DESIGN, DEVELOPMENT AND CALIBRATION OF A ROBOTIC WRIST FORCE SENSOR

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DECLARATION

The materials in this thesis are original except for quotations, excerpts, summaries and references, which have been duly acknowledged.

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ABSTRAK

REKABENTUK, PEMBANGUNAN DAN TENTUUKUR SENSOR DAYA PERGELANGAN ROBOT

Memandangkan peningkatan produktiviti dan pemasaran produk berkualiti yang seragam menjadi keperluan yang ditekankan oleh industri, penggunaan robot melaksanakan fungsi pengeluaran yang pelbagai dalam persekitaran kerja yang lebih fleksibel dengan kos yang lebih rendah ditumpukan. Penggunaan robot bagi mengatasi masalah rumit dan memberikan ketepatan tinggi berkembang pesat dalam pelbagai bidang seperti perubatan, aeroangkasa, pertanian, pertahanan dan sebagainya. Kini, industri sedang beralih kepada sistem pengeluaran fleksibel, di mana robot digunakan bagi pengeluaran produk yang berbeza dan kompleks. Di sini darjah kebebasan robot memberikan sumbangan yang ketara. Bagi robot sejenis yang mempunyai perbezaan darjah kebebesan, beza kos adalah tinggi. Tambahan pula sensor daya pergelangan robot adalah terhad kepada aplikasi tertentu sahaja. Peningkatan dalam darjah kebebasan dan kewujudan sensor daya pergelangan robot am membolehkan robot memperluaskan bidang aplikasi. Usaha sedemikian telah dibentangkan di dalam tesis ini di mana robot yang kurang darjah kebebasan telah dipertingkatkan dengan penambahan lengan tambahan. Sensor daya pergelangan umum telah direkabentuk dan ditentu-ukur bagi aplikasi seperti mengskrew, pemasangan secara tekanan, memotong dan mengukur profail permukaan. Dalam tesis ini, rekabentuk struktur sensor daya pergelangan robot yang digunakan pada robot empat paksi jenis Fanuc LR-Mate 100i adalah modifikasi daripada sensor Maltese Cross. Rekabentuk lengan tambahan 90 darjah yang menukar pergerakan 'roll' kepada 'yaw' pada pergelangan robot digunakan bagi mengesan objek dan menjelajah permukaan. Analisis sensor daya pergelangan menggunakan fungsi 'Singularity' dibentangkan. Kajian ini telah mengenalpasti lokasi yang paling sesuai bagi memasang strain gauge pada 'beam'. Simulasi bagi analisis ini juga digunakan untuk mengkaji ciri-ciri dan histerisis 'beam'. Tesis ini juga membincangkan intergrasi sistem dan modul perisisan yang telah dihasilkan dengan menggunakan perisian MATLAB 6.1 dan CIMPLICITY HMI untuk antaramuka sensor daya pergelangan robot bagi menjalankan tugas yang diingini. Kit tentu-ukur yang direkabentuk khas digunakan untuk menentu-ukur sensor daya pergelangan. Analisis tentu-ukur telah dibuat bagi nilai-nilai sudut condongan, α, sudut arah permukaan, β, daya tindakbalas, R, daya menegak, P_V dan daya melintang, P_H. Informasi α, β dan R yang telah diperolehi dari kit tentu-ukur dimasukkan dalam 'Back Propagation Neural Network' untuk ditentu-ukur. Aplikasi 'neural network' dalam tesis ini mengatasi masalah yang disebabkan oleh parameter yang tidak boleh dimodelkan yang wujud dalam persamaan tentu-ukur. Keluaran dari 'neural network' ini digunakan untuk pengiraan sudut 'pitch' dan 'yaw' yang diperlukan untuk memposisikan probe sensor daya pergelangan serenjang kepada permukaan yang tidak diketahui.

