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A REVIEW OF ROBOTIC SENSING AND TACTILE OBJECT RECOGNITION, AND THE DESIGN OF A DIRECTIONAL SENSOR

BY

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ABSTRACT

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A REVIEW OF ROBOTIC SENSING AND TACTILE OBJECT RECOGNITION, AND THE DESIGN OF A DIRECTIONAL SENSOR

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Sensors give robots the ability to perform an increasingly wide range of tasks in a safe, more rapid, yet economical manner. The first aim of this research was to review robotic sensor technology, primarily of a non-visual nature. Sensors currently used in practice and also devices at a research stage of development are reviewed and their applications are discussed.

A second objective was to find the orientation of the surface of a workpiece, relative to a robot gripper. Initially, the angles between the sensor and the surface of contact of the workpiece were restricted to $\pm 10^{\circ}$. In a second stage, the range of the angles was increased to $\pm 40^{\circ}$. A tactile directional sensor was designed and a prototype was built and partially assessed.

The ability to recognize objects would considerably increase the range of robot applications. Vision and touch are the main senses used by humans for object recognition purposes. Artificial vision has been the subject of considerable research interest. Visual methods of object recognition were therefore not the major concern of this thesis. Tactile recognition can complement vision systems or replace them in conditions such as poor light. Tactile object recognition was reviewed and the author's recognition algorithms are presented in appendix A, although they should be regarded as a first step towards a tactile recognition system. The proposed recognition method assumes that tactile data, similar to that expected from the directional sensor designed, that is an array of tactile data, is available.

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INTRODUCTION

To further increase the present stage of automation robots need to be efficient, precise, intelligent and flexible, the two last factors of which represent the main difference between robots and automated machines. In order to develop these sophisticated-flexible robots, sensors are incorporated to them, which enable robots to learn and react according to changes in their environments, in a similar way to the human response.

The first objective of this research was to design a directional sensor that could determine the orientation of an object, relative to a known plane. Initially, a sensor was to be designed for a restricted range of objects which exhibit parallel faces. Also the angles, relative to a coordinate system fixed to a robotic hand and the surface of contact of the object, were assumed to lie between $\pm 10^{\circ}$ [1].

In a second stage of the design, the workpieces were considered with either parallel or non-parallel faces and the range of the angles was increased to $\pm 40^{\circ}$. Furthermore, the major requirements of the sensor are that it should be inexpensive, small (its sectional area should not be bigger than 1-sq-inch), repeatable, robust, simple to assemble, easy to calibrate and manufacture. Such a directional sensor is intended to be utilized, for example, in assembly operations when the exact orientation of the object is necessary.

The sensor designed has a matrix arrangement of nine optical component pairs where the detectors are fixed in a main block. Opposite each detector, a pin carrying an infrared light source, is mounted. Each pin can move unidirectionaly inside the block, due to the displacement of its external end, which is in direct contact with the object. The design, manufacture and development of a prototype (a four-pin version) are presented. A suggestion for a possible improvement of the matrix design is also provided.

A second objective of this thesis was to review robotic sensor literature, mainly of a non-visual nature. All over the world there are laboratories, universities and industries concerned with robot and/or sensor development. Appendix B lists the main centres of robotic research and development. In order to carry out the review reference sources were consulted as detailed in appendix C. The review describes sensor devices classified according to the transducer technology used for their operation. Both practical and experimental devices are presented.

The review has indicated that an object recognition procedure, which humans do mainly through sight and touch, would further increase robot applications. Although vision is the most complete sensory aid for robots, it was not a major concern of this research. Tactile sensing can give information about the interaction between a gripper and a workpiece, which is not available by any other means [2], [3]. Also Bejczy [4] and Okada[5] have quoted several instances, where tactile sensing is more appropriate than vision, such as in conditions of poor lighting or dust, or where parameters like surface hardness can be used for recognition purposes. Therefore a third objective emerged which involved reviewing tactile methods of object recognition.

Tactile object recognition methods are still at a research stage and not many practical examples were found. However, the literature reviewed has shown that the data from the proposed matrix sensor could be explored for recognition purposes. Recognition algorithms were produced by the author, but have not yet been implemented, as an attempt to use the matrix data to discriminate different shapes.

This thesis comprises five chapters. Chapter 1 introduces robotics and sensor technology. The state-of-the art of sensors is reviewed in chapter 2. Chapter 3 describes the design of the directional sensor and provides an assessment of a prototype. Object recognition through tactile sensing is reviewed in chapter 4 and an overview of the author's recognition method is presented, the algorithms of which are given in appendix A. The work is discussed in chapter 5 and future developments of tactile sensors are presented based upon evidence gathered from published literature.

CHAPTER 1

INTRODUCTION TO ROBOTICS

Robotics is an emerging subject, which combines the knowledge in most of the established branches of engineering, Control Theory and Computer Science. This chapter introduces robotics and sensor technology. First a brief robotic history is presented, subsequently robot definitions are discussed; finally, a third section is dedicated to robotic sensors, because they are thought to be the key factor in the development of the next generation of robots.

1.1 Robotic History

Slaves were "created" by the popular literature, in human bodies but possessing no desire for freedom, tireless, unpaid and very predictable in their actions, e. g. Dracula' slaves. A natural evolution within the popular literature was the creation of such slaves not in human body, but instead, in a mechanical configuration. Then, with the spread of the cinema and TV broadcasts, the evolution of such "creatures" altered into a revolution. They became very intelligent, precise, flexible but some times unpredictable; in other words, they became the robots of the "Star War" movie.

The word robot was introduced by a Czech writer, Karel Capek, in a play called "Rossum's Universal Robots" first performed in 1920 [6]. In that play, a machine-slave was called "robot", derived from the Czech word "robota", which means "forced labour".

Since the Second World War, technology has advanced in the direction of automation. Automation has considerably decreased the costs of operations, as it has released man from performing tasks which can be done in a faster, safer and/or more precise way by machines [7], [8]. This economic aspect was the necessary feedback to stimulate an increase in automation.

Simultaneously, the exploration of the potential of nuclear power, the deep oceans and outer space seemed to be lucrative and important for man. Engineers began to design equipment like manipulators and teleoperators to use in these new environments, which are dangerous and potentially hostile to man. As an example, the first teleoperator-robot found in this bibliographical search was built in the sixties, by the Atomic Energy Commission of NASA [9].

Robots were thus a direct result of automation in industrial environments and were crucial for the exploration of outer space. Both sectors gave the required technological support and industry alone was responsible for the economic benefits of the robot evolution.

At the beginning of the seventies, the 1st International Symposium on Industrial Robots exhibited the first "industrial robot", which was employed for spot welding operations in the car industry; the same industry that, a few years before, had demanded heavy automation [10]. The applications in dye-casting, forging and spray painting tasks followed immediately. Since then, other robot applications have become evident and many more designs have been developed and used.

1.2 Robot Definition

Engelberger* once said: "I cannot define a robot, but I can certainly recognize one" [11]. This statement enforces how difficult it is to define a robot and to date there is not a definition which is accepted universally.

* J. Engelberger is called the "father of robotics". He is the founder and president of Unimation, Connecticut, USA.

Robots are defined in most dictionaries as a man-like machine, highly flexible and completely automated. This robot concept was certainly drawn from the science-fiction literature, as most of the present robots are neither man-like, nor highly flexible. Table 1 shows the American and Japanese robotic classification, where differences are due to the robot definition of the Robot Institute of America (RIA) and the Japanese Industrial Robot Association (JIRA) [6], the latter also defines as robots, what the Americans refer to as just automated machines. Therefore the robotic statistics of Japan give higher numbers than their corresponding American counterpart figures.

ROBOT CLASSIFICATION	
JIRA	RIA
1. manual handling robot	-
2. fixed sequence robot	-
3. variable sequence robot	1. variable sequence robot
4. playback robot	2. playback robot
5. numerically-controlled robot	3. numerically-controlled robot
6. intelligent robot	4. intelligent robot

TABLE 1 - Japanese and American robot classification

JIRA classes 1 to 5, represent the first generation of robots. Its main components are mobile mechanical structures, motors, power transmission devices, computer(s) and interface(s). To achieve more flexibility and to expand robotic applications, sensors must be added, either to determine the relative position of the robot components or to enable the machine to interact with its environment.

The definition of the International Standard Organization is given here to summarize the robot concept, although restricted to the current state-of-the art, i.e: "A machine formed by a mechanism, including several degrees of freedom, often having the appearance of one or several arms ending in a wrist, capable of holding a tool or a workpiece or an inspection device. In particular, its control unit must use a memorizing device and sometimes it can use sensing and adaptation appliances, taking into account environment and circumstances. These multipurpose machines are generally designed to carry out a repetitive function and can be adapted to other functions" [12].

1.3 Sensor Technology in Robotics

A potentially wide range of applications was envisaged for the first generation of robots. However they were unable to perform a task, if it was presented in a slightly different way from that originally specified. Also a number of tasks, once thought to be purely repetitive, require frequent intervention by the operator.

In order to interact with their environment, humans are provided with five senses. Sensors have already been developed to provide robots with hearing, vision, touch and even smell capabilities. A robot with a smell sensor, for example, is employed upon a British Leyland assembly line, where windscreens are fitted to car bodies [13]. Examples of hearing (ultra-sonic), touch (or tactile) and vision (optical) sensors are presented within chapter 2.

However, most of the current robots do not have sensors. For example Unimation, which is the biggest American robot company, does not provide sensors for the majority of its robots. The state-of-the art of sensor technology is still very primitive compared with their human equivalents. Research and development in this area is therefore needed in order to increase the variety of robot applications.

Two main points to be considered in the design of sensors are firstly, a knowledge of transduction theory, which could be applied to the design, and secondly, the availability of practical materials or components, which behave according to this theory.

Transducer theory is briefly treated in the next chapter. The development of materials is an extensive subject and is not within the scope of this thesis. There are a number of publications on research and tests of materials for robotic sensory applications, such as in graphite filaments [14] and Dynacon elastomers A, B and C [15]. The reader is also referred to [16], for theory about new magneto-elastic materials and their applications to sensor design for measurement of force and torque. Magneto-elastic materials have been developed by the US Naval Surface Weapons Center since 1960.

Yet to be considered is the processing of data given by the sensors and its use in the control of robots. As far as robotics is concerned, intelligent sensors are needed. Microcomputers are now largely available at relatively low cost, therefore they represent ideal components for sensor systems. However far from the perfect sensory system and flexibility displayed by most of today's "Hollywood science-fiction robots", sensors are the key factor for robots to be capable of adapting themselves to changes in their environment.

CHAPTER 2

A SENSOR REVIEW

Development of sensors for applications in robots began in the sixties, but the technologies applied are far older and experiences with transducers in industrial control have formed the basis for this development. This chapter reviews sensors that have already been implemented in practice and also devices that are still at a research stage of development and their applications are discussed.

2.1 Summary of Applications

As quoted previously robots were first developed for industrial and exploration operations. Today's research has however, spread to other sectors, namely medical, agricultural, military and educational; although practical applications lag far behind the theoretical and experimental work. Examples of tasks to be performed by robots with and without sensors are below presented. Sensory aids will be discussed where they are speculated to have an impact in future.

A typical industrial task is taking a randomly-positioned workpiece from a bin. A solution is proposed by Witwicki [17] using proximity sensors to determine the gripper position and protect it from collisions. In another example visual and tactile sensors are used together to allow the acquisition and reorientation of the pieces from the bin [18]. Sensors in the micro-electronic industry are developed, for example, to measure mask-structure, contact force in connectors and slider-to-disk clearance in disk drives [19]. A process of grinding welding beads on the roof of car bodies was developed using a robot with tactile sensors which can give geometric feedback of the bead and surface [20].

Many operations in the exploration sector must be carried out unmanned therefore sensors are necessary to be incorporated into robots. Exploration of outer space requires operations such as handling, assembly and surveillance. Also services in space, which is now the main proposal of NASA [2], are included within this sector. Two typical tasks are the repair of satellites and antennas, both for communication purposes. In undersea exploration robots could, for example, locate sunken ships, recover black box from aircrafts, collect rock samples or inspect oil pipes [21], [22]. Finally, in the exploration sector are included dangerous environments such as nuclear power stations, where material handling, maintenance and assembly are necessary.

In medicine robots can have applications in micro-surgery, prosthetics and external aid for bed ridden or handicapped patients. Nightingale has developed an anthropomorphic hand for prosthetic applications where sensors are used to enable the hand to control force, detect slip and judge weight of objects such that the hand can grasp both heavy and delicate objects [23].

A few researchers have even applied robots to sectors such as agriculture. However, Harmon [7] stated that difficulties to introduce robots in agriculture are due to the fact that the automation already achieved seems to be satisfactory to date. Also, he notes, tasks like harvesting and milking are too difficult for robots, although so primitive for man. One of the few practical examples in this sector is a robot with proximity sensors utilized for sheep shearing. The sensors "feel" the profile of the animal in anticipation of the shears [24].

Robots with sensors in military applications can perform operations such as surveillance, missile manoeuvres and searching mined fields. But the literature is scarce for security reasons.

Finally, the educational robot [25] explores every sensory aid. All types of sensors are to be designed and developed as they could mean a future practical application and enable one to learn and train into robotics which is the main purpose of education.

The table 2.1 summarizes the robot applications within sectors. The main divisions of each sector are given and, the robotic tasks and their sensory aid are exemplified.

SUMMARY OF ROBOT APPLICATIONS			
SECTORS	SUB-SECTORS	TASKS	SENSORY AID
1.Industrial	Automotive Electronics Forge Lamination Textile Food etc	welding, assembly, inspection, cutting, machine feed, load/unload, painting, etc	orientation, position, measurement, tracking, force, slip, object recognition, etc
2.Exploration (& services)	Outer Space Deep Oceans Earth (in dangerous environments)	recovery, assembly, replace, inspection, load/unload, etc	locating, orientation, measuring, tracking, position, etc
3.Medical	Micro-surgery Prosthetics Orthotics etc	drill, grasping, nursing etc	position, force, slip, recognition, etc
4.Agriculture	Livestock Crops	cutting, search, etc	tracking, recognition, etc
5.Military	Armament Surveillance Undersea Space	load/unload, search, inspection, repair, etc	object recognition, tracking, force, etc
6.Educational	Training Research	all above	all above

TABLE 2.1 The Robot Applications within Various Sectors

2.2 A Survey of Sensors and their Applications

This section reviews sensors presented in the robotic literature. Two other publications, **Harmon** [26] **and Dixon** [27], are also recommended for comprehensive examples and discussions of tactile/touch sensors.

A general classification of robotic sensors is based on the physical similarity with the human senses: touch (tactile), smell, vision and hearing. Another is based on the sensor applications: force, torque, displacement, slip, etc. Sensors can also be classified based on the transduction principle utilized for their operations. Such a classification was adopted for this review.

Transducer principles are briefly treated under each class. The reader is also referred to [28], [29] for more information on transducer theory and to Binford [30] for a discussion on the advantages and disavantages of the applied technologies in robotics. Seven class of sensors are described:

1. Optical
2. Piezoresistive
3. Sonic (ultra-sonic)
4. Conductive elastomer
5. Magnetic
6. Pneumatic
7. Other Technologies

2.2.1 Optical Sensors

Optical is the transduction principle most applied in robotic sensors. It has the advantage of non-contacting and negligible force for its operation. Optical sensors have been designed to detect the presence of an object or a defect, measure distances, find the position of a workpiece, and give the image of an object, just to quote some examples.

The detector of an optical sensor generates an electrical current in response to a beam of light directed towards it. The light emitted by the source is truncated by a device or a workpiece, this produces variation in the flow of the current generated in the detector. Light sources emitting different wavelengths have been used and naturally, the detector is matched to the source. A great number of the light/sensing devices are junctions of p and n types of semiconductor material. When light is directed towards the junction a movement of electrons is produced generating an electrical current. Other optical materials and principles have also been described, although less frequently. To summarize, the main types of optical sensors are infrared, laser, fibre optics, photocell and television.

Vision is the most complex type of sensory aid for robots and can provide information of fine detail. An example of vision system was developed by Philips Research Laboratories [31]. It has been applied to unpacking and assembly lines. The system consists of three television cameras, one upward-facing mounted underneath a conveyor to determine the exact position and orientation of an object and two others that locate a special part of the workpiece used by the manipulator to grip the object.

In another example a vision system is used on a robot that picks workpieces directly from bins [18]. One camera is mounted in the robot wrist and another in the work station. The movement of the wrist camera is directed towards the bin, generating a binary image which enables an adequate gripping area of the workpiece to be located. The other camera is used to find the orientation of the gripped object. The system currently can only handle relatively light weight objects, the research therefore is now directed towards its application for heavier objects. The reader is referred to [30], [32] and [33] for further vision examples.

A sensor with ambient light independence based on infra-red (IR) was described in [34]. A modulated IR beam is sensed by a diode coupled to a synchronous dectector. A cone of emitted light intersects a sensitive cone of the detector. This intersection is called sensitive volume. Any object present in that volume is detected by measuring its reflected signal.

A gripper with IR-sensor, which separates individual pieces of fabric from a stack using a fine jet of air and sensors, was developed at Hull University [35]. A tactile sensor is used to measure the thickness of the gripped material. It is an optical-IR sensor formed by a light source placed at the tip of the lower jaw and a detector placed on the upper jaw. The light passes through the fabric that has been gripped to the detector. The system is simple, clever and it is claimed to operate with success.

The Jet Propulsion Laboratory (JPL) has developed a proximity sensor system to avoid collisions where the light source and detector are integrated into an electronic instrumentation near the computer instead of in the sensor itself [2]. The optical-head is located inside robot fingers and is connected to the source and detector by fiber optic cables. The JPL claimed that the system improves the signal quality. Certainly it introduces simplification in the design of the optical head and solves the problem of space in the fingers of a gripper (see figure 2.1).

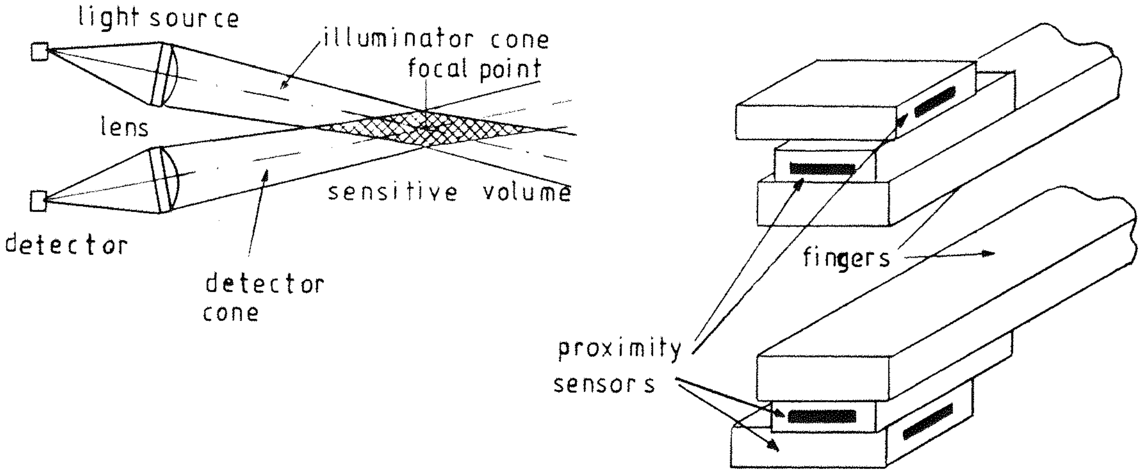


Figure 2.1 Optical Proximity Sensor Concept

An example of laser-based sensor is presented by Ueda, Matsuda and Matsuyama [36]. It was developed for spray painting and welding of a curved plate, keeping a robot hand at a constant distance from a workpiece surface. It is basically formed by a laser generator, a rotating mirror, two phototransistors and a photo detector. The laser beam is projected onto the mirror and is reflected and scanned by a phototransistor (say "A") and later reflected onto the surface of the object which sends a horizontal component of light to another phototransistor (say "B"). The time between the light to be sensed from "A" to "B" can be measured by a number of clock pulses and that leads to the calculation of the distance between the sensor (robot hand) to the workpiece surface. A control system keeps that distance constant as required by the welding and painting operations.

