the array onto the video line. Both two and three phase registers are currently constructed from CCD's. In a two phase device (figure 3-5), a potential well is first created under all of the odd numbered gates, and an optically generated charge collects in it for a preset time. Then, the gate voltage is removed from all the odd gates trapping the charge in a small depletion region formed by the metal-semiconductor junction. The gate voltage is then applied to all the even numbered gates creating a deeper potential well under them than the small one due to contact: The charge flows "downhill" into the potential well under the even gates. Then, the voltage is removed from the even gates and reapplied to the odd gates causing the charge to flow under the odd gates again. Figure 3-6 [22] is a description of the shifting action of a three phase register. Images are not shifted out directly through the imaging array because the image would pass through areas where more light is being collected: Charge from the newly collected light blurs the image. To avoid blurring, all the rows of the image are shifted in parallel to another set of CCD shift registers, and then shifted serially onto the video line. The shifting registers are shielded from light, so the image stays clear.

Figure 3-4: A typical CCD [22] copyright 1977 IEEE.

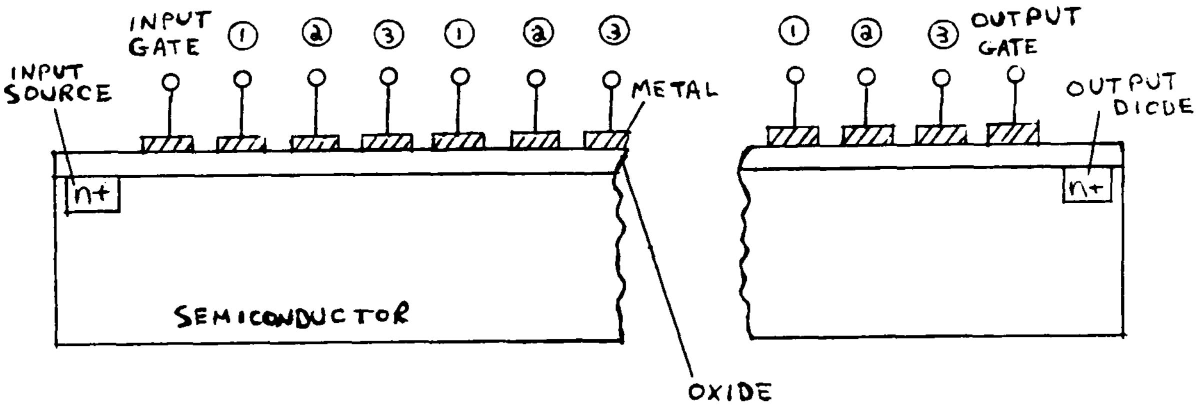
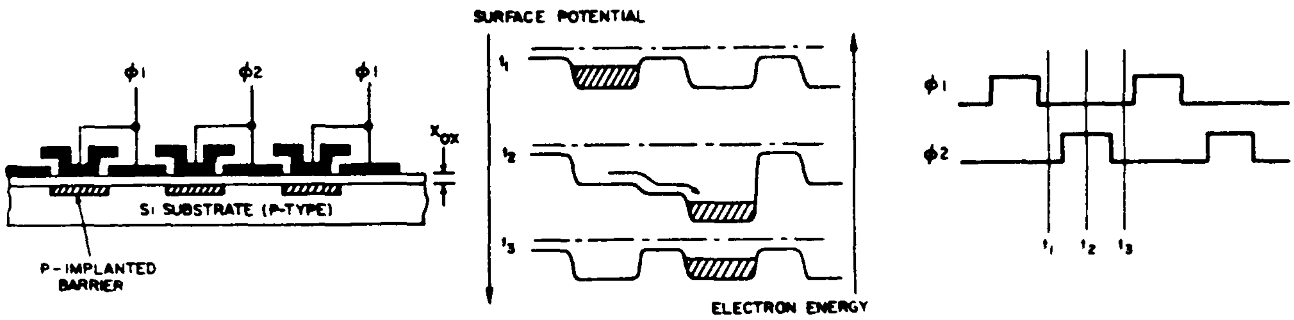
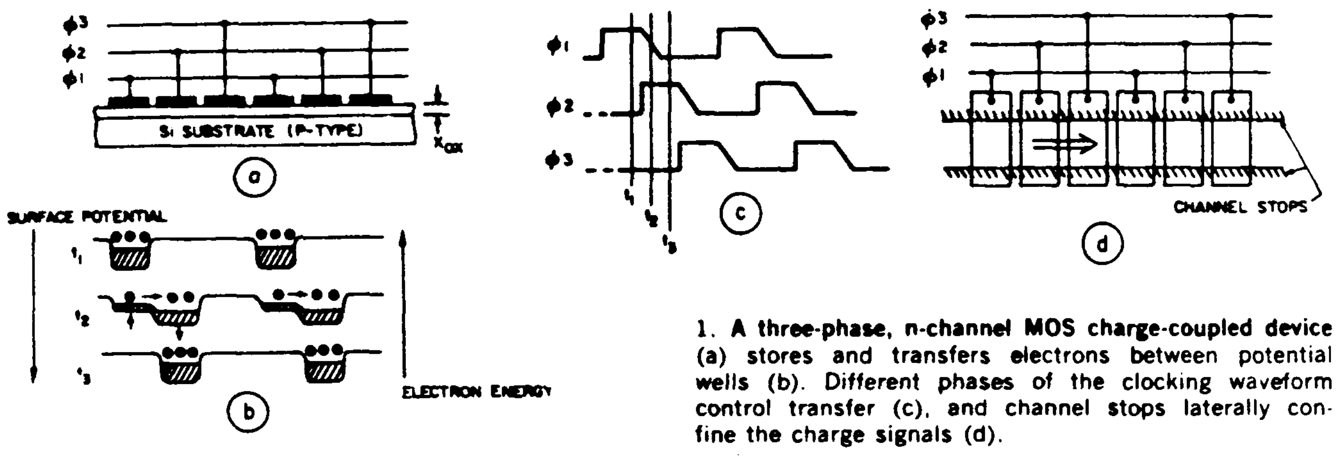


Figure 3-5: Action of a two phase CCD shift register [22] copyright 1977 IEEE.



Two manufacturers currently produce different charge-coupled device imagers: RCA and Fairchild. RCA's SID 51232 silicon imaging device [23] is intended for generating standard interlaced 525 television pictures. The device contains a 512 X 320 array of 3-phase n-channel silicon CCD's (figure 3-7). The image area is an array of charge-coupled devices containing 320 parallel vertical columns of 256 elements. Each element is a grouping of three adjacent gate electrodes in the vertical direction. Light striking the image area creates a pattern of charges on the image array that is transferred all at once to a 320 X 256 storage array. Once the image is in place in the storage area, a new one is created in the image area while the old one is shifted out of the storage area one row at a time for use. The storage area is covered from ambient light to prevent contamination of the image. Fairchild's CCD 211 imager [24] contains a 244 x 190 array of CCDs

Figure 3-6: Action of a three phase CCD shift register [22] copyright 1977 IEEE.



(figure 3-8). Between each of the 190 columns in the array is a CCD register called a vertical transport register. After a set light collection time, the charge in the image CCDs is transferred out of the array in two sequential fields of 122 lines each: Either the odd numbered lines or the even numbered ones are shifted out. Once the image has been transferred in parallel into the 190 vertical transport registers it is shifted one row at a time into a horizontal transport register, and from there each row is transferred serially to the video line. When the entire image in the odd rows has been moved out, the even image will be shifted and the odd elements will be enabled to collect light: One image is always formed while the other is transferred. Only the imaging elements are exposed to light: The transport registers are shielded. The device is made to approximate the image size of Super 8 movie lenses, and it can be used with most low power video cameras.

3.1.5 The Planar Diode - Analog Position Sensor

This sensing device uses a light sensitive planar diode [26] (figure 3-9) and LEDs to measure distances. The position sensing chip has four terminals: one on the positive and negative sides of both the vertical and horizontal axes. A beam of light striking the planar diode generates charge carriers, and the movement of the carriers constitutes a current. The resistance that the current sees between where it was generated and each of the four electrodes on the axes depends on how much of the semiconductor material is between the current and each electrode. The position (x-y coordinates) where the spot of light hits the diode is calculated from the fraction of the optically generated current leaving the diode through each of the four terminals.

Two schemes have been devised for using the planar photodiode in the film plane of a camera: In the first, a beam of laser light is reflected from the object in question, and collected by the position sensing chip. The

Figure 3-7: RCA's CCD imager [23].

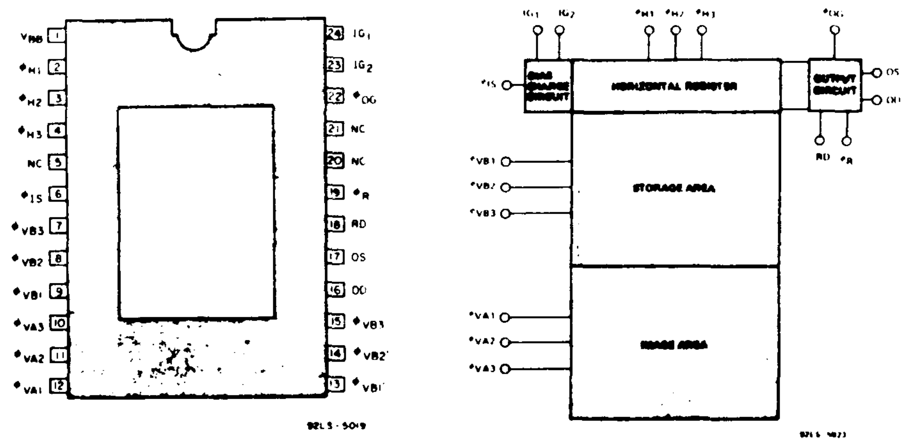


Figure 1 — Connection Diagram (Top View)

Figure 2 — Block Diagram

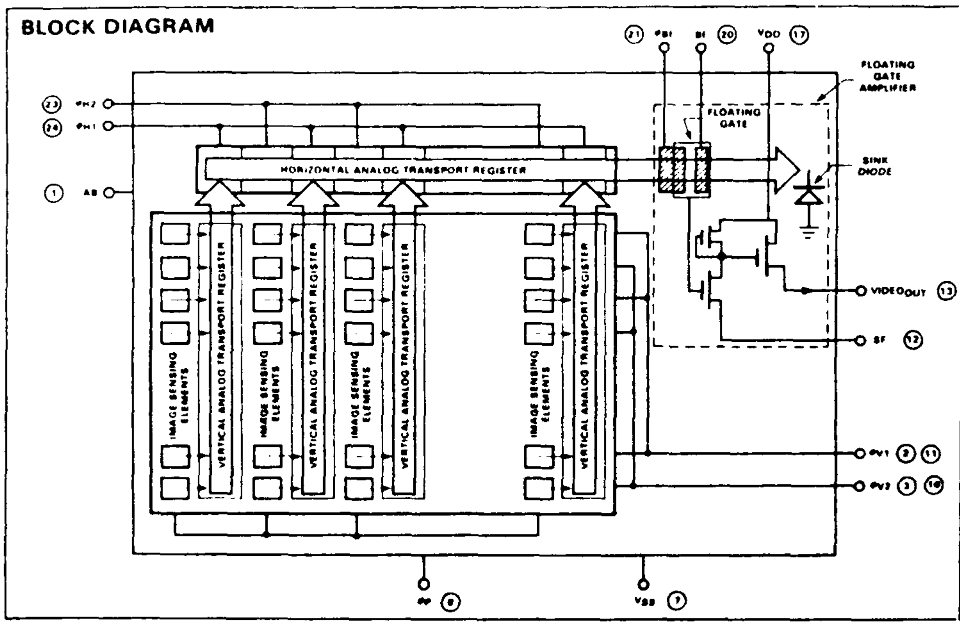
Connection Names

V_{BB}	Substrate Bias Voltage
ϕ_{H1} ϕ_{H2} ϕ_{H3}	Horizontal Register Clocks
ϕ_{IS}	Output Register Source Clock
ϕ_{VA1} ϕ_{VA2} ϕ_{VA3} ϕ_{VB1} ϕ_{VB2} ϕ_{VB3} $\phi_{VB1'}$ $\phi_{VB2'}$ $\phi_{VB3'}$	Vertical Register Clocks
OD	Output Transistor Drain
OS	Output Transistor Source
RD	Output Reset Transistor Drain
ϕ_R	Output Reset Transistor Gate Clock
ϕ_{OG}	Output Gate Clock
IG_1 IG_2	Input Gates

direction of the incident laser beam is controlled by movable mirrors and monitored constantly. The distance to the item is calculated by triangulation. Each measurement requires time enough to direct the laser beam and then detect the position of the reflected beam on the planar diode. The position sensor chip [26] requires from 100 to 200 microseconds for each measurement, which corresponds to 5000 or 10,000 points per second, whereas a television camera requires about 1/30 of a second to detect a spot of light. Special techniques can make a television camera faster, but they require special hardware. The planar diode can be used to measure the reflectivity of stationary objects, but it can have trouble detecting some low reflectivity materials. The laser sensing system is used to measure the shape of items for robotics applications.

In the second scheme LEDs are used with the position sensing chip: The prototype has six LEDs, which can be turned on and off independently, set in a circular ring, 60 degrees apart, so that their light forms a cone of rays (figure 3-10). The tip of the cone (where all six beams of light converge) is set to the midpoint of the sensing range of interest. The position sensor consists of a planar diode in the film plane of a camera centered above the ring of LEDs. The LEDs are turned on and off sequentially so that the planar diode receives light

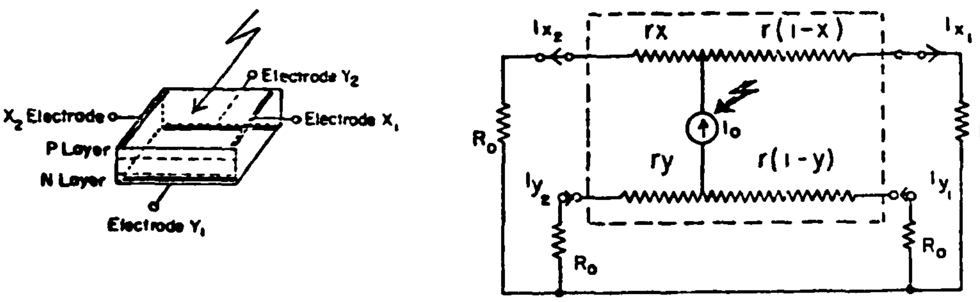
Figure 3-8: Block diagram of Fairchild's CCD imager [24].



PIN NAMES

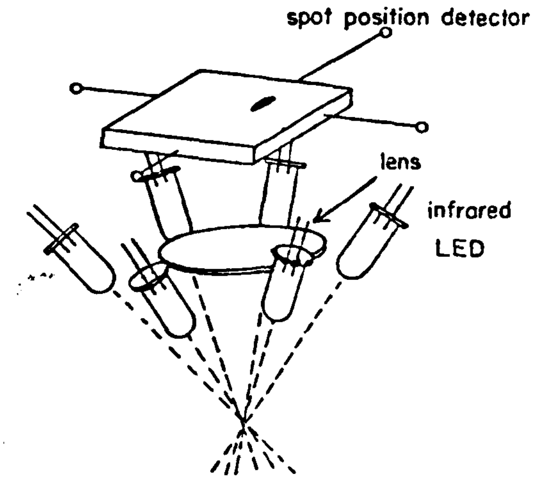
AB	Anti-blooming Bias
SF	Source of Floating Gate Amplifier
$VIDEO_{OUT}$	Video Output
ϕ_P	Photogate Clock
ϕ_{V1}, ϕ_{V2}	Vertical Analog Transport Register Clocks
ϕ_{H1}, ϕ_{H2}	Horizontal Analog Transport Register Clocks
BE	Bias Electrode
ϕ_{BE}	Bias Electrode Clock
V_{DD}	Power Supply
V_{SS}	Ground
TP1 - TP11	Test Points

Figure 3-9: The planar diode [25].



from only one LED at a time. The direction of an emitted ray and the line of sight from the planar diode to the light spot on an item are always known quantities, and the distance from the sensor to an object is determined by triangulation. The LEDs are turned on and off so that the reflected beams of light rotate around a circle. If the object is closer to or further from the sensor than the converging point of all the incident light beams, the image from all the LEDs will be a circle whose radius is proportional to the the distance from the converging point to the object's surface. If the object's surface is between the LEDs and their converging point, the image spots rotate around a circle with the same phase as the rotation of the incident light beams, but if the surface is further than the converging point they rotate in the opposite direction. If the surface is slanted with respect to the plane of the sensor then the whole image will be an ellipse instead of a circle, and the principle axes of the ellipse point to the orientation of the item's slant. This device can help robots measure proximity and orientation.

