Proceedings of IEEE International Conference on Applied System Innovation 2018
IEEE ICASI 2018- Meen, Prior & Lam (Eds)

A Novel 6-DOF Force/Torque Sensor for COBOTs and its Calibration Method

Tan-Phat Phan
Department of Electrical Engineering
National Chiao Tung University
Hsinchu, Taiwan
phantanphat512@gmail.com

Paul C.-P. Chao
Department of Electrical Engineering
National Chiao Tung University
Hsinchu, Taiwan
pchao@mail.nctu.edu.tw

Jia-Jun Cai
Department of Electrical Engineering
National Chiao Tung University
Hsinchu, Taiwan
zxc924101@gmail.com

Yu-Jen Wang
Department of Mechanical Engineering
National Sun Yat-sen University
Kaohsiung, Taiwan
yjwang@mail.nsysu.edu.tw

Sheng-Ching Wang
Department of Mechanical Engineering
National United University
Miaoli, Taiwan
lywang@nuu.edu.tw

Kyle Wong
HIWIN Technologies Corp.
Taichung, Taiwan
kylewong@hiwin.tw

Abstract

This paper intends to design a 6-DOF force/torque sensor along with its readout circuit for collaborative robots (Cobots) working environment. There are two major technologies to develop by this paper. The first technology is the capability of sensing contact forces and torques by a newly-designed six degrees-of-freedom (DOF) force/torque sensor at a fast speed to facilitate feedback control towards anti-collision for the Cobots with wide measurement range, precision, with a smaller size and lower costs. For the force/torque sensor structure, the finite element method (FEM) is established. The sensor is designed and optimized based on finite element analysis (FEA) while “maximum likelihood estimation (MLE)” is utilized to increase accuracy in estimation of force/torque by using appropriate statistical model. The second technology is the anti-collision control. If the collision occurs, the Cobot has an ability to response safely and instantaneously. The proposed control scheme and assisting 6-DOF sensor are capable of performing Cobots anti-collision in welding, grinding, polishing, assembling, etc. with high precision.

Keywords: Force/Torque Sensor, maximum likelihood estimation (MLE), Collaborative Robots (Cobots), Anti-Collision.

Introduction

The act of measuring of force/torque is supreme in Cobots applications such as welding, polishing, grinding, assembling, holding objects or interaction between human and Cobots. While the most important approaches of torque/momentum measured dimension relate to resistive or/and piezoresistive strain gauge schemes, some of the contemporary approaches relate to principles such as infrared (IR) light, magnetoelastic, optical and SAW method stand for the surface acoustic wave method.

Chao et al. [1], and Wu et al. [2] introduced the six-dimensional force sensors with the design of several cross beams. Liu et al. [3] announced a six-part force/torque sensor in the combination of four similar T-shaped legs on the square frame. Kim et al. [4-6] proposed some six-axis force/torque sensors for the robot built on some parallel-plate beams. Liang et al [7] designed a six-dimension force/torque sensor established on E-type membranes. Besides those, there are a large number of different types of six-axis force/torque sensors based on the elastic structure with a complex mechanical design [8-11]. Although there are varieties of different techniques for measuring the forces and moments, the most commonly used are established on strain gauges. In the force/torque sensors established on this technique, the elastic body play an important role. Chao et al. [1] announced a calibration method based on calibration matrix with the lowest condition number, the strain gauge sensitivity, the quantity of strain gauges mounted to the sensor structure, and a numerical analysis to figure out the specification of the force/torque sensor. A technique published by Liu and Tzo [3] in which the force sensing element is based on an analysis called finite element model in combination with an optimal design to increase the measurement sensitivities, and a novel six-component force/torque sensor was achieved with excellent measurement isotropy and sensitivity. The accuracy of force/torque sensors is the fundamental of performing force sensing task, especially in the Cobots environment. Minimizing the coupling errors plays an important role in improving the accuracy, resulting in various decoupling algorithms. The general decoupling technique based on the Least Square Method (LSM) [12] is applied to calculate the counterfeit-inverse matrix of calibration data. Another decoupling algorithm is called shape from motion [13-14]. In this paper, a 6-DOF force/torque sensor is designed to be used as an important part of the large segment of the industry. The sensor is designed and optimized based on finite element analysis associated with maximum likelihood method [15]. The aim is not only to design a sensor suitable for industry robot but also has a readout circuit for extracting force/torque values in a digital format for communicating with other devices easily. For the force/torque sensor structure, the finite element method (FEM) is established, and the finite element analysis software COMSOL is applied to the model and simulate the above analysis to achieve high sensitivity and high stiffness. For this novel 6-DOF force/torque sensor, using 16 strain gauges is adequate to measure the forces/torques. Because the strain gauges are sensitive devices and combine with an electrical measuring circuitry called haft and full Wheatstone bridge to obtain the high-quality signal. The analog readout circuit plays an important role in acquisition system. High accuracy, low noise, and low power consumption are essential factors in a readout circuit, especially for the industrial Cobots. The readout circuit consists of instrument amplifiers (IA), a low-pass filter (LPF), a sigma-delta 14-bit analog-to-digital