An intelligent tactile sensor for object identification and seam tracking in industry was designed by Presern and al. [37]. The sensor is a finger-like device with two degrees of freedom. Two masks are fixed at the top of needles and their positions are recorded by six phototransistors generating tactile data for a recognition method. The system processes the data in real time and is claimed to be very efficient.

Cassimis [38] describes a control system using an array of microcomputers which increases the uses of simple sensors. For example, the system uses a simple optical sensor comprising a lamp and photodiode and processes other known information, such as the coordinates of the robot hand, to find the dimensions of a workpiece.

Optical sensors have also been combined to form a matrix of tactile/touch sensors. Examples are given in [39], [40], [41] and [42].

2.2.2 Piezoresistive Sensors

A second transducer principle is represented by piezoresistant materials. They respond to a variation in their volume with a variation of their resistivity. Strain gauges are an application of this effect. The resistance (R) of a a conductor of uniform cross-section (A) and length L, made of a material with resistivity ρ, is given by:

$$R = \frac{\rho . L}{A} \qquad (1)$$

The resistance varies with the volume of the conductor and also as a function of the resistivity which depends on the mechanical strain of the material. Taking the derivative of (1), the mathematical expression of the variation of resistance is given by:

$$dR = \frac{A(\rho dL + L d\rho\ ) - \rho L dA}{A2} \qquad (2)$$

After substitutions and calculations on (2), the mathematical expression of the gauge factor [28] is found to be:

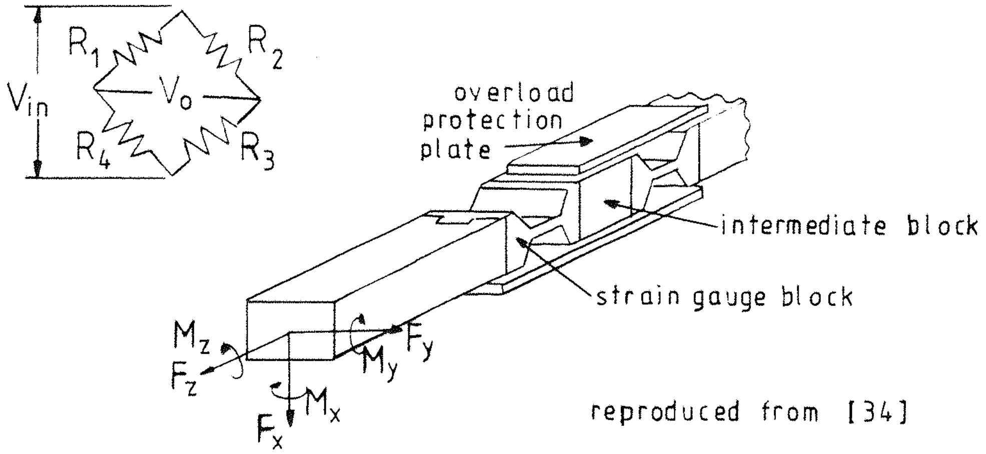
$$\frac{dR/R}{dL/L} = 1 + 2v + \frac{d\rho/\rho}{dL/L}$$

where: 1 is the resistance due to length change.
2v is due to area change (v is the Poisson's ratio).
The last term is due to the piezoresistance effect.

Strain gauges are usually connected in a balanced Wheatstone bridge configuration. The bridge is unbalanced during its operation by a voltage/current, in limits due to the effect of a load, that generates an output voltage across the bridge which is therefore a function of the load. Piezoresistive devices have mainly been described as force and torque sensors.

A tactile sensor with a matrix of sensitive elements was developed by Stute and Erne [20]. The sensor is used to grind a welding bead on an automobile body. The sensor has to be sensitive to variations in the height of the bead and to the curvature of the car body. It consists of a steel tip which in contact with the welding bead produces a bending of strain gauge elements. The output of the strain gauges permits the measurement of the height of the bead. The control is very complicated but the research has now been directed at simplifying, increasing the flexibility and reducing the costs of the control system.

A sensor to measure components of a force in three axis, their respective moments and, also to determine position and orientation of an object was described by Wang and al. [34]. The sensor is formed by modules which comprize two blocks, strain gauge and intermediate block; the latter being used to connect strain gauge blocks together (see figure 2.2). A Wheatstone bridge is located at the central part of the strain gauge block, which can bend only in one plane. The authors demonstrated how to calculate the gripping force and its location from the sensor output. They use series of modules to form a six degree-of-freedom force sensor to measure the components of a force (Fx, Fy and Fz) and their respective moments (Mx, My and Mz) relative to a cartesian-coordinate system. The idea of using modules gives flexibility and increases the range of applications of this sensor.



reproduced from [34]

Figure 2.2 A Module of the Gripping Force Sensor

The sensor proposed in [43] is formed by a rigid platform supported at four points. A strain gauge at each support gives the magnitude of the reaction at that point and also the x-y coordinates of any force acting on the platform. Two applications are discussed using that sensor, putting a peg in a hole and a cartesian-coordinate drilling operation.

2.2.3 Sonic Sensors

A third transducer principle utilized in robotics is based on sound waves. The travel time of the sound wave is given by:

$$dt = \frac{dL}{c}$$

where: dL is the distance between transmitter and receiver.
c is the air-acoustic velocity.

The majority of the devices measure dt, then dL can be calculated, which can be monitored, for example, to keep a robot at a fixed distance distance from a wall. All sonic devices found in this review are ultra-sonic devices, what means that the frequency of the sound wave is above the range audible to human hearing. They have been designed to avoid collisions (safety sensors), detect the presence of a workpiece and for inspection operations as well.

Wang and al. [34] described an ultrasonic sensor which consists of an acoustic emitter and a microphone receiver, both with narrow sensitive cones of operation. Any object located at the intersection of the two cones reflects an echo back to the microphone. The system can measure the time from the emission of the sound wave until its reception, then the distance between the object and the robot hand can be calculated. The sensor is claimed to be very sensitive and able to provide accurate distance information.

An ultrasonic system has been developed by Nagasakiya Co Ltd in Japan and implemented for automatic freight calculation in a warehouse [44]. The system measures a package moving on a conveyor at a constant speed using two pairs of ultrasonic emitters/receivers and one photocell sensor. One pair of ultrasonic sensors is located above the conveyor, downward-facing and another is horizontal-facing the object. The time of travel of the soundwave from its emitter to the receiver at each sensor gives the height (first sensor) and the width (second sensor) of the package. The length is measured at the third sensor by breaking and restoring a photoelectric beam, as each package passes in front of the cell. The system has been used for automatic sorting of packages. The idea is interesting and with improvement could be applied in assembly lines.

A combination of ultrasonic proximity sensors and other sensors is used for the navigation of a mobile robot [45]. Sonic emitters and detectors are located within the robot and monitored to avoid obstacles. For example, the sonic system keeps the robot distance to a wall approximately constant, when the former moves along the side of a corridor.

2.2.4 Conductive Elastomer Sensors

Conductive elastomers "are flexible materials whose electrical conductivity varies as a function of a pressure on the material" [15].

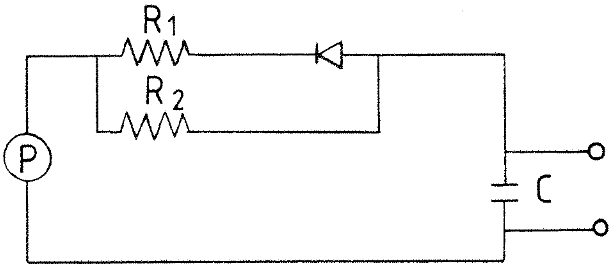


Figure 2.3 Equivalent Circuit for Elastomers

The figure 2.3 represents an equivalent electrical circuit for an elastomer according to Snyder et al. [15]. The response of the elastomer to a pulse of pressure is a non-linear function, as the fall time of the conductivity is faster than the rise time. The mathematical expression describing such a model is given by:

$$G_e = (G_p - G_o)\ (1 - e^{-at}) + G_o$$

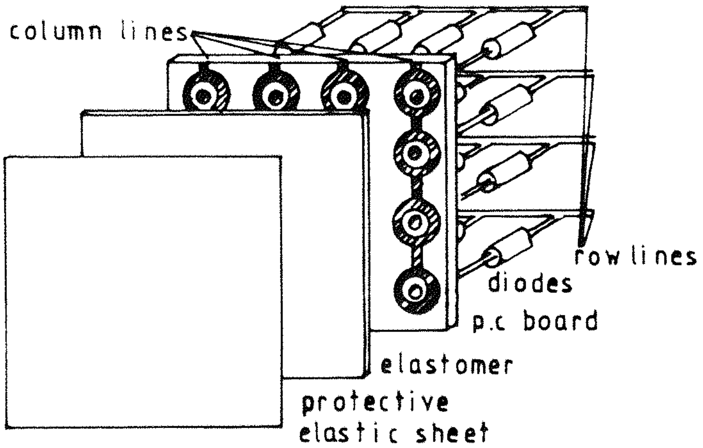
where: $G_p = 1/k_1 . e^{(k_2/p)}$ the steady state response of the elastomer to pressure.

G_o is the steady response to no pressure.

a is the time constant with positive pressure.

Sensors using conductive elastomer technology have been designed to prevent damage to workpieces, to determine the presence of an object and to detect slip.

Snyder and Clair [15] developed a tactile sensor to detect the presence of an object together with its location and orientation. An elastomer layer is fixed over a printed circuit board etched with sensitive elements (pairs of concentric rings). Each center ring is connected to a diode, which is connected to an electronic circuit. An exploded view of the sensor is given in figure 2.4. The elastomer produces a variation in the output voltage of the sensor due to pressure in its surface and the system can discriminate the element of the sensor which is actually in contact with an object.



Copyright © 1978 IEEE [15]

Figure 2.4 Tactile Sensor Using Elastomer

An artificial skin was made to enable a prosthetic hand to pick up an object automatically [46]. The sensor consists of three layers: an outside layer made of a conductive material to which a voltage is applied, a central layer made of a conductive rubber and an inside layer that is a matrix of electrodes. When pressure is applied to the sensor surface by an object, the resistance between the surface and the electrodes varies. This can be measured and used to detect the presence of the object.

A matrix of 256 tactile elements is used to recognize six objects however the author envisages further development of the sensor to recognize texture, to determine thermal conductivity and to extend its object recognition capability [47]. The sensor is formed by two conductive components, a flexible printed circuit board and a sheet of conductive silicone rubber, that is layers of silicone rubber impregnated with graphite or silver, alternating with similar non-conductive layers. Both components are electrically conductive only along one direction and, so, placing them together with their conductive lines perpendicular to each other, the device is pressure sensitive at each intersection. Exactly the same lay-out is proposed in [48], where the rubber sheet is either latex or silicone. The design is discussed but no results have yet been produced.

2.2.5 Magnetic Sensors

Magnetic principles have been used to transduce sound waves in equipment such as microphones and phono pick up, to measure velocity and displacement, and as recording devices as well. Robotic magnetic sensors have used properties such as eddy current, variable reluctance proximity pick-up or utilized the Hall effect. The basic principle of all devices is that a conductor moving relative to a magnetic field sets up a difference of potential at the conductor. Magnetic devices have been described to detect the presence of an object, slip and even for shape recognition purposes.

Two different magnetic sensors to detect slip were designed by Ueda and al. [49]. The first sensor consists of an electromagnetic transducer, a vibrator and a steel ball all immersed in an oil damper. The steel ball touches an object and any displacement of the object produces a rotation in the ball. The ball transmits its movement to the vibrator thereby causing a perturbation in a magnetic field which produces an electrical signal output.

The second sensor, designed by the same group [49], consists of a rubber roller with a magnet attached to its end. The roller rotates along its axis, when an object slips at its surface. The magnet moves with the rubber roller while a magnetic head stays motionless, this generates a variation in the magnetic field between the magnetic and head. It fails to detect slip when its direction is parallel to the axis of the roller.

A tactile sensor used for object recognition was described by Page and al. [50]. It is formed by a thick rigid mount with a square matrix of circular holes. A thin ferrous rod is inserted into each hole. The rods can move axially in their guides according to the contours of the object. The height of the rod in the upper part of the mount are registered by associating a winding with each one. A variable e.m.f. is generated by the movement of the rods, which is used together with information about the hand lowering, to found the measurements of the object.

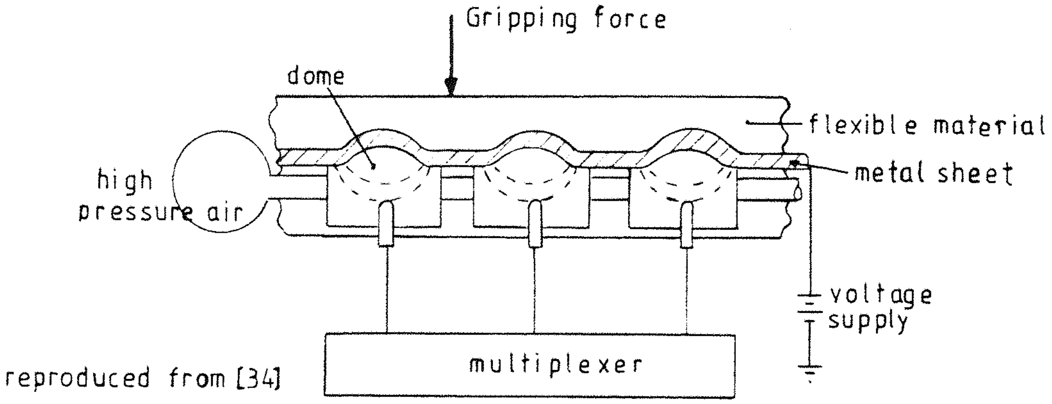
A matrix of magnetic sensitive points is proposed by Hackwood and al. [51] to measure force and torque. Each sensitive element is formed by a dipole embedded into a compliant medium, which are over a layer comprising four magnetic-resistive detectors mounted at 90° to each other. A force on the surface of the sensor deforms the medium, consequently the magnetic flux between dipole and detectors is also altered. The variation of the magnetic flux is sensed and transformed into force and torque (about the Z-axis) measurements.

2.2.6 Pneumatic Sensors

The final main principle is represented by the pneumatic sensors. A perturbation in the air pressure is transmitted through a medium of compressed air and triggers an usable electrical signal as output. Pneumatic sensors have been designed to find the orientation of an object, to sense force and to locate a workpiece.

A pneumatic whisker sensor, used in assembly operations, is described in [34]. It gives the location where an object touches a robot gripper. A wand can be retracted into a cylinder by a vacuum source or pushed out by air pressure. When the wand touches an object it deflects making an electrical contact, which generates an output current.

In the same reference a different pneumatic sensor is also described. The device provides force measurement of up to 50 grams/sensitive-point. It consists of a matrix of spherical domes under air pressure (see figure 2.5). An object touching the surface will deform the dome(s), producing an electrical contact, which allows current to flow through a multiplexer to a control circuit.



reproduced from [34]

Figure 2.5 Schematic Representation of the Sensor

Hanafusa and Asada [52] developed a proximity sensor to accurately detect the edge of an object without contact using a cone jet of air. Unfortunately no further indication of the sensor design is given.

A pneumatic system consisting of three proximity sensors, each one formed by a pneumatic cylinder was proposed by Belforte and Quagliotti [53]. One cylinder moves forward approaching an object and stopping at a fixed distance. The two other cylinders then approach the surface together. These two cylinders are actuated to rotate in a plane orthogonal to the surface and to stop, when both their axes are perpendicular to that surface. At that condition, the cylinders have the same angle of orientation of the object face and therefore that angle can be determined.

2.2.7 Other Technologies

This is the group formed with sensors that cannot be classified in any of the seven previous types. There are a number of sensors that utilize electrical properties such as capacitance, or are electrical devices such as limit and proximity switches. Several others are based upon technologies ranging from hydraulic to voice recognition. This group has sensors for all robotic applications, i.e., to detect slip, to detect the presence of an object, pattern recognition, to measure force and so on.

A very primitive whisker sensor was built in the University of Wollongong, Australia [54]. It consists of one metal guitar string and a plastic tube separating two copper sheets. The string is fixed in the first sheet and passes through a hole into the second sheet (external surface of the sensor). When the string touches an object it deflects and closes a circuit between the two sheets. This generates an electrical signal that is interfaced to a computer and transformed by software into the detection of the presence of an object. It is inexpensive and very simple but may not be sufficiently robust for industrial environments.

A directional slip sensor was developed at JPL [2] that can output sixteen different slip directions. The sensor consists of a sphere with a needle attached to its base. At the opposite end of the needle a conductive plate is fixed. The sphere can be moved by an object in contact, that slips and thus produces a movement of the plate. The plate can contact one of sixteen conductive points inside the sensor and hence the point of contact gives the direction of the slip movement. Figure 2.6 shows a diagram representing the sensor concept.

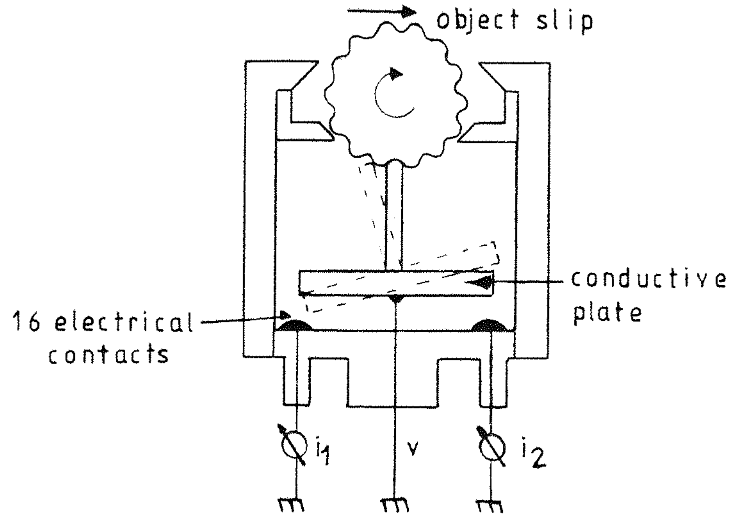


Figure 2.6 Electromechanical Sensing Concept

Two other slip sensors are described by Tomovic and Stojiljkovic [55]. The first sensor consists of a small needle protruding from the contact surface. As the object slips it forces the needle to vibrate and this produces an electrical contact inside the sensor that provides the detection of slip. A second sensor is made of a small conducting ball, partially covered with non-conducting fields in a pattern resembling a chess-board. The ball is free to rotate when a slipping force is applied and this rotation produces electrical contact at two points inside the sensor, thereby generating frequency modulated pulses. The authors claimed that the device is easy to miniaturize and this together with reducing the area of the conducting fields, gives high sensitivity. However both are very difficult to achieve.

The Laboratoire d'Automatique in France has developed a sensor for an object recognition system [56]. It is a conductive coating and a printed circuit on which there are a matrix of isolated sensitive points. Around each of these points there is a guard ring to which a voltage is applied. The impedance of the sensor varies according to an applied pressure to its surface. This generates a variation in current at every test point. An object touched by this sensor leaves an imprint, due to pressure exerted on each sensitive point, a computer processes the imprint and outputs the recognition of the object.

An example of a hydraulic sensor was developed by Fishel to determine gripping force of a claw [57]. The sensor is intended to allow the collection of objects from the seabed without damage. The claw, consisting of a pair of jaws linked by a hydraulic actuator, is attached to a submersible vehicle. The actuator produces a differential pressure proportional to the gripping force in two hydraulic lines. The pressure is transmitted to the submersible, where it is transformed into an electrical signal, which finally can be converted into a force reading. The control of the hydraulic system is also located within the submersible. The system is meant for undersea work and is claimed to be safe and practical.