Figure 3-10: Orientation of LEDs and planar diode [25].



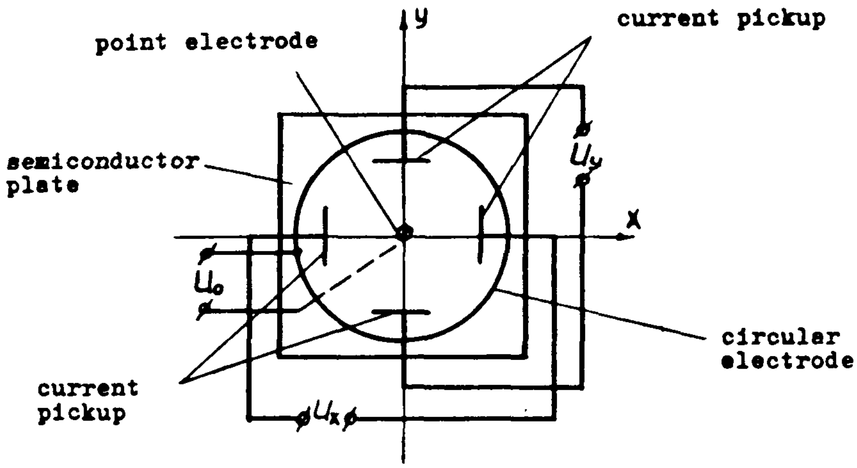
3.1.6 Semiconductor Position and Image Device

This device is similar in principle to the planar diode except that it relies on the drift caused by an applied electric field to move charge carriers. The sensor consists of a disk of semiconductor material with an electrode placed in its center and its outside rim grounded (figure 3-11). A voltage applied to the center electrode creates a drift field radially outward in the material. Two pairs of current electrodes are placed on each of the positive and negative sides of both the x and y axes as in the planar diode. A beam of light striking the disk generates minority charge carriers in the spot where it hit, and the drift field causes these carriers to flow radially outward. The amount of current received by each of the four current electrodes indicates the position of the spot of light on the disk.

The sensor can function as an image analyzer via a complex algorithm: First, the energy center of the image is placed in the center of the disk by moving the disk sensor around with respect to the item. When the image is centered the output of the four current electrodes will be the same. If the geometric dimensions of an object and how they relate to its image are known, the distance to the object can be determined from the outputs of the four current leads.

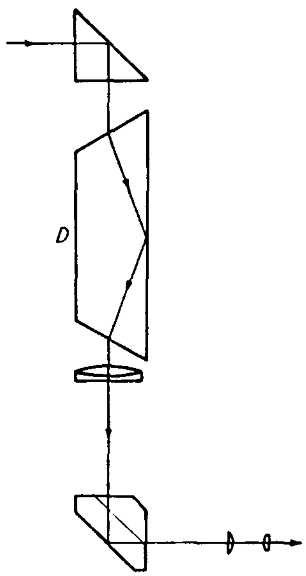
An object's profile is obtained by rotating its image about the image's energy center with a Dove's prism, a special four-sided prism that incorporates a single reflection (figure 3-12). The prism need only be rotated

Figure 3-11: The disk image sensor [27].



through an angle of 180 degrees because an image rotates through an angle twice that of the image. As an image rotates about the center of the disk, information about it is taken, in the form of current, from one of the four electrodes. Each full rotation of the image produces a current waveform that corresponds to the orientation of the item. The orientation combined with the location of the image's energy center of the object gives a complete two dimensional profile of the object and its location.

Figure 3-12: Dove prism used in a periscope; reprinted with permission from [28]; copyright 1964 Pergamon Press Ltd.

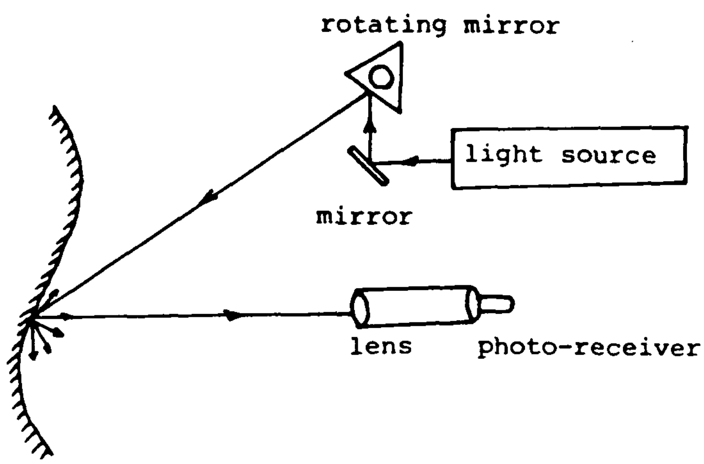


3.1.7 Scanning Laser Proximity Sensor

The sensor consists of a light source, a rotating mirror, and a photo-receiver (Figure 3-13). Laser light is projected onto a triangular mirror rotated by a four-pole synchronous electric motor. The incident light from the helium-neon laser is reflected and swept by the spinning mirror across the target surface. The vertical angle of the reflected light is synchronized to the source voltage of the motor. The moment the laser light hits a point on the object surface that point emits diverged light. A photoreceiver consisting of a phototransistor and a lens system is mounted a suitable distance away from the spinning mirror. The lens system allows the phototransistor to receive light from only one point on the object surface. Since the triangular mirror rotates synchronized with the source frequency of the motor, the photoreceiver detects light pulses three times in two cycles of the source frequency.

A high frequency clock is enabled at the moment of the zero point on the source voltage wave, and clock pulses are counted until the light pulse is received. The number of pulses corresponds to the angle of the mirror at the moment the photodetector received the light pulse, and the distance to the item's surface is determined by triangulation. The sensor's accuracy increases with increasing vertical distance between the mirror and the photoreceiver. but a trade-off exists. If the vertical distance is increased too much, the amount of light received decreases. In the extreme case, the amount of light received becomes too small for the receiver to detect. The sensor works poorly with deep black material or transparent material such as glass. Highly polished metals are also bad targets because they reflect too much light. This sensor enables an industrial robot to weld curved objects.

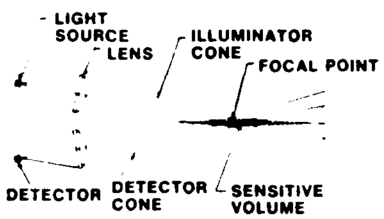
Figure 3-13: Scanning laser sensor [29].



3.1.8 Reflected Light Proximity Sensor

This sensor is made up of a light source and a detector, each with its own lens. The source and the detector are mounted eight millimeters apart on the hands of a robot facing in the same direction (figure 3-14). They are tilted symmetrically toward each other to form a sensitive volume a few centimeters in front of the sensor that moves with the robot's hand. The volume should move ahead of the hand in a known direction and distance relative to the hand and when a solid object encounters the sensitive volume, the detector receives light reflected from the object. The amount of light received depends on the distance from the item to the sensing head and on the reflectivity of the target object. The output voltage is a bell shaped function of the distance (figure 3-15) so the distance is a double-valued function of the voltage, which can cause problems. Several proximity sensors can be mounted on each hand or on the robot's mechanical fingers to provide a number of sensitive volumes in a pattern around the hand.

Figure 3-14: Light source and detector [30].



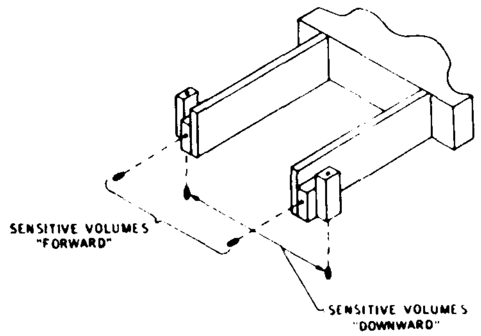
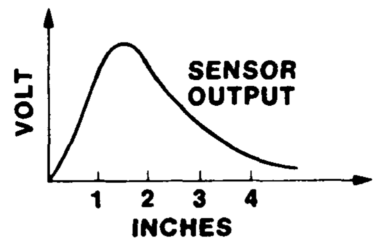


Figure 3-15: Output as a function of distance [30].



Several improvements to the original sensor can be made: The source and detector can be removed from the mechanical hand by introducing fiber optics into the system. This makes the source and detector easier to replace and makes the mechanical hand more streamlined. Low attenuation (0.5 dB/meter) fiber optic cables have been used to connect the light source and detector to the sensing head: The Jet Propulsion Laboratory system has fiber optic cables 5.5 meters long.

The double-valued output function can be eliminated by mounting the sensor heads inside the mechanical fingers so that the length of the optical path inside the fingers equals the distance from the sensing head to the point where the sensor output voltage is a maximum (the top of the bell-shaped curve). Then only the outer leg of the curve is used for distance measurement, and the distance is always a single valued function of the output. Light emerges from the fingers through holes in strategic places, and the optical path may be changed to another desired direction with small mirrors inside the fingers.

Another improvement has to do with the light source: By pulsing the light source at a frequency of 6 kHz, noise from ambient light is eliminated. Signals are detected at the same 6 kHz rate through a sample circuit, and the fast sensing electronics also allow for fast tracking of proximity changes.

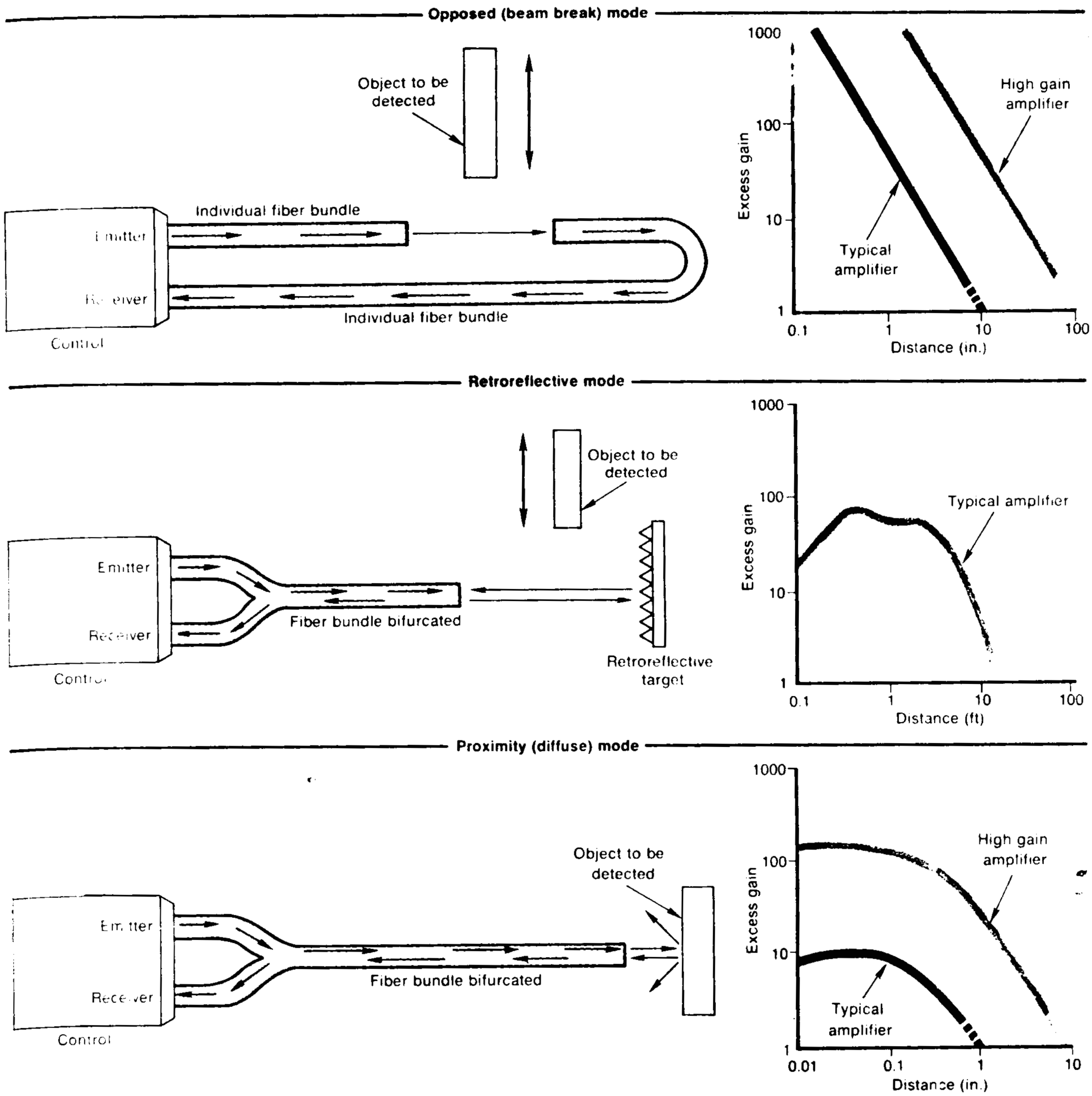
3.1.9 Fiber Optic Systems

Fiber optics scanning can be divided into three main techniques (figure 3-16). The first is opposed or beam break scanning, in which the light emitter and the light receiver face each other. The sensor detects objects that break the beam of light shining from emitter to detector. Beam break scanners are accurate to a few thousandths of an inch, but they cannot detect transparent or translucent materials.

Another mode of fiber optics scanning is retroreflective scanning. The emitter and receiver are coaxial, and a retroreflective target reflects the light beam back to the receiver when no object is present. This type of sensing is better than opposed scanning for translucent materials materials because the light must pass through the item twice, but shiny objects cannot be scanned because they reflect light back to the receiver. A practical scanning distance is between one and two feet, and theoretically the scanner could operate at a distance up to 30 feet.

The third mode of fiber optic scanning is proximity or diffuse scanning. The emitter and receiver are again coaxial, but the receiver measures the amount of light reflected from the object. The sensor has a range of several inches due to the attenuation of the fibers. Translucent and transparent materials are acceptable targets for diffuse scanners because most materials reflect some amount of light. This sensor is better than the last two in that it can determine both if the object is present, and to some extent, how far away it is. A disadvantage is that the receiver could detect shiny objects in the background of the sensing area.

Figure 3-16: The three fiber optics scanning methods [31].



3.1.10 Optical Encoders

Optical encoders are one of the older and more widely used position and motion sensors. They can detect linear and angular displacement for contact sensors, but robotics experimenters have not worked much with encoders.

Optical encoders operate by light interruption. A grid of opaque and transparent areas interrupts the light from an LED to a detector. In linear and rotary optical encoders a disc or plate containing opaque and transparent segments spins between the LED and the detector. Encoders can be either absolute or incremental: Absolute encoders produce a digital word with several discs and detectors, which corresponds to the exact position of the encoder shaft. Incremental encoders generate pulses that are counted to compute the position of the encoder shaft with respect to a reference.

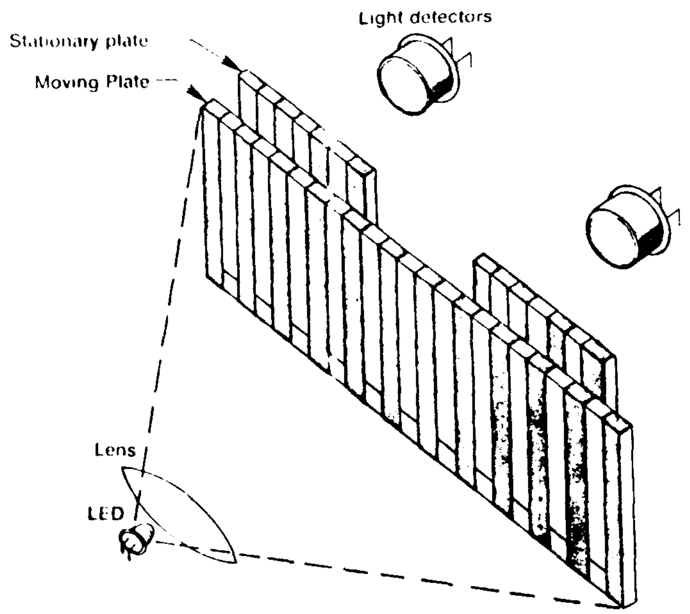
Incremental encoders are cheaper and more common, and they can generate several types of output functions. Sine waves, square waves, and trains of equally spaced pulses are the most common. Inside many devices the detectors collect light that passes through 20 or more slits instead of a single one. This allows for easier alignment and less trouble with disc defects like scratches and dust. The light interrupters for these encoders are usually two grids of opaque and transparent material: One grid is mounted on a stationary mask, while the other is mounted on a moving disc (figure 3-17). The disk moving past the stationary mask produces triangular shaped output from the light detectors that is often changed into digital information by detecting when the waveform passes through a predetermined value. For example, a pulse can be generated at the zero crossings of the output waveform. The pulses are then counted to determine linear or angular displacement, and average frequency of rotation or average linear velocity can be determined by counting the pulses over a period of time.

