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Position Sensing of Industrial Robots-A Survey

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Abstract: This study offers a comprehensive coverage for many methods, systems and applications employed for robot positioning. The scope of material found reflects the width and breadth of what has been achieved in robot positioning and forms a basis for further research into possible new designs and applications.

Key words: Accuracy, motion, movement, navigation, positioning, robot

INTRODUCTION

A robot is a system of fixed or mobile mechanical manipulators linked to a computer and follow a reprogrammable sequence of instructions. Simple robots are widely used in production engineering, especially where a variety of goods are to be produced with minimum changeover time. The performance of robots is being continually improved, especially by the provision of sensors and automatic planning and recovery from errors and they can handle increasingly complex tasks (Pearsall and Trumble, 1995).

A set of spatial locations, traced by the robot may be stored in a program for repeating the movement (Morris, 1985). For a precisely moving robot, it is important to know the position of the robot or its parts. The systems for robot positioning may be grouped into four categories: mechanical, acoustic, electromagnetic and magnetic. Some systems are suitable for a position measurement of a stationary robot, other allow a measurement during a motion of a robot. Mechanical systems require a physical contact between the robot and the measuring device and sometimes are integrated into the robot design. Acoustic and electromagnetic systems utilize the directionality and the time of flight measurement of sent and received signals to calculate the angular position and the linear distance of the object of interest. Whilst acoustic systems usually utilize ultrasound frequencies, electromagnetic systems include optical, laser and radar systems, both require a free line of sight between the transmitter and the receiver. Magnetic systems utilize the spatial configuration of static magnetic fields of the Earth and solenoids for the position calculation. These fields are considered constant during the time of measurement.

It may be possible to categorize systems into a non-directional signal and a directional beam. The directional systems focus the beam of a signal onto a target and then the direct (or reflected) received signal is detected. Both, spatial angle of transmission and time of flight of the signal, may be utilized to determine the position of a target. A non-directional system sends a non-focused, spherical signal and the time of flight (or directionality) of the transmitted signal to many receivers is determined to calculate the position of the transmitter. For distance determination Figueroa and Barbieri (1991) proposed to measure the phase difference between sent and received acoustic signals.

Magnetic systems combine both features, when a magnetic field is sent into the surrounding space and its strength and directionality determine the position of a target.

Mobile robot positioning technologies has been reviewed by (Borenstein *et al.*, 1996, 1997), where definitions of seven categories for positioning systems are provided: (1) Odometry, (2) Inertial Navigation, (3) Magnetic Compasses, (4) Active Beacons, (5) Global Positioning Systems, (6) Landmark Navigation and (7) Model Matching. The requirements for mobile robot navigation system are quoted to be small size, lightweight, freely programmable, avoiding obstacles and low cost. This work however, does not describe position sensitive devices- PSD, radar systems and magnetic systems used for location of underground target such as in caves and mines.

As indicated in published literature, various measuring techniques are not free of drawbacks. A mechanical contact with the end effector adds the extra-unwanted loading on the robot servos and links (Van Brussel, 1990). The audio devices, based on the time-of-travel, are sensitive to variations in temperature, humidity and pressure and should be calibrated for every measurement task (Figueroa *et al.*, 1992b); (Figueroa and Mahajan, 1994). Optical devices require a free line of

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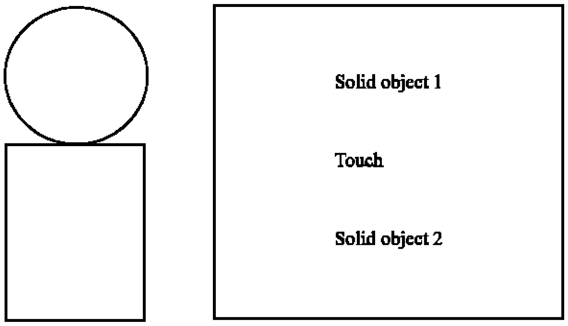