Finally let us consider a more sophisticated system: voice recognition. The present systems cannot adequately recognize differences in accent, intonation and timbre although research in this area is very active. One example of such a system is given in [2]. It is a discrete word voice recognition and speech synthesizer developed for operations in space with a teleoperator/robot commanded from earth.

CHAPTER 3

A DIRECTIONAL SENSOR

A tactile sensor was designed and built to provide sensory information that would enable a gripper to be reorientated, while performing tasks where the exact orientation of the object is required, despite the fact that the object is presented in a random manner. Examples of such operations are assembly and loading a machine. Initially, a sensor was designed for restricted workpieces, which have parallel faces. In addition, the angles between the sensor and the surface of contact of the workpiece were assumed to lie between $\pm 10^\circ$ [1]. However, these angles were increased in second and third attempts of tactile design, because additional applications were envisaged for sensors with wider angles.

3.1 The Approach to the Design

The first design, an optical-window sensor, is shown in figures 3.1 and 3.2. It consists of a half-ball bearing, with a pin attached to its base, and mounted in a black housing. The housing incorporates two light sources positioned at right angles to each other, and four detectors, two in front of each light source. A spring links the pin to the housing and returns the ball to its central position, if the sensor is not touching an object.

In many other optical sensors [58] [34], the workpiece itself truncates the light received by a detector, but in this design, the pin performs the truncation. It cuts the two beams of light and shadows the detectors, according to the position of the area of contact of the sensor, that is the half-ball bearing surface. A schematic representation showing a cut through the pin and the optical components is given in figure 3.3.

FIGURE 3.1 Optical-window Sensor Components

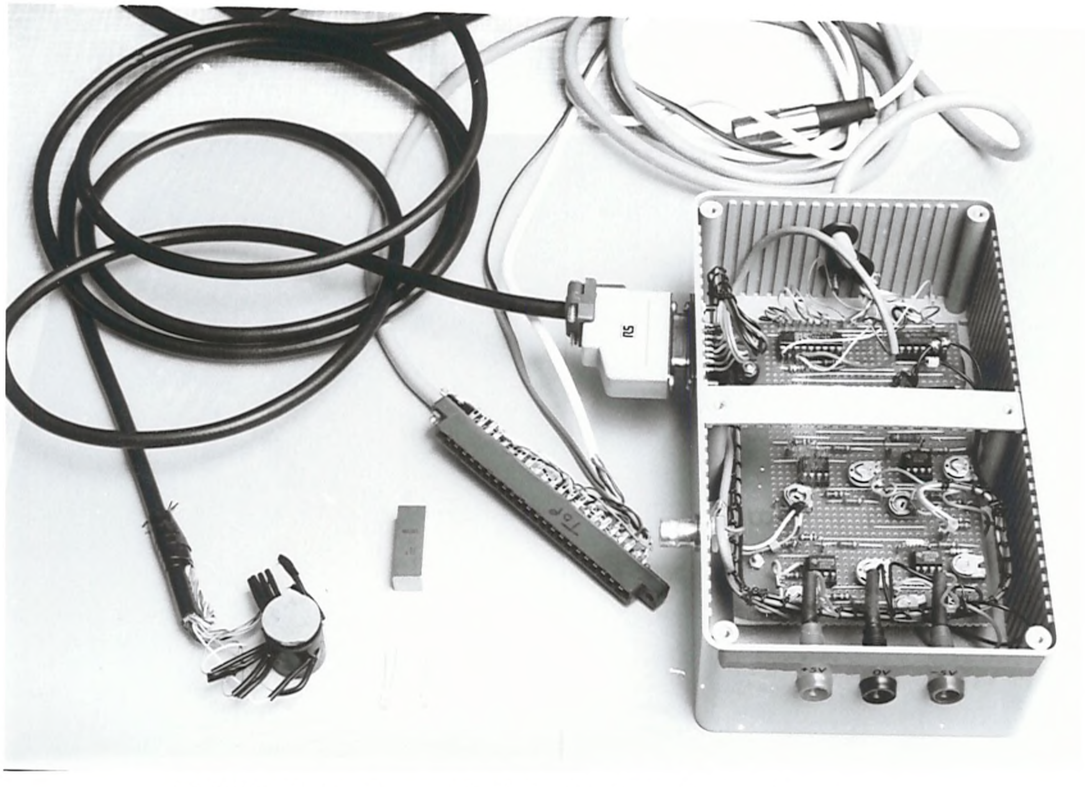


FIGURE 3.2 Assembled Optical-window Sensor

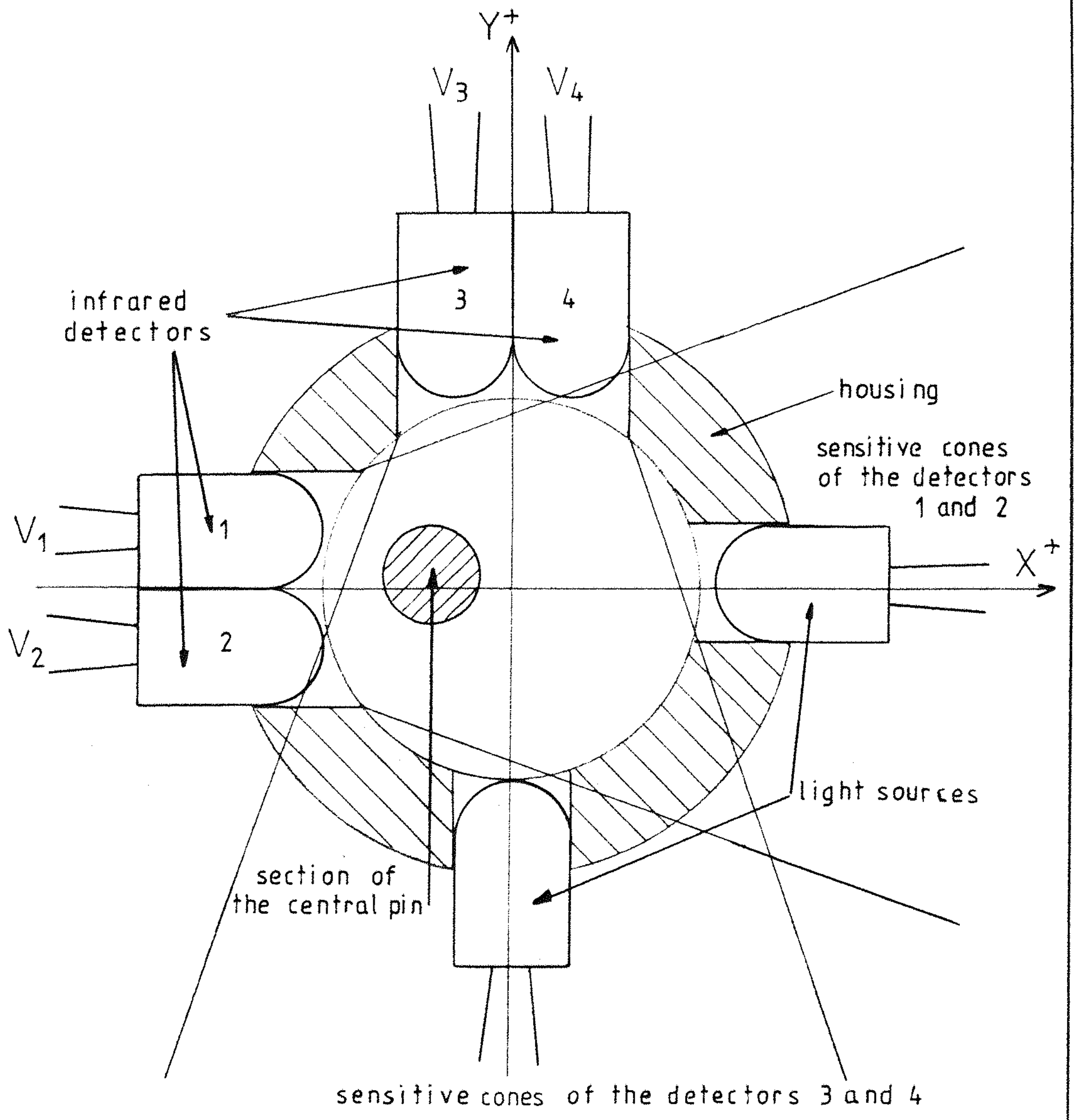


FIGURE 3.3

A Schematic Diagram of the Optical Window Sensor

The mechanical arrangement of the optical-window design is simple, easy to manufacture and the device is inexpensive. However, the design exhibited a considerable number of problems in practice, particularly due to fact that the same voltage output was recorded for different values of angles [59]. Therefore it was considered an advance to develop a second improved design.

A second design, originated from the mouse used to input signals to a computer, was proposed. This design has a similar mechanical arrangement to the first, but instead of optical components, it uses potentiometers. It consists mainly of a half-ball bearing, two rubber rollers mounted at right angles, two potentiometers and a housing, which acts as a bearing for the ball. Figures 3.4 and 3.5 show the components and the assembled sensor respectively. All components are arranged within the housing and connected to an electronic circuit board. Finally a spring ensures that the ball is returned to its original position, when contact with an object ceases.

The half-ball bearing is in contact with the two rubber rollers, the shafts of which are each linked to one potentiometer. The movement of the truncated ball is transmitted to the potentiometers through the point of contact of the rubber rollers and ball. Hence, the angle of displacement of the surface of contact of the sensor (i. e. the flat surface of the half-ball) is proportional to the angle of displacement of the potentiometer (see figure 3.6).

It is critically important to prevent any movement of the ball without the corresponding movement of the rubber rollers. Therefore each shaft of the rollers is mounted on two cylinders, which can move up and down providing an individual adjustment to remove gaps between its roller and the ball. Furthermore, the surface of contact of the ball was made rough to prevent slippage.

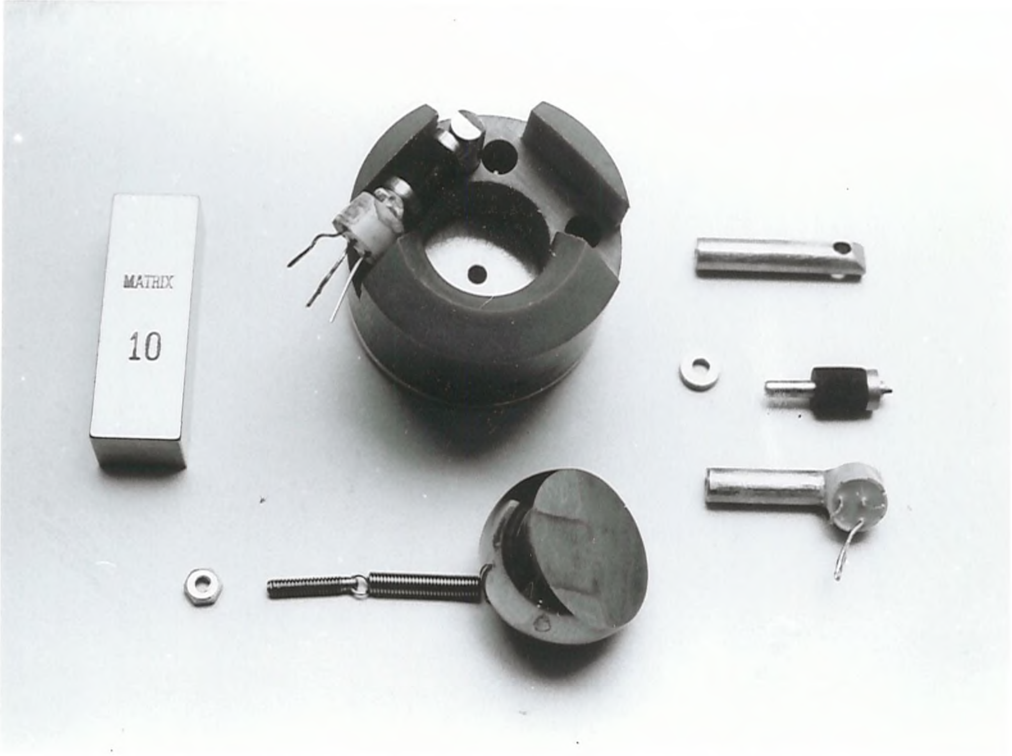


FIGURE 3.4 Potentiometer Sensor Components

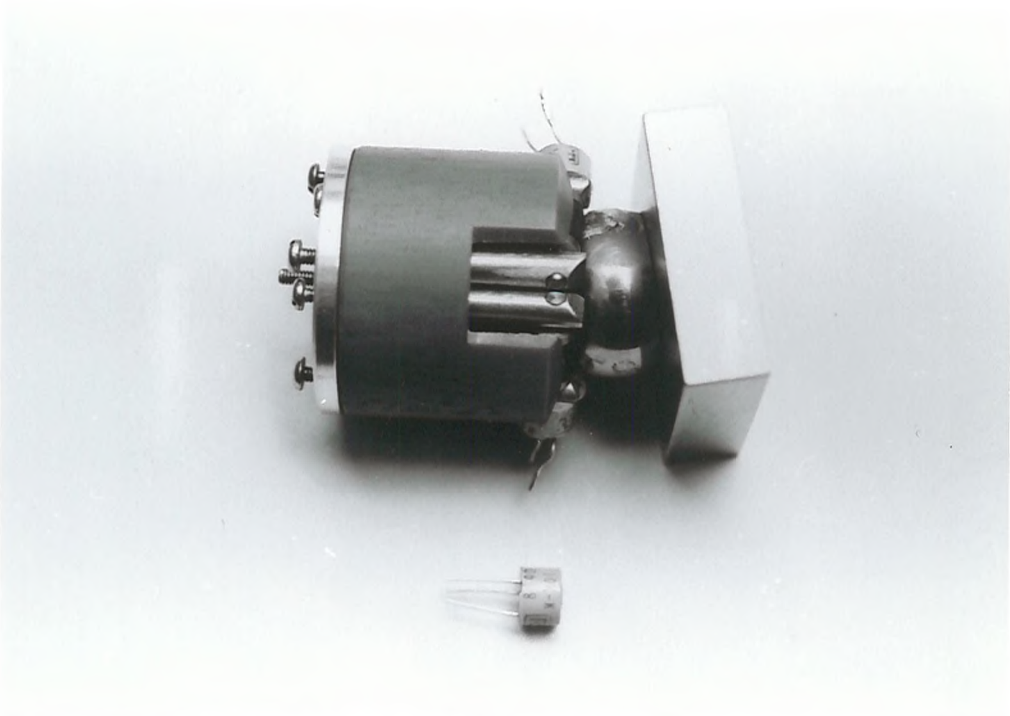
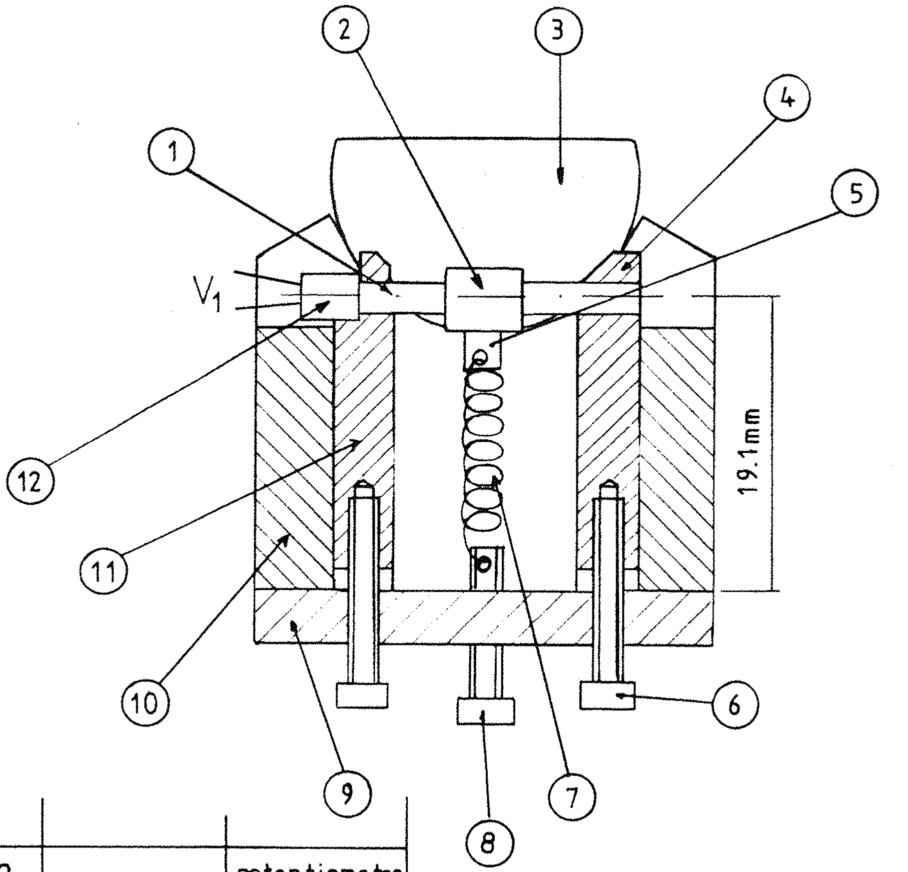


FIGURE 3.5 Assembled Potentiometer Sensor



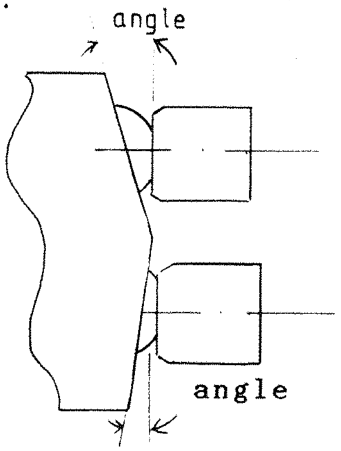
12	2	-	potentiometer
11	2	brass	bearing
10	1	nylon	housing
9	1	al.	cover
8	1	steel	screw
7	1	spring	$\phi 2 \times 15$
6	4	steel	screw
5	1	steel	pin
4	2	brass	bearing
3	1	steel	ball bearing
2	2	rubber	roller
1	2	steel	shaft
POS	QUANT	MATERIAL	IDENTIFICATION

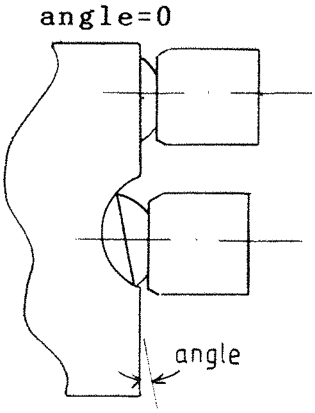
scale 2:1

FIGURE 3.6

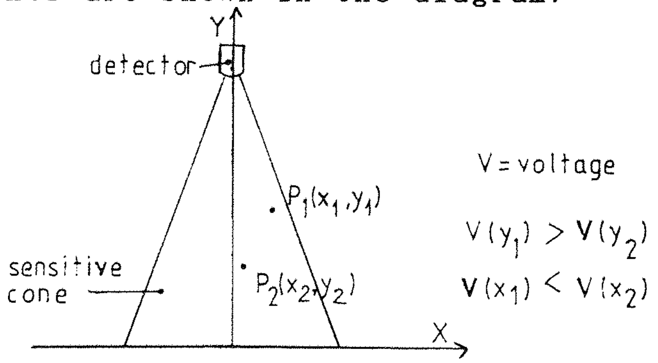
A Sectional View of the Assembled Potentiometer Sensor

Due to the inherent geometry of the first two designs, the only information they can provide is directional angles. Furthermore, such angles have severe restrictions, as for example, they must been within ±10° in the first design. Also, the touched surface must be a single plane, otherwise the gathered angles would not be correct. To illustrate, the two schematic workpieces below would generate "false" readings:





The mathematical model of the first design is too complicated. In addition, as quoted previously, ambiguity was generated due to a great variation of sensitivity in the radial direction. In another words, there are at least two points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ which generate the same voltage output at the detector, because the difference in sensitivity of the electronic components in both directions, radial (X) and axial (Y), compensate each other. The two points are shown in the diagram:



The mechanical construction of the potentiometer design resulted in some considerable problems being experienced. For example, the movements of the potentiometers did not achieve complete success during operation. The potentiometer used is not suitable, i. e., it is intended for pre-set operations only. As a consequence, the initial torque to move the potentiometer is too high. An attempt to redesign this sensor was carried out, but a suitable, inexpensive and miniaturized potentiometer (i.e. with a low starting torque and designed for continuous and frequent movements) was not available on the market.