ISBN 978-1-5386-4342-6

TABLE I
THE PARAMETERS OF THE ELASTIC STRUCTURE

	Cross-elastic beam	Compliant beam
Length (mm)	l = 18.9	h = 14
Width (mm)	b =4.5	b =4.5
Thickness (mm)	t =5	d = 1.4
Young's modulus (Pa)	68 × 109	
Poisson ration	0.33	
Density	2.71 × 103	

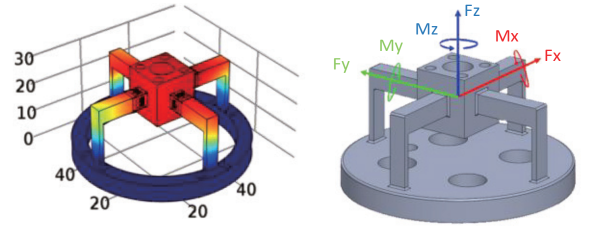

Fig. 1 Finite element model

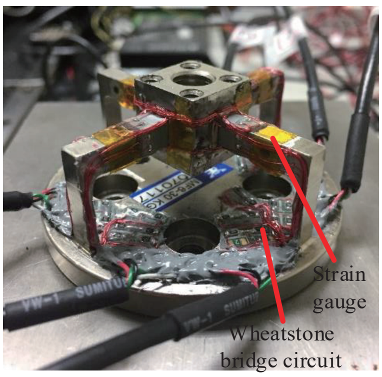

Fig. 2 Prototype of the force/torque sensor

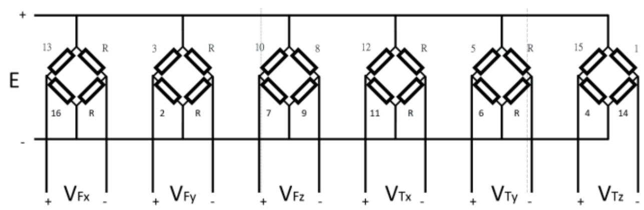

Fig. 3 Wheatstone bridges circuit

converter (ΔΣ ADC) and a moving average filter. To minimize the coupling errors of different axes, which cause the major negative effect on the force/torque sensor's accuracy, a calibration procedure must be processed to assist the model of the decoupling algorithm. Generating the stable and reliable reference force/torque source is necessary for this work. Hence, an innovative calibration machine was proposed, and a calibration procedure was implemented using this system design. Again, on the collision occurs, we must clearly know the working position of the robot arm and the joints of the system in order to adjust the attitude of the way in response to the attitude of the robot in the space, according to kinematics to calculate the rotation angle of the joints. Moreover, a prototype of the force/torque sensor was implemented and tested. In this study, the results are better than some commercial sensors.

Force/Torque Sensor Design

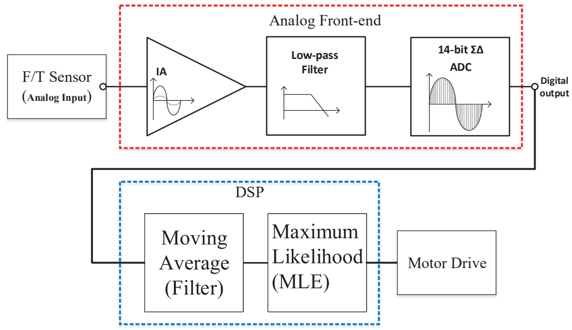

Fig. 4 The readout circuit.