ABSTRACT

DESIGN, DEVELOPMENT AND CALIBRATION OF A ROBOTIC WRIST FORCE SENSOR

With a pressing need for increased productivity and delivery of end products of uniform quality, industries have been focusing on robots to perform variety of manufacturing functions in a more flexible working environment and at lower production cost. The usage of robots to circumvent complicated problems and to provide high accuracy is also vastly expanding in many areas such as in medical, aerospace, agriculture, military etc. However, since industries are shifting to a new trend of flexible manufacturing system where robots deal with multiple product manufacturing and varied complex tasks, the degree of freedom (dof) of the robot has significant contribution. For a robot of same type having different number of dof, the cost difference is quite high. Furthermore, the availability of robotic wrist force sensor (wfs) is limited to specific applications only. Hence, the improvement of the dof allows the robot to expand its application sphere and the presence of general-purpose robotic wfs will allow the robot to perform multiple applications. Such an effort is laid in this thesis where, robot with insufficient dof is improved by adding an additional arm and a general purpose wfs is designed and calibrated to suite any required applications such as screwing, press fitting in assembly, slicing and measurement of surface profile. In this thesis, the structural design of robotic wfs is presented. The wfs design is a modified Maltese cross sensor used on the five axis articulated Fanuc LR-Mate 100i robot. The design of a 90-degree additional arm in modifying the roll movement into the yaw movement at the tip of wfs probe so that the robot can to be utilized in tactile sensing and surface exploration is also discussed. The analysis of the wfs beam is performed using singularity function. This analysis identifies the most suitable location to place the strain gauge on the crossbeam of wfs. Simulation of the analysis is also used to study the characteristics of the beam. The system integration is also discussed and software modules are also developed using MATLAB 6.1 and CIMPLICITY HMI software to interface the wfs and the robot to perform the desired tasks. A specially designed calibration kit is used to calibrate the wfs. The calibration study is made for various values of inclination angle, α*, surface direction angle,* β*, reacting force, R, vertical force,* P_V *and horizontal force,* P_H*. The information* α*,* β *and R, obtained from the calibration kit, are fed into a back propagation neural network for calibration. The application of neural network in this thesis overcomes the problems of un-modeled parameters that exist in the calibration equation. The output of the neural network is used to compute the necessary pitch and yaw angles to position the wfs probe normal to unknown surface.*

ABBREVIATION

wfs	wrist force sensor
dof	degree of freedom
WCS	world coordinate system
TCS	tool coordinate system
UCS	User coordinate system
MCIS	mechanical interface coordinate system
CCS	cartesian coordinate system
TCP	tool center point

SYMBOL

P_i	force in i= x, y or z direction
P_v	vertical force
M	bending moment (moment of couple)
σ_y	yield strength
σ_u	ultimate strength
E	Young Modulus
ν	Poisson ratio
ε	strain
dR^*	changes in resistance
h	beam thickness
I^*	moment of inertia
b	beam width
L	beam length
R^*	unstrained gauge resistance
N	number of active gauges
S_g or G	gauge factor of strain gauge
V	bridge circuit voltage
I	bridge current
α	inclination angle
β	slope direction angle
θ_1	pitch angle
θ_2	yaw angle

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CHAPTER 1

INTRODUCTION

1.1 Robot Sensors

Integration of sensors into a machine changes it from a dumb to an intelligent machine. This active area of research in robotics shows a great promise for improving the intelligence of an industrial robot to take up highly decision making tasks. Industrial robot could then greatly expand its versatility and its application sphere if sensors are added (Fuller, 1999). Generally, the function of robot sensors may be divided into two principal categories: internal state sensors and external state sensors (Fu, 1987). Internal state sensors deal with the detection of variables such as joint arm position and velocity, which are used for robot control. The external state sensors, on the other hand, deal with the detection of variables such as range, proximity, touch, force and torque. The external state sensing allows a robot to interact with its environment in a flexible manner.

1.2 Force Sensing in Robotics

Force and torque sensors are used primarily for measuring the reacting forces and moments developed at the interface between mechanical assemblies. Although the industrial robots execute programs by repeating a pre-set sequence of motions, these robots may be inadequate for performing a variety of manufacturing tasks where part sizes and positions vary. Tasks that deal with different part sizes and orientation require robot motions with intelligence and precision through sensor information. Force sensors are universally accepted as very useful external sensors that enable robot to interact with environment changes with a level of intelligence. The wrist force sensors (wfs) are force measuring devices. They are most commonly used in industrial robots. They are mounted between the gripper and the last link of the robot. Several types of wfs for various measurement ranges have been developed. Figure 1.1 shows IPIT-IM four-component modular wfs that uses silicon strain gauges. The four components are the vertical force and torques in (X, Y, Z) axis. The main advantages of this sensor are that it measures individual force and torque components directly and has a high eigen frequency and measurement accuracy. Another advantage of this modular sensor is that in case of a structural failure, it is possible to replace only a single module without abandoning the whole sensor.

Figure 1.1: IPIT-IM Four-Component Modular Sensor

The most promising design for a six-component strain gauge force sensor is based on a Maltese cross elastic element with membrane elastic joints (Gorinevsky, Formalsky & Schneider, 1997). The six components are forces and torques in each of x, y, z directions. Figure 1.2 shows the IPIT-IM six-component Maltese cross sensor, which was designed for the industrial robot PUMA-560. Figure 1.3 depicts another force sensor for higher payload capacity that reaches 100kg.

