DESIGN OF INSTRUMENTED GRIPPER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology

In

Mechanical Engineering

By

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CERTIFICATE

This is to certify that the thesis entitled, “ DESIGN OF INSTRUMENTED GRIPPER ” submitted by ADITYA BHANJA in partial fulfillments for the requirements for the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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ACKNOWLEDGEMENT

We would like to articulate our deep gratitude to our project guide Prof. B.B.Biswal who has always been our motivation for carrying out the project. An assemblage of this nature could never have been attempted without reference to and inspiration from the works of others whose details are mentioned in reference section. We acknowledge our indebtedness to all of them. Last but not the least, our sincere thanks to all of our friends who have patiently extended all sorts of help for accomplishing this undertaking.

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ABSTRACT

The design and development of dexterous robotic end effectors has been an active research area for a long, while. This paper reviews the design and construction of a versatile robotic gripper used to grasp objects of arbitrary shape, size and weight. This is achieved through a mechanical design that incorporates multiple fingers and multiple joints per finger, through the installation of proximity and force sensors on the gripper, and through the employment of an innovative and practical control system architecture for the gripper components. The gripper is installed on a standard six degree-of-freedom industrial robot, and the gripper and robot control programs are integrated in a manner that allows easy application of the gripper in an industrial pick-and-place operation where the characteristics of the object can vary or are unknown.

CONTENTS

INTRODUCION 7

1. ROBOTIC SENSING 8
2. PROPRIOCEPTORS 8
3. EXTEROCEPTORS 10
4. GRASPING FORCE CONTROL AND MONITORING OF ROBOTS 14
5. ROBOT CONTROL 14

LITERATURE REVIEW 16

1. SENSING 17
2. SENSOR SPECIFICATION 18
3. SENSOR TYPES 19
4. EXTRINSIC SENSORS 20
5. HIGHLY COMPLAINT SENSORS 20
6. DATA PROCESSING 21

OBJECTIVE OF THE PROJECT WORK 24

DESIGN OF 6-AXIS FORCE SENSOR 26

1. CALCULATION OF FORCE AND POSITION IN ROBOT’S GRIPPER 27
2. MODELLING OF THE SENSOR 28
3. AUTOCAD DESIGN OF THE SENSOR 30
4. DESIGN OF THE SENSING ELEMENT OF EACH SENSOR 31
5. DESIGN RESULTS 33
6. RATED OUTPUTS 34

SELECTION OF A PROXIMITY SENSOR 35

1. OVERVIEW OF PROXIMITY SENSOR 36
2. MEASURED RESULTS 37

SELECTION OF A DISPLACEMENT SENSOR 38

1. WORKING OF LVDT 40
2. OUTPUT CHARACTERISTICS OF LVDT 42
3. LVDT SUPPORT ELECTRONICS 43
4. ADVANTAGES OF LVDT 44

GRIPPER CONTROL 47

CONCLUSION 49

REFFERENCE 51

CHAPTER 1

INTRODUCTION

1. Introduction

Robotics has matured as a system integration engineering field defined by M. Bradley as "the intelligent connection of the perception to action". Programmable robot manipulators provide the "action" component. A variety of sensors and sensing techniques are available to provide the "perception". During robotized production automation the human inspection has to be replaced by using sensors. They collect and give information about the processes, operations and the mechanical robot peripheries (end-effectors, fixtures and tools) eliminating the disturbances. The end-effectors are devices, which are built into the last robot wrist. They are grippers, tools for drilling, milling, grinding, polishing, painting, welding, assembling, gluing, measuring operations. All of them should have various built-in sensors such as proximity sensors, force/torque, and pressure sensors and remote centre compliance to monitor and facilitate the desired operations.

1.1 Robotic sensing

Since the "action" capability is physically interacting with the environment, two types of sensors have to be used in any robotic system: - "proprioceptors" for the measurement of the robot's (internal) parameters; "exteroceptors" for the measurement of its environmental (external, from the robot point of view) parameters.

Data from multiple sensors may be further fused into a common representational format (world model). Finally, at the perception level, the world model is analyzed to infer the system and environment state, and to assess the consequences of the robotic system's actions.

1.2 Proprioceptors

From a mechanical point of view a robot appears as an articulated structure consisting of a series of links interconnected by joints. Each joint is driven by an actuator which can change the relative position of the two links connected by that joint. Proprioceptors are sensors measuring both kinematic and dynamic parameters of the robot. Based on these measurements the control system activates the actuators to exert torques so that the articulated mechanical structure performs the desired motion.

The usual kinematics parameters are the joint positions, velocities, and accelerations. Dynamic parameters as forces, torques and inertia are also important to monitor for the proper control of the robotic manipulators.

The most common joint (rotary) position transducers are: potentiometers, synchros and resolvers, encoders, RVDT (rotary variable differential transformer) and INDUCTOSYN. The most accurate transducers are INDUCTOSYNs (+ 1 arc second), followed by synchros and resolvers and encoders, with potentiometers as the least accurate.

Encoders are digital position transducers which are the most convenient for computer interfacing. Incremental encoders are relative-position transducers which generate a number of pulses proportional with the traveled rotation angle. They are less expensive and offer a higher resolution than the absolute encoders. As a disadvantage, incremental encoders have to be initialized by moving them in a reference ("zero") position when power is restored after an outage.

Absolute shaft encoders are attractive for joint control applications because their position is recovered immediately and they do not accumulate errors as incremental encoders may do. Absolute encoders have a distinct n-bit code (natural binary, Gray, BCD) marked on each quantization interval of a rotating scale. The absolute position is recovered by reading the specific code written on the quantization interval that currently faces the encoder reference marker. The number of code tracks on the scale increases proportionally with the desired measuring resolution, limiting the encoder's resolution. This can be avoided by using pseudo-random encoding which permits absolute encoders needing only one code track.

Joint position sensors are usually mounted on the motor shaft. When mounted directly on the joint, position sensors allow feedback to the controller with the joint backlash and drive train compliance parameters.

Angular velocity is measured (when not calculated by differentiating joint positions) by tachometer transducers. A tachometer generates a DC voltage proportional to the shaft'' rotational speed. Digital tachometers using magnetic pickup sensors are replacing traditional, DC motor-like tachometers which are too bulky for robotic applications.

Acceleration sensors are based on Newton's second law. They are actually measuring the force which produces the acceleration of a known mass. Different types of acceleration transducers are known: stress-strain gage, piezoelectric, capacitive, and inductive. Micromechanical accelerometers have been developed. In this case the force is measured by measuring the strain in elastic cantilever beams formed from silicon dioxide by an integrated circuit fabrication technology.

Strain gages mounted on the manipulator's links are sometimes used to estimate the flexibility of the robot's mechanical structure. Strain gages mounted on specially profiled (square, cruciform beam or radial beam) shafts are also used to measure the joint shaft torques.

1.3 Exteroceptors

Exteroceptors are sensors that measure the positional or force-type interaction of the robot with its environment. Exteroceptors can be classified according to their range as follows:

- contact sensors
- proximity ("near to") sensors
- "far away" sensors

1.3.1 Contact sensors

Contact sensors are used to detect the positive contact between two mating parts and/or to measure the interaction forces and torques which appear while the robot manipulator conducts part mating operations. Another type of contact sensors are the tactile sensors which measure a multitude of parameters of the touched object surface.

1.3.2 Force/Torque sensors

The interaction forces and torques which appear, during mechanical assembly operations, at the robot hand level can be measured by sensors mounted on the joints or on the manipulator wrist. The first solution is not too attractive since it needs a conversion of the measured joint torques to equivalent forces and torques at the hand level. The forces and torque measured by a wrist sensor can be converted quite directly at the hand level. Wrist sensors are sensitive, small, compact and not too heavy, which recommends them for force controlled robotic applications.

A wrist force/torque has a radial three or four beam mechanical structure. Two strain gages are mounted on each deflection beam. Using a differential wiring of the strain gages, the four-beam sensor produces eight signals proportional with the force components normal to the gage planes. Using a 6-by-8 "resolved force matrix", the eight measured signals are converted to a 6-axis force/torque vector.