Many encoders have two sets of light detectors that produce different output waves. The two output waves can be made 90 degrees out of phase from one another, so that the way one of the output waveforms lags or leads the other indicates the direction of the shaft rotation. Currently, optical shaft encoders are available from many manufacturers.

3.2 Magnetic and Inductive Sensors

Magnetic and inductive sensors change magnetic energy into an electrical signal. Some of them can only determine whether a ferrous object is present, but others can measure the velocity and proximity of any metallic object. The simplest magnetic sensor is a coil of wire wrapped around a permanent magnet. A ferrous object approaching the sensor changes the magnetic flux through the coil and generates a voltage at the coil's terminals. This simple sensor operates by the principle of variable reluctance and requires no power

Figure 3-17: Light interrupters for an optical encoder [32].



source. The device is good for sensing linear and rotary motion since only a change in flux is registered: It can be used to measure the displacement of a gear with ferrous teeth by counting the output pulses from the teeth as they pass by. This type of sensing is accurate to within several hundredths of a mechanical degree [32]. When determining the speed of a rotating shaft the frequency of output pulses is measured and converted into digital information. The whole process is accurate to within less than 1/10 of a percent [32].

Along with being accurate, most magnetic or inductive sensors can operate in harsh environments. As long as no solid state electronic components are present in the sensing head, magnetic or inductive devices can operate over a wide temperature range (-65 to 300 degrees Fahrenheit [32]). An exception to this is the Hall-effect sensor, which relies on semiconductor material for its operation. Magnetic sensors are also not harmed by shock: Some withstand shock levels of over 30,000 g's [32]. Magnetic devices may be coated with non-magnetic materials because they can sense ferrous items right through the coating, and a sensor sealed in a special coating can operate completely immersed in water or an inert liquid. Magnetic sensors in stainless steel cases can work in very harsh places, such as in salt-sprays or in heavy sand and dust environments. Some even withstand differential pressures of 20,000 psi during operation [32].

Inductive sensors consist of coils of wire with or without an air coil, and most require an oscillator. Inductive sensing methods that use an LC tank circuit may also rely on capacitive sensors: The capacitive part of the tank circuit merely becomes the sensing head instead of the inductive part. Some inductive sensors, such as linear variable differential transformers, must be used in conjunction with contact sensors. The contact sensor from section 2.2.3 detected displacement with linear variable differential transformers. High frequency inductive sensors rely on eddy currents to detect metal objects. Magnetic and inductive devices in the form of detectors and proximity switches are currently used as robotic sensors.

3.2.1 Oscillator Techniques for Inductive Sensing

An inductive sensing coil is incorporated into the LC circuit of an oscillator. The sensing coil amounts to a variable inductance in the circuit, and ferrous or nonferrous metals approaching the coil change its inductance. The sensing range for ferrous objects is greater because they change the coil's inductance much more than nonferrous objects. The techniques discussed below can be used with a fixed inductor and a capacitive type sensor, and both of the methods involve changing the frequency of an oscillator with the varying inductance/capacitance.

In the first method, known as the frequency shift [33], the frequency of the oscillator is the output of the sensor. The output waveform is put into a frequency to voltage converter to obtain an output voltage. When nothing is near the sensor coil the oscillator will operate at a certain frequency and the F-V converter will have a certain voltage output. Metal brought near the coil changes its inductance, which changes the frequency of the oscillator and the voltage out of the F-V converter. The proximity and nature of the approaching item can be determined from the amplitude and sign of the voltage shift at the output of the F-V converter.

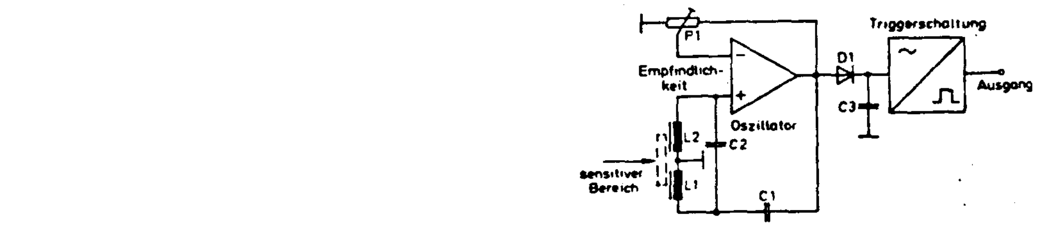
In the second method, called off-resonance [33], the inductor is incorporated as part of a parallel LC circuit connected to the output of an oscillator. The oscillator frequency is set to the resonant frequency of the LC circuit when nothing is near the sensor coil: At the resonant frequency of the LC circuit the voltage across it is a maximum. When the inductance of the sensing coil is changed by approaching metal the resonant frequency of the LC circuit shifts, but the oscillator is still operating at the old resonant frequency. This causes the voltage across the LC circuit to drop from its maximum, and the nature and the proximity of the metal object can be determined from the amplitude of the voltage drop.

3.2.2 Industrial Inductive Proximity Switches

Inductive proximity switches are found in industry wherever metal parts must be monitored. Most of them include an oscillator that is controlled by the inductive sensing coil or coils. Figure 3-18 shows the operating principle of an inductive proximity switch.

Referring to the figure, the amount of feedback is determined by the coupling between sensing coils L1 and L2. The gain factor is adjusted with potentiometer P1 until the circuit oscillates freely, the output of the

Figure 3-18: Switching principle of an inductive proximity switch [34].



oscillator (the higher the frequency the better) is rectified and converted into an impulse with a trigger circuit. The magnitude of the output pulse is selected so that it is suitable for controlling a switching circuit, a thyristor or a triac switch, or relay coils. Thyristors and triacs are 4 layer pnpn solid state high power switching devices. The thyristor is often made with the proximity circuit on the same integrated circuit chip.

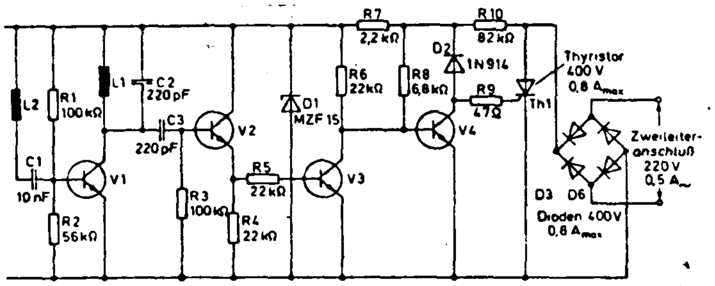
A metal object approaching the sensitive region near the two coils produces eddy currents and an induction voltage in the region. The eddy currents take away the essential energy of the coils, and the output of the oscillator falls to zero. When the oscillator stops, the output of the proximity switch falls to zero or to its lower voltage. The approaching metal part need not be magnetic: Non-magnetic workpieces must simply come closer to the sensing coils before the circuit will change state. Table 3-1 summarizes the switching distances for different work materials for a standard industrial proximity switch with a nominal switching distance of 10 mm. The measurements are based on the nominal switching distance for steel (steel 37).

Table 3-1: Switching distances for various work materials [34].

Work Material	Switching Distance
Steel	10 mm
Nickel	8.5 mm
Brass	5.4 mm
Aluminum	5.0 mm
Copper	4.6 mm

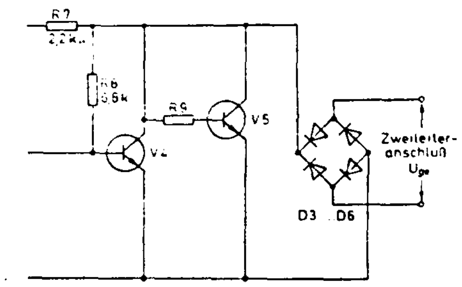
Manufacturers sense metal with both two and three wire inductive proximity switches: Two wire switches are connected in series with a load. Depending on its inner circuitry, the device can switch the load current on or off when metal parts approach it. Two wire switches are often connected to relays or thyristors: Figure 3-19 is a diagram of a discrete version of a two wire switch connected to a thyristor.

Figure 3-19: Discrete circuit of a two wire proximity using a thyristor [34].



The switch in figure 3-19 is connected in series to a load. Transistor V1 works as an oscillator that begins oscillating when the magnetic coupling between sensing coils L1 and L2 becomes strong enough. The output voltage of the oscillator goes through capacitor C3 to transistor V2, which acts as an emitter follower. Transistor V3 conducts only through the positive half cycle of the oscillator's output and thus acts as a rectifier. Transistor V3's output is a pulsating d.c. voltage, and when it drops to zero transistor V4 becomes cut off, increasing the short circuit priming voltage for the thyristor. The thyristor then turns on and shorts the output of the bridge rectifier, which produces the effect of a short circuit between the output terminals: ie a closed switch. The short circuit remains until the oscillator stops oscillating (metal near the coils): Then the thyristor switches back to normal and the output terminals act as an open switch. If only a d.c. power source is available, a transistor can be substituted for the thyristor (figure 3-20).

Figure 3-20: Previous circuit without the thyristor [34].



Manufacturers also detect metal with three wire proximity switches such as the one shown in figure 3-21. When the oscillator isn't operating transistors V2 and V3 are cut off and V4 is on. With V4 on, the output voltage lies at about zero (actually the Vce drop of the transistor). When the oscillator is oscillating transistors V2 and V3 turn on, cutting off V4 and causing the output voltage to rise. This reverse biases diode D3, and gives the action of a closed switch. Diode D4 protects the switch from voltage spikes on ground.

Figure 3-21: Discrete three wire proximity switch [34].

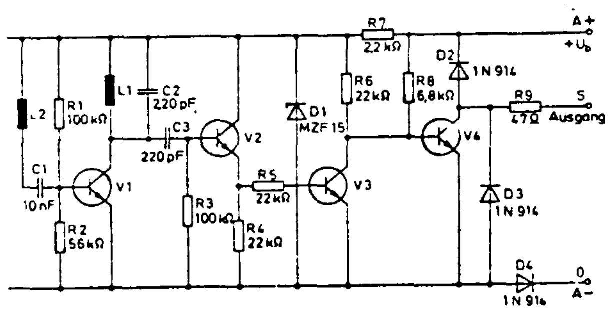
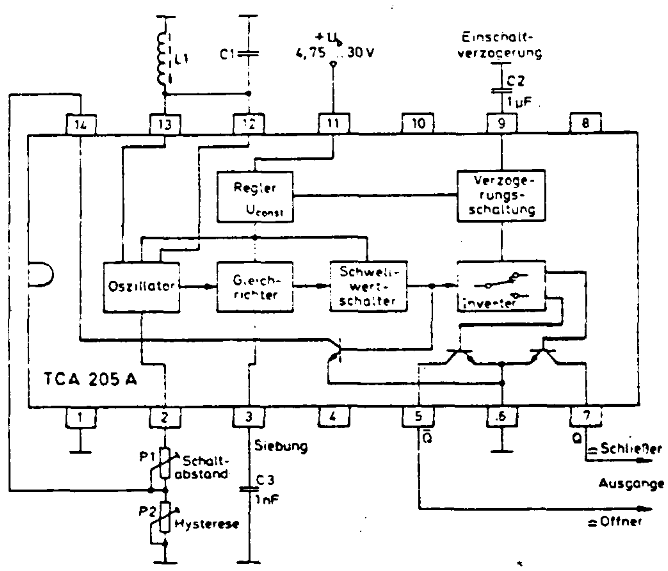


Figure 3-22 shows an integrated proximity switch made by Siemens Corporation. The oscillator oscillates freely when pins 12 and 13 are connected together, and an externally connected tank circuit determines the frequency of the oscillations. The tank circuit and a potentiometer determine the oscillator's amplitude. When metal parts draw near to the circuit, the oscillator's output becomes attenuated. When the amplitude falls below an inner threshold level, the circuit switches causing voltage output Q to sink to zero and output Qbar to rise to the working voltage. These proximity switches are currently used in automated manufacturing in West Germany.

Figure 3-22: An integrated proximity switch [34].



3.2.3 Hall-Effect Sensing

3.2.3.1 Theory [35]

The Lorentz force equation (given below) states that if a magnetic field is applied perpendicular to the motion of a moving charge the charge will be deflected. (Vectors are denoted by bold type). The Lorentz force equation:

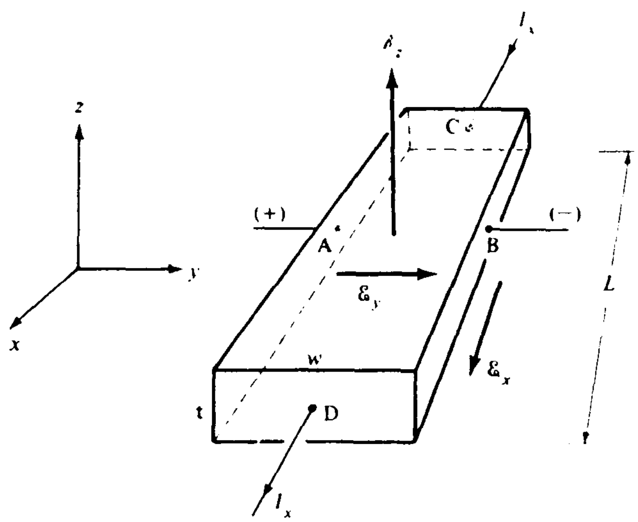
$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

The force on the moving charge is represented by **F**. **E** is any electric field present, **B** is the magnetic field, and **v** is the velocity of the charge.

Most Hall generators consist of a small rectangular piece of semiconductor material (figure 3-23). Since the figure shows the axes and the direction of current and the magnetic field, it will be referred to in the discussion that follows. The moving charges are supplied in the form of a current through the material that flows in the positive x direction in the diagram. The external magnetic field is applied perpendicular to the current flow in the positive z direction. The magnetic field and the charge velocity vectors are crossed, producing a force in the y direction. A force on a charge constitutes an electric field, and since the field must be along the same axis as the force, the electric field must also be in the y direction. The velocity and the magnetic field are perpendicular, so their cross product is equal to their product and the Lorentz force equation reduces to:

$$F_y = q(E_y - vB_z)$$

Figure 3-23: Diagram illustrating the Hall-effect principle [35] p. 89; reprinted with permission from Prentice-Hall, Inc. copyright 1980.



The total force on the piece of semiconductor material must equal zero: If this were not the case, the piece of material would accelerate in the y direction. The material does not move, so the force in the Lorentz equation is set equal to zero yielding the following result: $E_y = Bv$. Since the velocity of each charge carrier is hard to determine, it is replaced by the average velocity of all the carriers $\langle v \rangle$, yielding: $E_y = \langle v \rangle B$. The current density in the positive x direction is related to the average velocity of the charge carriers by two different expressions depending on the polarity of the charge carrier. Negative carriers (electrons) are the primary charge carriers in n-type semiconductors, and positive carriers (holes) are the principle charge carriers in p-type semiconductors. The expressions are as follows:

$$J_x = -qn\langle v \rangle \quad \text{(for n-type)}$$
$$J_x = qp\langle v \rangle \quad \text{(for p-type)}$$

The n represents the number of charge carriers in each cubic centimeter of n-type material, and it usually reduces to the number of donor atoms per cubic centimeter (N_d) added to semiconductor materials to make them n-type. The p represents the same quantity for p-type material, and it usually reduces to the number of acceptor atoms per cubic centimeter (N_a) added to intrinsic material. Solving the current density equations for the average velocity and substituting the result into the reduced Lorentz equation, one obtains:

$$E_y = \frac{BJ_x}{qp} \quad \text{(for p-type)}$$

$$E_y = \frac{-BJ_x}{qn} \quad \text{(for n-type)}$$

For the simplified case of a constant area A and a current independent of dimensions: $J = I/A$. The piece of material shown in figure 3-23 has $A = wt$, so $J_x = I_x/wt$. For a constant width w and an electric field independent of dimensions the voltage associated with E_y (labelled as V_{ab} in the figure) is just E_y times w. Substituting in these changes one obtains:

$$V_{ab} = \frac{BI_x}{qt(N_a)} \quad \text{or} \quad V_{ab} = \frac{-BI_x}{qt(N_d)}$$

The Hall coefficient R_H is a proportionality constant that relates the current and the magnetic field in the above expression. It depends on the material as well as its doping: For the case where $n = N_d$ and $p = N_a$, the Hall coefficient is given by the following two expressions:

$$R_H = \frac{1}{q(N_a)} \quad \text{(p-type)}$$
$$R_H = \frac{-1}{q(N_d)} \quad \text{(n-type)}$$

Placing the Hall coefficient into the voltage equations one obtains:

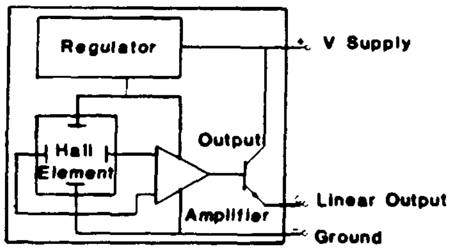
$$V_{ab} = (BI_xR_H) / t \quad \text{(for both types)}$$

The polarity of the voltage depends whether the semiconductor is p or n type. For a given semiconductor with a given doping and a constant current, the voltage is proportional only to the magnetic field. Hall effect sensors can measure the proximity, displacement, and velocity of objects with magnets attached to them.