Furthermore, the author's review of up-to-date robotic sensors has indicated that the first two designs have restricted applications. A matrix of points represents a more advantageous design for a directional tactile sensor, as a matrix can give the same information of the first two designs and also provides input data for tactile object recognition procedures.

A third device, which involved a matrix of optical elements, was therefore designed and a prototype was built and partially assessed. The angle of orientation of the object was allowed to be within $\pm 40^{\circ}$, which would increase the sensor applications, and the workpiece was subsequently no longer restricted to just parallel faces.

To summarize, the first two designs, the optical-window and the potentiometer sensors, have limitations, but could be developed further. The author however, decided mainly in the interest of time not to proceed with their development and also because a wider range of prospective applications was envisaged for the third design. The reader is referred to [59], for more detail about the sensor designs and their assessment.

3.2 The Matrix Design

The proposed sensor uses a matrix of nine spring-loaded pins, which can have a longitudinal movement in a fixed block. An infrared light source is mounted inside each pin and opposite to a matched infrared detector, which is fixed to the block. The distance between the two electronic components is therefore variable.

The phototransistor used in this design is a npn junction matched to an infrared (IR) light source. The main advantage of IR systems is the almost complete ambient light independence. On the other hand, the light is invisible to the human eye and this can lead to problems during calibration, also the output is greatly modified at high temperatures. However, the IR was employed in the sensor design of this project for two reasons. First the electronic components, light source and detector, offered commercially are inexpensive and claimed to be highly sensitive. Second there was no requirement (or intention) to consider applications in high temperature environments.

The output current produced at the phototransistor is a function of the distance between the detector and its corresponding light source and so is the voltage [59]. Monitoring the output voltages V_1, V_2, V_3 ... V_9 of the detectors, it is possible to determine the corresponding displacements x_1, x_2, x_3 ... x_9 of the light sources, relative to a known plane in the detectors. These displacements correspond to measurements of the workpiece at points of contact with the sensor rod. The proposed design was not fully developed, but rather a simplified version with four-pins was built and tested instead. Figures 3.7 and 3.8 show the prototype and its components respectively, and figure 3.9 illustrates a section cut through the four-pin version.

3.3 The Matrix System

This system comprises the sensor, an electronic printed circuit board, a microcomputer and a power supply (see fig. 3.10). A sensor is intended to be fixed into each finger of a two-fingered robotic hand. The fingers are assumed to have a smooth movement along a common axis. The distance between fingers is considered to be variable from zero to 140mm.

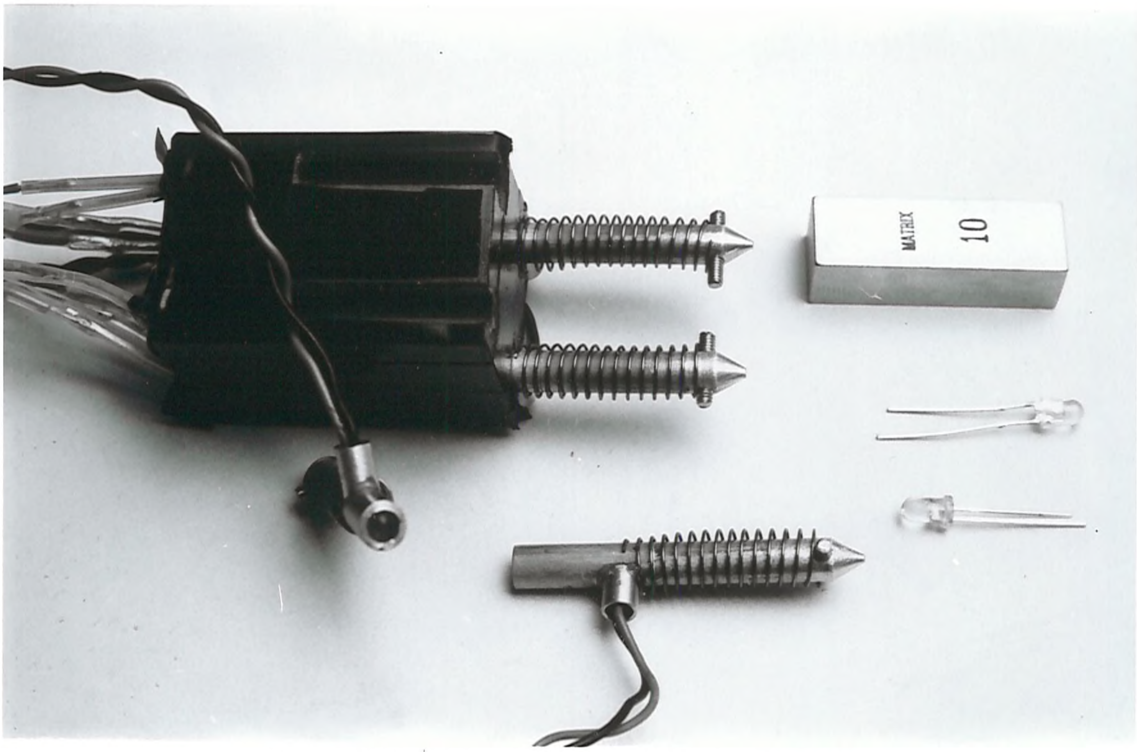


FIGURE 3.7 Matrix Sensor Components

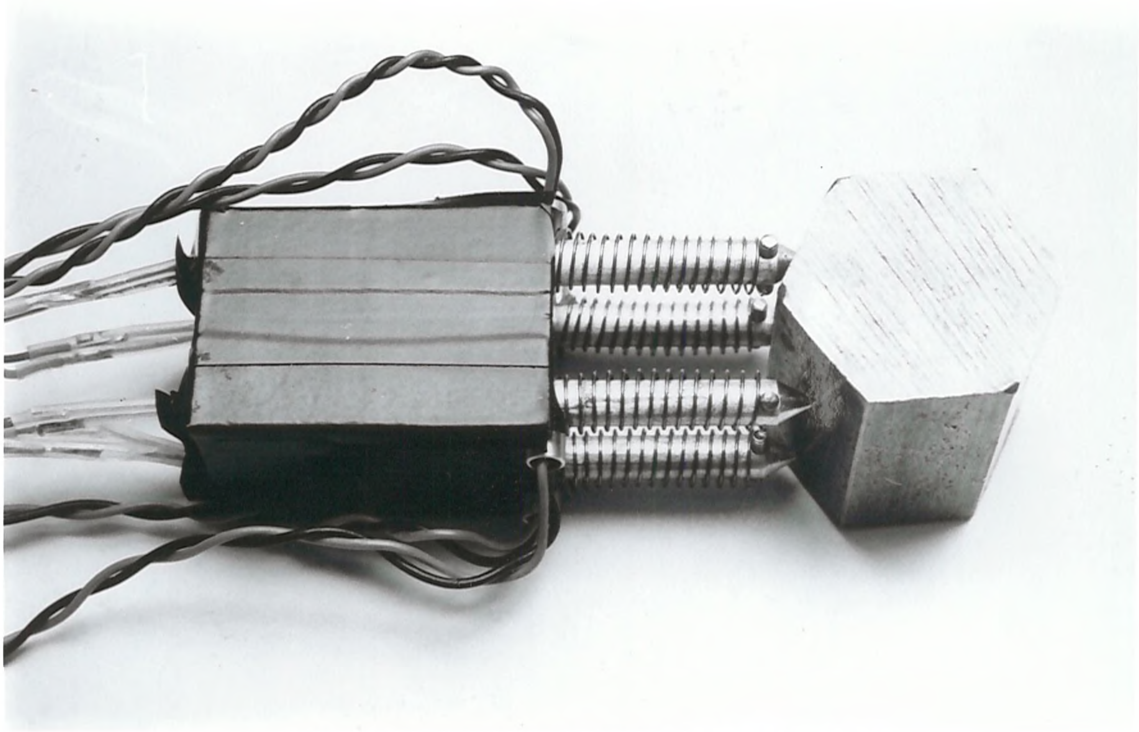
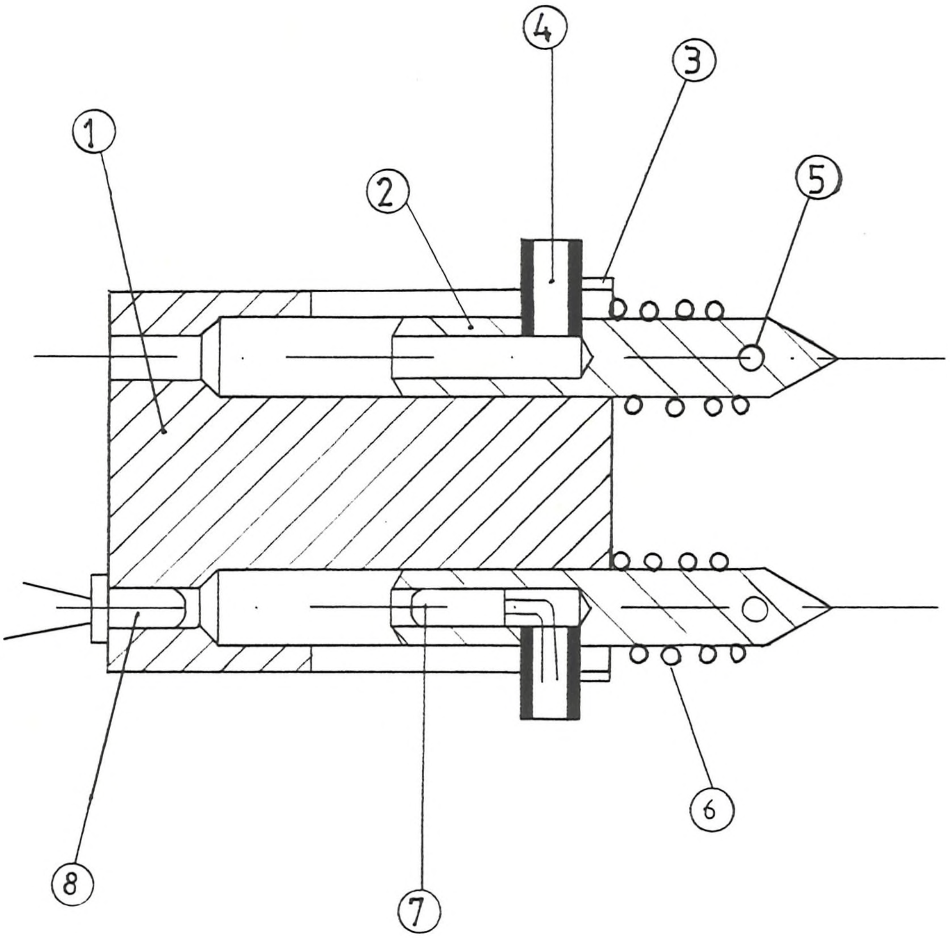


FIGURE 3.8 Assembled Matrix Sensor



POS	QUANT	MATERIAL	IDENTIFICATION
8	4	-	IR detector
7	4	–	light source
6	4	spring	Φ6 Φ5 x 25
5	4	al.	pin M 2x 8
4	4	-	tube
3	1	–	rubberband
2	4	al.	probe
1	1	black nylon	housing

Scale 2:1

FIGURE 3.9
A Sectional View of the
Matrix Prototype

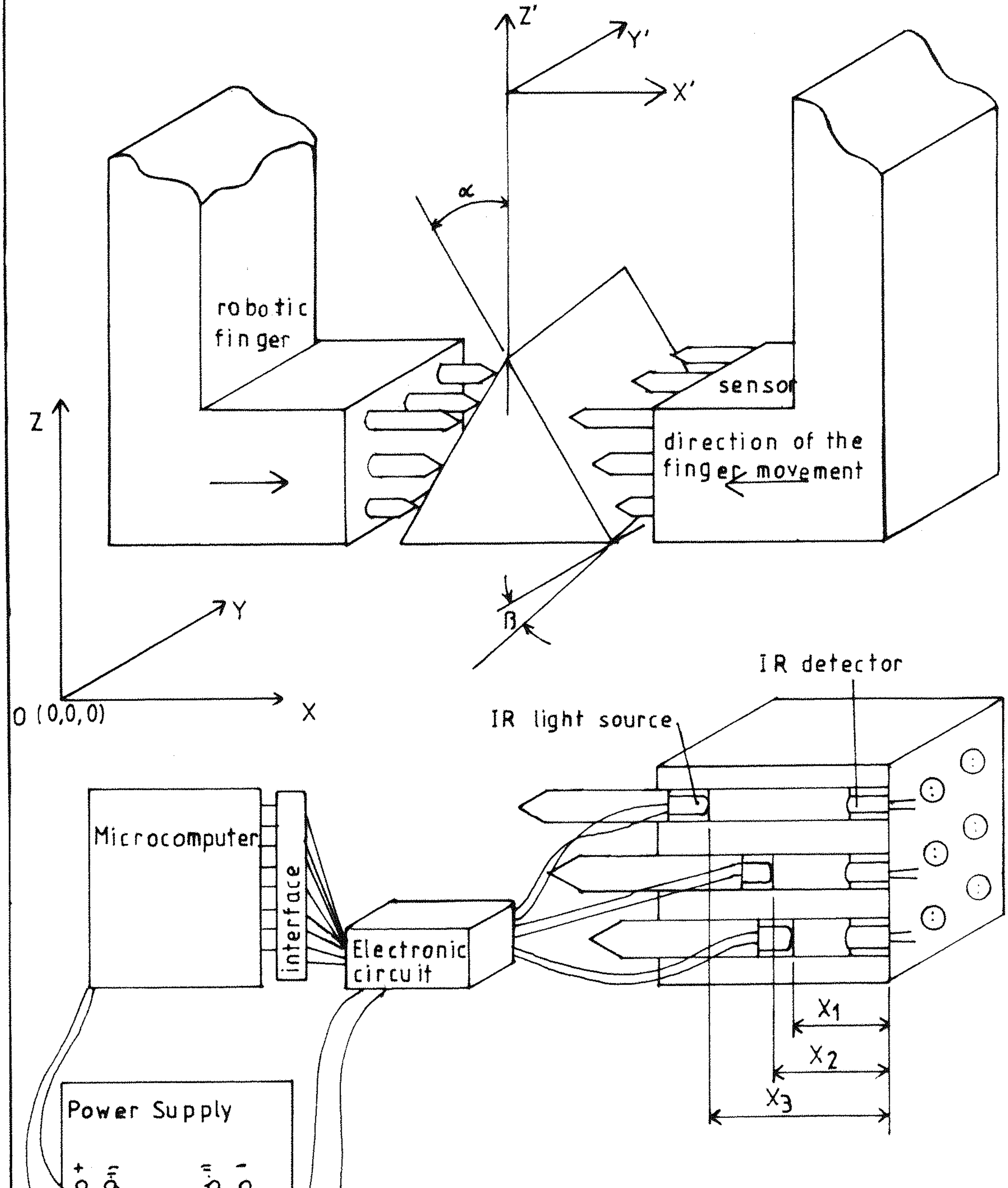


FIGURE 3.10

Schematic Representation of the Matrix System

The output voltages of the sensors are amplified, multiplexed, digitized, and finally fed into the micro-computer. The readings are transformed into information for subsequent calculations, which are intended to be used for appropriate manipulative action by the robotic hand.

Assuming that the object lies between the right and left fingers, which are positioned at 140mm apart, the two fingers should be moved to close the gap between themselves, until every pin has had a displacement, or alternatively, any pin has reached its maximum length of travel. At the attainment of either of these two conditions the rods will be touching both sides of the object as much as possible. Software can then be implemented to perform the following functions:

1) Find-Orientation - This procedure is intended to calculate the angles α and β as defined in the section 3.4.1. These angles determine the surface of contact of the workpiece relative to the gripper.

2) Object Recognition - This function is intended to identify an object within a given set. The object is scanned to form two matrices of tactile data. These matrices allow the computation of physical properties of the object, which eventually lead to a Classification procedure. Finally, this procedure reproduces the shape of the workpiece, or gives an Error condition, in order to warn an operator.

3.4 The Matrix Principles

A rectangular cartesian coordinate system was chosen as illustrated below in figure 3.11. The plane XY is coincident with a surface of reference (e.g. ground or working table). The Z-axis is orthogonal to the plane XY and cuts this plane at the point X=Y=0. It was considered that the hand moves only in the quadrant where X, Y and Z have always positive values.

It was also considered that the gripper finger tip planes are always parallel to the YZ-plane. Assuming that the robotic gripper software is able to produce the finger coordinates, then x_R, y_R, z_R (right finger) and x_L, y_L, z_L (left finger) are always available. Lights and photocell sensors mounted within the gripper fingers, for example, can be used to locate an object and define the starting point of a working-space.

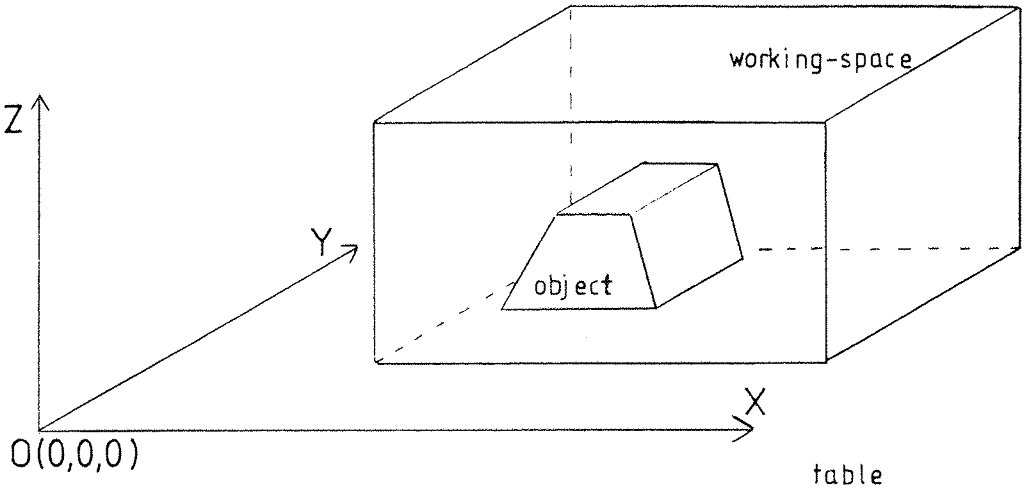


Figure 3.11 Rectangular Cartesian Coordinate System

The figure 3.12 shows the working space defined by the maximum distance between left and right fingers of the robotic hand (=140 mm), the distance from the table to the palm of the hand (=75 mm) and an arbitrary dimension, the latter was chosen to be 125 mm.