1.3.3 Tactile sensing

Tactile sensing is defined as the continuous sensing of variable contact forces over an area within which there is a spatial resolution. Tactile sensing is more complex than touch sensing which usually is a simple vectorial force/torque measurement at a single point. Tactile sensors mounted on the fingers of the hand allow the robot to measure contact force profile and slippage, or to grope and identify object shape.

The best known of tactile sensor technologies are: conductive elastomer, strain gage, piezoelectronic, capacitive and optoelectronic. These technologies can be further grouped by their operating principles in two categories: force-sensitive and displacement-sensitive. The force-sensitive sensors (conductive elastomer, strain gage and piezoelectric) measure the contact forces, while the displacement-sensitive (optoelectronic and capacitive) sensors measure the mechanical deformation of an elastic overlay.

Tactile sensing is the result of a complex exploratory perception act with two distinct modes. First, passive sensing, which is produced by the "cutaneous" sensory network, provides information about contact force, contact geometric profile and temperature. Second, active sensing integrates the cutaneous sensory information with "kinesthetic" sensory information (the limb/joint positions and velocities).

While the tactile sensor (probe) itself provides the local cutaneous information, the robotic manipulator provides the kinesthetic capability which moves the tactile probe around on the explored object surface. The sequence of local cutaneous data frames is integrated with the kinesthetic position parameters of the manipulator resulting in a global tactile image (geometric model) of the explored object. Various multi-sensor fusion techniques are available for this integration process.

1.3.4 Proximity sensors

Proximity sensors detect objects which are near but without touching them. These sensors are used for near-field (object approaching or avoidance) robotic operations. Proximity sensors are classified according to their operating principle; inductive, hall effect, capacitive, ultrasonic and optical.

Inductive sensors are based on the change of inductance due to the presence of metallic objects. Hall effect sensors are based on the relation which exists between the voltage in a semiconductor material and the magnetic field across that material. Inductive and Hall effect sensors detect only the proximity of ferromagnetic objects. Capacitive sensors are potentially capable of detecting the proximity of any type of solid or liquid materials. Ultrasonic and optical sensors are based on the modification of an emitted signal by objects that are in their proximity.

1.3.5 "Far Away" sensing

Two types of "far away" sensors are used in robotics: range sensors and vision.

Range sensing

Range sensors measure the distance to objects in their operation area. They are used for robot navigation, obstacle avoidance or to recover the third dimension for monocular vision. Range sensors are based on one of the two principles: time-of-flight and triangulation.

Time-of-flight sensors estimate the range by measuring the time elapsed between the transmission and return of a pulse. Laser range finders and sonar are the best known sensors of this type.

Triangulation sensors measure range by detecting a given point on the object surface from two different points of view at a known distance from each other. Knowing this distance and the two view angles from the respective points to the aimed surface point, a simple geometrical operation yields the range.

Vision

Robot vision is a complex sensing process. It involves extracting, characterizing and interpreting information from images in order to identify or describe objects in environment.

A vision sensor (camera) converts the visual information to electrical signals which are then sampled and quantized by a special computer interface electronics yielding a digital image. Solid state CCD image sensors have many advantages over conventional tube-type sensors as: small size, light weight, more robust, better electrical parameters, which recommend them for robotic applications. Currently, there is a multitude of commercial computer interface boards ("frame buffers") providing 512-by-512 digital images with 8 bit/pixel at standard TV video-rate (single frame time of 1/30 sec). Virtually all existent vision sensors are designed for television which is not necessarily best suited for robotic applications. Because of the reduced resolution, parallax errors, and robot hand obstructing the field of view, the common wisdom approach of placing camera above the working area is of questionable value for many robotic applications. Mounting the vision sensor in the robot hand may be a better solution which eliminates these problems.

In the robotized production some important monitoring tasks can be solved by using force/torque/pressure sensors:

- grasping, force measurement and monitoring of robot grippers and fixtures;
- measuring and monitoring robotized operations applying force/torque sensors;
- development and application of task-oriented devices, fixtures and drive units, etc. using force/torque sensors,
- grasping force control of robot grippers and fixtures using pressure sensors.

For monitoring of grasping forces 1-axis sensors are widely use, which can be mounted into the robot gripper. For the tasks of peg in hole fitting, torque-limited rotation and trajectory tracking 6-axis force/torque sensors are used. In this case sensors built into the last robot wrist (between the last wrist and the *end-effector)* or into or under the fixture can be used. For other operations 2-3-axis force sensors or other force and pressure sensors are used, which can be located in the robot workspace (into the fixtures and tools or under the fixtures).

1.4 Grasping Force Control and Monitoring of Robot Grippers

The grasping and clamping force monitoring is necessary in the following cases:

- In the case of deformable, thin-walled work pieces,
- High surface quality of work pieces to be handled,
- For increasing the reliability of the handling and inserting operations.

The grasping (clamping) forces are directly proportional to the air pressure of cylinders. It means: the grasping forces can be controlled and monitored by controlling and monitoring the air pressure values. For measurement of actual pressure value a pressure sensor based on strain gauge technique can be used among others. The direct measurement of grasping force values can be realized by force sensors built into the gripper or fingers.

1.5. Robot control

Computer-based robot controllers perform the following tasks:

- maintain a model of relationships between the references to the actuators and their consequential movements using measurements made by the internal sensors.
- maintain a model of the environment using the exteroceptor sensor data;
- plan the sequence of steps required to execute a task;
- control the sequence of robot actions in response to perform the task;
- adapt robot's actions in response to changes in the external environment;

Robots need a tactile sense for intelligent robotic manipulation. This paper will give an overview over the most common issues and topics in grasping and manipulation. To put things in perspective, a historical overview is presented followed by a section on likely applications. After that, a review of sensing issues starting with a reflection on the human tactile sense and how it relates to robotics. Partly because we can use it as benchmark, partly because the human sensory system and manipulation capacity is both a grand challenge to mimic and also a great source of inspiration.

CHAPTER 2

LITERATURE REVIEW

2. Literature Review

A review of some sensor hardware follows and eventually some examples of experimental results can be looked at.

2.1 Sensing

2.1.1 Human Sensing

The information quality needed to perform certain robotic manipulation and grasping tasks still remains unknown. Neither is it known exactly how humans manipulate objects. Even if we did know, it is not certain that an anthropomorphic approach would be the best. But there is still much to be learned from what is known about the human sensory system.

A condensed overview of human sensing is presented by Howe . He puts tactile sensing in perspective from a human mechanoreceptor viewpoint. To fulfill all robotic tactile sensory needs with a single type of sensor is difficult, if not impossible. This is a problem that we humans also have. To overcome it we are equipped with different types of receptors. The fast adapting (FA) mechanoreceptors can sense vibrations but not static stimulation, whereas the slowly adapting (SA) mechanoreceptors respond to static stimuli.

Without visual feedback, humans have a rather dim perception of the position of their limbs. This is because the human proprioception is poor, especially compared to what can be achieved in a robot. Even without visual feedback, a robot can - thanks to high resolution encoders -identify its position and orientation in space much more accurately than humans. This is an advantage that can be exploited, particularly in certain haptic exploration tasks.

Proprioception - The ability to sense the position, location, orientation, and movement of the body and its parts. Compared to a robot, humans also respond to sensory information with a large latency. For the fastest reflexes we see latencies of 20-30 ms and much longer times for voluntary responses .

2.1.2 Passive and Active Sensing

Sensing can be divided in many ways. But one of the more important dividing lines is that between passive and active sensing. Passive sensing concerns the analysis of static tactile data, whereas active sensing is when motion is actively used to extract more information.Some types of features, particularly small ones, cannot be sensed accurately through static touch; motion is required." An example is detecting edge sharpness. Placing a finger on the edge will give only little information regarding its sharpness compared to sliding it across the edge.

A dexterous hand can also actively manipulate its environment to retrieve information on properties impossible to estimate in other ways. For example, by tilting an object weight or center of gravity can be estimated. By dragging a finger along a surface, friction and texture can be approximated, and so on.