Fig. 1: Mechanical method

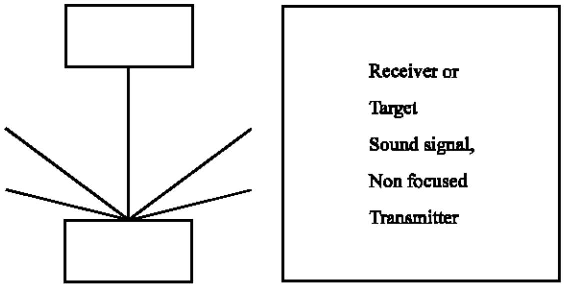

Fig. 2: Acoustic method, using non focused signal

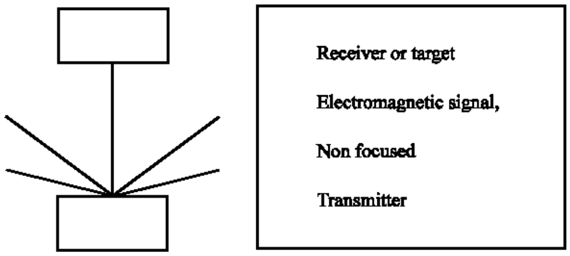

Fig. 3: Electromagnetic method, using non focused signal

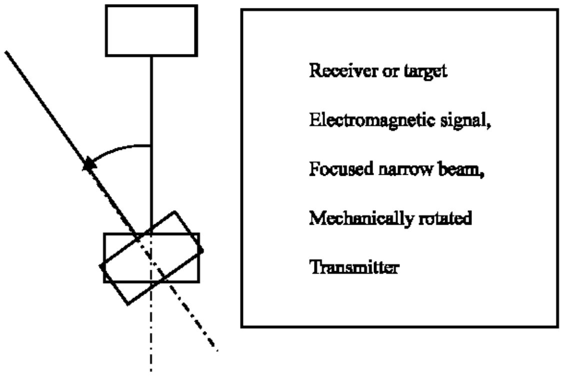

Fig. 4: Electromagnetic method, using focused signal

sight (Driels and Pathre, 1991; Sultan and Wager, 2002). The resolution of CCD [(electrical) charge coupled device]

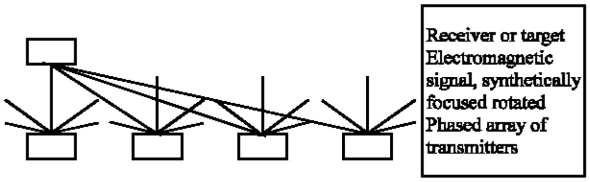

Fig. 5: Electromagnetic method, using synthetically focused, or rotated electromagnetic signal

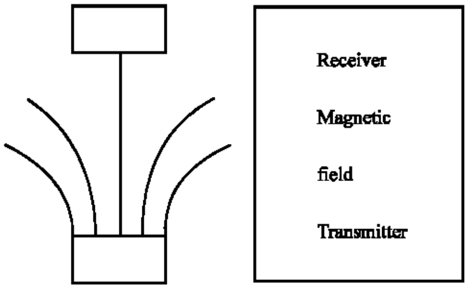

Fig. 6: Magnetic method, using magnetic field considered constant during measurement

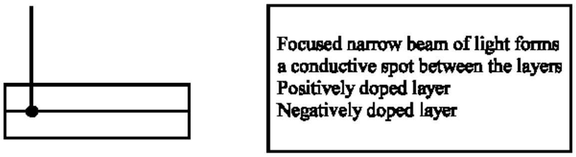

Fig. 7: Position sensitive device, as Wheatstone bridge made from semiconductor

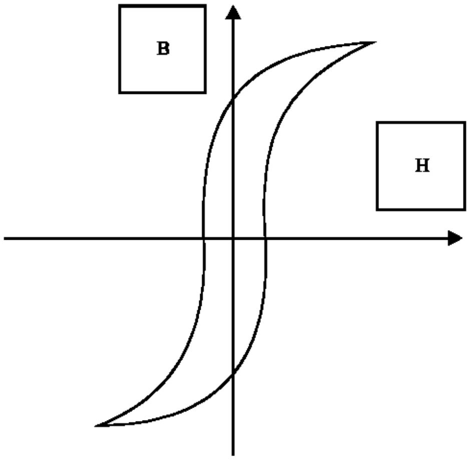

Fig. 8: The diagram illustrates approximated magnetization phenomena in a ferromagnetic material, utilized in fluxgate detectors. Hysteresis and change in magnetic permeability μ are shown. In real material the function B(H) is non-proportional, non linear on the diagram

cameras may be not adequate (Rzeznik, 1997) and laser devices may be dangerous to use, (Kyle, 1995). Figure 1-8 show basic methods of position sensing.

MECHANICAL METHODS

To improve the accuracy of a robot positioning, a new method of a sensor based, decoupling control to compensate for the effects of coupling torque and load variations, experienced in SCARA-type robots, has been proposed by Shirashi *et al.* (2000). The plant is first normalised with the use of a disturbance observer and then a nonlinear feedback control is accomplished by this normalised system, based on information from acceleration sensors installed at the end of the robot end effector. As the result, for a high-speed reciprocal motion with the payload of 10 kg mounted on the robot end effector, the authors were able to achieve satisfactory decoupling using this method. Improvements were also made in steady state characteristics.

The effects of temperature variations on the positioning errors of robotic manipulators were studied by Ottley (2000a) who also then carried out a calibration procedure, which resulted in the improved kinematic performance of the robot.

A commercially available, heavy-duty materials handling transfer and positioning system of precision tracks, with accurate rack and pinion drive was described by Ottley (2000b). Accuracy was reported in the range of ± 0.1 mm^3 for positioning objects as heavy as 630 kg with speeds of 200 m min^{-1}. This mechanical system may be an alternative to the non-contact remote ones for some applications.