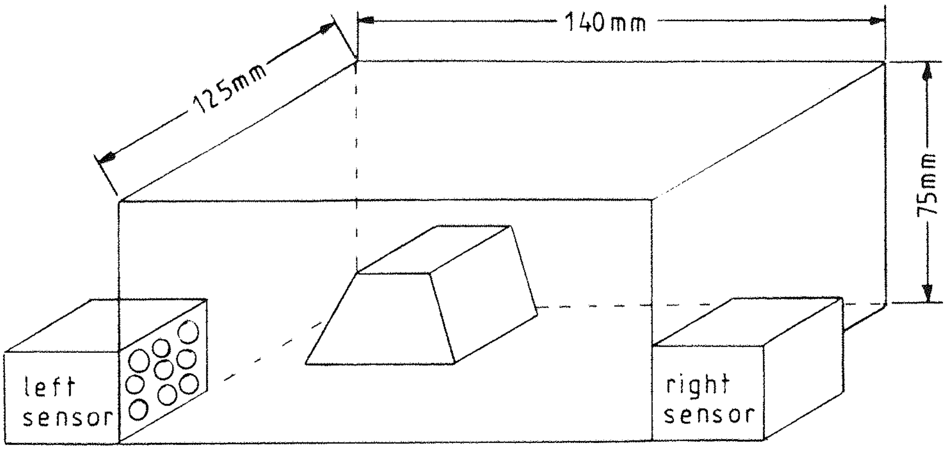
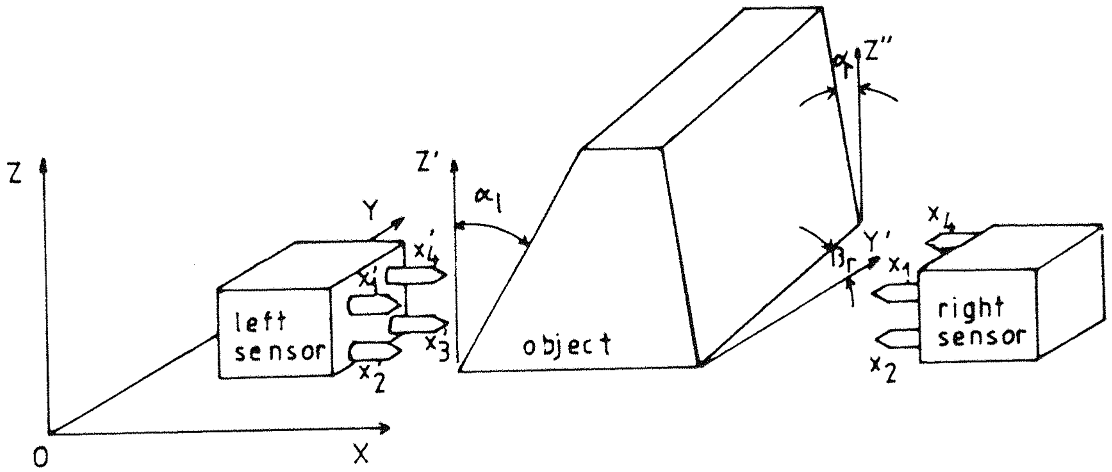


Figure 3.12 The Defined Working-space
(height=75mm, width=125mm, length=140mm)

3.4.1 Defining a Plane Surface of Contact - four-pin design

Assuming that the two fingers touch an object, the right and left sensors provide the measurements of the object, on its right and left side respectively. These measurements are equivalent to coordinates of the sensor rods in the X-axis direction, minus the corresponding coordinate of their finger. They are used to calculate α and ß (see figure 3.12).



$\alpha = \alpha_l$ or α_r and $\beta = \beta_l$ or β_r

Fig. 3.13 Alpha and Beta Angles
These angles define a surface, that is in contact with a sensor.

Mathematically, just three pins are enough to define the orientation of a plane surface, but mechanically four pins are recommended due to the balance of the spring forces. In the following equations, it is considered that a sensor with just four pins (as in the prototype) provides tactile data for each side.

Assuming that every pin has touched the workpiece, each surface plane (right and left), is defined by the angles, α and ß, where both angles must be within ± 40°. This angle limitation is a design constraint, due to the maximum displacement of the sensor rod and the distance between two adjacent rods.

The prototype includes a redundant pin, therefore each angle can effectively be calculated twice. The actual angle is considered to be the average value of two calculations, α' and α'', and an error ($E\alpha$) between them is also computed. The same considerations are applied to β. In the equations, L is the distance between two rods of the sensor, which is equal to 16mm for the prototype.

a) α = angle between the lateral surface of the object and the Z-axis

α_r is the angle defined by the right sensor

α_l is the angle defined by the left sensor and it is defined identically as α_r, except that the x' displacements are used instead.

$$\tan \alpha'_r = (x_1 - x_2)/L \text{ and}$$
$$\tan \alpha''_r = (x_4 - x_3)/L \text{ (by redundancy)}$$
$$\therefore \alpha_r = (\alpha'_r - \alpha''_r)/2 \text{ (average of previous values)}$$

$$E\alpha_r = (\alpha'_r - \alpha''_r)/\ \alpha_r \times 100\% \text{ (error)}$$

b) β = angle between the lateral surface of the object and the Y-axis

β_r is the angle defined by the right sensor

β_l is the angle defined by the left sensor, which has also identical equations to β_r, but using the x' displacements.

$$\tan \beta'_r = (x_4 - x_1)/L \text{ and}$$
$$\tan \beta''_r = (x_3 - x_2)/L \text{ (by redundancy)}$$
$$\therefore \beta_r = (\beta'_r - \beta''_r)/2 \text{ (average of previous values)}$$

$$E\beta_r = (\beta'_r - \beta''_r)/\beta_r \times 100\%$$

The above calculations apply to plane surfaces only. If the left and right surfaces are parallel, β represents the orientation of the object itself. If the nine-pin version is used, six pins are redundant and do not need to be considered in the calculations, therefore the equations are still valid. Also, scanning the surface may not introduce any additional information, except if two surfaces are touched at the same time by one sensor. However, if the object has an odd shape or more than one lateral plane surface, the calculations are rendered invalid. To summarize, it is necessary to construct a logic based upon same knowledge of the geometry of the workpiece set.

3.4.2 Matrix of Recognition - nine-pin design

Figure 3.14 illustrates the movements performed by the robotic hand, in scanning the lateral surfaces of the working-space. First, the gripper moves along the +Y_axis direction at the height of the table. Second, the hand goes up 25mm (height of the sensor), then moves along the -Y_axis, another step up of 25mm and finally, a last movement in the +Y direction again.

The fingers are moved apart, followed by a gripper movement of one step (each step is equal to 25mm) and then, the fingers are closed until the touch is completed, at that time tactile data are collected (nine points). This procedure is repeated to construct two matrices with the data produced from the right and left sensor, called MR and ML respectively.

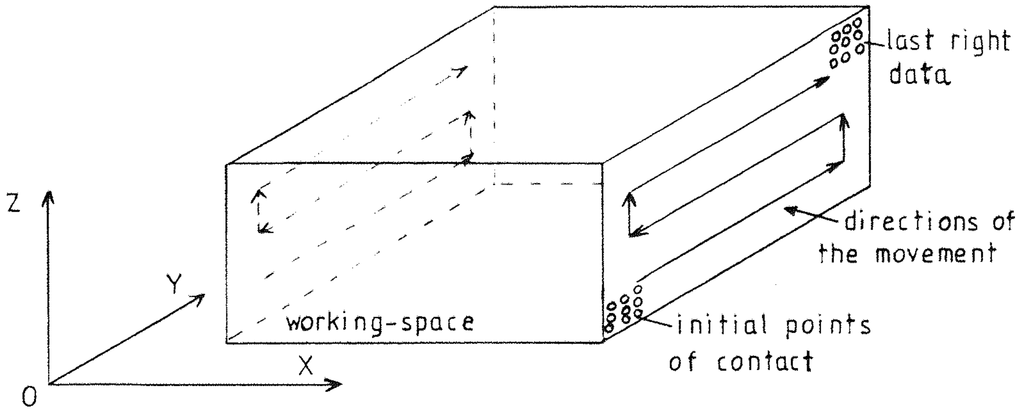
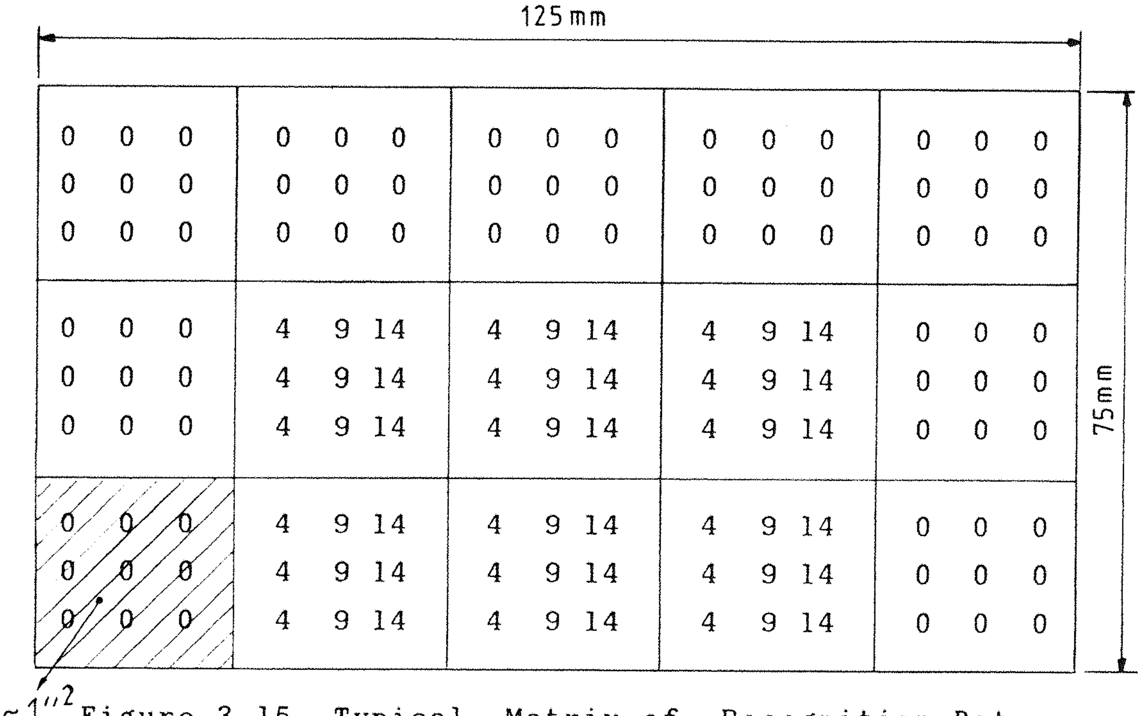


Fig. 3.14 Forming the Matrices of Recognition
The working-space is scanned by two sensors according to the directional paths shown.

Each element of the matrices, m(x,y), corresponds to a displacement in millimetres of a sensor rod, when the device was touching the workpiece. Each $m(x,y)=x_k$, where x_k is the measurement of a point upon the workpiece. The matrices, MR and ML, have each 9 lines and 15 columns, therefore k=1 to 135. A typical matrix is shown in figure 3.15, where the squares represent the nine points generated simultaneously by one sensor, however they are not grouped in any logical order.



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	4	9	14	4	9	14	4	9	14	0	0	0
0	0	0	4	9	14	4	9	14	4	9	14	0	0	0
0	0	0	4	9	14	4	9	14	4	9	14	0	0	0
0	0	0	4	9	14	4	9	14	4	9	14	0	0	0
0	0	0	4	9	14	4	9	14	4	9	14	0	0	0
0	0	0	4	9	14	4	9	14	4	9	14	0	0	0

Figure 3.15 Typical Matrix of Recognition Data
A square, with physical dimensions of 25x25 mm^2, represents data generated by one touch, which comprizes nine individual elements of the matrix.

To summarize, both lateral surfaces of the working-space are represented in a computer as matrices of scanned points, which are "x" measurements of the object. These matrices can be used as a basis for limited object recognition giving:

1) An approximate shape of the object by reconstructing its profile, from the non-zero points adjacent to external zero points. In the above example the shape is rectangular.

2) Two approximate external dimensions of the object. Again in the given example, length= 75mm and height=50mm. The third dimension is given by the distance between the two fingers less the external length of the rods.

3) Several geometrical properties of the object can be computed. The author's recognition method assumes that these data are available to calculate a number of such properties, as described later in chapter 4.

3.5 Calibration

Different experiments have been carried out to calibrate the optical components and the sensor. A final calibration procedure gives the necessary relationships between the voltage readings and distance measurements. It is left to the user to reset potentiometers in order to eliminate off-set and to guarantee that the gain of each operational amplifier is that which is expected.

3.5.1 Electronic Circuit

The user calibration procedure involves the adjustment of the electronic circuit, while monitoring the sensor output. The electronic circuit has two types of potentiometers for each sensor rod as shown in figure 3.16, which should be preset before operations.

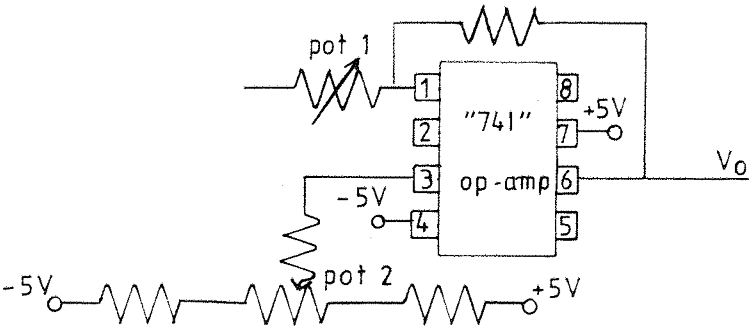


Fig. 3.16 Schematic Representation of Part of the Electronic Circuit

The first potentiometer is connected to pin 3 of the operational amplifier (op-amp) and has to be calibrated to compensate off-set. The second potentiometer gives the gain of the op-amp (pins 2 to 6) and should be calibrated to give 2.5 volts for 14mm displacement of the sensor rod.

Experience will determine if the resetting operations shall be carried out daily, or weekly, or some unspecified time interval, according to the behaviour of the sensor output and required precision. If the frequency of resetting is not satisfactory, this can be decreased by employing superior, but more expensive electronic components. A decision is to be made when practical applications are particularly detailed. Initial laboratory tests indicate, that two resetting operations within a week lead to reasonably stable results.

3.5.2 Detector Response using Slip Gauges

Different experiments were carried out to calibrate the sensor [59]. They indicated that the detector is very sensitive to rotation and therefore precaution has to be taken to avoid rotation between the light source and the detector.

The last experiment, the slip gauge calibration procedure, aimed to plot curves for detector response versus its distance to the light source, which is due to the movement of its corresponding sensor rod. Curves were plotted for every light-source/detector pair, and each pair was tested ten times to find a figure of repeatability. These curves are to be used by software to transform the voltage readings into distance measurements.

The prototype sensor was fixed, with the external ends of its rods just touching a perfectly plane surface of reference. Slip gauges of variable width were put under each rod, while the electronic circuit linked to the device was monitored, effectively giving the output voltage corresponding to the gauge width.

The graph of figure 3.17 illustrates the results of one pair of components from the prototype. The three curves represent the minimum output voltages, the arithmetic means of the ten experiments, and the maximum output voltages. The greatest difference observed, between maximum and minimum values, was 0.10V at 11mm of displacement (detector 1). This graph represents the overall worst performance, which was also given by detector 1.

3.6 Discussion of the Matrix Design

The advantages of this sensor lies in its analytical simplicity and its application for object recognition, although the latter facility is limited. Also a matrix design is versatile, because greater resolution can be achieved by increasing the number of pins by applying a different technology, with smaller components to allow more sensitive points to be built into a given area.

The matrix device is a low-cost sensor since it employs widely available materials and does not require very precise mechanical tolerances. The cost of the prototype was calculated to be about £ 81.40 [59],` which includes materials and the estimated cutting time at £ 8 per machine-hour. The real machine cutting time was much greater than the calculations, but this is regarded as perfectly acceptable considering that this is the first device built.

The main difficulty expected with this design is that of achieving the mechanical movements, whilst being sure that every pin is touching the object wherever possible, but as yet the device has not been tested in the gripper fingers.

The slots in the main block, that allow movement of the leads, also permit external light to reach the detector, which might introduce alterations in the output voltages.

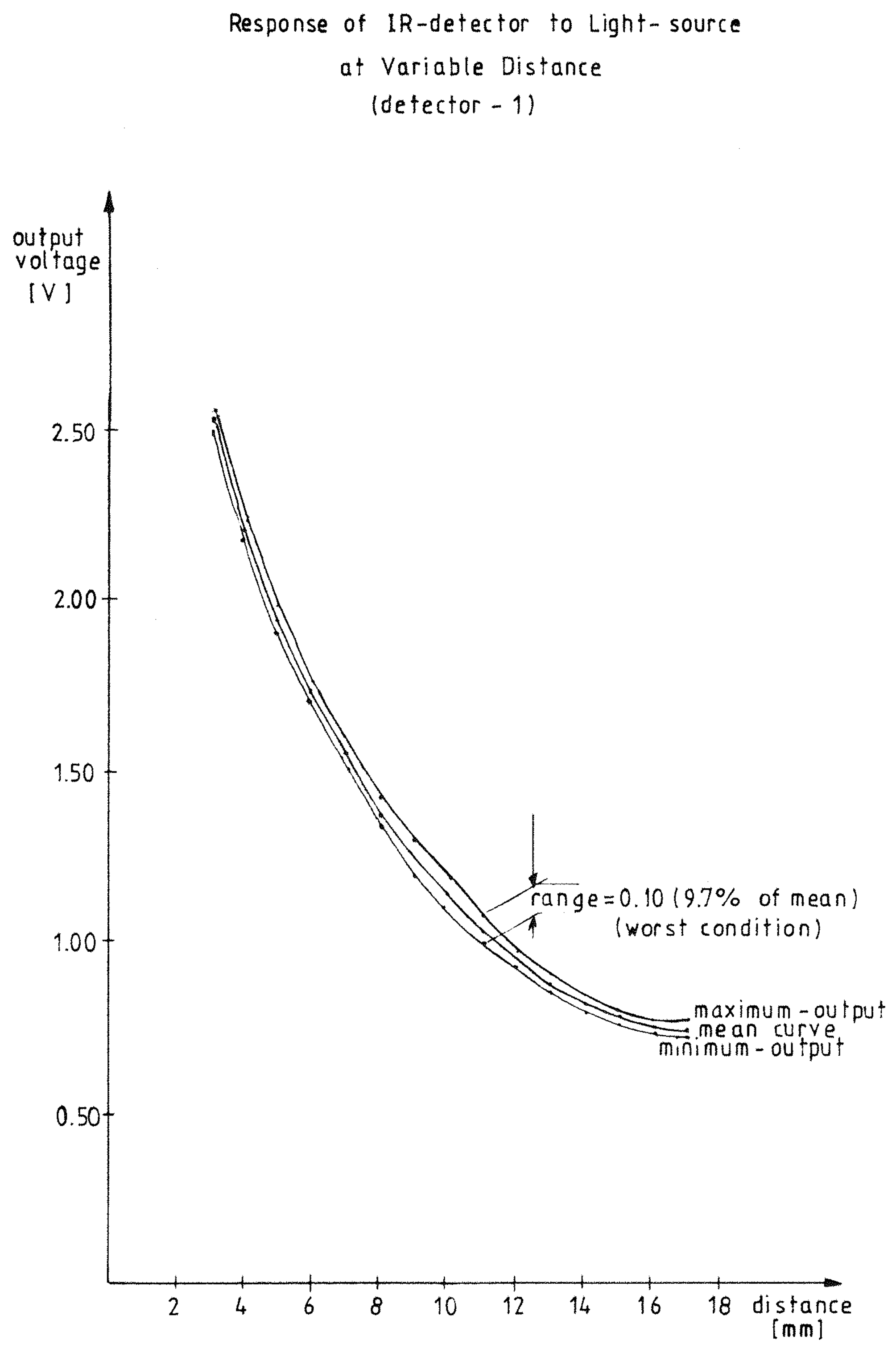


FIGURE 3.17

Graph of Detector Voltage vs
Variable Distance of Light Source

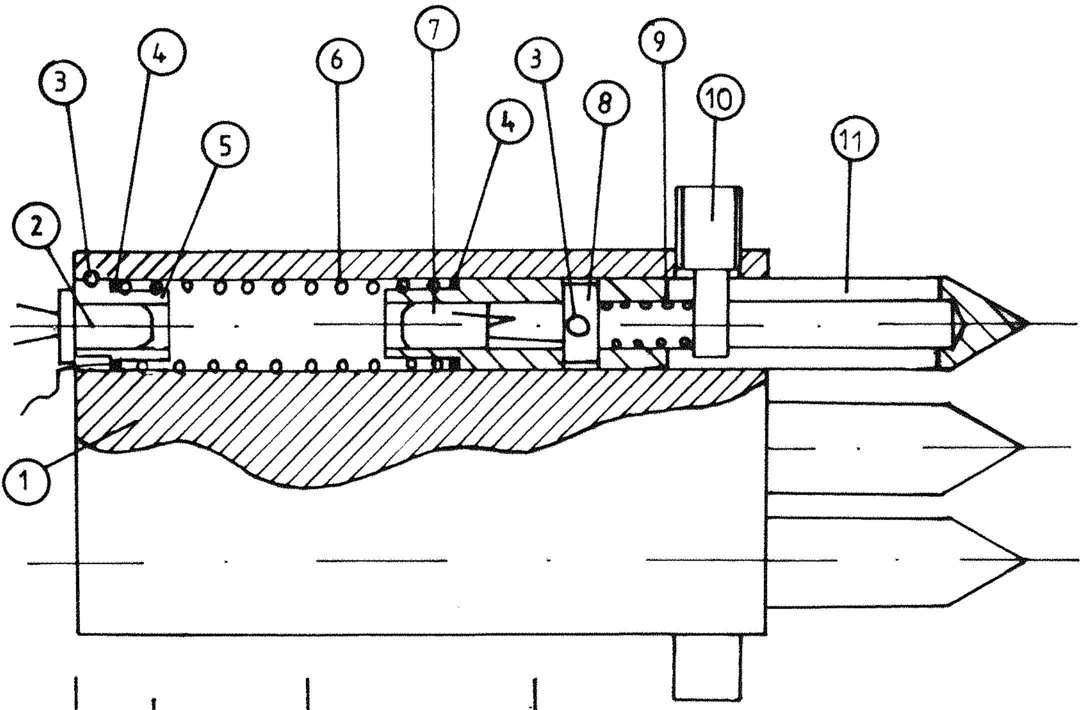
Although tests did not show this has any significant effect on performance, a slightly more elegant design was produced and is shown in figure 3.18. The external dimensions of this design are increased, when compared to the original design. This factor is highly undesirable for the required sensor and consequently this new version was therefore left for future development.