3.2.3.2 Hall-Effect Sensor

A device called the linear output Hall-effect transducer (LOHET) [37] has a voltage output proportional to the magnetic field present at its sensing surface. The sensor is made from a Hall-effect integrated circuit and several transistors (figure 3-24). The device has a linear output for magnetic fields in the range -400 to +400 gauss. If a 12 volt power supply is used, the output ranges from 3 volts to 9 volts with a null output of 6 volts. The 6 volt output swing over the range of 800 gauss gives the sensor a sensitivity of 7.5 millivolts per gauss. One model of the transducer has a radiometric output voltage (output proportional to supply voltage) and can operate over an 8 to 16 volt supply range. A radiometric output is useful in an automotive electrical environment where the supply voltage is unregulated. No accuracy is lost with a radiometric sensor if the other components of the system are also radiometric. The sensor can operate over a large temperature range (-40 to 150 degrees centigrade) and can be sealed in a non-magnetic case for operation in harsh environments.

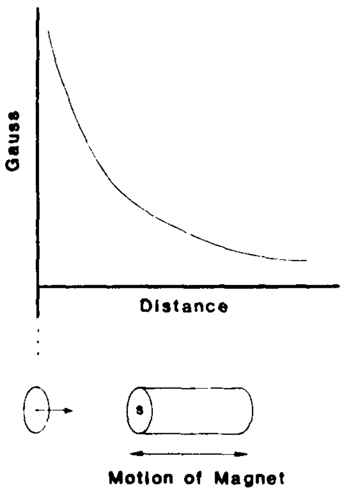
Figure 3-24: A block diagram of the LOHET [36].



The LOHET alone is not an effective sensing device: Some sort of magnet, either permanent or electric, must accompany it. Usually small permanent magnets are mounted on objects that move with respect to the sensor. The position of the magnet and the object can be determined from the sensor's output voltage. The LOHET can also detect metallic objects interrupting a field from a magnet as they pass between the magnet and the sensor. For instance, the speed of rotor blades can be measured by letting them spin between a magnet and a LOHET.

Magnets and sensors can be combined in a variety of ways: A magnet can be moved head on towards the LOHET. The magnetic field of the magnet as a function of distance is shown in figure 3-25. The voltage output of the LOHET is linearly proportional to the field, but the field is nonlinear, so this sensing configuration is only useful if a nonlinear output can be tolerated. The head on mode is good if a large change in magnetic field per unit distance is required, and its chief advantage is simplicity.

Figure 3-25: Magnetic field as a function of distance - head on [36].



A second simple technique is to slide a single pole (head) of a magnet sideways past a fixed sensor, and figure 3-26 shows the magnetic field as a function of the displacement. The pole of the magnet is maintained at a constant perpendicular distance from the sensor as it is slid by, typically 1.3 to 2.5 mm. Due to the symmetrical properties of the magnetic field, this mode of sensing is valuable for detecting deviation from a center line.

In the third sensing technique a two magnet assembly moves with respect to a LOHET (figure 3-27). Both a positive and a negative going magnetic field versus distance relationship is obtained by opposing two similar magnetic poles, giving information about the direction of the displacement as well as its magnitude. The magnetic field and the the output voltage are linear over a specified range, typically 2.5 mm or more. For the cost of another small permanent magnet this technique represents a great improvement over a magnet sensor, but it may not be able to function in every environment that the single magnet version can.

The fourth and final permanent magnet configuration (figure 3-28) is a two magnet version of the single pole slide-by. The opposing poles of two magnets are placed side by side and slid by a LOHET assembly, and the magnetic field produced as a function of displacement is an s-shaped curve. A very linear output is obtained over a very narrow range of displacement. This method is used where a precise linear output is necessary over a very narrow range of distances. An advantage of this as well as the other permanent magnet systems is that no power source is required as far as the magnets are concerned.

Figure 3-26: The single pole slide-by technique and magnetic field [36].

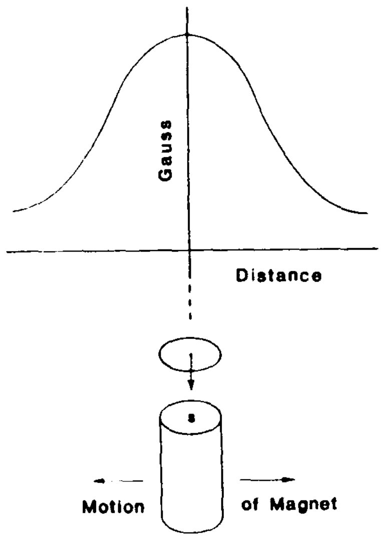
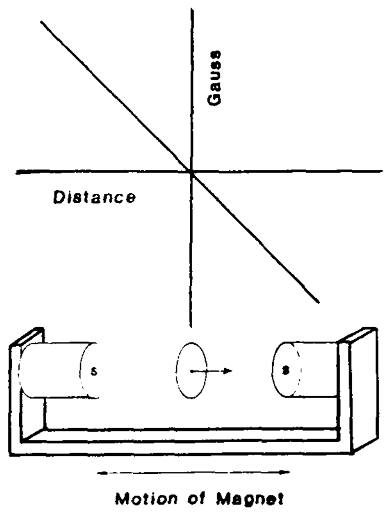


Figure 3-27: Two magnet head on sensor and field [36].



Another technique uses a LOHET and an electromagnet to measure current. A typical configuration consists of a coil of wire wound around a magnetic core (figure 3-29). The magnetic field from the coil is directly proportional to the current in the core. Many variations of this basic linear output current sensor can be made using differences in gap size, core material and diameter, and the number of turns of wire. Currents less than one ampere can easily be measured with this technique.

Figure 3-28: Diagram of the two pole slide-by method and field [36].

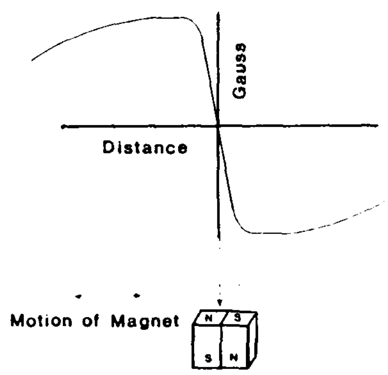
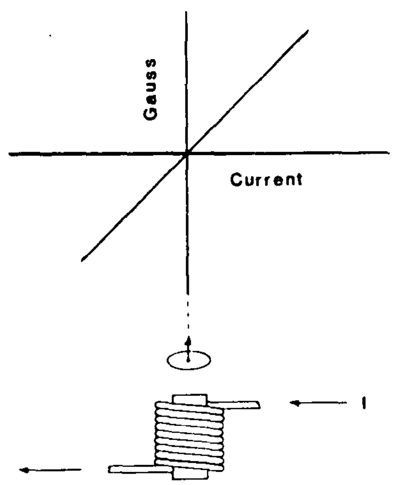


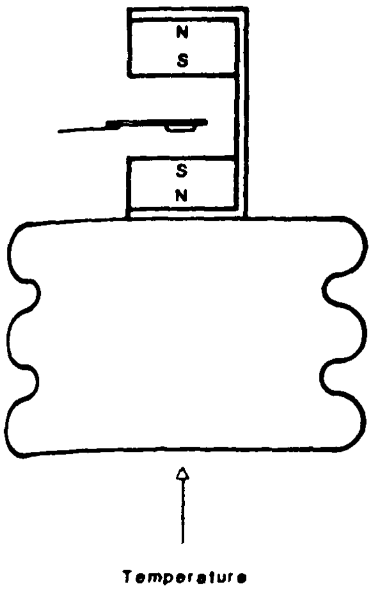
Figure 3-29: LOHET current sensor for small currents [36].



The automotive industry is currently experimenting with Hall-effect sensors in the form of LOHETs. LOHETs currently detect shock absorber height in load leveling systems: two small permanent magnets are mounted with their opposite poles side by side, on the moving parts of special shock absorbers made of non-magnetic material. The magnets are attached to the moving part of the shock absorber and the LOHET is attached to a fixed position on the outside surface of the shock absorber. As a shock absorber is compressed, the magnets move past the sensor generating a change in output voltaged and the output of the sensor as a function of the shock height resembles a logarithm. Since the magnets need no power source the shock absorber can be completely sealed, allowing it to operate more reliably.

Temperature sensing with a LOHET involves a magnetic assembly mounted on a bellows chamber (figure 3-30). The bellows chamber relies on the expansion and contraction of a gas to convert temperature changes to changes in displacement. A linear relationship between temperature and the output of the LOHET can be obtained by changing the bellows design and the geometry of the magnetic assembly. The system is good for applications where an accuracy of about 10% of the full scale is acceptable. The magnetic assembly has two magnets with opposing poles, as in figure 3-27, because that mode has a linear output over a broad range of temperature changes. The most promising area for this sensor is in applications such as automotive manifold temperature sensing.

Figure 3-30: LOHET temperature sensing system [36].



An experimental LOHET flow rate meter transforms the fluid flow rate into a mechanical displacement with a paddle (figure 3-31). The paddle turns a threaded shaft which moves a magnet in relationship to a LOHET. When the flow rate decreases a spring pushes the shaft back towards its initial position.

A different sensing configuration than the one mentioned before can be used to measure high currents, such as those in electric vehicles (figure 3-32). For currents greater than 25 Amps a single turn of magnetic material is placed around the cable in question with a LOHET resting in an air gap in the ring. This sensing mode offers no series resistance in the circuit and provides a linear measure of the current.

The information given about Hall-effect sensors and the LOHET gives no indication of any use in strictly robotics applications.

Figure 3-31: LOHET fluid flow meter [36].

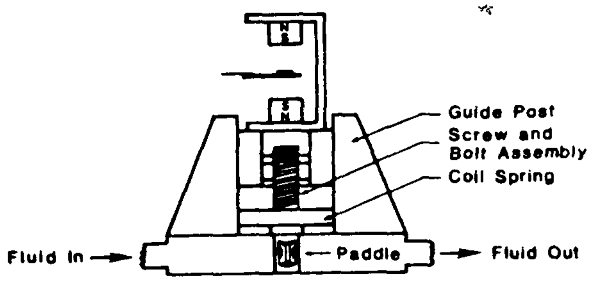
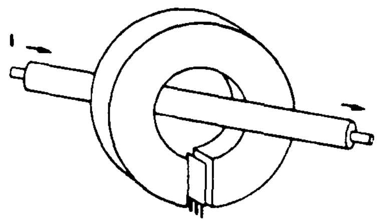


Figure 3-32: LOHET sensor for high currents [36].



3.2.4 Variable Reluctance Sensing

Variable reluctance sensors consist of a coil of wire wrapped around a permanent magnet and can only sense magnetic materials. Reluctance is analogous to resistance in an electrical circuit and magnetic flux is analogous to electrical current. A permanent magnet or electromagnet can be thought of as providing a constant magnetomotive force analogous to a constant voltage (electromotive force) source. Air represents a high reluctance relative to magnetic materials. A simple sensor consisting of a coil of wire wrapped around a permanent magnet is used as an example in the next paragraph to illustrate the variable reluctance principle.

When the sensor is near nothing but air the flux through the coil is at one constant value, just as the current would be in a simple electrical circuit with only a voltage source and a single fixed resistor, and the coil terminals read zero voltage. When a piece of ferrous material approaches the sensor the reluctance that the magnet "sees" drops, and the flux through the coil increases to a new constant value. The voltage produced at the terminals of the coil is proportional to the time rate of change of the flux: As long as the flux changes reasonably fast an output voltage occurs. If ferrous material approaches the sensor and then stops, the output voltage drops to zero as soon as the flux stops changing. Therefore, variable reluctance devices are good for sensing the speed of ferrous items, but not their proximity. A related problem with variable reluctance speed sensors is that their output drops to very near zero at very slow speeds. The reluctance of a workpiece depends on its magnetic permeability and its mass, dimensions, and geometry: The reluctance decreases with the increasing cross-sectional area of the workpiece. Care must be taken when operating these sensors because workpieces of different sizes can produce the same or different effects depending on the situation.

Variable reluctance devices consisting of coils and permanent magnets are used to sense the speed of rotating gears or shafts [32]. An increase in the mass of metal in front of the sensor constitutes a decrease in reluctance of the structure, which increases the flux through the coil and generates an output voltage of a certain polarity. A decreasing flux corresponding to an increase in reluctance generates an output voltage of the opposite polarity. The sensor is encased in a non-ferrous metal shell because a ferrous shell would foul up the operation of the device. The output voltage amplitude and waveform for analog sensor types are determined by the shape of the metal part that travels past the sensor. A standard gear or cog tooth moving past the sensor creates a near sinusoidal output waveform, a tooth from a star-wheel produces a series of sharp pulses. The peak to peak amplitude from a spur-gear is less than that from a star- wheel for a given speed and air gap, because the change in mass is less for the spur-gear. The output voltage is directly proportional to the speed of the rotating gear, and inversely proportional to the air gap between the sensor pole-piece and the rotating actuator. The analog output voltage can be changed to digital information by detecting when the output voltage amplitude increases above some threshold and producing a pulse when this occurs.

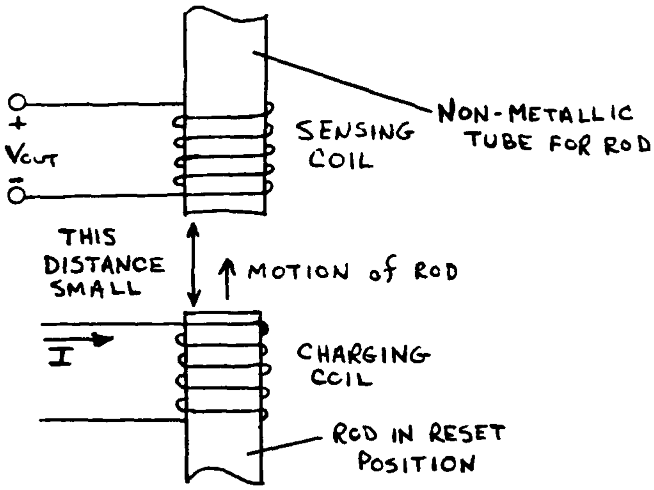
Robotics projects using variable reluctance senors have not been found in preparing this report. Variable reluctance transducers are inexpensive and require no power supply, so they have potential to become robotic sensors.

3.2.5 Coupled Field Sensing

Coupled field sensors consist of charging coils and sensing coils. The charging coil is usually excited with an a.c. current to produce a time-varying magnetic field. A piece of ferrous material in the vicinity of the coils couples the field from the charging coil to the sensing coil. Initially, the terminals of the sensing coil have no voltage between them. When the field is coupled between the two coils, a voltage appears at the terminals of the sensing coil.

A d.c. coupled field sensor is the motion detector for the robotic contact sensor [38] described in section 2.2.1. The system is fairly simple and consists of a charging coil, a rod, and a sensing coil (figure 3-33). A constant current is maintained through a charging coil that surrounds the rod, creating a constant magnetic field. In its reset position, the rod rests outside the sensing coil. When the rod is pushed into the sensing coil an induced voltage appears at the sensor coil terminals. The sensor consists of an array of these magnetically detected rods and produces a three dimensional profile of target objects.