2.2 Sensor Specification

There is of course no single sensor that excels with respect to all design criteria. The sensor specification will have to depend upon the task at hand. For this reason, a very large amount of tactile sensing technologies have been developed. But some criteria that always must be considered are :

- Variables and measurable range - pressure, shear forces, torques, slip, etc
- Resolution in space
- Response profile - accuracy, bandwidth, hysteresis, creep, aging, etc

In addition to these, some desirable properties should be added such as simple mechanical integration, low power consumption, and low cost.

Humans have a resulution in the fingertips of about 1 mm and are able to sense frequencies close to 1 kHz . A similar specification is often proposed for distributed tactile sensors, for example a spatial resolution of 1-2 mm and a frequency span up to at least 100 Hz .

2.3 Sensor types

Over the years, many tactile sensors have been proposed. Tactile information from a power grasp can be collected using distributed sensors covering the phalanges. A fingertip is typically more roomy and allows for a more space consuming force/torque sensor that can supply detailed information in the case of a precision grasp.Current sensor technologies although omitting "image recognition" sensors such as those developed by Ferrier, Hristu, and Brockett.

Some argue in favor of a compliant fingertip. An issue for a stiff fingertip is that it is more prone to contact transition problems and it also offers poor grip. This can to a certain extent be overcome by covering the sensor with a soft material. But more important, a compliant fingertip -not unlike the human - is also advantageous from a pressure distribution and stability point of view.

If we consider the very compliant fingertips as one sensor type, the remaining sensors can be divided into extrinsic sensors and intrinsic sensors. The intrinsic sensors measure forces within the grasping mechanism whereas the extrinsic sensor measures forces that act upon the mechanism. The predominant intrinsic tactile sensor is a small force/torque sensor mounted inside the fingertip. Extrinsic sensors are significantly more diverse, covering different kinds of single point and distributed sensors. Examples include force sensitive arrays to be mounted on the fingertip and those where the sensor module itself constitutes the fingertip.

The choice of whether to use extrinsic or intrinsic sensing depends upon the task at hand. The advantages of an extrinsic sensor include that they can be made to cover large areas - as when using a power grasp - and that the point of contact is explicitly measured. Most extrinsic sensors only measure pressure. But there are a few advanced extrinsic sensors capable of measuring shear forces on the tactile element level. An intrinsic sensor using strain gauges is typically more accurate and is often designed to measure all six degrees of freedom. But there is also a larger mass, often the fingertip itself, between the object and the intrinsic sensor. This can be a disadvantage when measuring small forces and it also makes the sensor sensitive to high accelerations. An additional downside is that when using a force/torque sensor inside the fingertip, we cannot tell the difference between multi-point and single-point contacts. Nonetheless, intrinsic sensing is often used in manipulation tasks using a precision grasp.

Using an intrinsic sensor it is possible to determine the contact location without measuring it explicitly. Data from a six DOF force/torque sensor inside the fingertip can be used to compute the point of contact.

2.4 Extrinsic Sensors

The typical extrinsic sensor is a tactile array, not unlike a laptop touch-pad, or a single-point pressure sensor. It typically senses normal forces and contact positions. The sensors often display a measurable resistance change as a result from compression of a semi-conductive polymer.

As an example, the Gifu hand is equipped with tactile sensors covering the phalanges of all fingers and the palm with a grand total of 624 measurement points. The fingertips are not covered by the distributed sensor and instead feature six DOF force/torque sensors.

An optical waveguide will show nearly no loss of light if properly designed. But when its boundary is affected by touch, frustrated total internal reflection will occur. The intensity changes can be measured either by a position sensitive detector or through positioned optical fibers and separate detectors .

Other measurable properties include birefringency effects resulting from internal stress (photoelasticity) and capacitivity changes resulting from compressing the insulator of a capacitor.

2.5 Highly Compliant Sensors

A fingertip exploiting the compliant and optical properties of closed cell polyurethane foam was recently developed by Hellard and Russell . Also recently, the deformation of a fingertip membrane filled with a transparent liquid was measured using a camera . The picture data was then used to compute the displacement of the membrane and from that the object shape information was derived.

2.6 Data Processing

The amount of tactile data from many and large tactile arrays can be overwhelming, and even if it can be managed, just getting it to a processor may be difficult. Consider a 16 x 16 tactile array; a minimum of 32 electrical wires are needed. Add to this that data from 256 sensors that need to be processed. As always, one has to prioritize, or try to come up with innovative designs.

DLR deals with this by distributing the A/D-conversion and signal processing. An example of this is their six DOF fingertip sensor[3] that features integrated electronics for signal processing. The sensor has a purely digital interface. Other force/torque sensors typically deliver analog signals that require an external signal processing unit.

In the 1970's, tactile sensing for robotic applications emerged as its own field of research. Research kept increasing during the next decade and led to one of the first overview papers on tactile sensing by Harmon in 1984 . The 1980's were also time for the first ad-vanced robotic grippers such as the DLR ROTEX gripper . It is equipped with laser range finders, tactile arrays, force/torque sensors, integrated actuator, and also analog and digital electronics for communication over a serial bus, all neatly packaged in one single device.

In some areas, there has been great progress since Harmon's article from 1984. But to a large extent, the problems today remain similar to what they were back then. He foresaw a rapid expansion within automation. This however, has not been the case. Lee addressed this very fact in 2000 when he pointed out that in structured environments, we are able to come very far without tactile information. Hence, he foresees that tactile sensing will be most useful in unstructured environments where object properties and/or the environment is not fully known.

The review paper of Lee and Nicholls gives an overview of tactile sensing in mechatronics up until 1998. The yearly number of published articles had steadily increased, an increase that has continued since then and which is exemplified by the development of novel tactile arrays manufactured in a silicon processes, that control is evolving, and that system integration is taken to a new level .

The focus has somewhat shifted over the years; from the development of new tactile sensing technologies towards data processing. At the same time, strong theoretical models of contact configurations and grasp dynamics have been developed . However, when it comes to the application of such models in association with tactile sensors, only little work has been done.

Tactile sensing for robotics is still in its infancy. While researchers in visual recognition or tracking can buy out of the box cameras , there is to our knowledge no widely available tactile sensor suite for robotic manipulation. There are a few robotic hands out there, some of which are commercial products. But they are then rather costly. Today, there is clearly a need for qualified manipulation hardware together with more advanced methods for actually using the tactile information.

Today, much attention is given to tactile sensing in minimally invasive surgery, keyhole surgery. The case is that much of the tactile information available in open surgery, will now be lost. Artificial tactile sensing can restore some of this loss of tactile information. Eltaib and Hewit give an overview of tactile sensing in minimally invasive surgery - MIS.

Even though there is a gap when it comes to actually manipulating objects using tactile information, more and more work is being done. Bicchi presents an overview of grasping where he mentions that one of the most needed advances in robotic grasping is to estimate object compliance. Coelho et. al. have developed models for grasp policies and grasp control and also verified them in simulation. Below are a few examples of real life experiments that until recently have been presented.

By combining tactile sensing with vision, Hosada et. al. present a system that learns to detect slip from tactile sensor information . Using information from an intrinsic sensor, Bicchi et. al. present a nice method to reduce the risk of slippage by controlling the normal force .

Laschi et. al present an anthropomorphic robotic grasping platform developed for evaluation of neurophysiolog-ical and other physiologically inspired theories such as biologically-inspired grasping coordination . A neural approach to software development will be used.

The DLR hand is one of the most refined robotic hands of today both with respect to mechanics and control. It has demonstrated the catching of a ball, playing the piano, and more . They have also implemented impedance control essential to more autonomous tasks.

CHAPTER 3

OBJECTIVE OF THE PROJECT WORK

3. Objective of the project work

The study of the previous literatures on the use and requirement of good number of sensors for robots reveal that the robots need to use sensors to understand the environment and act accordingly. However, the more sensors we integrate to the system, the more are the cost and the complexity. If the robot application is specified, it is better to select the required sensors and design them for the range of activities. The present project work is envisaged with development of a gripper integrated with a 6-DOF force sensor, couple of proximity sensors and LVDT. These sensors are to be fitted to the robot wrist that does simple assembly problems. Precisely, the objectives are to;

i) design and develop a 6-DOF force sensor,

ii) select a suitable set of proximity sensors,

iii) select a suitable Linear Variable Differential Transformer.