A mechanical system that consists of a parallel wire mechanism for measuring six degrees of freedom of a robot end-effector was detailed by Jeong *et al.* (1998). The position and orientation of the robot are obtained from the wire lengths as measured in the parallel wire mechanism. The complex nonlinear equations of the forward kinematics are solved by using the Newton-Raphson method and a unique solution is determined from the geometric configuration of the developed mechanism. Wire elongation error is compensated for to obtain accuracy in the order of ±0.05 mm and ±0.1 deg, for the position and the orientation, respectively.

ULTRASONIC METHODS

A geometric distance may be measured acoustically by either measuring the Time Of Flight (TOF) of a pulse as it travels the distance being measured, or by measuring the change in phase between the signals at the transmitter and the receiver, as these transducers move with respect to each other by an amount equal to the distance being measured. Figueroa and Barbieri (1991) point out that the range is limited by the wavelength used; eg for an 80 kHz acoustic wave, the range is approximately 2 mm. The frequencies of the signal sent from the transmitter may be divided in the receiver by, say 16 times, before the phase difference detection, then the range is increased 16 times, to 32 mm. In this study, the schematic of the phase detection circuit and the signal-processing diagram are presented.

In another work Figueroa *et al.* (1992a), presented a method to measure a three-dimensional position whereby an ultrasonic transmitter is fixed to a selected point of interest and many receivers are fixed to a frame of reference. The system is robust against reflections and the precision achieved is 0.2 mm for a range of 2 m. Only the first received signal is processed to avoid interference due to reflections and the phase detection is used to correct the initial time of flight estimate. The number of receivers allow for estimation of the speed of sound at every measurement of a distance, providing continuous self-calibration. The influence of the variations of the speed of sound in the air on accuracy is minimized.

The minimum number of receivers quoted by Figueroa and Mahajan (1194) and Figueroa *et al.* (1992a, b), is five, needed to self calibrate for the speed of sound. The authors describe some applications for positioning systems including an ultrasonic system and refer to such topics as mapping, path planning, feedback control and obstacle avoidance.

A measuring system was described Aoyagi *et al.* (1995), where the non-directional, point sound source used, is an electric spark discharge, being impulsive ultrasonic transmitter. Each of the three receivers is highly directional and is mechanically turned precisely, by servomotors, towards the transmitter. The accuracy of a spatial grid was measured by a numerically controlled machine tool and it was found to be about 0.3 mm in the XYZ space of $900 \times 400 \times 400$ mm^3. Positioning accuracy of PUMA robot was estimated to be about ±0.7 mm, ±0.4 mm, ±0.5 mm in X, Y, Z directions, respectively in the space of $600 \times 400 \times 200$ mm^3.

A method to calibrate an ultrasonic system over a known constant distance was presented by Figueroa *et al.* (1992b). The method of detecting the instant of arrival combines an envelope peak detection and a phase measurement. The accuracy was reported to be ±0.150 mm over a distance of 0.9 m, where the sources of errors quoted are variations of the speed of sound with the temperature changes, misalignment of the transmitter and the receiver that elongates the path of the sound travel.

An effective control system of a thrust and a moment modulation for a dynamically positioned sea vessel was presented by Liang *et al.* (1999). For positioning the ship in a fixed position, the system uses a stationary sounding beacon, placed at the bottom ground below the ship. Environmental parameters such as wind force, waterline, wave force, current force, are ignored. The mathematical model presented, proves that with reduced number of sensors, it is possible to effectively position the ship, at a cost lower than in the previous methods.

OPTICAL METHODS

The pattern recognition by optical methods presents one of the greatest challenges for researchers. Theories and techniques, for many of pattern recognition problems, were described by Bow (1992). However, this early research work is not readily implemented for robot navigation. Simplified task involves the location of a defined object, often illuminated.

A vision based, automatic theodolite, which tracks, focuses and centres on a target was presented by Driels and Pathre (1991). The target is made from a translucent material, with an incandescent illumination from inside, held by the robot end effector. Experiments showed that the identified model could predict the target position to a root mean square miss distance of 0.2 mm.

A method for calibration of a theodolite with application for robot metrology was described by Sultan and Wager (2002). This method, easy to implement, uses a graduated metrological precision bar, suspended freely, to align itself with vertical direction. Mathematical model, block diagram of computer programme and computer simulation results are presented.

The commercially available, PosEye position determination system, was presented by Schofield (2002). It consists of an electro optical sensor that reads the number of infrared reference markers placed in the surrounding space. These markers can be either active (infrared diodes) or passive (reflective tape). The system measures the angles of the directions of its lines of sights to these reference markers many times from different positions. The calculation of the position is based on a complex trigonometry, as relative to the reference markers. The sensor head can take measurements at 120 Hz. With time for calculation, the PosEye system can give absolute position measurement at 30 Hz, with the main restriction being computer power.

An optical position sensor for the measurement of the size or the position of an object, using an adjustable length, fluorescent fibre and a long luminescent source was presented by Laguesse (1989). The optical rays emitted from the source reach the fibre transversely and excite the fluorescence. Part of the emitted fluorescent light is guided by the fibre to photo detectors. The object to be measured is placed between the source and the fibre, obstructing part of the light emitted by the source towards the fibre. The one-dimensional size and the position of an object are calculated from the values of signal obtained by photo detectors. A physical model is developed, showing how to combine different measurements to reject possible sources of drifts such as source intensity variations. Experimental results agree with theoretical model and computer simulation investigates the influence of system parameters on results.