An object recognition function requires many points, in order to have a good resolution. A compromise between size, time for processing and resolution must be taken. Flexible software is needed to abandon points if they are not necessary and also to consider variations in the readings due to movement of the hand and not due to measurements of the object. The latter is avoidable by monitoring, in parallel, the distance between the two fingers.

A nine-pin version is proposed, but if it is necessary to determine points of the surface of contact with more detail and/or a larger area per touch, more pins can be built. In order to have a better definition of the sensor design some knowledge of the geometry of the workpieces is necessary.

The time for data acquisition using the scanning algorithm will probably be too long, but time is not always a constraint [21]. The main concern for this design was to produce a device that provides the orientation of limited shapes. This objective was fully achieved. Later, a second objective was pursued, which was to use the tactile data for a tactile recognition logic.

To summarize, the sensor is still at an early stage of development, but its design presents possibilities to be applied in practice. Due to lack of time, optimizations of the initial design were left for the future. As an example the acquisition time can be greatly reduced if the sensor is made as large as necessary to cover the whole surface of a workpiece in one touch.



POS	QUANT	MATERIAL	IDENTIFICATION
11	4	nylon	probe
10	4	metal conductor	screw
9	4	spring	Φ3Φ2 x 25
8	4	metal conductor	–
7	4	–	IR light source
6	4	spring	Φ6Φ5 x 25
5	4	nylon	–
4	8	metal conductor	washer
3	8	–	pin
2	4	–	IR detector
1	1	–	housing

Scale 2:1

FIGURE 3.18

Second Option of the Matrix Design

CHAPTER 4

TACTILE SENSING

This chapter indicates the state-of-the art of tactile sensing and reviews methods of tactile object recognition. The author's recognition method is proposed, the algorithms of which are presented in appendix A, although they have not yet been implemented.

4.1 The State-of-the Art of Tactile Sensors

Chalupa and al. state that "tactile sensors are usually located on a surface of the artificial hand. They indicate an immediate physical contact with an object ... in fact a pressure to electricity convertor" [60]. Other researchers, like Harmon [7], define tactile sensing as a continuous variable sensing of forces in an array and touch as simple contact sensing at one or just few points. This thesis does not make a distinction between touch and tactile sensors. The directional sensor, described in chapter 3, is therefore considered a tactile sensor, agreeing with both Chalupa's concept and Harmon's touch and tactile definitions.

Tactile sensors were designed to feel slip, orientation, position, etc. A typical application for a slip sensor is to use its information to increase the gripping force just enough to avoid slippage instead of arbitrarily high, which might damage the robot gripper or object. A directional sensor, for example, can be used to predict a necessary change in a gripper orientation, in order to compensate for the angle of an object, or even to halt the gripper, if an unacceptable angle was determined.

Typical operations involving tactile sensors are: assembly, loading a machine, arc-welding, acquisition and manipulation of objects underwater and outer space, adaptive grasping for rehabilitation and prosthetic systems, etc. Many more applications will certainly appear, as the range of robot tasks is always increasing. The reader is referred to Nicholls and Lee, for a discussion on tactile sensing tasks [61].

Bejczy [4] in his review of 1977 found only a total of 15 projects of tactile sensors and all were bench experiments. Harmon [7], in 1982, carried out a survey of tactile sensing among robot producers, researchers and manufacturers. The result was that 90% of the respondents said that they feel a strong need for tactile sensors and that vision and touch should be integrated together.

In 1983, Gindy pointed out that, although touch sensing is recognized as compulsory, in order to improve the present stage of industrial automation, its state-of-the art is very primitive; yet most of the available sensors have been developed for prosthetic applications [43]. This has also been confirmed by Bajcsy [62], who still in 1983 found only one industrial tactile sensor available in the market, and even this sensor possessed no written software to accompany the device. In short, much is said about the potential value of tactile sensors but little has already been achieved.

4.2 Object Recognition through Tactile Perception

The ability to recognize objects would considerably increase the range of robot applications. Object recognition systems are therefore attracting considerable research and development. Vision and touch are the main senses used in normal human recognition procedures, but this research has concentrated only upon tactile recognition. Tactile sensing is most appropriate to recognize objects either in conditions where visual images are doubtful, as for example in smokey atmospheres, or when characteristics such as hardness are required, which are not available through visual systems.

4.2.1 A Review of Other Work

Since the beginning of the seventies, researchers have been working on structural descriptions of objects, to allow a robot to recognize workpieces from tactile sensory data. Larcombe [3], in Great Britain, and Kinoshita [63] and Takeda [64], in Japan, have explored tactile perception capabilities for robotics application. A few years later, the US Naval Laboratory also published work on a tactile recognition system for an underwater robot programme [21]. These examples illustrate the early efforts to improve robot manipulation through tactile recognition.

The method for object description published by Larcombe reproduces patterns through five primitive units [3]. These units, called "tactemes", are point-like, edge-like, surface-like, cranny-like and nook-like. Larcombe proposes to define further relationships to determine, for example, rectangularity (the angle between edges). Context can also be used to help identification. Tactile data are used to form the tactemes of a workpiece. Then, these primitive units and a set of relationships give a complete description of the object, which can be matched with object descriptions from an existing data base. This work produced a simple and quite natural method of pattern reproduction. It can be applicable to different sensor devices, but much research is needed for practical application and to allow descriptions of complex shapes.

Kinoshita and al.[63], described a process to form profiles from thresholds of pressure using an array of on-off switches. The pattern of these switches represents the shape, when the hand is grasping an object. The object is gripped many times, thereby defining several sections upon which pattern recognition is based. For example, a cylinder has a circle profile for every threshold of pressure. This is the earliest publication reviewed that points out the importance of tactile recognition. Its method is similar to the human procedure. Kinoshita's ideas are still valid, however the gripper described is not suitable for industrial applications and the process would be too slow for the majority of applications.

Years later, Kinoshita described a different method using an array of twenty tactile elements to discriminate the shape of a partial surface of an object [65]. A prototype of the sensor was constructed using Hall integrated circuits, which are an integration of a Hall device and an amplifier on one chip. This sensor traces part of the surface along its profile. After this process a mathematical procedure is used to fit a straight or curved line to the tactile data. Unfortunately, the recognition method is not described in detail and the sensor design, though interesting, is still a laboratory experiment.

A hierarchical tree was built by Page to represent an object [50]. The tactile data provides "laminations" of the object, which are regions of approximately the same height. Several laminations are formed and described in terms of their peripheral contour, and upper and lower height values. Then, rules are applied to merge contours, define holes, etc. All combined with a connection tree, that relates the laminations, give the tree structure which describes the object. Although results were not produced the techniques described seem to be practical and able to discriminate simple shapes. Above all the method is simple and certainly deserves further attention.

Another tree structure is formed based upon tactile data [66], [67]. The root node of the tree has several descendents, each of them representing that a point of contact between a sensor and an object, is on a different edge of the latter. The tree has much redundant information, therefore an algorithm, which uses distance, angle (both information from tactile data) and model constraints, was developed to prune infeasible interpretations of the object. This description is only for very simplified objects and the authors do not deal with the acquisition of the tactile data, which is not yet well achieved. The most interesting feature of this work is the pruning procedure.

Multi-jointed fingers were used by Okada and Tsuchiya [68] for object recognition. The data are collected from both sensory and information concerning the position of the joints. The object pattern and size are determined based firstly upon the contact patterns, and secondly upon the bending form of the joints. The mathematical model of this system is very complex. The authors claim that the recognition was achieved in a high proportion of their experiments.

Umetani and Taguchi [69] proposed a pattern reproduction method for general shapes, which is based upon "shape vector". This is the vector composed from the outer angle of the equilateral polygon, which is an approximation of the external boundary of the object. The algorithm evaluates object properties, that are divided into four groups, namely vertex, symmetry, complexity and compactness. The mathematical representations of the properties are given and computed, in order to recognize the shape. The method is intended to be used for general shapes and examples are given, but the system appears to be at a rather theoretical stage.

Chalupa and al. [60] describes a system where the contact between an object and a matrix sensor forms a "print". The recognition algorithm is built up by first detecting the boundary of the object, which is encoded into a two-dimensional string of values. Then, syntactical analysis is performed to create a description based on two grammars, one for angular and other for oval patterns. Finally, a semantical analysis is carried out interpreting the string as corner positions, edge lengths, angle of edges, centers and symmetry axis lengths, which represent the final description of the considered object. The authors claim that 98% of the sampled shapes were recognized, but the results are not final due to the lack of a reliable matrix sensor. A major problem of robotic sensors is still the construction of a practical tactile device.

A combination of visual and tactile sensors is used in Aida and al.'s recognition process [70]. Open-loop and closed-loop symbiotic systems are discussed. In the former, vision is used just to decide the position of the object and tactile sensors follow its profile, in order to provide a matrix of geometric points defining its shape. The matrix is processed and its information is converted into visual signals generating a clear image of the object. In the closed-loop system, the tactile information controls parameters of the visual sensor, such as the threshold level of the visual processing system. The authors' tests were only by computer simulation, and even this had considerable simplications. The method is at a very theoretical stage.

A second combined tactile and visual recognition system is proposed by Luo and al. [71]. Vision is used to recognize an object through its top view and tactile sensors are applied to discriminate objects with similar top views. A two-fingered robotic gripper surrounds the object, then the gripper moves until one finger touches the object, thereby forming a tactile image. Subsequently, the process is repeated to form a second tactile image (using the other finger). This work is also at a research stage; no results were given. The acquisition of tactile data in two separate steps seems to be difficult to achieve in practice, due to possible movements of the object. The reader is also referred to Allen [72] for a third example of visual and tactile sensors integrated into one recognition system.

Progress in the area (tactile recognition) to date has been slow and so far publications have not described a recognition process that could match the human capability. Symbiotic systems of visual and tactile sensors represent the most promising approach for a flexible recognition method.

4.2.2 Overview of the Proposed Method

Figure 4.1 shows six workpieces, which were chosen arbitrarily, their tactile images and their corresponding property values are explained below. Looking from left to right (a), there are four types of boxes with a variable number and size of windows, a disc and a ring.

The tactile images (fig 4.1/b) are expected to be produced by a sensor similar to the "Matrix" sensor described in chapter 3. Each point of the images is stored in a computer, as an element of a matrix of recognition, which was defined in section 3.3.2).

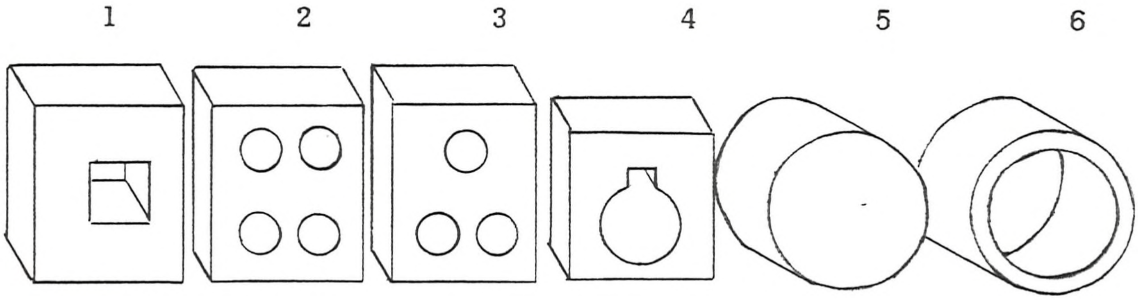
Properties such as area (A), vertices (V), perimeter (P) and/or number of holes (H), form a unique set of numbers, which enables each of the six objects of figure 4.1 to be distinguished. The latter property includes a true hole or any depression deeper than the maximum displacement of the sensor rod, or a zero-value for a no-hole condition.

Figure 4.2 shows the flow-chart of the proposed recognition method. The initial considerations made in the design of the recognition method are:

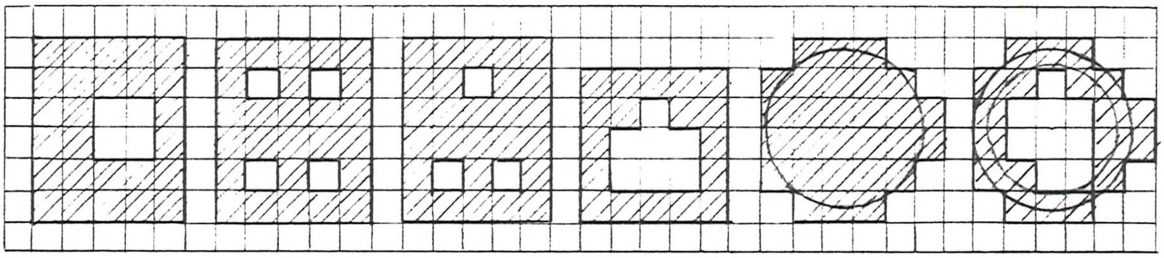
1. The directional tactile sensor of chapter 3 is available and the matrices of recognition (see section 3.4.2) can be formed. These matrices are called MR and ML, representing data from the right and left sensor respectively.

2. The object is in a stable position with one face in contact with the base (or table of reference) of the work-space defined in section 3.4.

3. There is only one object inside the work-space and its dimensions are within that volume.



a) Workpieces



b) Tactile Images
The shaded squares represent points where
a rod of the tactile sensor was displaced.

A=26	A=26	A=27	A=18	A=28	A=19
V=4	V=4	V=4	V=4	V=16	V=16
P=22	P=22	P=22	P=20	P=24	P=24
H=1	H=4	H=3	H=1	H=0	H=1

c) Corresponding Properties Values

Figure 4.1 An Arbitrarily-chosen Set of Workpieces

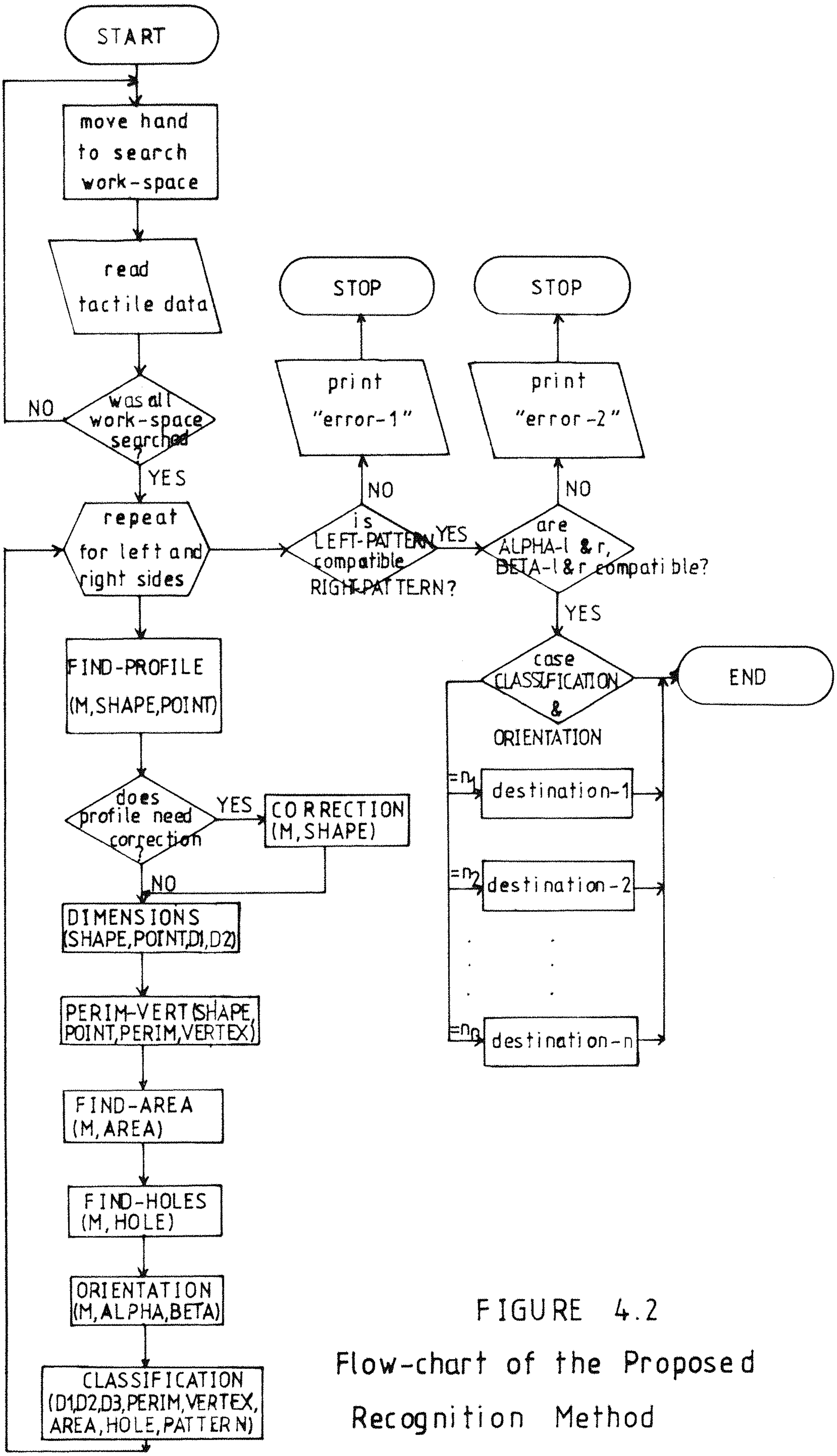


FIGURE 4.2

Flow-chart of the Proposed Recognition Method

The complete system is intended to be as general as possible, but the author believes that a sensor design and tactile object recognition research would be better conducted from the bottom to the top. With hindsight, the approach to this work was not the most suitable way to carry out the research.