CHAPTER 4

DESIGN OF THE 6-AXIS FORCE SENSOR

4. Design of the 6-axis force sensor:

4.1 Calculation of force and position in the robot's Gripper

In order to safely grasp an unknown object and accurately perceive the position of the object in the grippers, the equations to calculate the force of the gravitational direction and the length components *lx* , *ly* and *lz* in *x*, *y* and *z* direction should be derived. The force vector *F* of an unknown object in *x*, *y*, *z* frame,and the force vector *F'* of the gripper in *x'*, *y'*, *z'* frame can be respectively expressed as

$$\bar{F}' = F'_x\bar{a}'_x + F'_y\bar{a}'_y + F'_z\bar{a}'_z$$

$$\bar{F} = F_x\bar{a}_x + F_y\bar{a}_y + F_z\bar{a}_z = F_k a_k$$

where *Fx'*, *Fy'*, *Fz'* are the force components in each *x'*, *y'*,z' direction, *ax'*,*ay'*, *az'* are the unit vectors in each *x'*, *y'*, *z'*direction, *Fx* , *Fy* , *Fz* are the force components in *x*, *y*, *z* direction, *ax*, *ay*, *az* are the unit vectors in *x*, *y*, *z* direction, respectively, $F_k = \sqrt{F_x^2 + F_y^2 + F_z^2}$ is the magnitude of the force applied to the 6-axis force sensor and *ak* is the unit vector in the force direction. Finally, the force vector *F'* =−*mgax*, that is, *Fx'*= −*mg*, where *m* is mass of an unknown object and *g* is the gravity acceleration.

Because the 6-axis sensor measures the weight of an unknown object, the force vector *F*can be expressed as

$$\bar{F} = F_k\bar{a}_k = -\left(\sqrt{F_x^2 + F_y^2 + F_z^2}\right)\bar{a}'_x = -mg\bar{a}'_x$$

Thus, the weight of an unknown object *mg* can be calculated. The force Fx is the measured value from the Fx sensor, whereas the forces Fy and Fz are from the Fy and Fz sensor.

The length vector *l* of an unknown object, and the moment vector *M* of the moment components in *x*, *y*, *z* frame can be respectively written as

$$\bar{l} = l_x\,\bar{a}_x + l_y\bar{a}_y + l_z\bar{a}_z$$

$$\bar{M} = M_x\bar{a}_x + M_y\bar{a}_y + M_z\bar{a}_z$$

where l_x , l_y and l_z are the length components in *x*, *y* and *z* direction, and M_x , M_y and M_z are the measured values from the Mx, My and Mz sensors, respectively.

$$\bar{M} = M_x\bar{a}_x + M_y\bar{a}_y + M_z\bar{a}_z$$

Defining the moment vector *M* as the length *l* cross product *F* , the moment vector *M* , and the moment components M_x , M_y and M_z can be, respectively, represented as

$$\begin{aligned}\bar{M} = \bar{l} \times \bar{F} = \{&\bar{a}_x(l_yF_z - l_zF_y) + \bar{a}_y(l_zF_x - l_xF_z)\\ &+ \bar{a}_z(l_xF_y - l_yF_x)\}\end{aligned}$$

$$M_x = l_yF_z - l_zF_y$$

$$M_y = l_zF_x - l_xF_z$$

$$M_z = l_xF_y - l_yF_x$$

where M_x , M_y and M_z are the moment components in *x*, *y* and *z* direction, respectively.

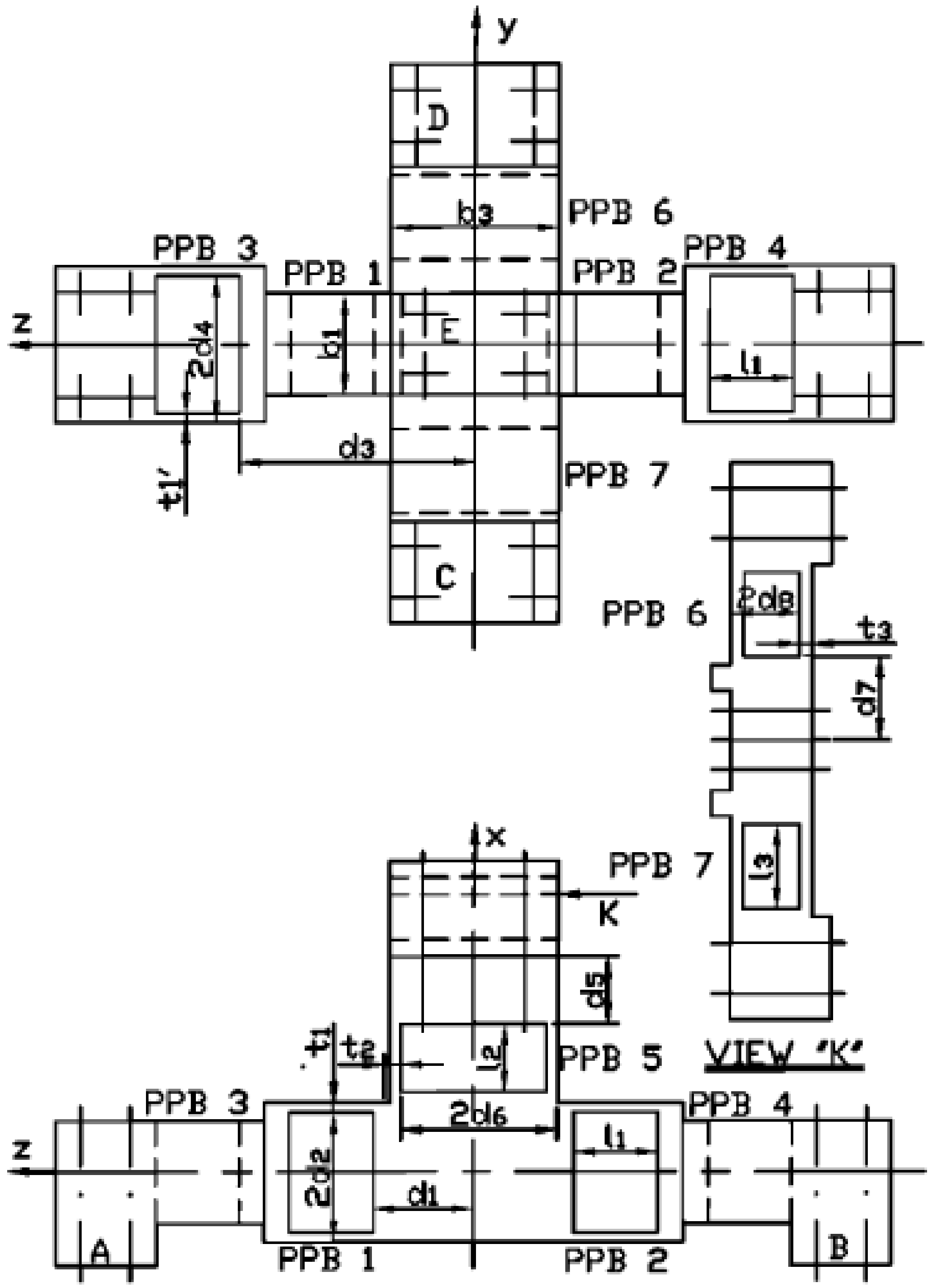
Thus, the position of the object in the grippers, that is,the distance lengths from the center point of the 6-axis force/moment sensor to the contact point of the object and the 6-axis force/moment sensor l_x , l_y and l_z in *x*, *y* and *z* direction can be calculated.