A method for obtaining a high-resolution position sensing of the centroid of a diffuse optical source using two, low resolution, sensing elements was presented by Haslett *et al.* (1993). Signals from sensors are processed in an analogue form by operational transconductance amplifiers, comparing values of two signals and then a one-dimensional position is calculated.

Position sensitive devices-PSD: In principle, a position sensitive device-PSD, is similar to a Wheatstone bridge, made from semiconductor. A linear, one dimensional, continuous sensing, analogue semiconductor device, detects a light spot on a sensitive semiconductor junction of positive and negative layers. PSD and R-HPSD (Riken hybrid position sensitive device), which offers improved resolution, were described by Idesawa (1990). Both are designed to provide one-dimensional data for robot positioning applications.

An optical proximity sensor that uses multiple cones of light for measuring the shape of a surface was described by Fuhrman and Kanade (1984). Beams of light are sequentially focused from the ends of fibre optic cables onto a target surface. An analogue light sensor, measures the position of the spots of light on the surface; the spatial locations of the spots are calculated by triangulation. By fitting a surface to the set of points, the distance, orientation and curvature of the target surface are calculated. There are no moving parts and the spot position sensor chip measures the position of the spot directly without scanning its field of view. Thus fast operation of the proximity sensor can be realized. Approximately 1000 measurements per second, with the precision of 0.07 mm and 1.5 deg have been achieved with earlier prototype versions of the sensor. Triangulation of data from the analogue light sensor, with a two-dimensional spatial resolution and multiple light sources, results in an increased accuracy. The fast, high spatial resolution light sensor chip with multiple light sources, measures the light spot position, surface orientation, curvature and distance. The light sources of a sensor are focused toward a point on the optical axis. The range is quoted to be 10 cm with a precision of 0.05 mm and 1.0 deg for surface orientation.

In other experiment, three light points were attached to a moving object and two-dimensional optical sensor determined their spatial position, where two position-sensing devices (PSD) were used. Radial error of distance of light points to sensors, quoted by (Uchida *et al*., 1996) was 3 mm over a distance of 600 mm. Errors in perpendicular directions were 0.05 mm over a distance of 400 mm and 0.1 mm over a distance of 400 mm.

A fringe pattern method for measuring the positions of a tracking mirror was developed by Zeng and Song (1999). This method uses multi-fringe patterns with a known inter-beam angle to compensate for variations of an angle and of a position of the tracking mirror, allowing the determination of the position of the tracking mirror with a high resolution over a large measurement range. The position vectors of the tracking mirror are expressed using a point-slope scheme. The fringe pattern position system consists of a fringe pattern projector, a beam splitter, a lens, two rectangular apertures, two position-sensitive detectors and electromechanical mirror positioning device to perform the measurement.

The six-degree of freedom position senor, described by Vann (1998), is a non-contact device that uses a laser diode to illuminate small reflectors on an object. The position of the object is determined from the reflected light by three position sensitive detectors inside the sensor. The position is measured in all three translations and all three rotations. The sensor is about the size of a pager. Reflectors can be varied in size to code task information, enabling the sensor to read from an object, which task to perform. Reflecting surfaces may be manufactured on the objects, minimizing cost and delay.

Camera systems: A structured light photogrammetry, viewed by a stereoscopic vision system with television cameras, that defines the position of a robot end effector, was reported by Shuttleworth *et al.* (1990). The line scan sensor features a linear array camera, where scanned data is stored to produce a two-dimensional picture or a three-dimensional spatial image. In another application, a continuous sensor detects a light spot on the sensitive semiconductor junction of positive and negative layers.

An achieved accuracy of 5% in a distance measurement, within the time of 0.4 sec for sensing of a relative distance between mobile robots, by employing sign boards with lights and CCD (charge coupled device) cameras mounted on robots was reported by Arai *et al.* (1993). The signboard consists of sections of two planes with four lights (light emitting diodes) each.

A laser, a CCD optigonometry and an automatic position shifting is a method for measuring car body 3-D surfaces introduced by Wang (1998). In the article, the principle and the measuring procedure of the method are analysed and the experimental system is described in detail. A laser light beam is reflected from a mapped surface and viewed by a CCD camera. From the position of the light dot in the camera and the position of the laser-camera assembly, the distance to the mapped surface is calculated before the assembly is moved to another location to repeat the measurement. The results of the experiment are provided and have shown that the measurement method and the system may be practically valuable.

A laser based measurement system, which uses the principle of a triangulation, was presented by Rzeznik (1997). The sensor consists of a laser diode to create a structured light pattern and a CCD camera to view the image of the laser light reflecting from the surface to be measured. Optics of the laser forms the light onto a thin plane surface. The intersection of this light surface with an object forms a bright light line, detected by the camera. The shape and dimensions of the viewed object are calculated from data obtained by the camera. The distance between the sensor and the centre of the field-of-view can vary from 200 to 2000 mm, depending on an application.