Each procedure of the flow-chart is below explained in more detail. The algorithms for these procedures are partially developed and described in a pseudocode in appendix A. However they have not as yet been programmed for a computer because the intention of this research was to present the method. An example of recognition is also provided.

The PATTERN-RECOGNITION programme is responsible to input data into the computer and control the whole system. The programme also computes a matrix of measurements, which is formed from the cartesian coordinates of the gripper fingers and the rod displacements (both defined in chapter 3). This matrix has the length of the object at each point where a rod was displaced.

The programme must be adjusted according to workpiece geometries. As an example, a set of objects might never have holes, in that case FIND-HOLE is meaningless, therefore given a set of workpieces, PATTERN-RECOGNITION should only call procedures for the computation of relevant properties.

FIND-PROFILE(M, SHAPE, POINTS) returns into SHAPE the indexes of the generic matrix M (equal to MR or ML), whose elements correspond to the points of the external boundary of the object. If the element m_{ixj} represents an external point of the object, then SHAPE(x,1)=i and SHAPE(x,2)=j, where each x corresponds to one tactile point. The total number of tactile points in the profile is therefore given by the last x, that is returned to the main procedure via POINTS. The profile is traced in a clockwise sense, starting in the left uppermost position of the matrix M. One position is equal to one square (1/9 sq-inch) and the same indexes of M (i and j) can appear in SHAPE more than once, but that position is never traced in the same direction twice.

DIMENSIONS(SHAPE, POINTS, D1, D2) gives the maximum height (D1) and width (D2) of the tactile image of the object. The real dimensions of the object must be within these two measurements.

PERIM-VERT(SHAPE, POINTS, PERIM, VERTEX) uses the matrix SHAPE, created in FIND-PROFILE to compute the number of vertices (VERTEX) and the perimeter (PERIM) of the object. Note that PERIM and VERTEX are usually only approximations of the number of vertices and the perimeter of the object (see examples in figure 4.1). However, they can still be useful in the recognition process as they should be approximately predictable and constant, for several tactile images of a given object.

FIND-AREA(M, AREA) procedure returns into AREA the number of rods of the sensor, which have displaced from the rest position, in order to touch an object. That is the area of the tactile image, which is again an approximation of the projection of the real surface of the object onto a plane parallel to the ZY plane.

FIND-HOLE (M, HOLE) returns into HOLE the number of holes, or zero for no holes (hole can also mean just a depression). A hole can have any shape; a "negative" of the matrix of tactile points is formed and then FIND-PROFILE is called to find the boundary of this hole (see example of appendix A).

ORIENTATION(M, ALPHA, BETA) is not yet developed. This procedure is meant to use the tactile data to calculate the angles of direction, ALPHA and BETA, to define plane surfaces relative to the sensor position, or to compare different positions of similar objects. Again for further improvement, the author feels that some specific knowledge of the geometry of the workpiece set is needed.

CLASSIFICATION(D1,D2,D3,PERIM,VERTEX,AREA,HOLE,PATTERN) is also not yet developed. The comments for the previous procedure also apply here. The intention is to code the object according to the calculated properties (e. g. area and perimeter) and return a value into PATTERN corresponding to the shape identified by the right (or left) sensor. As an example, if CLASSIFICATION uses the tactile data corresponding to the objects of figure 4.1, PATTERN will have the value 1, 2, ..., or 6, according to the object identified.

Finally by matching CLASSIFICATION and ORIENTATION, the robot is able to decide the object "destination". The gripper might have to correct its position, or to stop if an unacceptable error was detected, therefore several "destinations" are necessary and need to be defined. A very significant improvement would be achieved through the implementation of a CORRECTION procedure. This would draw a straight line for "stairs" in the tactile image for example. This procedure is shown in the overall system, but no development has yet been carried out.

CHAPTER 5

FINAL DISCUSSION

In this chapter the general conclusions of the research are presented. Predictions for the development of tactile sensors are given based on publications in the robotic literature.

5.1 Conclusions

The robot applications described in chapter 2 have shown that robots can perform an increasing number of tasks, but although automation has greatly increased in the last two decades, advances have been slower than was anticipated. The sensor review indicates that firstly, sensory systems are necessary in order to advance the current stage of robots and increase their range of applications. Secondly, sensor technology is still primitive and most of the devices reviewed were at a research stage of development.

Much research and development is therefore necessary in order to produce functional sensory systems for robots comparable to the human capability. The author believes, that due to the need for flexibility a combination of sensory systems is necessary. Perhaps a modular system can be designed where two or more sensors could be selected according to the particular application of a robot, with advantages of improved economy and reduced complexity for the user.

In order to further robotic sensors, research programmes need to concentrate on the development and/or testing of transducer materials and the design of the devices themselves. In parallel, software using the sensory data for robot control must be advanced.

The directional sensor presented in chapter 3 was designed and a prototype was manufactured according to the specifications given in the general introduction. A second possible feature of the device, not yet explored, is to determine gripping forces. Although the device is still at a research stage, the main objective was achieved which was to measure angles in two perpendicular directions. The final conclusions drawn from that experience, which will hopefully guide designers of tactile sensors, are:

1) The best approach to design a sensor is believed to be from bottom to top. This means defining the sensor application in every possible detail, and only after a prototype should refinements be attempted in the direction of a general solution.

2) Tactile/touch sensors can benefit from a matrix of points design. Two other designs were studied by the author, but regardless of their success, the matrix can give the same information plus data to provide an object recognition function.

3) The resolution and number of points in the matrix should be defined according to the intended application to avoid unnecessary complexity and costs.

The robot applications discussed have also indicated that an object recognition function is desirable in order to expand the range of robot tasks. Chapter 4 reviewed tactile object recognition and an overview of the author's recognition method was presented, based upon data of the proposed matrix design. However, the author knows, based on previous frustrating experiences, that the recognition algorithms, when implemented, will certainly require many corrections and alterations. The intention is only to propose initial ideas on how to explore the sensory data.

To summarize, this research has shown that sensors are a key factor for the next robot generation. Experiences, from three attempts to design a directional sensor, led to the conclusion that the success of sensor designs lies in their electronic component(s). This thesis proposed a review of robotic sensors, mainly of non-visual nature, a design of a directional sensor and a review of tactile pattern recognition. These three objectives have been achieved.

5.2 Predictions for Development of Tactile Sensors

Harmon [7] in his survey among personnel in robotics found five requirements for the touch-sensing transducer. He also predicted that 5 to 10 years of research (from 1983) may lead to such a sensor. In Harmon words these requirements are:

"1. A typical array consists of 10X10 force-sensing elements on a 1-sq-in, flexible surface, much like a human fingertip. Finer resolution may be desirable but is not essential for many tasks.

2. Each element should have a response time of 1-10 ms, preferably 1 ms.

3. Threshold sensitivity for the element ought to be 1 g, the upper limit of the force range being 1,000 g.

4. The elements need not be linear, but they must have low hysteresis.

5. This skinlike sensing material has to be robust, standing up well to harsh industrial enviroments."

Yet, Harmon' studies have shown that the most likely profitable areas for tactile sensor applications would be the industrial (inspection, assembly, grinding, etc) and exploration services (underwater, outer space operations and nuclear handling in general).

Many researchers believe that tactile sensors must sense as the human hand or, in another words, they must be able to feel pressure, direction, temperature, vibration, etc, in one device [73].

Finally it is generally thought, that due to the inherent differences between visual and tactile sensing their features could be integrated to advantage in robotic recognition systems. Visual has higher spatial resolution than tactile sensors, but the latter can measure parameters at the contact with the object, which are not available through visual information.

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APPENDIX

A. PROPOSED OBJECT RECOGNITION METHOD

These algorithms aim to demonstrate the methodology of the author's object recognition technique.

As such, they are presented in a pseudocode for future translation into any particular computer language. They have not yet been implemented.

1. Algorithms

1.1 Main Procedure

```
Procedure PATTERN-RECOGNITION:
declare
   MR, ML real matrix [1:11; 1:17] initial 0,
   D3 real matrix [2:10; 2:16],
   DR1, DR2, DL1, DL2 real,
   AREAR, AREAL real,
   VERTEXR, VERTEXL interger,
   PERIMR, PERIML real,
   HOLER, HOLEL real,
   POINTR, POINTL  interger,
   KEY   interger initial 0,
   SHAPER, SHAPEL interger matrix [1:100; 1:2],
   I, J, M, N interger

   comment:"lines 1 & 17 and columns 1 & 11 have no data"
   M=10
   N=2
   K=1 comment:"K=1 for the +Y direction; K=-1 for the -Y"
   do while ( KEY < 15)
     call MOVE-HAND comment:"hand searches work-space"
     do I from M to M-2 by -1
          do J from N to N+2*K by K
               read  MR(I,J) comment:"get the sensor  data"
               read  ML(I,J)
          end
     end
     KEY = KEY + 1
     N = N + 3     comment:  "new position of sensor in the
                              Y-axis direction"
     if KEY = 5 or KEY = 10 then begin M = M + 3; K=-K end
   end
   KEY = 0
   do while (KEY = 0) comment:  "to be used in  future  to
                      allow more objects in the work-space"
     call FIND-PROFILE (MR, SHAPER, POINTR)
     call FIND-PROFILE (ML, SHAPEL, POINTL)
     call DIMENSIONS(SHAPER, POINTR, DR1, DR2)
     call DIMENSIONS(SHAPEL, POINTL, DL1, DL2)
     call PERIM-VERT (SHAPER, POINTR, PERIMR, VERTEXR)
     call PERIM-VERT (SHAPEL, POINTL, PERIML, VERTEXL)
     call AREA (MR, AREAR)
     call AREA (ML, AREAL)
     call FIND-HOLE (MR, HOLER)
     call FIND-HOLE (ML, HOLEL)
     call ORIENTATION (MR, ALPHAR, BETAR)
     call ORIENTATION (ML, ALPHAL, BETAL)
     do I from 2 to 10
        do J from 2 to 16
          $D3(I,J)=2*const + |x_r - x_l| - |MR(I,J)| - |ML(I,J)|$
                    comment:"const is the length of a rod"
        end
     end
```

```
     if ALPHAR + E not= ALPHAL and BETAR + E not= BETAL
        comment:" E is an acceptable error"
        then begin
               print "Error-2, call operator"
               stop
             end
     call CLASSIFICATION(DR1,DR2,D3,PERIMR,VERTEXR,AREAR,
                         HOLER,RIGHT)
     call CLASSIFICATION(DL1,DL2,D3,PERIML,VERTEXL,AREAL,
                         HOLEL,LEFT)
     case (RIGHT)
     begin
          1. case (LEFT)
             begin                      comment:"DESTINATION-N"
               1. call DESTINATION-1  "means an error, or "
               2. call DESTINATION-2  "an adjustment, or a"
                     .         .      " final manipulative"
                     .         .      "operation  of  the "
               6. call DESTINATION-6  "       gripper     "
          .
          .
          .
          n: case (LEFT)
             begin
                .
                .
                .
             end
     end   comment: "finish of case (RIGHT)"
   end  comment: "finish of do while"
end PATTERN-RECOGNITION.
```

1.2 Finding the Boundary

```
Procedure FIND-PROFILE (M,POINT,SHAPE):
   declare
     M real matrix [1:11; 1:17]
     KEY interger
     I, J, POINT interger
     SHAPE interger matrix [1:100; 1:2]

   comment:"maximum number of points of boundary is 100"

   do I from 1 to 100
     do J from 1 to 2
       SHAPE (I,J) = 0
     end
   end
   KEY = 0
   I = 2
   J = 2
   do while M(I,J) = 0   comment: "find first position"
     if J < 10 then J=j+1
               else if I < 7
                       then begin
                              I=I+1
                              J=1
                            end
```

```
                    else begin
                           print "Error-no data in M"
                           stop
                         end
end
do while ("true")

comment: "boundary goes UP"
  if M(I-1,J) not= 0 & (KEY = 0 or KEY =1)
    then
    begin
      call PROFILE (POINT)
      I=I-1
      KEY=4
    end
    else if M(I-1,J+1) not= 0 & (KEY=0 or KEY=1)
           then
           begin
             call PROFILE (POINT)
             I=I-1
             J=J+1
             KEY=1
           end

comment: "boundary goes to the RIGHT"
           else if M(I,J+1) not=0 & KEY not=3 & KEYnot=4
                  then
                  begin
                    call PROFILE(POINT)
                    J=J+1
                    KEY=1
                  end
                  else if M(I+1,J+1) not=0 & KEY not=3 &
                          KEY not= 4
                          then
                          begin
                            call PROFILE(POINT)
                            I=I+1
                            J=J+1
                            KEY=1
                          end

comment: "boundary goes DOWN"
                    else if M(I+1,J) not= 0 & KEY not= 4
                           then
                           begin
                             call PROFILE (POINT)
                             I=I+1
                             KEY=2
                           end
                            else if M(I+1,J-1) not= 0  &
                                   KEY not= 4
                                   then
                                   begin
                                     call PROFILE(POINT)
                                     I=I+1
                                     J=J-1
                                     KEY=2
                                   end
```

```
   comment: "boundary goes to the LEFT"
   else if M(I,J-1) not= 0
           then
           begin
             call PROFILE (POINT)
             J=J-1
             KEY=3
           end
           else if M(I-1,J-1) not= 0
                   then
                   begin
                     call PROFILE (POINT)
                     I=I-1
                     J=J-1
                     KEY=3
                   end
                   else if M(I-1,J) not= 0
                           then
                           begin
                             call PROFILE (POINT)
                             I=I-1
                             KEY=4
                           end
                           else if M(I-1,J+1) not= 0
                                   then
                                   begin
                                     call PROFILE(POINT)
                                     I=I-1
                                     J=J+1
                                     KEY=4
                                   end
                                   else
                                   begin
                                     if KEY=0
                                        then
                                        begin
                                          print "One point
                                                 data"
                                          return
                                        end
                                      KEY=1
                                    end
   end  comment: "finishes do while"
end FIND-PROFILE.
```

1.3 Creating SHAPE Matrix

```
Procedure PROFILE(K):
          declare K interger initial 0

   comment: "this procedure creates SHAPE and returns to
             the main procedure after FIND-PROFILE call"

   if SHAPE(1,1)=I & SHAPE(1,2)=J
      then begin
              print "profile completed"
              return (main procedure)
           end
```

```
   K=K+1
   SHAPE (K,1)=I
   SHAPE (K,2)=J
end PROFILE.
```

1.4 Computation of Width and Height in Millimetres

```
Procedure DIMENSIONS(SHAPE,POINT,D1,D2)
   declare
     SHAPE integer matrix [1:100; 1:2],
     GREAT, LESS, K, POINT interger
     D1, D2 real
   D1=(SHAPE(1,1)-1)*(25.4/3) comment:"first  position of
                               SHAPE gives the highest line"
   GREAT=1
   LESS=11
   do K from 1 to POINT
      if SHAPE(K,2) > GREAT then GREAT=SHAPE(K,2)
      if SHAPE(K,2) < LESS  then LESS=SHAPE(K,2)
   end
   D2=(GREAT - LESS)*(25.4/3)
   comment:"the dimension between the two  columns
               with data most apart to each other"
end DIMENSIONS.
```

1.5 An Approximation of the Perimeter and Vertices

```
Procedure PERIM-VERT(SHAPE,K,PERIM,VERTEX):
   declare L,K interger
           KEY,TEST,VERTEX interger initial 1
           SHAPE interger matrix [1:50;1:2]
           PERIM interger initial 1
           SHAPE(K+1,1)=SHAPE(1,1)
           SHAPE(K+1,2)=SHAPE(1,2)
   do L from  to K
     comment:"the  variable TEST holds the situation  of
             the previous position"
     TEST=KEY
     if SHAPE(L,1)=SHAPE(L+1,1) & SHAPE(L,2)+1=SHAPE(L+1,2)
       then  KEY=1  comment:"next point is at  the  same
                             line and next column"
       else
       if SHAPE(L,1)+1=SHAPE(L+1,1)&SHAPE(L,2)=SHAPE(L+1,2)
         then KEY=2 comment:"next point is at next line
                             and same column"
         else
         if SHAPE(L,1)=SHAPE(L+1,1) &
            SHAPE(L,2)-1=SHAPE(L+1,2)
           then KEY=3 comment:"same line, previous column"
           else
              if SHAPE(L,1)+1=SHAPE(L+1,1) &
                 SHAPE(L,2)-1=SHAPE(L+1,2)
                then KEY=4
                comment:"next line and previous column"
                else
                if SHAPE(L,1)-1=SHAPE(L+1,1) &
```

```
              SHAPE(L,2)=SHAPE(L+1,2)
              comment:"previous line, same column"
              then KEY=5
              else
              if SHAPE(L,1)+1=SHAPE(L+1,1) &
                 SHAPE(L,2)+1=SHAPE(L+1,2)
                 comment:"next line and next column"
                 then KEY=6
                 else if SHAPE(L,1)-1=SHAPE(L+1,1) &
                         SHAPE(L,2)+1=SHAPE(L+1,2)
                 comment:"previous line, next column"
                        then KEY=7
                 comment:"previous both line & column"
                        else KEY=8
case (KEY)
begin
  1: case(TEST)
     begin
        1: PERIM=PERIM+1
        2: print "error"
        3: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
        4: print "error"
        5: begin VERTEX=VERTEX+1 ; PERIM=PERIM+2 end
        6: PERIM=PERIM+1
        7: begin VERTEX=VERTEX+1 ; PERIM=PERIM+2 end
        8: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
     end comment:"finishes case(TEST)"
  2: case(TEST)
     begin
        1: begin VERTEX=VERTEX+1 ; PERIM=PERIM+2 end
        2: PERIM=PERIM+1
        3: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
        4: PERIM=PERIM+1
        5: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
        6: begin VERTEX=VERTEX+1 ; PERIM=PERIM+2 end
        7: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
        8: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
     end comment:"finishes case(TEST)"
  3: case(TEST)
     begin
        1: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
        2: begin VERTEX=VERTEX+1 ; PERIM=PERIM+2 end
        3: PERIM=PERIM+1
        4: begin VERTEX=VERTEX+1 ; PERIM=PERIM+2 end
        5: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
        6: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
        7: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
        8: PERIM=PERIM+1
     end comment:"finishes case(TEST)"
  4: case(TEST)
     begin
        1: begin VERTEX=VERTEX+3 ; PERIM=PERIM+3 end
        2: begin VERTEX=VERTEX+2 ; PERIM=PERIM+2 end
        3: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
        4: begin VERTEX=VERTEX+2 ; PERIM=PERIM+2 end
        5: print"error"
        6: begin VERTEX=VERTEX+3 ; PERIM=PERIM+3 end
        7: begin VERTEX=VERTEX+4 ; PERIM=PERIM+4 end
        8: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
     end comment:"finishes case(TEST)"
```

```
       5: case(TEST)
          begin
             1: print "error"
             2: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
             3: begin VERTEX=VERTEX+1 ; PERIM=PERIM+2 end
             4: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
             5: PERIM=PERIM+1
             6: print "error"
             7: PERIM=PERIM+1
             8: begin VERTEX=VERTEX+1 ; PERIM=PERIM+2 end
          end comment: "finishes case(TEST)"
       6: case(TEST)
          begin
             1: begin VERTEX=VERTEX+2 ; PERIM=PERIM+2 end
             2: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
             3: print "error"
             4: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
             5: begin VERTEX=VERTEX+3 ; PERIM=PERIM+3 end
             6: begin VERTEX=VERTEX+2 ; PERIM=PERIM+2 end
             7: begin VERTEX=VERTEX+3 ; PERIM=PERIM+3 end
             8: begin VERTEX=VERTEX+4 ; PERIM=PERIM+4 end
          end  comment: "finishes case(TEST)"
       7: case(TEST)
          begin
             1: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
             2: print "error"
             3: begin VERTEX=VERTEX+3 ; PERIM=PERIM+3 end
             4: begin VERTEX=VERTEX+4 ; PERIM=PERIM+4 end
             5: begin VERTEX=VERTEX+2 ; PERIM=PERIM+2 end
             6: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
             7: begin VERTEX=VERTEX+2 ; PERIM=PERIM+3 end
             8: begin VERTEX=VERTEX+3 ; PERIM=PERIM+3 end
          end  comment "finishes case(TEST)"
       8: case(TEST)
          begin
             1: print "error"
             2: begin VERTEX=VERTEX+3 ; PERIM=PERIM+4 end
             3: begin VERTEX=VERTEX+2 ; PERIM=PERIM+2 end
             4: begin VERTEX=VERTEX+3 ; PERIM=PERIM+3 end
             5: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
             6: begin VERTEX=VERTEX+4 ; PERIM=PERIM+4 end
             7: begin VERTEX=VERTEX+1 ; PERIM=PERIM+1 end
             8: begin VERTEX=VERTEX+1 ; PERIM=PERIM+3 end
          end  comment: "finishes case(TEST)"
     end  comment: "finishes case(KEY)"
   end comment: "finishes loop and start other position"
   if KEY=8 or KEY=3 then begin
                            VERTEX=VERTEX+1
                            PERIM=PERIM+1
                          end
end  PERIM-VERT.
```