4.2 Modelling of the sensor

The structure of newly modeled 6-axis force/moment sensor which may detect the forces Fx, Fy and Fz, and the moments Mx, My and Mz for the intelligent robot’s gripper system. The sensing elements of the 6-axis force/moment sensor are composed of by fixing E block part of two sensors with screws. One is a 5-axis force/moment sensor, which is composed of the Fx, Fy and the Fz sensors, and the Mx and My sensor, the other is the Mz sensor. Block A and B, and C and D are fixed to the frame of robot’s gripper with screws. The sensing elements of the Fx sensor and the My sensor are PPB 1 and 2, those of the Fy sensor and the Mx sensor are PPB 3 and 4, those of the Fz sensor are PPB 5, and those of the Mx sensor are PPB 6 and 7. PPB 1, 2, 3 and 4 are composed of two plate beams with the width *b*1, the heights *t*1 and *t*2 the length *l*1, and the distance from the central line to the end of the beams *d*1, *d*2, *d*3, *d*4, respectively, those of PPB 5 is with *b*2, *t*2, *l*2, *d*5, *d*6, and those of PPB

6 and 7 are with *b*3,*t*3, *l*3, *d*7, *d*8, respectively.The PPB 1–7 are symmetrical on the *x*-axis, *y*-axis and *z*-axis. The forces and the moments are applied to the plate beams through the lower load-transmitting block A and B that is located at the lower part, and the upper load-transmitting block C and D that is located at the upper part of the 6-axis force/moment sensor.

4.3 Autocad design of the sensor



4.4 Design of the sensing element of each sensor

The sensing elements (PPBs) of each sensor in the 6-axis force/moment sensor are designed having high translational and tortional stiffness, and low interference error. The design variables of each sensor are the rated capacity, the rated strains, the widths, the lengths, the heights of the plate beams, the distances from the central line to the end the beams, and the locations of strain gages considering the size of the strain gage. The variables for designing the 6-axis force/moment sensor are determined as follows:

(1) The rated capacities of the Fx, Fy and Fz sensors are determined at 50N respectively, and those of the Mx, My and Mz sensors are 5Nm respectively in consideration of grasping force of the intelligent robot.

(2) The rated strains of each sensor are determined at about 1000μm/m (about 0.5 mV/V) in consideration of the same rated outputs and sensitivities in each sensor.

(3) The attachment locations of strain gages for all sensors are determined at 1.5mm from the end of the plate beams in the length direction, and the center of the plate beams in the width direction in consideration of the size of the used strain gages (1.52mm × 2.54 mm).

The sizes of the sensing elements were calculated by substituting the determined variables .The table shows the design results of same capacity and different capacity of each nsensor in the same rated strain (rated output). The sizes of the sensing elements in the rated capacities of Fx = Fy = Fz = 50N, Mx = My = Mz = 5Nm are as follows: the width $b1$, $b2$ and $b3$ are 12 mm, 12mm and 20 mm; the length $l1$, $l2$ and $l3$ are 10 mm, 8mm and 10 mm; the height (thickness) $t1$, $t1'$, $t2$ and $t3$ are 1.1 mm, 1.1 mm, 1.3mm and 1.2 mm; the distances $d1$, $d2$, $d3$, $d4$, $d5$, $d6$, $d7$ and $d8$ are 12 mm, 7.7 mm, 28 mm, 8.6 mm, 10 mm, 10 mm, 10mm and 4.8 mm, respectively, as shown in table. And the translational stiffness for the Fx sensor is 298 N/m, for the Fx sensor is 298 N/m, for the Fz sensor is 85 N/m, and the tortional stiffness for the Mx sensor is 644861 Nm, for the My sensor is 464866 Nm, for the Mz sensor is 354816 Nm. As shown in table, the modeled structure of the 6-axis force/moment sensor can be designed with various rated capacity in the same rated strain (rated output). The used material is Al 2024-T351.

4.5 Design results of same capacity and different capacity of each sensor in the same rated strain

Force (N)			Moment (Nm)			Length (mm)		Height (mm)				Width (mm)		Distance (mm)							
Fx	Fy	Fz	Mx	My	Mz	$l_1 l_3$	l_2	t_1	t_1'	t_2	t_3	$b_1 b_2$	b_3	d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8
50	50	50	5	5	5	10	8	1.1	1.1	1.3	1.2	12	20	12	7.7	28	8.6	10	10	10	4.8
50	30	40	5	3	4	10	8	1.1	0.9	1.2	1.2	12	20	12	5.2	28	6.5	10	10	10	4.0
50	70	60	5	7	6	10	8	1.1	1.3	1.5	1.2	12	20	12	10.2	28	7.6	10	10	10	5.6
30	50	40	3	4	5	10	8	0.9	1.2	1.2	1.2	11	20	12	8.0	28	5.5	10	10	10	4.8
70	50	60	4	3	6	10	8	1.3	1.1	1.4	1.2	12	20	12	4.6	28	7.2	10	10	10	5.6

Fx sensor		Fy sensor		Fz sensor		Mx sensor		My sensor		Mz sensor	
Rated strain (μm/m) and stiffness (N/m, Nm)											
1032	298	1032	298	1056	85	1040	644861	1040	464866	1032	354816
1032	298	926	163	992	81	1022	515475	1025	377457	1031	325148
1032	298	1036	492	951	117	1036	666600	1033	568327	1027	388864
1010	150	947	355	1082	74	1016	567356	1014	460210	1085	354816
1036	492	1032	298	1093	91	1022	601688	1038	381253	1027	388864

4.6 Rated output in theory and characteristic test

Sensor	Analysis	Rated output (mV/V)	Error (%)
Fx sensor	Theory	0.5237	6.0
	Test	0.4925	
Fy sensor	Theory	0.5237	4.5
	Test	0.5001	
Fz sensor	Theory	0.5396	4.0
	Test	0.5611	
Mx sensor	Theory	0.5278	3.3
	Test	0.5102	
My sensor	Theory	0.5278	3.4
	Test	0.5097	
Mz sensor	Theory	0.5237	4.6
	Test	0.4998	

4.7 Interference error from characteristic test

F/M	Sensor					
	Fx	Fy	Fz	Mx	My	Mz
Interference error (%)						
Fx = 50 N	–	−0.44	0.63	−0.05	−1.12	0.61
Fy = 50 N	−0.77	–	−1.51	−2.12	−0.64	2.50
Fz = 50 N	0.10	0.90	–	−0.46	1.84	0.74
Mx = 5 Nm	−0.04	1.51	1.11	–	1.03	0.74
My = 5 Nm	−0.70	−0.22	−0.48	1.76	–	1.73
Mz = 5 Nm	−0.14	−2.45	2.20	−2.67	−2.79	–