Figure 3-33: Magnetic detection system for a robotic tactile sensor.



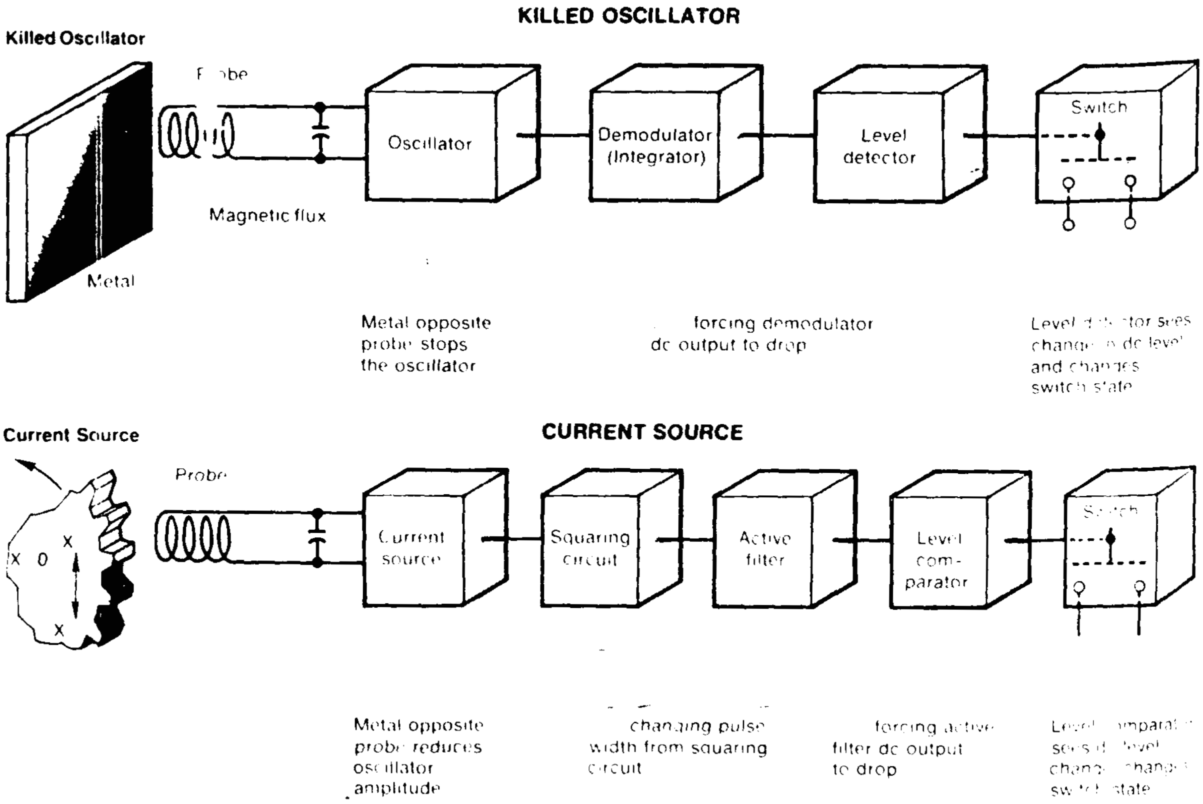
A.C. coupled field sensors [33] with time varying magnetic fields detect the presence of large ferrous objects. The transmitting coil is connected to a low frequency a.c. source (60z Hz power is acceptable). The receiving coil is placed at right angles to the magnetic field of the transmitting coil, and its output terminals are connected to an amplifier. The sending coil will induce a small current/voltage in the receiving coil but it should not be large enough to do anything. When a piece of ferrous metal approaches the coils, it couples the field generated in the sending coil to the receiving coil, which increases the current/voltage in the receiving coil. The increased current/voltage can throw a switch or activate a counter.

For small couple field devices, both the transmitting coils and the receiving coils can be made from modified filter chokes. The "I" sections of the cores are removed by knocking them out with a hammer and chisel. The remaining "E" sections of the cores are placed at right angles to form the two coils. Manufacturers currently detect or count large ferrous objects, such as steel beams with coupled field sensors.

3.2.6 Eddy Current Sensing

Eddy current devices are used to detect both ferrous and non-ferrous metals. The sensor generates a high frequency magnetic field via a sensing coil and a high frequency current. When a metal item approaches the sensing coil, the high frequency magnetic field induces eddy currents in the metal that change the amplitude of the oscillations in the sensing circuits . Two methods are used to detect changes in the oscillations of the sensing circuit: the killed oscillator and the current source (figure 3-34). In the killed oscillator, a demodulator circuit converts the oscillation amplitude to a d.c. voltage, and a level detector throws a switch when the d.c. voltage decreases below a threshold level. In the current source, a squaring circuit converts the amplitude into a train of pulses whose widths vary with frequency. An active filter converts the pulse train into a d.c. voltage and a comparator throws a switch when the d.c. voltage falls below a threshold level.

Figure 3-34: Killed oscillator and current source eddy current techniques [32].



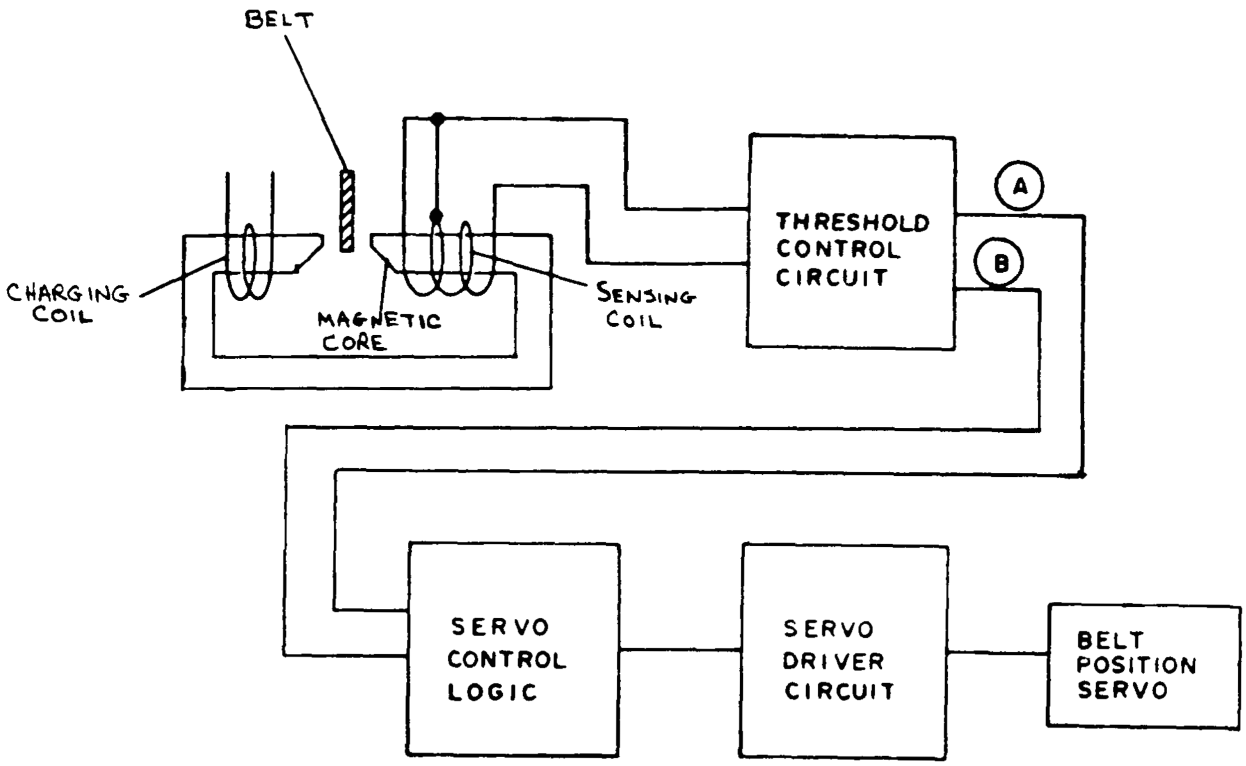
Most eddy current sensors can measure metallic discontinuities in a moving target at a rate of around 5 kHz, and some models can register these discontinuities at a rate of about 20kHz [32]. They do not have problems registering very low speeds because they do not rely on a time rate of change; an object that approaches the sensor and then stops will still be detected. The maximum speed depends on the method used to sense oscillator amplitude. Devices with demodulators tend to be slower than those that convert the amplitude into pulses. Current source devices can be used for displacement sensing because they can generate pulses with very high positional accuracy. The degree that the object changes the oscillator amplitude is used to calculate the distance to the object.

Eddy-current sensors can operate near dust, dirt, and metal particles without being contaminated by them. The sensing distance is limited to the diameter of the sensor coil: A typical range is 0.6 inches to 3 inches. Eddy-current sensors must be packaged in non-metallic packages because they cannot sense through metal. These sensors have been employed for a long time in the non-destructive testing of metal parts such as pipes, beams, or rails. Some robotic proximity switches use eddy-current.

3.2.7 Magnetic Edge Detector

This device is not a robotic sensor, but it is a practical application of magnetic sensing. The sensor detects the vertical position of a metallic character belt of the type used in line printers. Characters and timing marks are etched into the belt at a precise distance from its bottom. The bottom edge of the character belt is detected and vertically adjusted to position the characters correctly as they move along the print line. The edge of the belt is located in the gap of a stationary magnetic core that is part of a detector that includes a transmitting coil on one pole and a receiving coil on the other (figure 3-35). The transmitting coil is energized with a high frequency signal (about 1MHz) because the presence of the belt is easier to detect with high frequencies than with low frequencies.

Figure 3-35: Magnetic character belt edge detector [39].



The receiving coil is tapped in three locations: at 0 turns (one end), 961 turns, and 1500 turns (the other end). The first two leads are connected together, and the output voltage is measured from these leads to the third lead. The receiver coil's voltage output is a maximum when the first two leads are connected together: The configuration represents a tuned condition.

The transmitting coil is connected to a function generator that produces a 1 MHz sine wave with an amplitude of 25 volts peak to peak. When the belt moves into the gap, the output voltage drops, probably due to eddy currents. Table 3-2 summarizes the output voltage as a function of belt position over its linear range. The output voltage can be varied with different core materials, gap sizes, and input signals.

Table 3-2: Output voltage versus character belt position [39].

Belt's distance from reference (inches)	Voltage output of coil (Volts p-p)
+0.050	7.3
+0.025	6.6
0.000	5.8
-0.025	5.0 (edge now
-0.050	4.3 in gap)

The receiving coil is connected to a two level threshold circuit that produces two digital outputs: A and B. The digital outputs are connected to control logic that determines whether the belt is too high or too low. Table 3-3 shows the digital outputs and how they are interpreted.

Table 3-3: Digital output of the magnetic position sensor [39].

Output	A	B
belt high	0	0
belt low	1	0
belt OK	1	1
invalid	0	1

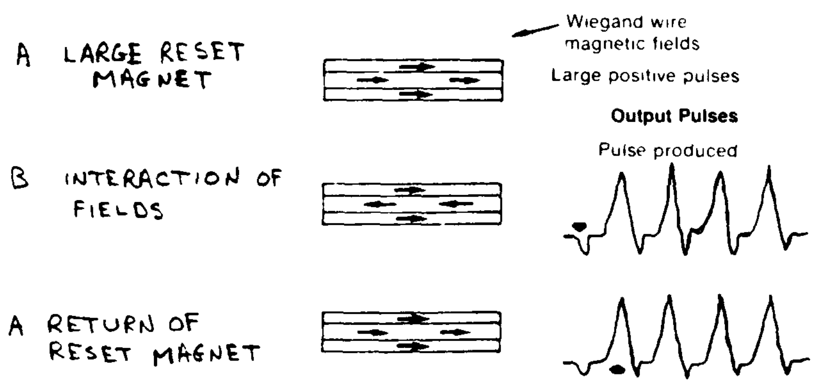
The sensor is inexpensive and not easily contaminated with dust or ribbon particles. It is not sensitive to horizontal movement of the belt towards or away from one of the core's pole faces or to velocity variations of the belt. A robot could detect or maintain the position of a metallic item with this sensor.

3.2.8 Wiegand Wire Sensing

Wiegand wire sensors produce output voltage pulses and require no external electric power source. A Wiegand wire is made up of a core and a shell, each containing an internal magnetization that can be switched by an external magnet. A coil of wire wrapped around or placed near the Wiegand wire senses the switching of the internal magnetic fields. The output voltages produced have a maximum amplitude of 12 volts and a maximum frequency of 80 kHz. Depending on the mode (symmetric or asymmetric), the sensing coil can produce single polarity or dual polarity pulses.

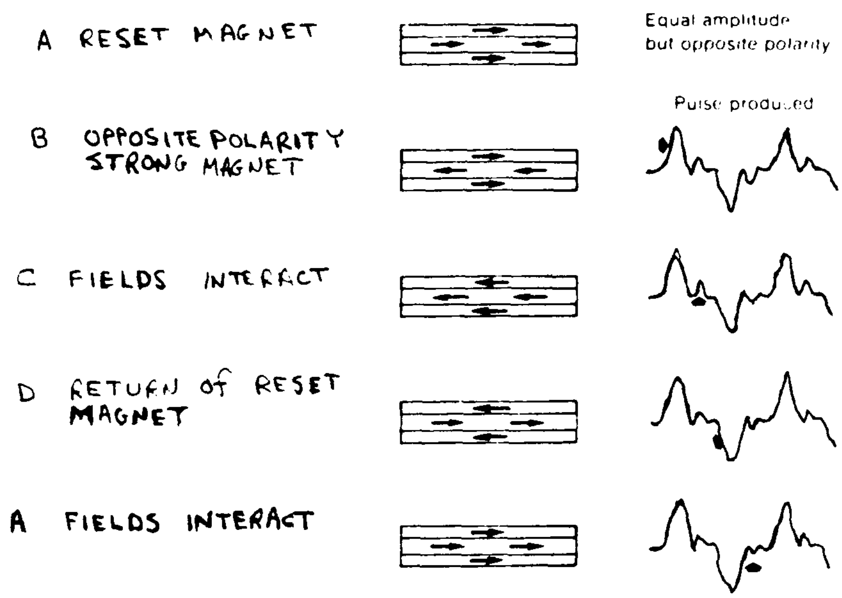
In the asymmetric mode (figure 3-36), a strong magnet first magnetizes both the core and the shell of the Wiegand wire in a single direction. Then, a less powerful magnet brought near the sensor reverses only the core polarity, and the core and shell are now magnetized in opposite directions. The core and shell magnetic fields interact to product a slow change in core polarity that generates a small voltage pulse proportional to the time rate of change of the flux at the terminals of the coil. Finally, the strong magnet is brought back to reset the core magnetization back to its original direction. When the wire is reset, the core and shell magnetic fields interact to produce a fast change in flux and hence a large voltage pulse in the sensing coil.

Figure 3-36: Asymmetric Wiegand wire switching [32].



In the symmetric mode (figure 3-37), a powerful magnet again magnetizes the core and shell in one direction. Then another magnet of equal strength but opposite polarity (it could be the opposite pole of the same magnet) is brought near the Wiegand wire to force the core magnetization to switch polarity quickly. The quick change in core polarity generates a large voltage pulse in the coil, and as the field strength increases, the shell magnetization also switches polarity to produce a small voltage pulse. Once the second magnet has been removed, the first magnet or pole is brought back near the Wiegand wire to reset the core's polarity quickly. This quick change induces another large voltage pulse but of opposite polarity in the sensor coil. The shell then also switches polarity, producing a small inverted voltage pulse. Once the shell switches, the Wiegand wire is in its reset position again.

Figure 3-37: Symmetric Wiegand wire switching [32].

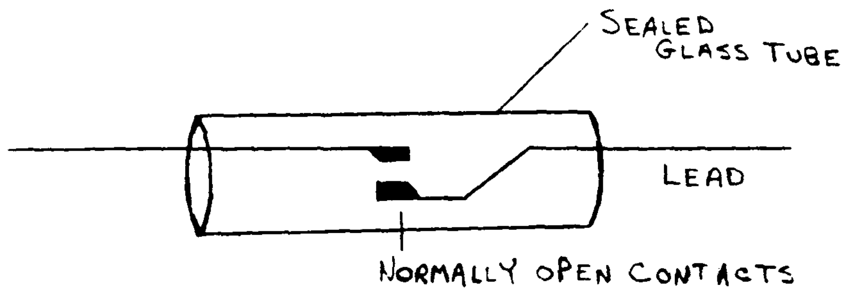


Wiegand wires can be used to sense position and velocity. Magnetic field changes are made by moving Wiegand wires and magnets past one another or by interrupting magnetic fields with metal blades. A sensing coil may register changes in the speed of closely spaced Wiegand wires moving as a unit past a magnet assembly. Devices that use metal blades to block the magnetic field reaching a Wiegand wire can produce very repeatable pulses if the same wire and magnets are used to produce each pulse. The characteristics of Wiegand wires change less than 10% from -196 degrees to +175 degrees centigrade. Wiegand wire modules are available in 15mm or 30mm lengths to produce 2.5 volt or 8 volt pulses respectively.