1.6 Computation of the Projected Area

```
procedure FIND-AREA(M,AREA):
   declare AREA, TOTAREA real
           I, J interger
           M real matrix [1:11 ; 1:17]
```

```
   AREA=0
   TOTAREA=0
   do I from 2 to 10
      do J from 2 to 16
         if M(I,J) not= 0 then AREA=AREA+1
      end
   end
   TOTAREA=AREA*25.4*25.4   comment:"any dimension can  be
                 used to transform tactile units into area"
          print "total area of projection is" ; TOTAREA
end FIND-AREA.
```

1.7 Search for Holes or Depressions

```
procedure FIND-HOLE(M,HOLE)
   declare I,J,L, CHANGE, POINTZERO interger
           HOLE interger initial 0
           ZERO,M real matrix [1:11 ; 1:17]
           ZEROSHAPE interger matrix [1:50; 1:2]
   do I from 1 to 17
      M(1,I)=-99
      M(11,I)=-99
   end
   do I from 2 to 10
      M(I,1)=-99
      M(I,17)=-99
   end
   CHANGE=1
   do while (CHANGE=1)
      CHANGE=0
      do I from 2 to 10
         do J from 2 to 16
            if M(I,J)=0 & (M(I-1,J)=-99 or M(I,J-1)=-99 or
                           or M(I,J+1)=-99 or M(I+1,J)=-99)
              then begin
                      M(I,J)=-99
                      CHANGE=1
                   end
         end
      end
   end  comment: "finishes do while"
   do I from 2 to 10
      do J from 2 to 16
         if M(I,J) not= 0
            then ZERO(I,J)=0
            else ZERO(I,J)=-99
      end
   end
   do I from 2 to 10
      do J from 2 to 16  comment: "searches any number of
                                     holes"
         if ZERO(I,J) not= 0
           then
           begin
             POINTZERO=0
             call FIND-PROFILE(ZERO,ZEROSHAPE,POINTZERO)
             if POINTZERO > 0
               then
               begin
                 HOLE=HOLE+1
```

```
        do L from 1 to POINTZERO
         ZERO(ZEROSHAPE(L,1),ZEROSHAPE(L,2))=0
        comment:"a same hole is not search twice"
        end
       end
      end
   end
  end
end FIND-HOLE.
```

2. Example

As said previously the system is not yet implemented, therefore no computer simulation can be presented. The following example is intended to help the understanding and give an idea of the expected output from the algorithms.

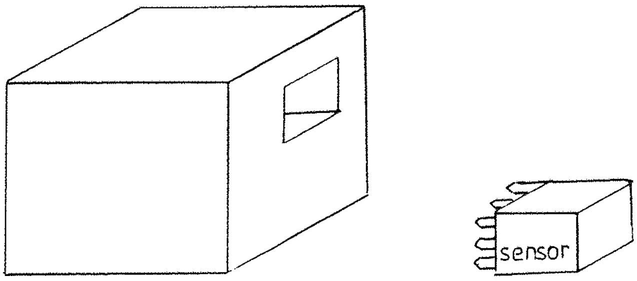

Figure A.1 The Sampled Object

A matrix MR is formed with tactile data from one sensor. MR has the following values:

col line	2	3	4	5	6	7	8	9	10	...	17
2	0	0	0	0	0	0	0	0	0	...	0
3	0	0	0	0	0	0	0	0	0	...	0
4	0	0	0	0	0	0	0	0	0	...	0
5	0	0	0	3	3	3	3	3	0	...	0
6	0	0	0	3	3	0	0	3	0	...	0
7	0	0	0	3	3	0	0	3	0	...	0
8	0	0	0	3	3	3	3	3	0	...	0
9	0	0	0	3	3	3	3	3	0	...	0
10	0	0	0	3	3	3	3	3	0	...	0

Figure A.2 Tactile matrix (MR)

2.1 DIMENSIONS: DR1=50mm ; DR2=42.3mm ; D3=?

2.2 FIND-PROFILE and PERIM-VERTEX

The main programme (PATTERN-RECOGNITION) calls the procedure FIND-PROFILE to create the matrix SHAPE, which is formed by the indexes of the points that are in the external boundary of the object. Subsequently, PERIM-VERT uses the matrix to compute the vertices (VERTEX) and perimeter (PERIM) of the image of the object.

col	SHAPE		VERTEX(initial 1)	PERIM(initial 1)
line	1	2		1
1	5	5		1
2	5	6		1
3	5	7		1
4	5	8		1
5	5	9	1	2
6	6	9		1
7	7	9		1
8	8	9		1
9	9	9		1
10	10	9	1	2
11	10	8		1
12	10	7		1
13	10	6		1
14	10	5	1	2
15	9	5		1
16	8	5		1
17	7	5	TOTAL=4	1
POINT=18	6	4		1
19	5	5		
20	0	0		TOTAL=22
.	.	.		
.	.	.		
100	.	.		

Figure A.3 Examples of SHAPE, VERTEX, PERIM and POINT

2.3 FIND-AREA

AREA=26 units (non-zeros elements of MR) or 16,774mm².

2.4 FIND-HOLE

line \ col	2	3	4	5	6	7	8	9	10	...	11
2	0	0	0	0	0	0	0	0	0	...	0
3	0	0	0	0	0	0	0	0	0	...	0
4	0	0	0	0	0	0	0	0	0	...	0
5	0	0	0	0	0	0	0	0	0	...	0
6	0	0	0	0	0	-99	-99	0	0	...	0
7	0	0	0	0	0	-99	-99	0	0	...	0
8	0	0	0	0	0	0	0	0	0	...	0
9	0	0	0	0	0	0	0	0	0	...	0
10	0	0	0	0	0	0	0	0	0	...	0

ZERO

ZEROSHAPE line \ col	1	2
1	6	7
2	6	8
3	5	8
POINTZERO=4	5	7
5	0	0
6	.	.
.	.	.
.	.	.
50	0	0

Figure A.4 Matrix ZERO ("negative" of MR) and ZEROSHAPE

ZEROSHAPE has the indexes of the boundary of a hole or depression: number of HOLE=1.

B) ROBOTIC RESEARCH INSTITUTIONS AND THEIR PROJECTS

This appendix presents a compilation of robotic centres of research and development and their respective areas of interest or projects, when possible. The centres are described according to their country of origin and, inside each country there are usually two groups, academic and industrial institutions.

1. USA

Robots Institute of America (RIA) is the American organization that coordinates activities, makes standards, provides statistics, robot classification, etc, into robotics. A survey of the American robotic centres is provided by Bejczy [74] with projects started up to 1972, Dixon [27] reviewed projects up to 1978, and finally Harmon [26] described research which began before 1981.

1.1 Academic Centres and/or Government Laboratories

a) Stanford University Artificial Intelligence Laboratory: a hand-eye programme and problems of computer control of manipulators.

b) Stanford Research Institute: project on artificial intelligence in robotics, control language for manipulator, and experimental system of an anthropomorphic arm with tactile sensing.

c) MIT Mechanical Engineering Department: development of a flexible manipulator control language, called MANTRAN.

d) MIT Artificial Intelligence Laboratories: a mechanical hand with tactile sensors, hand-eye coordination, television visual system, on line computer to assemble objects and AI project in linguistic programming.

e) Case Western Reserve University: a computer controlled manipulator for remotely disassembling a nuclear reactor model with sensors to avoid obstacles.

f) Jet Propulsion Laboratory (JPL): programme in an integrated robot research, which consists of rover (i.e. a mobile vehicle equipped with a manipulator), supervisor, computers and sensors.

g) Charles Stark Draper Laboratories, in Cambridge, Mass (MIT): remote center of compliance, integrated touch and force sensors in a hand used to package objects compactly and supervisory control for a manipulator.

h) US Naval Research Laboratory (NRL): an underwater robot project.

i) Industrial Automation Group of the American National Standards Institute: robotics software.

1.2 Industries with In-house Research Centres

a) Unimation: the biggest robotic company.

b) Cincinnati/Milacrom: can supply different robots.

c) GE: adapt robots to the company's particular needs; project in object recognition; project CONSIGHT for a production-line robot to pick up non-oriented parts from a moving conveyor belt using vision. Can supply from workstations to robots for complete automation.

d) International Business Machines Corp (IBM), boca Raton: a robot programmed throught IBM personal Computer. A project to use a robot for assembly operation through a tactile and a frame sensory system. Can supply from workstations to robots for complete automation.

e) Texas Instruments: research and development.

f) International Robomation/Intelligence, Carlsbad, Calif: vision system for its M50 robot.

g) Object Recognition Systems Inc, in Princeton, N. J.: a robot that can bin-picking and pneumatic grippers with sensing.

h) Computer Aided Manufacturing International Inc, in Arlington, Texas: software standard for robotics AI.

i) Westinghouse Electric Corp, in Pittsburgh, Pa: a robot controller.

j) Lord Corp, Cray, NC: first commercial non-visual sensor.

k) Driscoll: research on a computer-programmed integrated vision and manipulator.

l) Hughes Aircraft Co: pioneer underwater teleoperator/ robot UNUMO, Mobot.

m) Intelledex Inc, in Corvallis, Oregon: first robot with plug-in sense of vision.

2. Japan

The Japanese equivalent to RIA is called Japanese Industrial Robot Association (JIRA). The reader is referred to [75] for the major robot manufacturers in Japan, according to JIRA. The following institutions are a selection of this group.

2.1 Academic centres and/or Government Laboratories

a) Electrotechnical Laboraboratory of MITI (Ministry of International Trade and Industry): research such as six-legged robot with sensors. With major robotic companies a programme to produce an universally applicable robot.

b) University of Tsukuba, Sakura (Professor Yutaka Kamayana and S. Yuto): a mobile robot with sonic sensor to avoid obstacles, under development is an end-effector for the mobile robot.

c) Tokyo University (Automation Research Laboratory: work on two-legged robot.

d) Tokyo Institute of Technology: working on mobile robots (Prof Hirose) based on movements of animals such as a snake-like crawler.

e) University of Nagoya.

f) University of Waseda.

2.2 Industries with In-house Research Centres

a) Hitachi's Production Engineering Research Laboratory: developing a six-degree-of-freedon robot with binary vision to assembly toys randomly placed, a five-legged robot project to go up stairs inspecting nuclear power plants, a multifingerred hand called HI-T-Hand, a robot with TV and pressure sensing pad.

b) Fujitsu's research Laboratory: PROTO robot with visual object recognition and sort of small components parts for assembly.

c) Mitsubishi

3. Europe

3.1 RUSSIA

3.1.1 Academic Centres and/or Government Laboratories

a) The State Committee on Science and Technology (GKNT).

b) The Special Design Bureau for Technical Cybernetics (OKBTK) at the Leningrad Polytechnic Institute Imeni Kalinin (LPI) is the head organization for robotic development. The Bureau has a cooperative group of 50 institutes and firms in Leningrad area. The OKBTK-LPI is headed by Dr Ye. I. Yerevich, who is the leader on theory and robotic development such as AI and practical applications. Example: TSIKLON-3B a robot with ears and AI and a robot that can pick, screw a light bulb and flip the switch. Also research on sensors: laser eyes, TV, tactile and power sensors, an ultrasonic locator of objects linked to a computer to grasp an irregularly shaped object, orientation of parts to assembly, etc.

c) Leningrad Institute of Aviation Instrument Building (LIAP).

d) Institute of Oceanology, Leningrad Polytechnic Institute and The Leningrad Institute of Aviation Instrument Making: project for control an underwater manipulator through tactile information and position.

e) Moscow State University (Institute of Mechanics): a six-legged robot with force feedback and vision system.

f) Institute of Applied Mathematics, Moscow: a research on assembling a gear box using positional sensors.

g) The Electrotechnical Institute.

h) Precision Mechanics and Optical Design Bureaus.

i) Pozitron Production Corporation: research on robot modules.

j) Institute of Cybernetics (IK) in Kiev: project in voice recognition and development of sensors.

3.2 ENGLAND

<u>The British Robot Association</u> (BRA) is the British equivalent for RIA. The reader is referred to [76] for more details about the UK robotic research and companies.

Another organization concerned with robots is The Science and Engineering Research Council (SERC), which is part of the UK Government Department of Education and Science. SERC policy is to help grant projects with partnership between academic groups and British companies. The reader is referred to [77] and [78] for comprehensive discussions about UK robotic centres and their R&D programmes and trends.

3.2.1 Academic Centres and/or Government Laboratories

a) Hull University: PhD course, intensive robot research.

b) Cranfield Institute of Technology: same as Hull and MsC.

c) Warwick University: use of tactile perception for robot.

d) Edinburgh Artificial Intelligence Department: study of the dynamic control of heavily loaded manipulators and also the description of relationships among 3-D bodies of an assembly process.

e) Aberystwyth (University College of Wales): research into error recovery for sensory robots.

f) Nottingham University: project to recognize parts for assembly operations, a five degree-of-freedom assembly manipulator with visual feedback linked to a computer.

g) Other academic institutions doing research in robotics are: Liverpool Polytechnic, Cambridge, Loughborough, Aston University (Birmingham), University of Birmingham, Imperial College, Cardiff (UWIST), etc.

h) National Engineering Laboratory (NEL): extensive robotic R&D such as in automatic small batch production, sensors, assembly, etc.

i) Production Engineering Research Association (PERA): vision, flexible feeders, semi-robotic welding, etc.

3.2.2 Industry and Academic Cooperation

a) Loughborough University with Martonair Ltd: a project to study problems in designing and controlling a modular robot system whose module can be put together in different arrangements. Manipulator and dynamic control.

b) Hull University with GEC/Marconi: study of automated assembly.

c) Cranfield Institute of Technology with several partners: study of automated assembly.

d) Salford University with Fairey Automation: Study of automated assembly.

e) Oxford University with BL Technology, GEC Electrical Projects and Fairey Automation: study of sensor systems to control arc welding operations.

f) Imperial College of London and Glengrove: study of automatic "deboning" of meat.

g) Patscentre International: a robot with vision used to recognize and decorate chocolate.

h) Cambridge and Cambridge Electronic Industries: application of multi-variable control theory to robotics

3.3 FRANCE

The Association Française de Robotique Industrielle (AFRI) is the French equivalent for RIA.

3.3.1 Academic Centres and/or Government Laboratories

a) Laboratoire d'Automatique ed d'Analyse das Systemes du Centre National de la Recherche Scientifique.

b) University of Lille: projects in loading sides of meat from processing plant to a truck, visual systems for inspection of materials and a sensor for microsurgery.

c) Compiege University of Technology: project on visual recognition and natural language multi-expert system.

d) French Commissariat a'l'Energie Atomique: programme on robots for nuclear energy reactor.

3.3.2 Industries with In-house Research

a) Renault-Acma.

b) Citroen.

c) Françoise de Mecanique.

4 Other Countries [12]

In Europe, research is heavily carried out in Germany and Sweden, but not much information was found due to a language problem. To a less extent, examples are also found in Italy, Netherlands and few others. Outside the three main R&D geographical areas, there is published work from Australia. Examples of major institutions of this group are presented below.

4.1 Sweden

a) ASEA is the biggest European robot company and the world leader in robot technology. Its main product is a robot with high accuracy, for welding, grinding and deburring.

b) Esab

4.2 Germany

a) Volkswagen.

b) Siemens.

c) University of Stuttgart.

d) Institute of Machine Tool and Production Technology, Berlin.

4.3 Netherlands

a) Philips

4.4 Italy

a) Fiat.

b) Oliveti.

c) Milano Institute.

4.5 Bulgaria

a) Scientific Manufacturing Combinat of Robots "Beroe" at Starazagora and The Robotics Research Centre of the Sofia Higher Engineering Institute: research on loading/unloading and spray painting.

4.6 Romania

a) Polytechnic Institute of Bucharest: research on architecture, control and software of modular systems.

4.7 Yugoslavia

a) Mihailo Pupin Institute: controls in robotics, a prosthetic hand and sensors.

4.8 Australia

a) University of Western Australia: sheep-shearing process.

b) University of Wollongong: simple sensors and software.

5. International Cooperation

(see [12] for more examples of cooperation between Japanese and foreign companies)

5.1 UK-French-German tripartite research study on off-line programming systems for robots (Edinburgh, Grenoble, Aachen and Karlsrushe).

5.2 Russia and Bulgaria, Czechoslovakia, Poland, Hungary and Yugoslavia - Bulgaria is the coordinator of research (Council for Economic Mutual Assistance-CEMA).

5.3 Versatran of USA and CEMA: a robot production.

5.4 Unimation and Kawasaki

5.5 GE, Hitachi and Volkswagen

5.6 Westinghouse, Komatsu and Olivetti

C. GENERAL REFERENCE SOURCES

In order to carry out a review the author's reference data set was formed. The difficulty was to restrict the number of publications trying to keep more relevant work. Five types of references were mainly consulted:

1. Reference books
2. Thesis reference books
3. Data base
4. Proceedings
5. Periodicals and journals

Keywords were chosen in order to use the reference books. The first set of works utilized for the review was AUTOMATION, TRANSDUCERS, ROBOTICS, ROBOT(S), INDUSTRIAL ROBOTS, MECHANICAL HANDS, MANIPULATORS. A vast amount of publications were found ranging from different aspects of automation and robots, in conclusion the set was too general. A second set was formed, namely SENSORY AID, SENSOR(S), SENSOR DEVICES, INFRARED SENSORS, PATTERN RECOGNITION, ARTIFICIAL INTELLIGENCE. Infrared sensors was useless because mainly it describes sensors for militar surveillance, atmosphere monitoring or aid for aircraft night flight. The reference books used in this review were:

.Robotics Technology Abstracts
.The Engineering Index
.Computer & Control Abstracts
.Machine Intelligence

The names of institutions and known researchers (see appendix B) were helpful when using thesis references. Two books were consulted:

.Dissertation Abstracts International
.Index to Theses

Data bases are also available through computer connection. Two robotic data bases are quoted, but only the first was assessed in this research due to budget restrictions, and just one keyword was consulted (TACTILE SENSOR).

.ROBODATA (from Robotics Technology Abstracts - Cranfield Institure of Technology, GB)
.Batelle-Institut e. V. Frankfurt (Batelle London Office, 15 Hannover Sq, tel. 493 0184)

Proceedings from robotic events were consulted. The more relant publications were found on the proceedings of the below annual robotic events:

.International Symposium on Industrial Robots - ISIR - (16th in 1986)
.Conference on Robot Vision and Sensory Control - RoViSeC - (6th in 1986)
.Annual Bristish Robot Association Conference - BRA - (9th in 1986)
.European Conference on Automated Manufacturing - (4th in 1986)

Finally, the periodicals and one journal, which were continously consulted according to their most up-date issues, are:

.The Industrial Robots
.Sensor Review
.Robotics Age
.Robotics Today
.International Journal of Robotics Research
.Robotics & Computer Integrated Manufacturing