CHAPTER 5

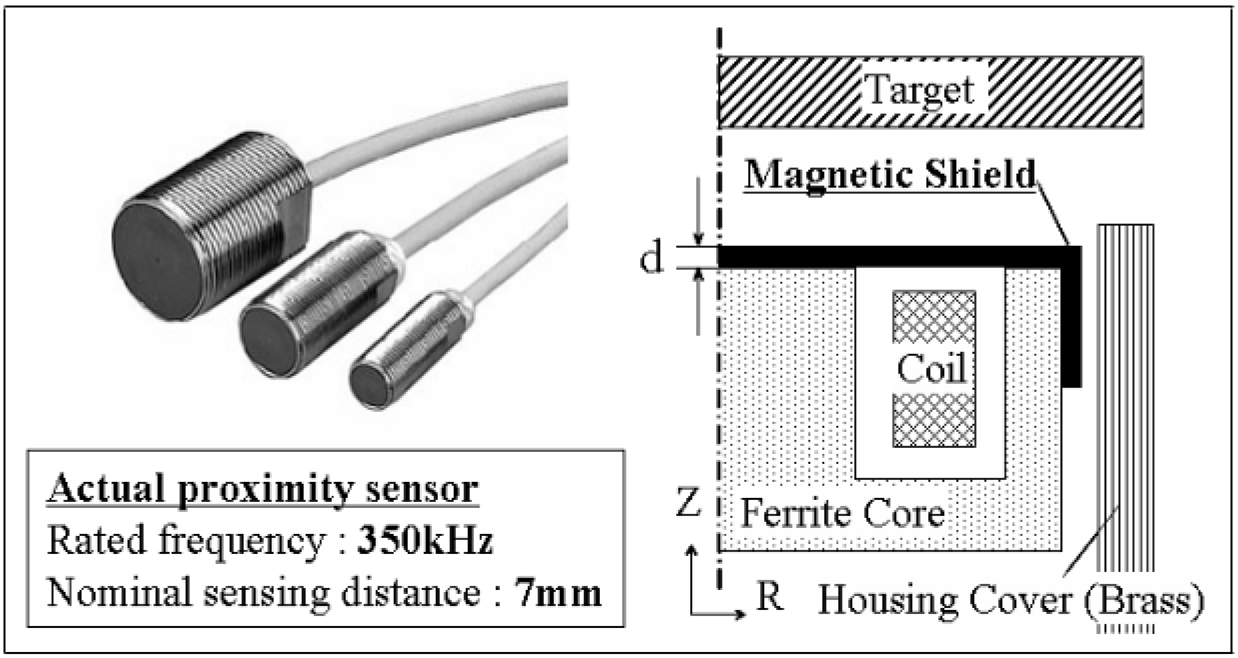
SELECTION OF A PROXIMITY SENSOR

5. Eddy-current Type Proximity Sensor with Closed Magnetic Circuit Geometry

Eddy-current type proximity sensor is a non-contact type sensing device to detect the approach of a conductor by increase of AC resistance of an excitation coil due to eddy current loss in the conductor.

5.1 Overview of proposed proximity sensor

A picture of the actual proximity sensors and schematic diagram of the proposed sensor with the additional cap-shaped magnetic flux shield is shown.



Sensing index of the sensor is *Q'*, the ratio of coil quality factor *Q* value with and without target conductor. Decrease of *Q'* means the enhancement of sensitivity.

Equations about *Q* and *Q'* are described as follows.

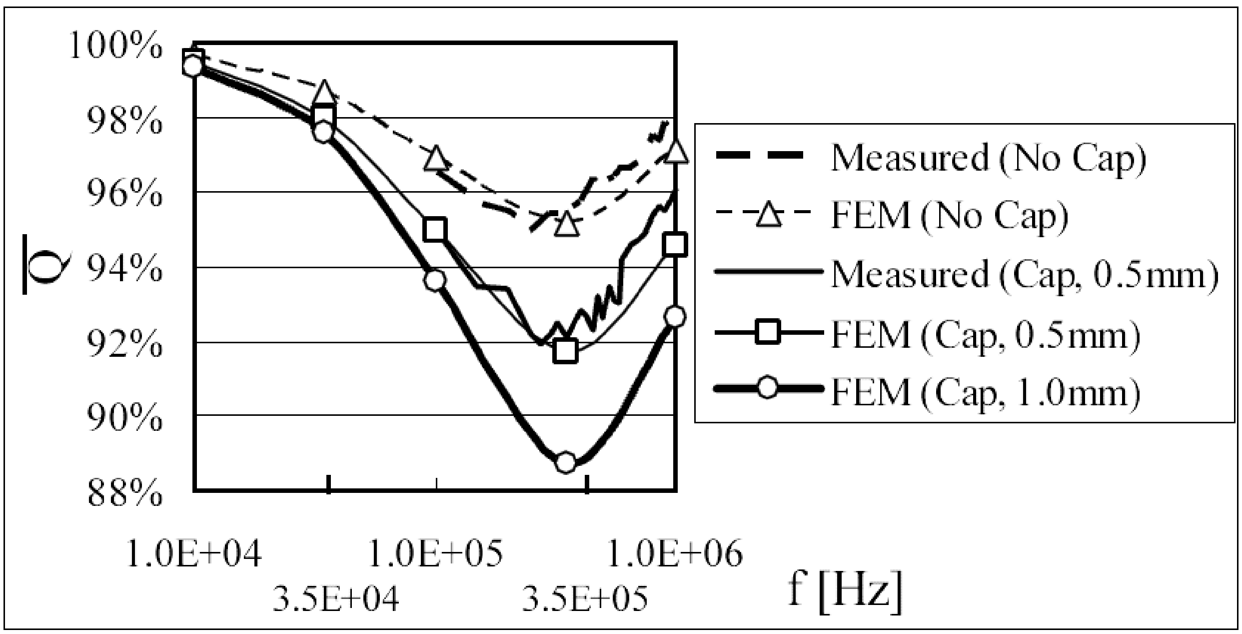
$$Q = \frac{\omega L}{R}, \quad \overline{Q} = \frac{Q_t}{Q_\infty}$$

where Qt and $Q\infty$ are *Q* values with and without the target. *L* and *R* are obtained from coil output current value by FEM. Conductivity *σ* and *μ* of the cap-shaped shield are 3.9×10−8 [1/Ωm] and 8 respectively according to the data sheet of the material. *σ* and *μ* values of the other parts and dimensions of the sensor are shown in the presentation due to space limitation.

5.2 Measured and FEM results

Measured and FEM results of *Q′* with and without capshaped shield are shown. Note that the cap thickness “d” of the tested sensor is 0.5mm and “d” for FEM calculations are 0.5 and 1.0mm.

It is predicted that *Q′* results with the cap degrade due to decrease of the flux to reach the target. However, *Q′* thereof are enhanced relative to the conventional sensor (no cap).



The cap thickness 1.0mm at 350kHz shows the best result. Therefore, several conductivity and μ of the cap thickness 1.0mm are calculated by FEM. Lower conductivity and higher μ contribute to enhancement of *Q′*. In addition, *Q′* tends to degrade where μ is 30 $\sim$ 40. It means that optimal values of conductivity and μ should be found.

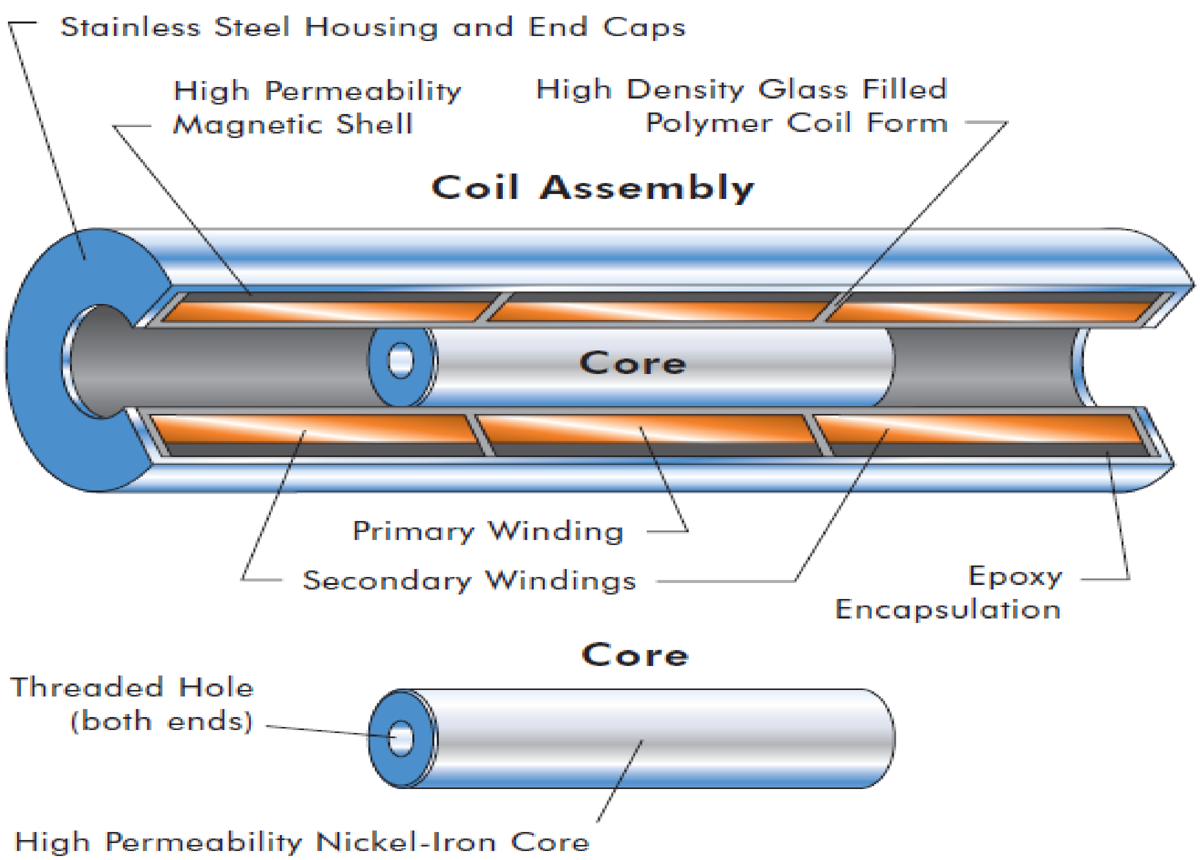
CHAPTER 6

SELECTION OF A DISPLACEMENT SENSOR

6. Linear variable differential transformer

Linear Variable Differential Transformer, a common type of electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electrical signal. LVDT linear position sensors are readily available that can measure movements as small as a few millionths of an inch up to several inches, but are also capable of measuring positions up to ±20 inches (±0.5 m).