Laser systems: The measured coordinates are obtained by a triangulation of a laser light beam that mechanically tracks a target reflector. The non-contact optical measurement (both static and dynamic) of spatial locations of a target reflector placed on a robot was used to check critical locations, monitor the performance and improve the positioning by the calibration as described by Kyle (1995).

A laser transmitter and a theodolite are mounted together in a robotic module. The theodolite detects target points, calculates their coordinates and sends results to a remote data processing centre. The range is reported by Mathias (1990) to be from 3 to 300 m and the accuracy is 5 mm. The laser intensity is within safety standard values 3A, considered not dangerous to a naked eye, but may be so when observed with an optical system. Any change in laser transmitter parameters should be checked for conformity with laser safety standards. This optical system is too bulky to attach to the end effector of an industrial robot.

In a system reported by Vincze *et al.* (1994), a laser tracks a reflector attached to the robot end effector. The intensity profile of a diffraction pattern of the reflector uniquely defines orientation. The tracking mechanism dynamically follows the movement of the robot at an accuracy of 0.2 mm.

The location of precision spheres, mounted in the work space of a robot, is determined by conventional metrology methods. The positioning of the sensor is governed by three light beams that define its exact position with respect to the spheres. This method, presented by Everett and Ives (1993), for a robot calibration, requires manual operation, is time consuming and is not suitable for the determination of the position of the end effector of the moving robot.

A commercially available device, that uses a triangulation to measure a distance, depending on the direction of a sent and a reflected light beam, was described by Stauffer (1986). The discrimination, if the measured distance is greater or smaller than the preset distance, is achieved by the system of two transmitters sending two signals coded differently. This three-zone proximity sensor can detect the defects, which subtend as small as 26 miliradians.

A system proposed by Brooks (2001) to inspect car bodies, uses a measurement robot to manipulate the spatial position of a laser sensor. Until this development, car bodies were inspected on-line with arrays of laser sensors fixed in a position over the production line.

RADAR SYSTEMS

As almost all radar systems use the time of propagation of an electromagnetic wave to calculate the distance traversed, it poses a great challenge for a measurement of small time intervals for short distances typical for robotic applications. Principles of radar were described in the collective work by the staff of The Radiophysics Laboratory Council for Scientific and Industrial Research, Australia (1947), Skolnik (1962, 1970) and Skolnik *et al.* (1970). These methods, however, may be developed, with image processing, for obstacles avoidance.

Components of radar systems were described by Reintjes and Coafe (1952). Wire connections and electrical alternating current machines with rotors, are used for a remote transmission of an angular positioning of a radar antenna.

Various types of antennas were described by Johnson and Jasik (1984), who point out that a phased array antenna is composed of a set of individual radiators, distributed and orientated in a linear or two-dimensional configuration. The position of the beam in space is controlled electronically by adjusting the phase of the signals at the individual radiators. There is no need for a mechanical motion in the scanning process. Rapid and accurate beam scanning in microseconds permits the radar to perform multiple functions either interlaced in time or simultaneously. The width of the antenna beam may be changed electronically by means of phase spoiling to search certain areas more rapidly, but with less gain. The beam steering functions can be programmed rapidly and accurately with computers. This technique may be used for surface mapping. Some frequencies are not easily radiated from antennas, resulting in very low efficiencies.

Various types of antennas and their arrays were described by Kraus *et al.* (1988) and Kraus (1992), who states that the radar techniques are applicable for distances above 1 km.

An application of a broadband radar to a volumetric sensing and a distance measurement was presented by (Burchett and Upton, 1998). A broadband radar radiates a short pulse of electromagnetic energy. This energy is spread across a large number of discrete frequency components corresponding to multiples of the pulse repetition frequency. The overall bandwidth of the system is typically greater than 1 GHz, with the system radiating at a very low power. The time difference between the transmitted and the reflected pulses is the measure of a distance travelled by the pulse both ways, from the transmitter to an object and from an object to the receiver. The receiver features controlled time windows, where signal may be detected, which provides range of distances to the object. The sensor can operate within a 2 m range; with an accuracy of 0.03 m. Radiated power is less 100 μW in average.

MAGNETIC FIELD DETECTORS

A laboratory equipment of a great sensitivity for measuring static and quasi-static components of the magnetic field of the Earth, in different frequency bands, have been described by Lokken (1964).

The theory of operation and the fundamental limitations of the second-harmonic type of magnetic modulator, as applied to the amplification of small D.C. signals, were presented by Williams and Noble (1950).

The resolutions of various methods for measuring the strength of a magnetic field were compared by Gordon *et al.* (1972a). Quoted resolution values (in Oersteds) were: fluxgate-10^{-7}, thin film-10^{-6}, superconducting-10^{-10}, proton precession-10^{-6}, optically pumped scalar-10^{-7}, optically pumped vector-Rb-10^{-9}, He-10^{-7}, Hall effect-10^{-3}.