3.2.9 Magnetic-Reed Switches

Magnetic-reed switches are similar to Wiegand wires in that they can only detect metal objects or magnets themselves. A magnetic-reed switch is a switch that stays open in the absence of a magnetic field, and stays closed in the presence of one. Metallic objects can interrupt the magnetic field in the vicinity of a reed switch, allowing it to open. The basic construction of a magnetic-reed switch consists of a sealed glass tube that contains two contact blades arranged so that they are separated in the absence of a magnetic field (figure 3-38). The ends of the contact blades are made of iron or some other highly magnetic material. When a magnetic field approaches the tube the contacts snap closed and remain so until the the field is taken away. A solid lead is brought out of each end of the tube for connection to an electrical circuit. The sensitivity of a switch depends on the size of the magnet used with it: The switching distance increases with increasing magnet size. The switch shown in the figure can also be called a dry-reed switch.

Figure 3-38: Magnetic-reed switch construction; [33] reproduced with permission of the publisher.



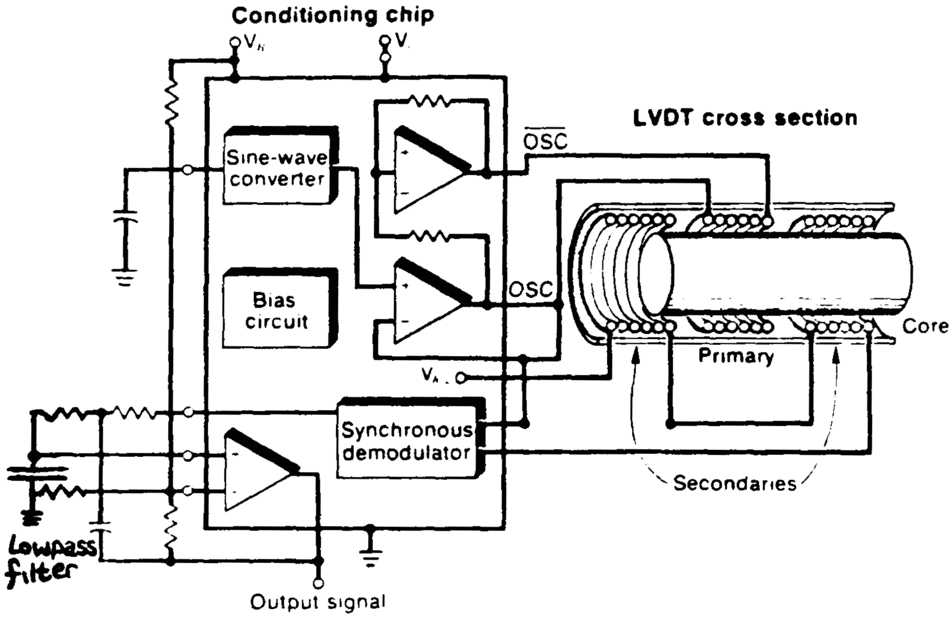
Reed switches can detect objects with magnets mounted on them, and they can also count metallic objects if the objects travel between a magnet and the switch. A reed switch could detect the speed of a turbine or a fan by letting the blades interrupt the field of a magnet as they spin. Arrays of switches could sense the displacement of metal rods such as in the sensor of section 2.2.1. Magnetic-reed switches have been used as industrial detectors for some time. One of many commercially available models is General Electric's type 2DR50.

Wiegand wires and reed switches can replace Hall-effect sensors in some sensing applications because they all are actuated by magnetic fields, but Wiegand wires and reed switches can only produce pulses or throw switches. Hall-effect sensors such as the LOHET produce analog proximity information. Wiegand wire sensors could be used some robotics applications to detect the motion of a ferrous rod for a contact sensor such as the one in section 2.2.1.

3.2.10 Linear Variable Differential Transformers

Linear variable differential transformers (LVDTs) are made up of a primary coil and two secondary coils, wound on a cylindrical form. An iron core moves back and forth inside the coils and affects an output signal that indicates the core's position. A stable drive signal is applied to the primary coil, and a synchronous demodulating circuit decodes phase changes in the secondary coils' output voltage. The output of the demodulating circuit must be carefully filtered to remove harmonics. The output of the system is a signal corresponding to the displacement of the core. Signal conditioning circuits for LVDTs now are manufactured on a single chip that contains a programmable frequency oscillator, a synchronous demodulator, and an amplifier that produces a buffered output voltage (figure 3-39).

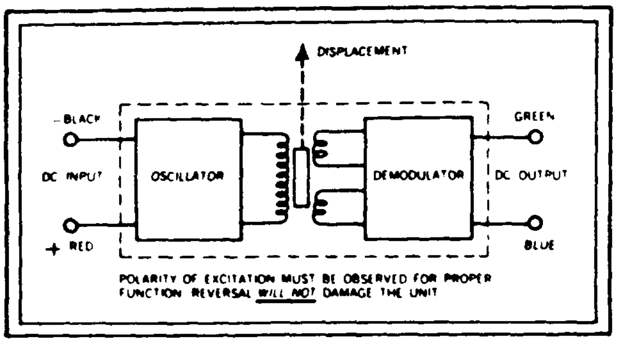
Figure 3-39: Signal conditioning chip for LVDTs [40].



Linear variable differential transformers are considered noncontact devices even though they are primarily detectors for contact sensors. LVDTs may be used in conjunction with many robotic sensors that employ movable rods because they can measure small displacements with great accuracy. The tactile weld seam tracking system described in section 2.2.3 made use of numerous linear variable differential transformers.

LVDTs are available from many manufacturers: Two such models are the series 200 and series 240 d.c. to d.c. displacement transducers from Trans-Tek Transducers Inc. [41]. These models have a LVDT and a direct current voltage for their input and output (figure 3-40). A built-in oscillator changes the d.c. input voltage to a.c., and excites the primary winding of the transformer. The moving magnetic core between the windings affects the voltage signal induced in each of the two secondary coils. The two secondary circuits each consist of a winding, a full-wave rectifier, and an RC filter. The two output circuits are connected in series opposition so that the output is a d.c. voltage proportional to the core displacement form the electrical center. The polarity of the output voltage is a function of the direction of core displacement. The sensor cannot be harmed by displacing the the core too far: It simply stops working and starts again as soon as the core moves back within the safe sensing range. The sensors have a safe sensing range of + or - 3 inches, and they cost $152 to $238.

Figure 3-40: DC to dc LVDT displacement sensing device [41].



CIRCUIT DIAGRAM

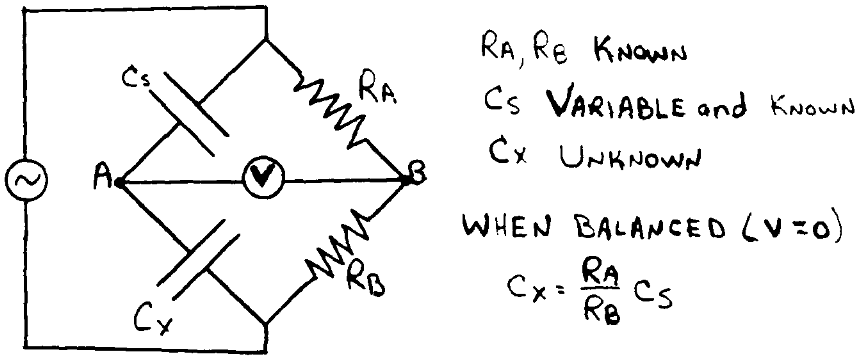
3.3 Capacitive Sensors

Capacitive sensors are based on electric fields just as magnetic sensors are based on magnetic fields. For the simplified case of a fixed area parallel plate capacitor, the capacitance is given by $C = \varepsilon A/d$. ε is the dielectric constant of the material between the plates, A is the area of the plates, and d is the gap between the plates. For constant area probes, the capacitance can be varied by changing the dielectric properties of the materials in the gap between the plates or by changing the size of the gap or by changing both. The proportionality of capacitance to dielectric constants makes capacitive sensors good for sensing metals and many other materials, such as wood, ceramics, oil, gravel, and synthetic materials. Capacitive probes can be operated at a frequency where any of these materials acts as a dielectric. The dependence of capacitance on the gap size between the electrodes is also useful for sensing. A probe functions as one capacitor plate and a grounded metallic target functions as the other, and the capacitance varies with the distance between the sensor and the target. A model of the tactile weld seam detector described in section 2.2.3 relies on capacitive proximity sensors to determine the position of a rod.

Capacitance changes are usually detected as a.c. impedance changes. Impedance (Z) relates a.c. voltages and currents in the the same way resistance relates d.c. voltages and currents: $V = IZ$. The impedance of a capacitor is related to the angular frequency ω of its power source and its capacitance, and is given by $Z = 1/j\omega C$, where j is the square root of -1. Capacitive impedance is purely imaginary or reactive, and causes the current to lag the voltage by 90 degrees in phase. Capacitive sensing systems, except for constant charge sensors like the one described in section 3.3.5, require a.c. power to detect objects.

A simple method for measuring capacitance changes in the form of impedance changes is to place a constant amplitude a.c. voltage across a probe and measure the current through it. The a.c. current through the probe is a measure of the changing capacitance. Another method used to detect small impedance/capacitance changes is a bridge circuit that resembles a wheatstone bridge (figure 3-41). The value of the known capacitance is adjusted until the voltage across the middle of the bridge (between points A and B in the figure) is equal to zero. When this occurs the bridge is balanced and the capacitance of the probe is given by the simple expression in the figure.

Figure 3-41: Bridge circuit for measuring capacitance changes.



Detecting capacitance changes with a bridge proceeds as follows: First, the bridge is balanced with nothing near the probe. An object approaching the probe changes its capacitance and throws the bridge off balance, causing a voltage to appear across the middle of the bridge. The amplitude of the off balance voltage is a measure of a change in the sensor's capacitance.

Variable capacitance probes can also change the frequency of oscillators and the resonant frequency of LC tank circuits. The two oscillator methods described in section 3.2.1 (frequency shift and off-resonance) also apply to capacitive sensors: A changing capacitance has the same effect as a changing inductance. Rather than duplicate the discussion in this section, see section 3.2.1 for a description the frequency shift and off resonance techniques.

The most common capacitive probes are flat disks or flat metal sheets. Probes are electrically isolated from their housings by guard electrodes insuring that the electric field produced is perpendicular to the sensor. Systems can make measurements in 100 microseconds with resolutions of 1/10 of a micron, and probe diameters range from thousandths of an inch to several feet [32].

3.3.1 Loaded Oscillator Sensing Technique

A capacitive is used to shunt the output of an oscillator operating in the radio frequency range. When an object approaches the sensor, the capacitance of the probe increases and its impedance decreases, shorting the output of the oscillator. The oscillator's output can be rectified into a d.c. voltage that can be used in its analog form or can throw a switch via a comparator.

The loaded oscillator method is often used in capacitive proximity switches. In the 1920's and 1930's, loaded oscillator proximity switches were used in animated displays in store windows. A sensing plate was mounted on the inside of the window, and connected to a loaded oscillator type switch. The switch operated some animated display, such as a an electric train. The display turned on when a person's hand was placed on the outside of the window opposite the sensing plate. Currently, capacitive proximity switches are used in robotics and manufacturing.

A simple rf (radio frequency) loaded oscillator circuit can be built with several transistors. Figure 3-42 [33] shows such a circuit with all its component values. Referring to the figure, Q1, L1, L2, C1, C2, C3, R1, and R2 form a basic loaded oscillator circuit. Variable inductor L1 and variable capacitor C2 are adjusted until the circuit oscillates when nothing is near the sensing plate. The output voltage of the oscillator is rectified by diodes that produce a positive voltage (reverse bias for PNP) at the base of Q2. A negative bias voltage (forward bias for PNP) is also applied to the base of transistor Q2 through R5. When the circuit is oscillating (nothing near the sensing probe), the positive voltage from the rectifier is enough to keep Q2 cut off and the relay in its reset position. When an item approaches the sensor, Q1 stops oscillating and the positive output voltage from the rectifier (the diodes) drops to near zero. This forward biases the base of Q2 and causes the relay to switch to its other position. Many variations of this simple circuit with many different components are realizable. Newer versions of the circuit would use NPN transistors and possibly silicon controlled rectifiers (SCR's) instead of the relay.

3.3.2 Industrial Capacitive Proximity Switches

Figure 3-43 [34] shows the switching circuit of an industrial capacitive proximity switch that uses an R-C generator, whose frequency is determined by a Wien-bridge consisting of R1, R2, C1, and C2. The gain factor is regulated by potentiometer P1 so that the circuit does not oscillate in the open condition. When an object with a dielectric constant greater than that of air approaches the sensitive region, the capacitance of the probe increases along with its leakage factor. This results in a decrease in the feedback coupling voltage to the potentiometer and the oscillator starts oscillating. The output of the oscillator is rectified, filtered, and then converted to an impulse with a trigger circuit.

Currently, this switching circuit is used in West German automated manufacturing proximity switches.

Figure 3-42: A simple loaded oscillator circuit [33]; reproduced with permission of the publisher.

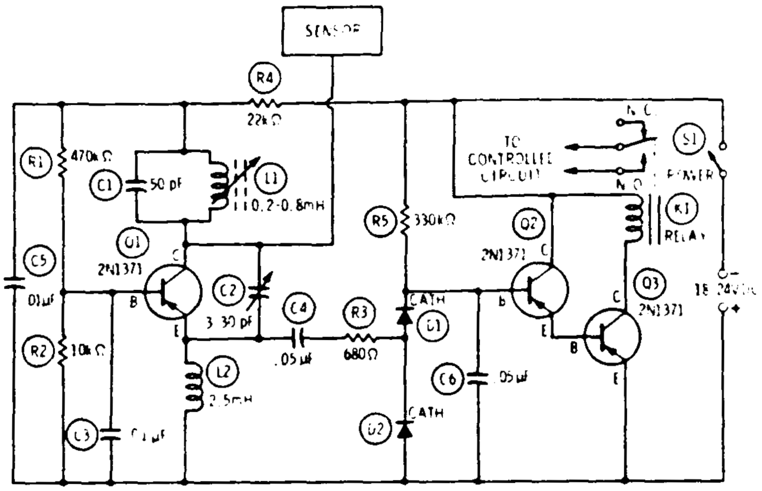
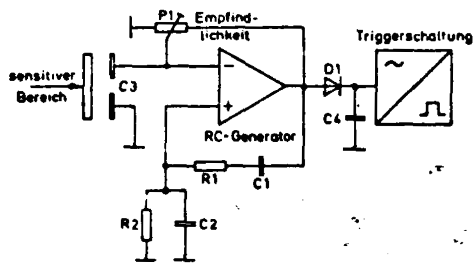


Figure 3-43: Switching circuit for a capacitive proximity switch [34].



3.3.3 Capacitive Proximity Sensors

These sensors consist of a flat probe that acts as one capacitor plate and a metallic target that acts as the other. A constant amplitude a.c. voltage applied to the sensing probe, and the current through the probe is inversely proportional to the distance between the sensor and the target. The type of probe used depends on the material that must be sensed; Probes for non-conducting material differ from those for conductors. The output from a probe for conductors is easier to make linear than the output from a probe for non-conductors.

Sensing probes made for conducting targets (figure 3-44) have a guard ring concentric with the sensing plate to isolate the sensor field from the sensor housing. This guard ring prevents anything save the target object's surface from influencing the electric field from the sensing plate. The capacitance of the sensor plate and the object is inversely proportional to the distance to the object. Probes for non-conductors (figure 3-45) are built much the same way. The only difference is that the guard ring is set back inside the sensor housing to allow for an electric field between the sensing plate and its housing. The sensor housing is always grounded for both conducting and non-conducting models. The electric field between the sensing plate and the housing varies with the distance to the non-conducting target. These sensors can be round, square, or rectangular depending on the dimensions of the target. Doughnut shaped sensors can de used to sense rod diameters.