Figure shows the components of a typical LVDT. The transformer's internal structure consists of a primary winding centered between a pair of identically wound secondary windings, symmetrically spaced about the primary. The coils are wound on a one-piece hollow form of thermally stable glass reinforced polymer, encapsulated against moisture, wrapped in a high permeability magnetic shield, and then secured in a cylindrical stainless steel housing. This coil assembly is usually the stationary element of the position sensor.



LINEAR VARIABLE DIFFERENTIAL TRANSFORMER

The moving element of an LVDT is a separate tubular armature of magnetically permeable material called the core, which is free to move axially within the coil's hollow bore, and mechanically coupled to the object whose position is being measured. This bore is typically large

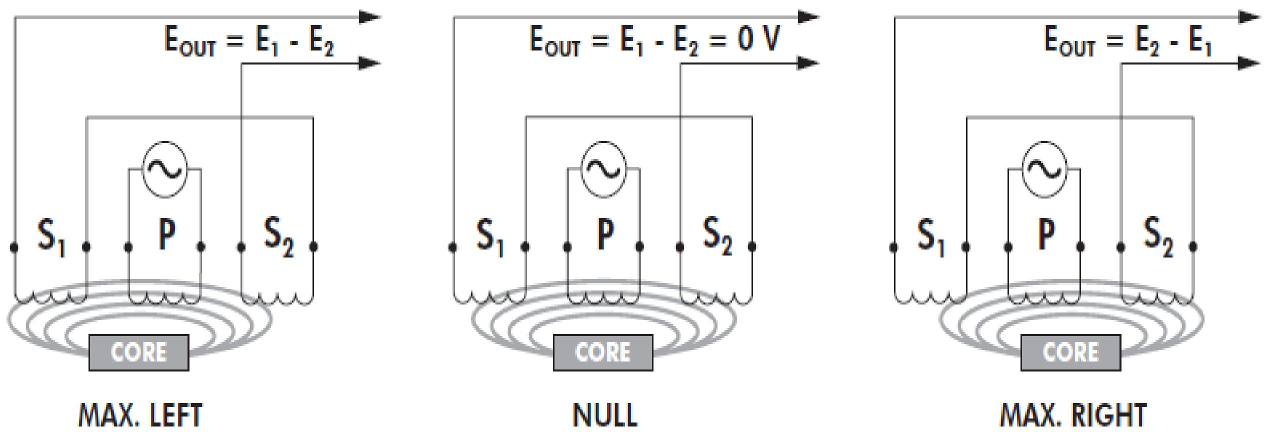
enough to provide substantial radial clearance between the core and bore, with no physical contact between it and the coil. In operation, the LVDT's primary winding is energized by alternating current of appropriate amplitude and frequency, known as the primary excitation. The LVDT's electrical output signal is the differential AC voltage between the two secondary windings, which varies with the axial position of the core within the LVDT coil. Usually this AC output voltage is converted by suitable electronic circuitry to high level DC voltage or current that is more convenient to use.

6.1 Working of a Linear variable differential transformer

Figure illustrates what happens when the LVDT's core is in different axial positions. The LVDT's primary winding, P, is energized by a constant amplitude AC source. The magnetic flux

thus developed is coupled by the core to the adjacent secondary windings, S1 and S2. If the core is located midway between S1 and S2, equal flux is coupled to each secondary so the voltages, E1 and E2, induced in windings S1 and S2 respectively, are equal. At this reference midway core

position, known as the null point, the differential voltage output, (E1 - E2), is essentially zero. As shown in Figure, if the core is moved closer to S1 than to S2, more flux is coupled to S1 and less to S2, so the induced voltage E1 is increased while E2 is decreased, resulting in the differential voltage (E1 - E2). Conversely, if the core is moved closer to S2, more flux is coupled to S2 and less to S1, so E2 is increased as E1 is decreased, resulting in the differential voltage (E2 - E1).