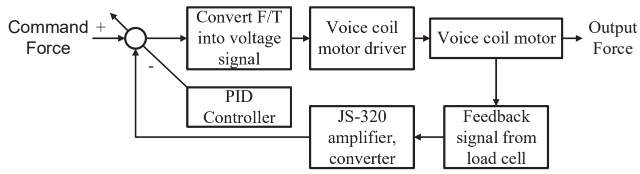

Fig. 5 The calibration machine's controller.

A. Mechanical Structure and Wheatstone Bridge Circuit

To meet the specification shown in Table I and the detection range of the sensor, F_x; F_y; F_z= ±300 N, M_x; M_y= ±15 N.m, M_z= ±20 N.m, a finite element model was built containing a rigid body structure and several sensing strain gauges, shown in Fig.1. The commercial FEA software COMSOL is used for modeling and simulation analysis to obtain high sensitivity along with high rigidity conditions. The design variables include rigid body geometry, strain gauges, strain gauge numbers, and strain gauge sensing positions. Some dimensions must be designed with a precise calculation. Including the base, sensing beam, connecting elbow and so on, using the repeated elements of the finite element model to achieve the optimal design.

A prototype of the new six-axis force/torque sensor has been successfully built as shown in Fig. 2. This mechanical structure and size of the sensor have been optimized to maximize sensitivities on the output signals for varied forces and torques in different axes. The final structure of the sensor is in four L-legs. Finite element modeling and analysis have been conducted and finalize the optimal locations of 16 strain gauges to be attached to. Through the COMSOL strain analysis, the exterior impact of strain distribution on the structure was observed.

B. Readout Circuit

The readout circuitry is also designed and realized in a printed circuit board (PCB). In the Fig. 4 shows the readout circuit consists of instrument amplifiers (IA), the low-pass filter (LPF), the delta-sigma 14-bit analog-to-digital converter (ΔΣ ADC) and a moving average filter. In the Wheatstone bridges circuit, there are 6 Wheatstone bridge circuits at the front end to be connected to 16 strain gauges numbered from 1 to 16. Among these 6 bridges, four half-bridges and two full-bridges [16] are designed and realized to acquire different combined resistance changes of strain gauges to output directly 3 forces and 3 torques shown in Fig. 3. The advantages of 6 bridges are not only temperature compensation with the active-dummy method but also the larger outputs, combine with using high precise resistors R in the circuit, the accurate output can be obtained. Fig. 7 shows measured the output of a certain bridge that corresponding to the sensed force along x direction, i.e., F_x. A high linearity of 99% between 0 and 3.5 volts is validated, a large range of voltage output, associated with the blue line in Fig. 7 is clearly seen. This indicates that with proper calibration effort in the near future, the dynamic range, resolution, accuracy, and linearity of the sensor can be achieved.

C. Calibration Matrix

Calibration methodology and machine are also under development in parallel with the sensor. A calibration method based on maximum likelihood estimation (MLE) is successfully developed and validated with initial feasibility. On

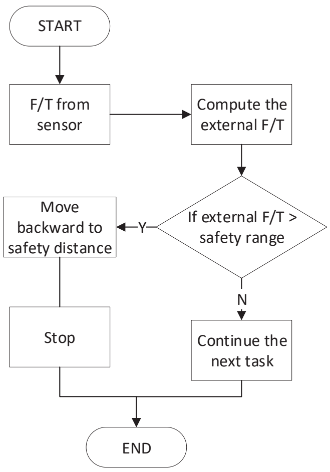

Fig. 6 The anti-collision algorithm for Cobot.

the other hand, the calibration machine is already successfully developed. The LabView software for control and computation shown in Fig. 5. is also successfully developed to drive voice coil actuators in the calibration machine to conduct a series of force and torque exertion to calibration the coefficients between force/torque and strain gauges readouts. Repeatedly, collect a large number of strain values and find the corresponding transformation matrix between strain and force/torque in an optimized procedure statistically using the equation (1).