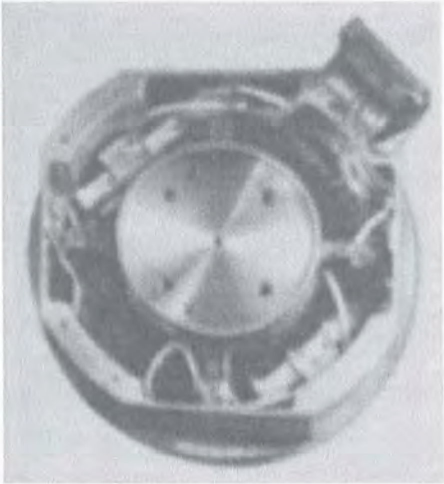

Figure 1.2: IPIT-IM Six-Component Modular Sensor

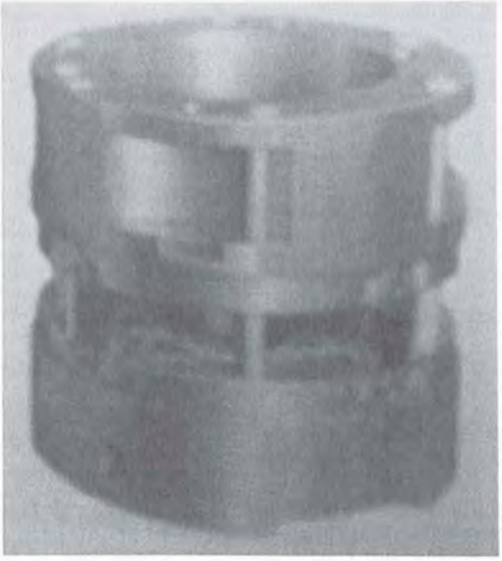

Figure 1.3: IPIT-IM Six-Component Force Sensor for Higher Payload

1.3 Applications of Force Sensing in Robotics

Robots are used in many diverse applications where each has its own set of complexity, and consequently, its own set of robotic requirements (McKerrow, 1995). The usage of force sensing in robotics has expanded the robotic applications especially in industries and later evolved into other areas such as agriculture, space, medical, military, education, etc. The earliest applications of robots with force feedback in industry were in materials handling, spot welding and spray painting (Hartley, 1983). One of the most successful developments in robotic force sensing is the sheep-shearing robot in Australia. Sheep shorn by robot has fewer injuries compared to those occur with human shearers (Trevelyan *et al.*, 1984). In medical field, robots designed for people with significant disability have greater sensor integration thereby pushing sensor technology to its limits to protect the user, and to perform the desired tasks in an unstructured environment (Nagarajan, 2002).

1.4 Need for the Project

a) Introducing Haptic in Industrial Robot

In today's world, robots play a major role compared to humans especially in high technology and precision industrial and medical sectors. For example, although humans effectively use their ability to sense the presence and perceive the size and shape of an object with the sense of touch, the capabilities of robot to percept and perform this task with a wfs are superior. Human perception cannot produce a mathematical description of the shape. Such description is essential for industrial quality control. Such a task falls into the category of exerting a preset pressure or force on something and maintaining this force for a period of time. Although robot vision may guide the robot arm through manufacturing operations, it is the sense of touch that can allow the robot to perform delicate gripping and assembly. This is where force controlled robots are very useful. Simple task such as cutting, slicing a very thin layer, feeling the surface area of a fragile object or inserting an object into a hole with a particular force can be done with great accuracy by a robot compared to a human being. Thus a robot with these capabilities, not only performs a task with perfection, but also can be controlled to any requirement in terms of timing, angle and torque.

Since tactile sensors can provide position data for contacting parts more accurately than that provided by vision, researchers are developing and improving various tactile sensing methods for robots in many areas. These areas include measuring softness and other mechanical properties of objects being touched (Bicchi, Rossi & Scilingo, 2000). Sensors that have been used in conjunction with robot arms to identify objects, determining surface friction, detecting slip, grasping stability, object mass measurement, probing the surfaces, control collision are also available (Bicchi, Salisbury & Brock, 1993). The design of multi-axis force (also known as force/torque) sensors (Bicchi, 1993) for robot grasping (Bicchi & Kumar, 2000), measurement of time-varying forces and torques applied to flexible mechanical structures (Bicchi, Caiti & Prattichizzo, 1999), realizing a robot gripper for manipulation of objects whose shape is not known (Bicchi, Marigo & Prattichizzo, 1999), automatic exploration of unknown object in order to reconstruct their geometric features from sensed information (Balestrino *et al.*, 1993), analysis of the physical and conceptual link between robot hands and intelligence in the area of tactile sensing (Bicchi & Buttazzo, 1991) and for developing an artificial tactile sensing system intended for investigating robotic active touch (Buttazzo, Bicchi & Dario, 1992) are available in the literature.