E_OUT = E1 - E2
S1
P
S2
CORE
MAX. LEFT
E_OUT = E1 - E2 = 0 V
S1
P
S2
CORE
NULL
E_OUT = E2 - E1
S1
P
S2
CORE
MAX. RIGHT

6.2 Output characteristics of a Linear variable differential transformer

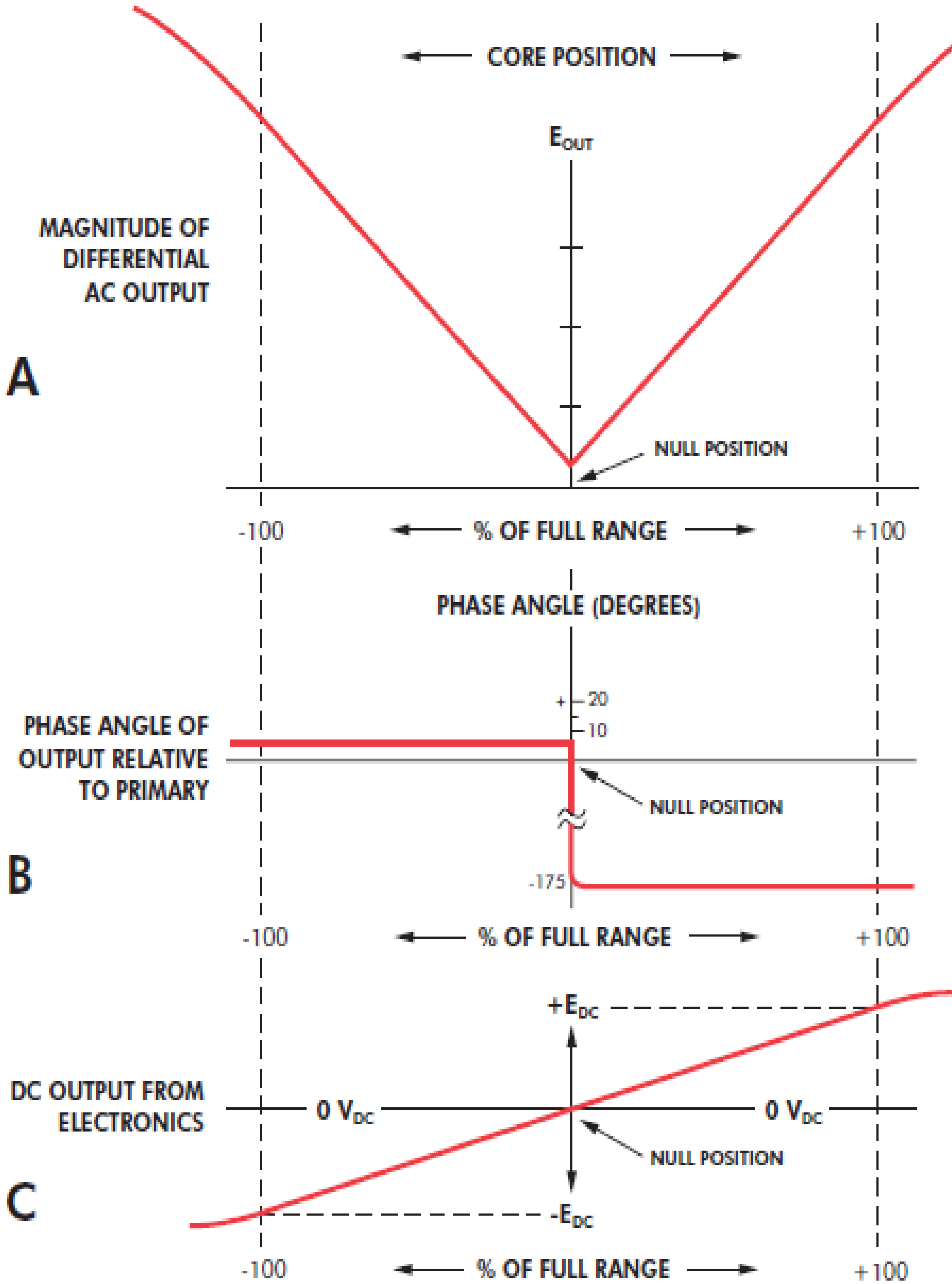


Figure A shows how the magnitude of the differential output voltage, EOUT, varies with core position. The value of EOUT at maximum core displacement from null depends upon the amplitude of the primary excitation voltage and the sensitivity factor of the particular LVDT, but is typically several volts RMS. The phase angle of this AC output voltage, EOUT, referenced to

the primary excitation voltage, stays constant until the center of the core passes the null point, where the phase angle changes abruptly by 180 degrees, as shown graphically in Figure B. This 180 degree phase shift can be used to determine the direction of the core from the null point by means of appropriate circuitry. This is shown in Figure C, where the polarity of the output signal

represents the core's positional relationship to the null point. The figure shows also that the output of an LVDT is very linear over its specified range of core motion, but that the sensor can be used over an extended range with some reduction in output linearity.

6.3 Linear variable differential transformer support electronics

Although an LVDT is an electrical transformer, it requires AC power of an amplitude and frequency quite different from ordinary power lines to operate properly (typically 3 Vrms at 3 kHz). Supplying this excitation power for an LVDT is one of several functions of LVDT support electronics, which is also sometimes known as LVDT signal conditioning equipment.

Other functions include converting the LVDT's low level AC voltage output into high level DC signals that are more convenient to use, decoding directional information from the 180 degree output phase shift as an LVDT's core moves through the null point, and providing an electrically adjustable output zero level.

A variety of LVDT signal conditioning electronics is available, including chip-level and board-level products for OEM applications as well as modules and complete laboratory instruments for users.

The support electronics can also be self-contained. These easy-to-use position transducers offer practically all of the LVDT's benefits with the simplicity of DC-in, DC-out operation. Of course, LVDTs with integral electronics may not be suitable for some applications, or might not be packaged appropriately for some installation environments.

6.4 Advantages of a Linear variable differential transformer

LVDTs have certain significant features and benefits, most of which derive from its fundamental physical principles of operation or from the materials and techniques used in its construction.

Friction-Free Operation

One of the most important features of an LVDT is its friction-free operation. In normal use, there is no mechanical contact between the LVDT's core and coil assembly, so there is no rubbing, dragging or other source of friction. This feature is particularly useful in materials testing, vibration displacement measurements, and high resolution dimensional gaging systems.

Infinite Resolution

Since an LVDT operates on electromagnetic coupling principles in a friction-free structure, it can measure infinitesimally small changes in core position. This infinite resolution capability is limited only by the noise in an LVDT signal conditioner and the output display's resolution. These same factors also give an LVDT its outstanding repeatability.

Unlimited Mechanical Life

Because there is normally no contact between the LVDT's core and coil structure, no parts can rub together or wear out. This means that an LVDT features unlimited mechanical life. This factor is especially important in high reliability applications such as aircraft, satellites and space vehicles, and nuclear installations. It is also highly desirable in many industrial process control and factory automation systems.

Overtravel Damage Resistant

The internal bore of most LVDTs is open at both ends. In the event of unanticipated overtravel, the core is able to pass completely through the sensor coil assembly without causing damage. This invulnerability to position input overload makes an LVDT the ideal sensor for applications like extensometers that are attached to tensile test samples in destructive materials testing apparatus.

Single Axis Sensitivity

An LVDT responds to motion of the core along the coil's axis, but is generally insensitive to cross-axis motion of the core or to its radial position. Thus, an LVDT can usually function without adverse effect in applications involving misaligned or floating moving members, and in cases where the core doesn't travel in a precisely straight line.

Separable Coil And Core

Because the only interaction between an LVDT's core and coil is magnetic coupling, the coil assembly can be isolated from the core by inserting a non-magnetic tube between the core and the bore. By doing so, a pressurized fluid can be contained within the tube, in which the core is free to move, while the coil assembly is unpressurized. This feature is often utilized in LVDTs used for spool position feedback in hydraulic proportional and/or servo valves.

Environmentally Robust

The materials and construction techniques used in assembling an LVDT result in a rugged, durable sensor that is robust to a variety of environmental conditions. Bonding of the windings is followed by epoxy encapsulation into the case, resulting in superior moisture and humidity resistance, as well as the capability to take substantial shock loads and high vibration levels in all axes. And the internal high-permeability magnetic shield minimizes the effects of external AC fields. Both the case and core are made of corrosion resistant metals, with the case also acting as a supplemental magnetic shield. And for those applications where the sensor must withstand exposure to flammable or corrosive vapors and liquids, or operate in pressurized fluid, the case and coil assembly can be hermetically sealed using a variety of welding processes. Ordinary LVDTs can operate over a very wide temperature range, but, if required, they can be produced to operate down to cryogenic temperatures, or, using special materials, operate at the elevated temperatures and radiation levels found in many nuclear reactors.

Null Point Repeatibility

The location of an LVDT's intrinsic null point is extremely stable and repeatable, even over its very wide operating temperature range. This makes an LVDT perform well as a null position sensor in closed-loop control systems and highperformance servo balance instruments.

Fast Dynamic Response

The absence of friction during ordinary operation permits an LVDT to respond very fast to changes in core position. The dynamic response of an LVDT sensor itself is limited only by the inertial effects of the core's slight mass. More often, the response of an LVDT sensing system is determined by characteristics of the signal conditioner.

Absolute Output

An LVDT is an absolute output device, as opposed to an incremental output device. This means that in the event of loss of power, the position data being sent from the LVDT will not be lost. When the measuring system is restarted, the LVDT's output value will be the same as it was before the power failure occurred.

CHAPTER 7

GRIPPER CONTROL

7. Control algorithm

1. Start.
2. Enter type of object to be grasped (hard,soft or medium).
3. Send ready to start signal to robot.
4. Gripper moves to predetermined height above pick location.
5. Gripper moves incremental distance down towards the object.
6. If the eddy current proximity sensor has triggered goto step-7 else to step-5.
7. Actuate stepper motor incrementally to close fingers.
8. If the LVDT gives the required displacement,then stop else goto step-6.
9. Send ready to lift signal to the robot.
10. If the weight of the object is equal to the required one then proceed to step-11 else release the object.
11. Robot lifts the object and places it at the desired location.
12. Send ready to open signal to pc.
13. Actuate stepper motor to fully open fingers.
14. Send ready signal to robot.
15. Robot moves vertically to clear the object,then moves to standby position.
16. Send ready signal to pc.
17. Program terminated successfully.
18. End.

CHAPTER 8

CONCLUSION

5. Conclusions

Although many sensor technologies and strong theoretical models have been developed, there is still much left to be done in intelligent grasping and manipulation. In particular, there is a gap in applying the theoretical models in association with tactile sensing.

In the past, progress has been slow and it will likely stay that way for a while. But the applications, in humanoids and other applications are closer than ever. The humanoids of today can walk and dance, but they can only perform very simple manipulation tasks. On the road towards more advanced manipulation lie many interesting challenges.

From a technology standpoint, with more and more research being published, better hardware, more powerful computing, the current development and an increased interest from commercial players and academia, the conditions for growth and advance are better than ever. The proposed sensor integrated gripper is sure to find applications in robotics as well as in many other related areas in a handy manner.

CHAPTER 9

REFFERENCE

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