Various methods for measuring a magnetic field were compared by Lenz (1990). These methods included a search coil, a fluxgate, an optically pumped scalar, a nuclear precession, SQUID, Hall effect, a magneto resistor, a magneto diode, a magneto transistor, a fibre optic and magneto optical sensors. Hall-effect sensors are based on an observation by E. H. Hall in 1879 that a voltage develops across a conductor in the presence of an external magnetic field. Hall sensor can directly sense a static magnetic flux, which simplifies the electronics of a system. Recent indium antimonite devices have lower sensitivity limit of 0.001 Gauss.

A position sensor based on an alternative measurement method for the giant magneto-impedance effect was presented by Atalay and Atalay (2002). The method measures the pulse width, instead of an induced voltage, between the ends of an amorphous wire as a function of an external D.C. magnetic field. The amorphous, as-received magnetic wire of composition (Co-0.94 Fe-0.06)-72.5 Si-12.5 B-15 was used in this study. The system employs two signals of frequencies of 400 Hz and 1 MHz, with voltages added together, passed through amorphous magnetic wire. An envelope detector circuit was used to demodulate the signal, which was then processed by a comparator and a band pass filter to determine a pulse width dependent on distance between a small permanent magnet and the detector wire.

MAGNETIC FIELD DETECTOR METHODS

Magnetic compass: The first recorded use of a mechanical magnetic compass was in 2634 B.C. in China when a piece of naturally magnetic iron ore (magnetite) was suspended by a silk thread, to allow its alignment with the lines of the Earth magnetic field, which are horizontal at the Equator and vertical at the magnetic poles. In other locations, the lines of the Earth magnetic field are at different angles with the horizontal direction. Many systems for detecting the Earth magnetic field were described by Borenstein *et al.* (1996). In this study the authors detail the Dinsmore Starguide, which is an adaptation of the well-known mechanical compass that has been designed for robot navigation. It consists of a miniaturized permanent magnet rotor, mounted in low friction jewel bearings, whereby Hall effect sensors are employed to detect the magnetic field of the rotor and its angular position.

The change of the electrical resistance of some metals with an externally applied magnetic field is utilized in magneto resistive sensors that feature high sensitivity, directionality and a flipping action associated with the direction of an internal magnetization. The open loop sensitivity of a magnetoresistive compass, as described by Lenz (1990), ranges from 0.001 to 50 Gauss. This covers the horizontal component of the magnetic field of the Earth, which ranges from 0.1 to 1.0 Gauss.

Fluxgate systems: A fluxgate is a saturable core magnetometer system that is a trade name of Pioneer Bendix. The name is derived from the gating action of the excitation coil, which is wound around the permeable sensor core and driven by an AC signal in and out of saturation, thus resulting in a time varying permeability. Expanding and collapsing fluxes induce positive and negative electromotive force (EMF) surges in a sensing coil around the core. The magnitudes of these surges vary with the strength of the external magnetic field and its orientation, with respect to the axis of the core and the sensing coil. This principle has been used in various configurations of coils and cores. Spaceship applications of fluxgate magnetometers were possible due to the achieved adequate sensitivity and the compactness of the design.

Fluxgates with a bar, rectangular and ring cores and various configurations of circuits for the signal processing were described by Geyger (1962) who points out that a ferro resonant circuit may be used together with a magnetically coupled multivibrator circuit, employing a switching transistor, to simplify the design and improve the sensitivity. Electromagnetic circuits of a fluxgate and a magnetic modulator and other nonlinear-magnetic control devices with saturating cores were presented by Geyger (1964).

A small magnetometer and a specially designed valve circuit and other circuit using standard laboratory equipment, for fluxgate signal measurement were presented by Palmer (1953). The sensor consists of a cylindrical coil with a direct current and the other winding is a parallel wire loop with a branch made of platinum and the other from mumetal, with a current alternating at the frequency of 5 kHz. The output from the cylindrical coil is filtered for a frequency of 10 kHz which is the second harmonic and the phase is compared with a 10 kHz reference frequency locked to a 5 kHz signal. The sensor was small since both the sensing winding and the core were made out as the same piece of a mumetal wire; however, due to a small core the sensitivity was very small.

An application of a magnetometer to geological survey was presented by Jensen (1961). The work shows a circuit diagram of a fluxgate magnetometer with two separate excitation windings on two cores of parallel rods and a sensing winding wound around the excitation windings and cores.

A portable, toroidal core fluxgate that was connected as bridge sensor was presented by Marshall (1971). In this study the differential peak detection is accomplished by two complementary transistors, which conduct on alternate half cycles of the excitation period. Excitation was achieved by separate windings with an independent power supply from batteries.

A miniature, two-axis fluxgate magnetometer, with a toroidal excitation core and winding and two perpendicular secondary windings was presented by Acuna and Pellerin (1969). In this work, simplified principles of operation were explained where a magnetization function was substituted with sections of proportional functions, shown as straight lines on the diagram.