Figure 3-44: Capacitive probe for conducting targets [32].

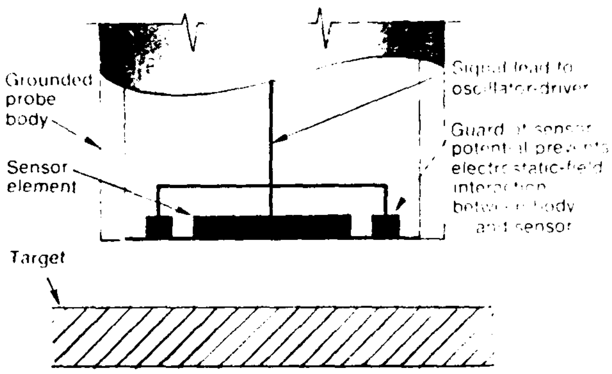
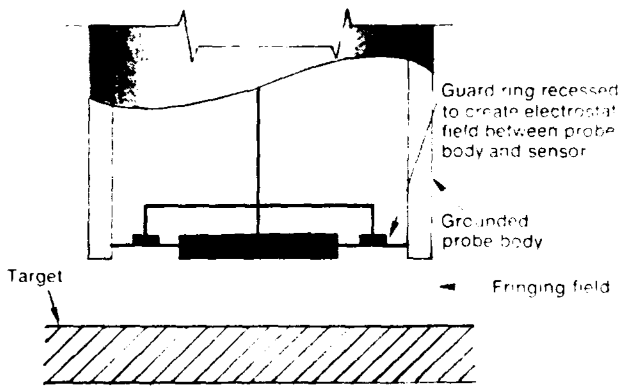


Figure 3-45: Capacitive probe for non-conducting targets [32].

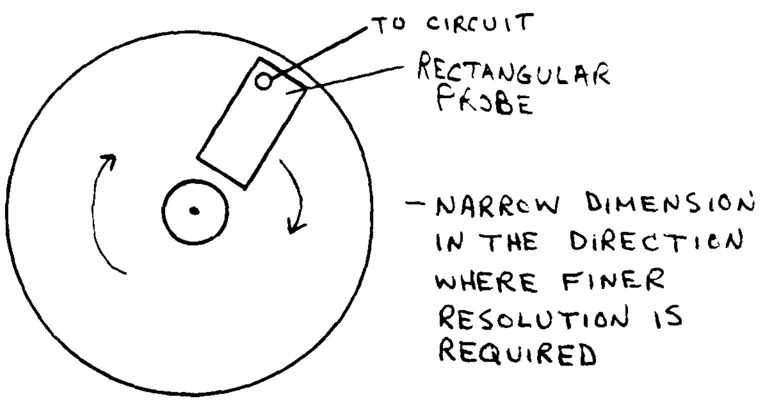


The maximum sensing distance to the target object depends on the size of the sensor: The smaller the distance the smaller the probe can be. Too small a sensor to air gap ratio will result in too weak a current signal. The safe maximum distance corresponds to a capacitance between the sensor and the object of about 1/4 pF, which is the capacitance of a one square inch plate one inch from a large conducting surface. A 1/10 square inch plate held 0.1 inch from the same conducting surface also corresponds to a capacitance of 1/4 pF and etc.

The probe size should be small compared to the size of the surface in question for accurate and linear distance measurement. If the sensor is too large, changes in the area of the target surface can be registered as changes in the distance. It is recommended that the distance between the target's edges and the sensor's edges be kept greater than three times the gap width between the two objects [32]. In general the largest possible sensor should be used for large unmoving objects, but once the sensor capacitance exceeds 1 pF, increasing the probe size further is not beneficial.

When the resolution for a moving target must be finer in one direction than for a direction perpendicular to the first (for example, right to left instead of front to back), a rectangular probe is used. The narrow sides of the rectangle are aligned in the direction that must have the finer resolution. The length of the narrow sides should be less than the width of the object in question but large enough so that the sensor can stay an ample distance from the object. Rectangular sensors are used to measure radial wave crests on rotating disks, such as the warp in phonograph records (figure 3-46). For measuring internal conical surfaces, sensors are mounted inside cone shaped probes. The flatness of a target surface can be measured with an array of probes: Each probe is zeroed against a flat control surface, and when an experimental surface is encountered, the deviation from the flat standard is registered in each probe. The outputs of the probes can then be scanned to indicate the average deviation from the standard. For very narrow surfaces such as turbine blade tips or razor blade edges the sensor size will always be larger than the target surface. Distance measurements can still be made, but the capacitance now depends not only on the object edge but also on its two sides. Capacitive sensors of this type have potential for use in robotics.

Figure 3-46: Capacitive sensor for detecting the warp in a record.



3.3.4 Small Dimension Displacement Sensor

This system relies on a varying capacitance to modulate the amplitude and phase of an a.c. signal. The sensor measures very tiny displacements for projecting micron sized patterns onto photosensitive masks or silicon wafers. One plate of this capacitive transducer is a lengthy grating of uniformly spaced lobes resembling a two sided comb, and the other plate is made up of two identical interdigitated comb-like structures (figure 3-47). The dimensions of the lobes that stick out on the sides of the plates are very small so that very minute displacements can be measured (Table 3-4 gives the exact dimensions). As one of the plates slides over the other, the capacitance of the whole structure changes periodically as the lobes line up totally and then misalign totally. The long grid is attached to a moving slide while the two combs are mounted in a fixed position.

Figure 3-47: The two capacitor plates of the sensor [42]; copyright 1981 IEEE.

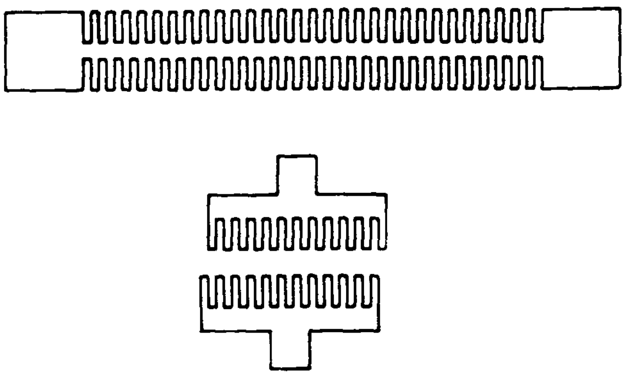
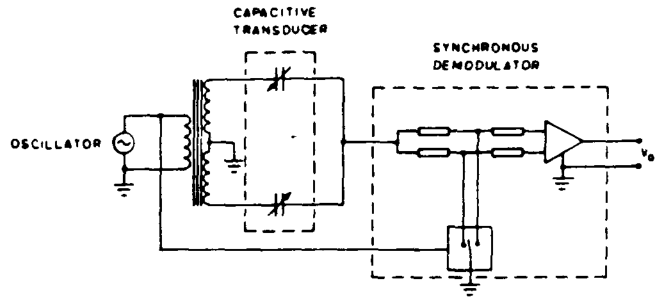


Table 3-4: Exact dimensions of the lobes in microns [42]; copyright 1981 IEEE.

Long Grating	Interdigitated combs
************	********************
Lobe width: 22	Lobe width: 14
Space width: 19	Space width: 27

A symmetric transformer couples a high frequency oscillator to the two separate stationary plates. A difference signal is taken from the long grating. The output signal from the long grating is synchronously demodulated to obtain a varying d.c. voltage level whose magnitude is directly related to the relative displacement of one to the transducer plates with respect to the other (figure 3-48) As the plates slide over one another the output voltage experiences near sinusoidal variations in amplitude. Absolute displacement from a reference point can be measured by counting the number of peaks in the output voltage. Average speed can also be determined by dividing the counted number of peaks by the elapsed time.

Figure 3-48: Principle of synchronous detection method for displacement [42]; copyright 1981 IEEE.



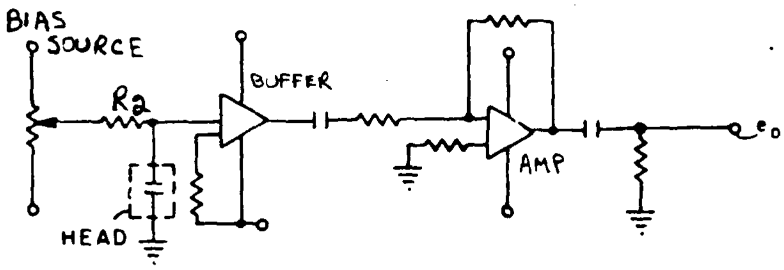
The system has a sensitivity of 2.6 millivolts per micron and is accurate within 4 nanometers due to thermal noise. The sensor must be precisely aligned before use: The long grating must be positioned along the axis of motion and the interdigitated combs must be aligned precisely parallel to each other. The plates have to be made parallel in the vertical plane and their separation must be precisely set (a typical separation is 20 microns). Precise adjustments are made possible by mounting the sensing plates in clear glass. The experimenters then measure the tiny distances necessary for aligning the sensor with a microscope. This sensor has a potential for use in robotics areas requiring very precise and tiny displacement measurements.

3.3.5 Constant Charge Height Measuring System

The sensor determines the height of a ferrite magnetic head above a rotating magnetic disk using the changing capacitance between the two. This system is different from most capacitive sensing systems because it does not require an a.c. voltage or an oscillator. The constant charge principle relies on the relationship $Q = CV$ for its output signal. Solving the previous expression for the voltage V and substituting in the relationship for a parallel plate capacitor one obtains: $V = Qd / \epsilon A$. Since the area of the head remains constant and nothing but air is present in the gap between the head and the disk, the voltage across the capacitor is directly proportional to the size of the air gap.

The sensor circuit consists of a bias source which supplies a voltage through a very large resistance (R2) to the magnetic head (figure 3-49). Changes in the capacitance between the head and the disk cause changes in the voltage across the "capacitor". Some of the charge leaks away through resistor R2 and causes an error, but as R2 becomes very large the error becomes negligible. Resistor (R2) would have to be infinitely large to really have a true constant charge system. The tiny voltage change from the capacitor is put through a high impedance buffer and follower whose output of the follower is then applied to a fixed high gain amplifier. The output voltage of the amplifier is a direct measure of the spacing between the head and the disk.

Figure 3-49: Circuit diagram of the constant charge sensor [43].



A constant charge capacitive system can measure most of the quantities that ordinary a.c. type capacitive sensors measure. This type of system could replace some conventional capacitive sensors in robotics.

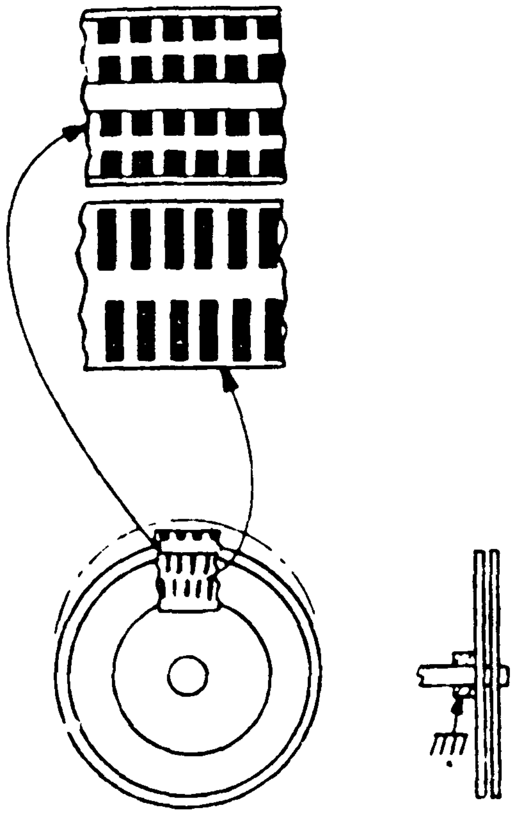
3.3.6 Rotary Motion Sensor

This system detects capacitance changes caused by two patterns of conducting pads sliding past one another. The design is similar in principle to the sensing device discussed in section 3.3.4. The patterns of conducting pads are mounted on two closely spaced wheels: One is fixed, and the other is free to rotate. Information about the direction of motion is supplied by two offset patterns of pads. One wheel has pairs of conducting pads in its pattern, and the other has single pads. Differential signal techniques are used to reduce noise by the cancellation of the common component of both signals.

The fixed wheel has the double pattern and the rotating wheel has the single pattern. The single pattern consists of concentric rings of pads around the outer edge of the fixed wheel facing the moving wheel, and the double pattern consists of four concentric rings of smaller pads (figure 3-50). The radial patterns align and misalign over and over as the moving disk rotates. The direction of rotation is detected through a quadrature (90 degree phase difference) offset between the inner and outer rows of the single pattern.

A pulsating source, such as a 555 timer in the astable mode, supplies voltage to the double pattern through a set of four resistors. The inner and outer rows of conducting pads in the double pattern are connected to

Figure 3-50: The patterns of conducting pads [44].

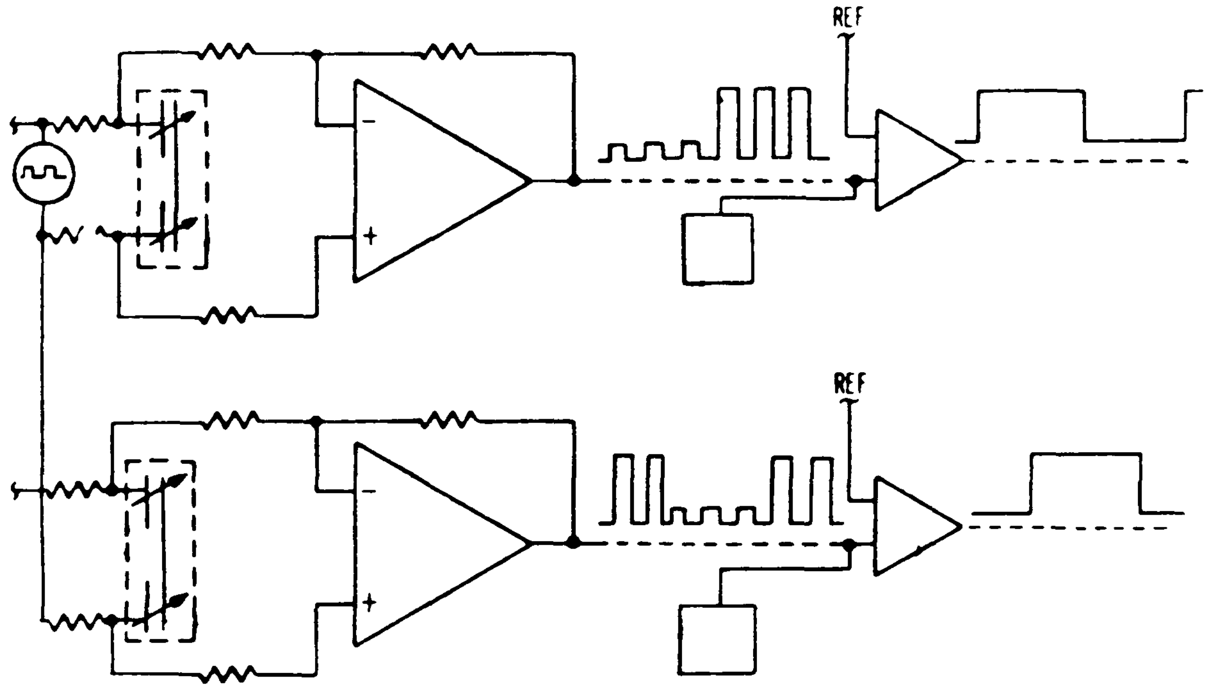


opposite terminals of the pulsating voltage source. The two output voltages of the sensor are measured across the inner and outer rows of pads in each of the two rings of the double pattern. These voltages are applied to the input terminals of two differential amplifiers (could be op-amps) through another set of four resistors (figure 3-51). The gain of the amplifiers is adjusted with a feedback resistor for each op-amp. The output of the amplifiers contains pulses at the frequency of the voltage source, and the amplitude of the pulses is modulated by the change in capacitance of the sensor. The two outputs can analyzed with special detectors or comparators that compare the amplitude of the pulses to a reference but ignore the zero voltage interval between pulses. Figure 3-51 also shows the two possibilities for analyzing the outputs.

3.4 Resistive Sensing

This section covers a single robotic sensor that determines the distance between a robot arc welder and the welding seam by means of the varying resistance of the welding arc. The sensing involves either the Gas Tungsten Arc Welding (GTAW) or the Gas Metal Arc Welding (GMAW) process. A constant current or a constant voltage is applied to the arc, and changes in the arc's resistance indicate corresponding changes in its

Figure 3-51: The circuit of the capacitive rotary motion sensor [44].



vertical distance from the welding surface. The sensor can provide for full three-dimensional seam tracking, as well as simple vertical distance control.