b) Improving Insufficient Degree of Freedom

Industrial robots are intended to serve as a general-purpose unskilled or semi-skilled laborer. Although robots are more reliable than humans in some applications they are mainly used for specific repetitive tasks. In flexible manufacturing system, there is a requirement for more degree of freedom (dof) for different applications since the same robot has to perform different tasks. Furthermore the cost difference between a robot of same type but with one extra dof is quite high. Many tasks do not require maximum dof. The limitations on dof do not allow these robots to be used for multipurpose applications. Furthermore the limitations also make the robots less utilized in research and development areas especially in exploring unknown surface. For instance, if a robot has 5 dof, its movement at its wrist is limited to pitch and roll or yaw and roll. In a surface exploration, it is beneficial to move the probe of the wrist force sensor (wfs) normal to the unknown surface. This will allow accurate measurement of the location of probe tip, measurement of the applied force and also allows the probe to move on an unknown surface in certain specific direction. This is necessary mainly because the wfs will not be subjected to any unwanted accidents due to large changes in the profile of the unknown surface upon contact or whilst the probe tip moving along the unknown surface. The absence of either pitch or yaw movement of the wrist of the robot does not allow the probe of the wfs to be articulated normal to the unknown surface and thus making the robot handicapped for surface exploration.

In the area of haptic and surface exploration, many research has been performed and it was found that the requirement of control of contact force, position and orientation are necessary to perform precise manipulation; these are prerequisites for tactile exploration of unknown surface (Allison & Mark, 1999; Allison, Michael & Mark, 1997; Allison *et al.,* 2000). Investigations for shape perception, based on rolling, and the other based on gliding on the surface of unknown objects (Hemami, Bay & Goddard, 1998), methods for curvature estimation (Charlebois, Gupta & Payandeh, 1996) and shape description using surface normal information (Charlebois, Gupta & Payandeh, 1997) have also been performed. Researchers in computer vision has also motivated in the development of methodology for obtaining global shape information (Dill, 1981; Elber & Cohen, 1993; Trucco & Robert, 1995; Yokoya & Levine, 1989). Surveys and investigation of tactile sensing for robots were also performed (Howe & Cutcosky, 1992; Nicholls & Lee, 1989; Grupen, Henderson & McCammon, 1989). It was also found that rolling could be executed using only instantaneous kinematics if a tactile sensor provides continuous updates of the contact location (Zang, Maekawa & Tanie, 1996; Li, Qin, Jiang & Han, 1998; Maekawa & Komoriya, 1995). Force sensing at intermediate sections of the kinematic chain are very useful robot interacting with surface (Eberman & Salisbury, 1989; Vassura & Bicchi, 1989). Information obtained when exploring objects using features were also laid (Ellis, 1984; Stransfield, 1988; Nicolson & Fearing, 1995; Son, Cutkosky & Howe, 1995). Several configurations have been proposed for sensorized wrist (Watson & Drake, 1975; Scheinmann, 1971; VanBrussel, Belien & Thielemans, 1985). Motion of the probe over the surface is required, as some of the features of an object cannot be sensed accurately through simple static touch (Allison & Mark, 1999). These applications clearly indicate that robot has to have sufficient dof to perform surface exploration.

1.5 Objective of Research

The objective of this research has eight folds as described below:

a) To design a strain gauge based robot wfs with specifications in accordance to wrist dimensions of FANUC LR Mate 100i industrial robot.
b) To identify suitable materials for fabrication and to fabricate the wfs.
c) To develop an instrumentation and signal conditioning circuits for the strain gauge bridges that measures 3-dimensional force.
d) To design and fabricate a calibration kit to calibrate the developed wfs.
e) To perform beam analysis and to simulate wfs beams for the study of performance characteristics.

f) To compare the results of beam simulation study with those of actual performance characteristics.
g) To design and fabricate an additional arm to FANUC LR Mate 100i industrial robot in order to overcome its insufficient dof.
h) To develop computer software to control the robot in articulating the wfs probe for surface exploration.
i) Compiling experimental data and the outcome of the research.

1.6 Organization of Thesis

This Chapter, Chapter 1 has discussed the introduction of force control, force sensing and the advantages of force sensor especially in the area of robotics. A brief survey on the application of force sensor in robotics has been given. Various types of wfs used either in R&D or in industries are covered. A set of objectives of this research work is also laid out.

Chapter 2 deals with the design and structure of the wfs. A modified Maltese cross sensor is introduced. The requirements for the design of a robotic wfs and the fabrication materials used in the design are covered. The mechanical structure module of the wfs and a specially designed additional arm to circumvent the problem of insufficient dof of the industrial robot used in this work are also explained. The usage of strain gauges as a sensing device is described.

In Chapter 3, a detailed study and analysis of the designed wrist force sensor beam is made. Here, a free body diagram is used to produce equations for the mathematical analysis. Singularity function is used to simplify the analysis and to derive equations such as for load deflection, sheer force, bending moment, slope

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