Mathematical formulas and diagram curves of magnetization functions of real materials for various configurations of fluxgates were presented by Primdahl (1970). In this study parallel gated fluxgates have been described: with a single core; Vacquier with two cores and three windings; Foerster with two cores and two windings for each core; Aschenbrenner and Goubau, with a toroidal core and two windings, one toroidal, the other cylindrical. Also included were orthogonal gated fluxgates with cylindrical secondary windings: Alldredge, with an excitation current in a single wire and a core along an axis of a cylindrical sensing winding. Other types not quite belonging to the categories quoted above were fluxgates with an elongated cylinder wound as a toroid and Schonstedt, with a helical excitation winding.

A fluxgate sensor with a ring core, a toroidal excitation winding and a sense winding wound around the toroid were presented by Beale (1992). During the signal processing, as described in this article, the output from a sensing coil was switched on and off according to drive pulses, before it was processed by a low pass filter of a low cut-off frequency, making the system measuring only a nearly static magnetic field.

Digital processing of data from a fluxgate that includes digital filters was presented by Russel (1978). This compact design for space ship applications included three sensors with ring cores arranged in an orthogonal triad. These sensors together with a flipper mechanism were placed 3 m from the outer surface of the spaceship, at the end of the magnetometer boom. The flipper mechanism was actuated by heating a bimetallic strip, which rotated the sensor by 90 degrees from a stable spring held position, to another. A flip took about 4 min at room temperature in vacuum and required about 5 W of power. In other developments, a fluxgate with a signal from a switching circuit of a receiver, processed by a filter, was presented by Strangeway (2001). An examples of a fluxgate with a synchronous demodulator were presented by Balogh (1999) and Phillips (2002).

A design for building an interface between a fluxgate magnetometer and a digital computer for readout was presented by Black (1989). In this design, a commercially available fluxgate compass was sourced from Radio Shack. It featured a ring core fluxgate that had a toroidal excitation winding and two perpendicular output windings wrapped around the toroid.

A fluxgate sensor with a ring core, a toroidal excitation winding and two sense windings wound around the toroid, was presented by Noble (1991). This study describes an excitation coil that was driven by a rectangular pulse train. Signal outputs from sense coils were switched on and off according to drive pulses, before being processed by low pass filters. The amplitude of the received pulse was a measure of the strength of magnetic field.

Fluxgate principles of operation for various configurations were presented by Gordon *et al.* (1972b). This study shows a photograph of a simple implementation of a fluxgate sensor. Described in detail are: Parallel gated fluxgates: With a single core and winding; with two cores and three windings; with two cores and two windings for each core; with a toroidal core and two windings, a toroidal and a cylindrical one and orthogonal gated fluxgates with cylindrical secondary windings: With excitation current in single wire core along axis of the cylindrical winding, or another types, a one with a tubular elongated cylinder core wound as toroid; or the other with a helical excitation winding and cylindrical secondary winding. The study employed proportional functions as an approximation of a magnetization function, shown on the diagram as sections of straight lines.

A magnetometer system to estimate remotely the location and size of long, horizontal ferrous rods was described by McFee *et al.* (1996). An experimental instrument estimated location of ferrous rods parallel to a plane of measurement by analysing simultaneously magnetic field and the position data of the sensor. The instrument consists of a unit containing a fluxgate magnetometer, a position sensor and signal processing circuits. It was connected to a unit containing a microprocessor, displays and associated electronics. An operator scanned the sensor unit over the measurement surface and the microprocessor estimated the location, the length of the rod and its diameter. The experiments to estimate the parameters of horizontal typical reinforcing rods under the horizontal plane showed that the axis position could be estimated with an error of less than 0.5 cm, the length with an error of less than 5 cm (less than 3.5%) and the depth with an error of less than the 0.4 cm at depths of 8 to 18 cm. The estimation of a rod diameter was unreliable due to the presence of a substantial remnant magnetization. The fluxgate sensor consisted of a toroidal drive coil on a ring core, a sense coil, wound around, which was rectangular in the outer shape and contained a drive coil inside.

MIXED AND OTHER METHODS

Various measurement methods for the position of the end effector of a robot were described by Van Brussel (1990). These were the methods of calibration and performance assessment for a stationary robot in a laboratory situation. Measurement tools employed were lasers and other measurement instruments that were in a mechanical contact with a precision cube.

A robot accuracy in the region of a programmed assembly process was mapped by Oitzman and Campbell (2000). The compiled map was then used to offset the computed assembly locations during the production process and it compensated for errors in the mechanism of the robot. During the mapping process, a region within the robot work space was mapped using a visual precision grid and a vision camera mounted on the tool flange of the robot. The grid and the camera precisely determined any inaccuracies in locating the robot tool. The method compensated for errors in a plane surface, but would eventually be developed to compensate for errors in space. The authors stated that the contribution of the temperature variations was ±0.016 mm and the gear backlash contribution was ±0.006 mm to the positioning errors.