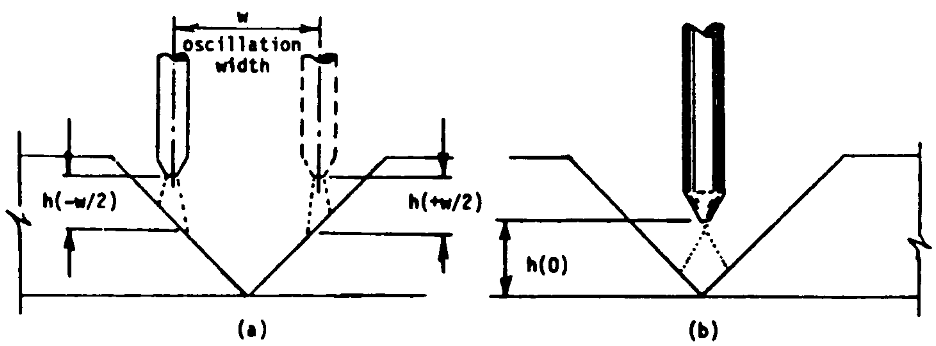
Position information can be obtained only from the welding arc if the fundamental relationship of arc voltage and arc current to torch-to-workpiece spacing is known: The relationship is different for each particular welding process. For the GMAW process the torch-to-workpiece distance h is related to to the arc voltage V(t) and the arc current i(t) by the following expression:

$$V(t) = r\{h - l(t)\}i(t)$$

In the equation, r is the average resistivity per unit length of the extension wire and l(t) is the arc length. The arc length l(t) also depends on the distance h, but the variation is small and non-linear. If a constant voltage source is used (which is normally the case with GMAW devices), the arc current i(t) varies inversely with the torch-to-work distance h. The current sensitivity to distance depends on many parameters, including different shielding gases and wirefeed rates. A typical current sensitivity for 75% Argon-25% Carbon dioxide shielding gas is around 1-1.5% of the average welding current per millimeter change in the distance. Similar results can be derived and verified for many other welding processes and parameters.

Figure 3-52 [45] shows the basic technique for through the arc position sensing. During operation, the torch moves back and forth (torch oscillation) from one sidewall to the other, as shown in figure 3-52a. This forces a variation in the arc length from which cross-seam and vertical position information may be obtained. The dependent arc parameter is arc voltage in the GTAW process (operated with a constant current) and is arc current in the GMAW process. Details are given below for the GMAW process.

Figure 3-52: Welding technique for through the arc sensing [45].



Cross-seam position information is obtained by sampling the arc current on the right and left-hand oscillation extremities. If the center of oscillation is offset from the joint center line, the right-hand torch-to-work distance will be different from the left-hand one, and the two current samples will be different. For instance, an offset to the right corresponds to a smaller distance $h(+w/2)$ and a larger current $i(+w/2)$ on the right-hand side. The difference between the two samples is proportional to the magnitude of the cross-seam distance error e_{cs}. Stated otherwise:

$$e_{cs} = k_1\{i(+w/2) - i(-w/2)\}$$

The vertical distance error e_v is proportional to the difference between the current sampled at the center of oscillation $i(0)$ and some predetermined reference current I_{ref}:

$$e_v = k_2\{i(0) - I_{ref}\}$$

Constants k_1 and k_2 depend on the geometry of the weld seam, the shielding gas, and other parameters. All the process parameters should be known in advance so k_1 and k_2 can be predetermined for any welding task.

Robot welders commonly use torch oscillation, so an automatic welder need not change its operation to accommodate through the arc resistive sensing. Resistive proximity sensing increases the accuracy of automatic welders dramatically.

3.5 Ultrasound and Sonar Sensors

Sonar sensors use high frequency acoustic waves to determine position, velocity, and orientation. The sound waves are usually much higher in frequency than humans can hear, hence the name ultrasound. A well-known example of ultrasound sensing is submarine sonar, where the knowledge of the speed of sound in water allows the submarine crew to determine the distance to an object through measurement of the time for a pulse to travel out and be reflected back. Mobile robots on land also measure distances with time of flight systems.

The usual method for measuring the time of flight of a pulse is to count the number of pulses from a clock between transmission and reception of the pulse. Sound travels at about 300 meters per second in air, so the frequency of the counted pulses must be sufficiently high to enable accurate distance measurements to be made. The shorter the distance range to be measured, the higher the frequency the pulses must have. Velocity can be determined with ultrasound by means of the doppler effect. The principle of the doppler effect is that objects moving toward the sound source (or the sound source moving towards the object) tend to push the emitted sound waves together increasing their frequency: To the human ear this means that the pitch of the sound increases. An object moving at a speed of 10 cm per second shifts the frequency of a 40 kHz sound pulse by about 10 Hz [46]. A 10 Hz doppler shift is sufficient to enable a robot to determine its velocity relative to its environment.

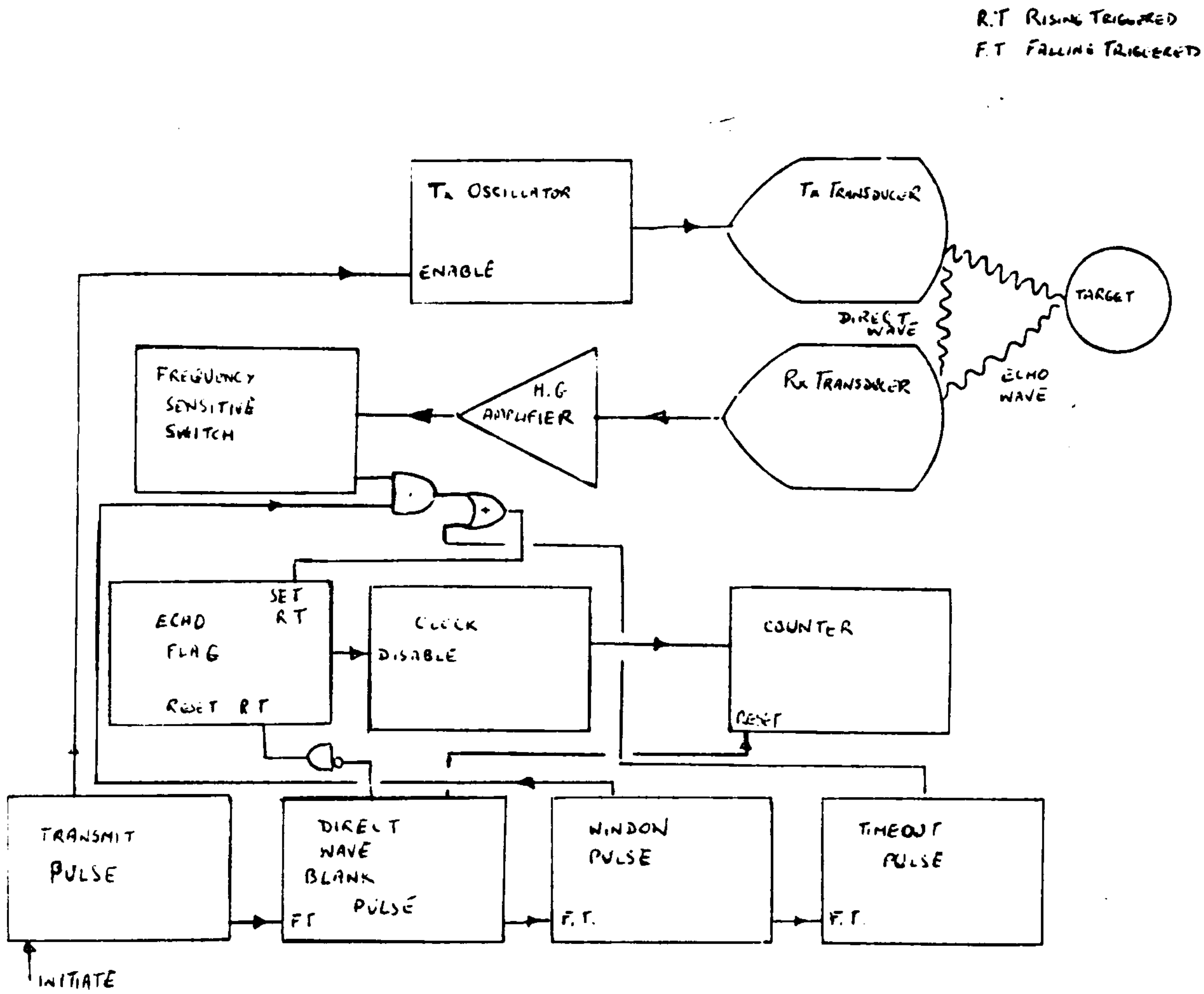
3.5.1 Sonar Sensing Techniques

Three main sonar sensing techniques exist. In the pulse mode, distances are determined by the time of flight of a short sound pulse. Robots use the pulse mode at larger distances to determine their own position relative to their environment and at short distances to determine the range of target object. In the phase mode, a continuous sound wave is transmitted and changes in the phase of the reflected wave allow movements of a target relative to to a robot to be measured accurately. The phase mode is used when a single dominant echoing target is present. In the frequency modulation mode, a continuous sound wave is transmitted as in the phase mode. The signal is frequency modulated, typically using a linear sawtooth modulation. The magnitude of a component of the reflected signal at a particular frequency is related to the delay between the transmission at that frequency and the return of an echo.

Pulse mode systems are the easiest to implement and figure 3-53 [46] is a block diagram one such system.

The system transmits a one millisecond pulse of 40 kHz The maximum length of the sampling window fixes the maximum range of the sensor. A counter runs while the sampling window is open until the echo pulse is received. The output of this counter is a measure of the distance to the target, and the frequency of the counter determines minimum range of the sensor. The sound detector used is a frequency sensitive switch that rejects all frequencies except a narrow band around 40 kHz. If necessary, the echo pulse can be amplified before it gets to the detector.

Figure 3-53: A pulse mode sonar sensing system [46].



3.5.2 Sonar Sensors for a Mobile Robot

The French robot HILARE senses proximity with ultrasound devices that transmit ultrasound pulses at 36 kHz. The sound emitter describes an angle of 30 degrees, so only reflections at an angle of 15 degrees or less from the perpendicular of the emitter-receiver assembly can be received (figure 3-54). To compensate for the small sensitive area of each assembly, 14 of them are placed at various locations on the robot (figure 3-55).

Figure 3-54: The emitter-receiver assembly [47].

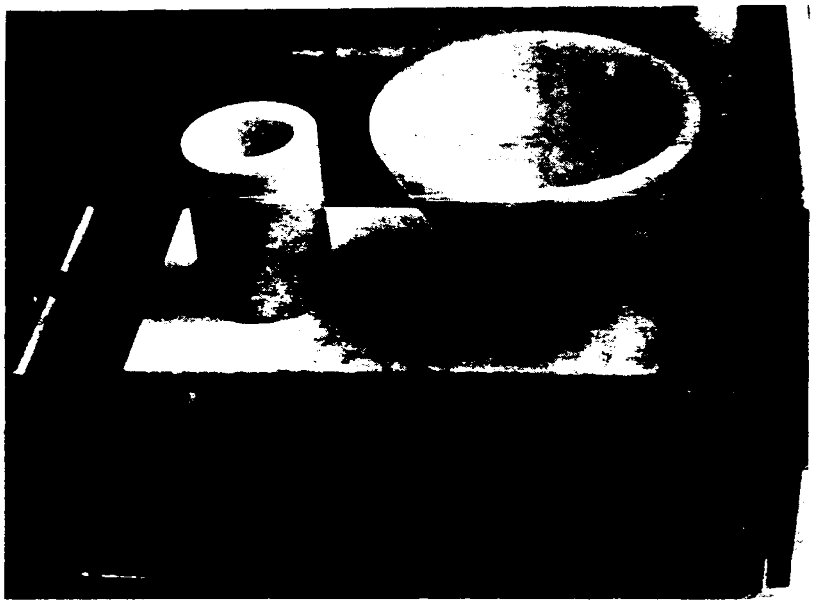
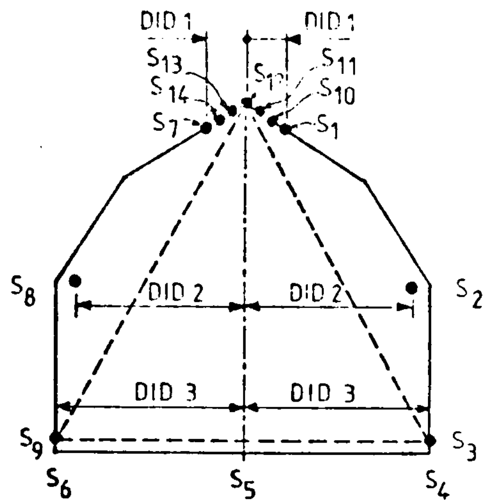


Figure 3-55: The locations of the 14 sensors on the robot [47].



The distance from the robot to an object is measured by counting the number of system clock pulses during the time it takes the pulse to travel to the target and echo back. The frequency of the system clock is 1536 Hz, and each emitter-receiver module can measure distances of around 2 meters with an accuracy of .5 centimeters.

The robot waits 10 milliseconds between two consecutive measurements, which consist of sending out and receiving a pulse with one of the 14 sensing elements. Several reasons exist for this seemingly arbitrary hold time: The robot must not move too far during the cycle of 14 measurements. With 10 milliseconds allotted for each sensor, one cycle requires 140 milliseconds. Since the robot moves at a speed of about 1 meter per second, it can only travel 14 centimeters during each cycle. The time must also be long enough to enable each sensor to measure an appreciable distance. The 10 millisecond time allows each sensing element to measure a distance of 1.65 meters. The time should be as short as possible so the robot can't move far, but as long as possible so that large distances can be measured. Another possible problem that can arise with too long a hold time is the echo from one sensing assembly being received by another. The 10 millisecond time helps to solve this problem but the main solution is the order in which the modules are activated. The modules are fired in such an order so that two consecutively fired elements are far apart.

3.6 Air Pressure Sensors

Air pressure sensors operate on a primitive principle, but they are inexpensive and easy to use. The sensor has a nozzle or jet that delivers a supply of high pressure air, and when an object nears the end of the nozzle it pushes against the high pressure air or obstructs the open end of the jet. The amount of back pressure in the air nozzle can be used to determine the proximity of the object or the obstruction of the air can be used to determine whether an object is present. Small nozzles can clog up in a polluted industrial environment, but clogging can be avoided if the air supply is filtered and a high pressure is used. The high pressure prevents anything from entering the front end of the nozzle. Scientist in Italy use air pressure sensors in robotics.

Two types of nozzle configurations exist: counter pressure and induction sensing [48]. A counter pressure nozzle is a thin cylindrical duct that has a small branch off of it. The pressure inside the nozzle is measured by a transducer inside the small branch off of the main duct. A large amount of air pressure behind the nozzle is essential to operate the device, and the nozzle must be close to the target object to function properly. For small diameter nozzles, a distance of 0 to .6 mm is recommended with good sensitivity found at a distance of around .2 mm from the object. Objects at larger distances can be sensed with bigger nozzles. Counter pressure sensors function as follows: A large air pressure behind the nozzle tries to push a great deal of air out of the front of the nozzle, and when an object becomes close enough to the nozzle (either by normal or tangential approach) it prevents some of the air from getting out. The amount that escapes when the obstruction is present depends on how far the object is from the nozzle tip. Air unable to escape the front of the nozzle builds up a back pressure inside the nozzle that is registered by the pressure transducer inside the branch off of the main duct. With a fairly large nozzle, the pressure increase as a direct measure of the proximity of the obstruction is acceptable for robotics.

In induction sensing, the nozzle has an annular duct around it that collects air from the nozzle. When no object is present little air is collected, but the recovered pressure is quite high even when the distance between the air jet and the target is relatively large (about 2mm). The effective range of either this or the counter pressure sensor can be increased by enlarging the dimensions of the sensors.

Flat parts can be identified with small sensors mounted a fixed distance away. Workpieces are placed about .2mm below the sensors on a disk and slowly rotated until they are properly oriented. A simpler way to orient objects is with jet obstruction, where a flat object moves over a plate with several holes in it for nozzles. An air leak out of a particular nozzle (hole) indicates that no object is present above it. This configuration, as well as the previous one, can easily be used to orient objects with holes in them. Italian robotics experimenters have oriented flat parts with air jet sensing.

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