Ultrasonic and electromagnetic waves together were employed by Abreu *et al.* (1999) to measure a spatial position of a walking vehicle. This study describes how combining electromagnetic and ultrasonic waves, produced by a spark generator, eliminated the need for any mechanical link between the robot and the control equipment. The spatial position was obtained from a distance data that could be calculated from the travel time of the acoustical wave from the sparking point to three static receivers. In the system described, the electromagnetic wave, produced by a spark generator, was used for synchronisation and the precision was reported to be 1 mm over the work distance of 5 m. The track data obtained by the position meter was used to calculate the parameters of the dynamic movement of the robot and to study the improvement introduced by the use of inclinometers. The system compensates for a variation of the speed of sound with temperature changes and determines the time of arrival of the signal of long duration.

The suspension system of gimbals for a magnetometer placed in an airplane for the measurement of the Earth magnetic field was described by Schonstedt and Irons (1953). In another work, the electronic and mechanical details of a design of an airborne magnetometer for measurement of direction and intensity of the Earth magnetic field were present by Schonstedt and Irons (1955). In these two articles, the sensor was suspended from the damped pendulum and was mounted in motorized gimbals, which allowed the change of the position by a mechanical rotation in two perpendicular directions, horizontal and vertical in respect to the frame of reference of the airplane. Disadvantages of these mechanical systems were inherent inertias and associated time constants that decreased accuracy in the situations of fast changes in the orientation of the magnetometer.

Non-contact capacitive sensors, for the measurement of the rotational angle of a shaft, were based on the change in capacitance of an adjustable capacitor. The accuracy of this type of the sensor as quoted by Brasseur (1998) was ±0.35 deg and resolution was ±0.02 deg over the absolute measurement range of more than ±720 deg. Dimensions were 50 mm in diameter and 8 mm in thickness. However, the accuracy of another sensor of this type as quoted by Fulmek *et al.* (2002) was ±7.5 deg and resolution was ±0.1 deg over an unlimited absolute measurement range of the rotational angle of a shaft that could be continuously rotating over an unlimited angle.

A spatially continuous sensor for the six degrees of freedom of the position and orientation of an object was described by Danisch (1999). In this study a thin array of a fibre optic curvature sensor was laminated on a ribbon substrate. Plastic optic fibres were formed into tight loops that had been processed to lose light along short and narrow loss zones on the one side of the fibre. As the loop is bent out of the plane, it loses an amount of light depending on the direction of bent, according to the subtension of modes by loss zones. This modulates the light signal from which the curvature of the ribbon was derived. By processing data from the array of sensors placed along the tape, the spatial position of any point on the tape could be calculated.

Spiral sensors that provided low cost position sensing were described by Braggins (1998). In this study an inductive position sensor was built utilizing a printed circuit technology. A resonant slider was positioned along a flat coil consisting of the excitation, sine sense and cosine sense coils. The coupling was by the magnetic field, without any mechanical contact, however, sliders needed to be in a close proximity to the coils. The system detected position of the slider along the coil, its relative angle and the distance to the coil. The applications included linear, rotary and spatial position sensing.

An overview of robot positioning methods with emphasis on global positioning systems, which employ receivers of signals from navigation positioning satellites were presented by Ashkenazi *et al.* (2000). Discussed are availability, application possibilities and future developments of these systems that depend upon sent signals that are beyond the control of the user.

MATHEMATICS AND DATA PROCESSING

For a simple class of robot regulators, a mathematical model of the robot control that consisted of a linear Proportional plus Derivative (PD) feedback and an integral action of a nonlinear function of position errors was presented by Kelly (1998). By using the Lyapunov's direct method and the LaSalle's invariance principle, a class of such nonlinear functions was characterized and provided explicit conditions on the regulator gains to ensure the global asymptotic stability. These regulators offered an attractive alternative for the global regulation as compared with the well known partially model based PD control with gravity compensation and PD control with desired gravity compensation.

A new criterion, the full least square method, which deals with the problem of the regression of measured quantities when measurement uncertainty affects both the regressed quantity and the independent variables, was presented by D'Antona (2003). In this study a compact matrix notation was applied for deriving the parameter vector of the regression model and its uncertainty variance-covariance matrix. Examples and comparison of the results obtained by other similar methods were given.

A kinematic calibration of a pose measurement of a medical parallel manipulator by optical position sensors was presented by Shaoping and Ming (2003). In this study a calibration method of a base and a tool transformations employed optical position sensors, OPTOTRAK 3020, commercially available from NDI Corporation. The sensor consisted of markers made of diodes emitting infra red light and cameras employing the lateral effect photodiodes. An iterative least square procedure was applied to identify the error parameters in the transformations of the positions of the base and the end effector of the robot. Simulation and experiments results demonstrated the effectiveness of the method.

CONCLUSIONS

In this study, position-sensing methods for industrial robots have been reviewed. These methods utilize a variety of physical phenomena and may be suitable for different applications when they are developed beyond the experimental stage. For every application in the determined industrial environment there are requirements of accuracy, versatility, reliability and the lowest cost.

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