$$Y_{N\times 6} = X_{N\times 6} \times \beta_{6\times 6} \qquad (1)$$

where,

$$\begin{bmatrix} F_{X_1} & F_{Y_1} & F_{Z_1} & T_{X_1} & T_{Y_1} & T_{Z_1} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ F_{X_N} & F_{Y_N} & F_{Z_N} & T_{X_N} & T_{Y_N} & T_{Z_N} \end{bmatrix}_Y = \begin{bmatrix} V_{1_1} & \cdots & V_{6_1} \\ \vdots & \ddots & \vdots \\ V_{1_N} & \cdots & V_{6_N} \end{bmatrix}_X \times \begin{bmatrix} \beta_{1,1} & \cdots & \beta_{1,6} \\ \beta_{2,1} & & \beta_{2,6} \\ \vdots & \ddots & \vdots \\ \beta_{6,1} & \cdots & \beta_{6,6} \end{bmatrix}_\beta$$

Anti-collision algorithm

This Cobot is used for demonstrating the capability of the anti-collision algorithm we designed with assistance from the force/torque sensor. Towards this goal, the forward/inverse

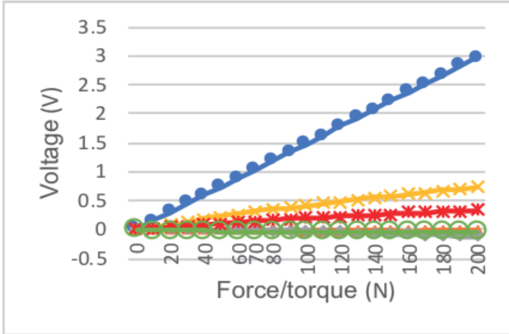

Fig. 7 F_x output signal.

Fig. 8 Hardware connection to Cobot for an anti-collision strategy

kinematics of the Cobot were successfully derived and simulation completed using the anti-collision as shown in Fig. 6 to validate the effectiveness of the established model. For actuating the Cobot, a new commercial controller platform is utilized using CompactRIO 9030 as shown in Fig. 8, to conform to a commonly used communication protocol for Cobots, EtherCAT connection is applied for fast speed of responses. For anti-collision, the communication between CompactRIO and motor's driver by using EtherCAT had been successfully built, which is essential to minimize the response speed of the Cobot to prevent collision between operator and robot.

Experiment result

A. Force/torque sensor

By reason of the trade-off between high sensitivity and high rigidity, the size and shape of every component of the force/torque sensor structure should be designed carefully. After accomplishing some simulations, a prototype of the new six-axis force/torque sensor was successfully fabricated including strain gauge attachment. A readout circuit and calibration method are also achieved with advantages of temperature compensation with the active-dummy method together with the larger outputs of the sensor. The development of the calibration machine and its control using LabView are successfully established. Through this calibration machine, a large number of data set of strain values are generated and collected by the readout circuit from this novel 6-DOF force/torque sensor independently. Those values are then used to predict the correct force/torque values by using maximum likelihood algorithm. As a result, a high linearity of 99% between 0 and 3.5 volts is validated, shown in Fig. 8.

The anti-collision is developed simultaneously. Force/torque

ISBN 978-1-5386-4342-6

values are read by the controller through readout circuit, then compute the external force/torque. When the Cobot carries some heavy objects, the external force/torque should be computed carefully. If the external force/torque larger than the allowable force/torque, the Cobot will plan to go backward to the safe place or reduce the force/torque where the contact happens.

Conclusion

A prototype of this innovative 6-axis force/torque sensor was successfully fabricated along with a large dynamic range of 0 – 3.5 volts and high linearity of 99%. This shows promising future for developing our 6-axis force/torque sensor.

For anti-collision, the communication between CompactRIO and motor's driver by using EtherCAT had been successfully built, which is essential to minimize the response speed of the Cobot to prevent collision between operator and robot.

Reference

[1] L. P. Chao and K. T. Chen, "Shape optimal design and force sensitivity evaluation of six-axis force sensors," *Sensors Actuators, A Phys.*, vol. 63, no. 2, pp. 105–112, 1997.

[2] B. Wu, J. Luo, F. Shen, Y. Ren, and Z. Wu, "Optimum design method of multi-axis force sensor integrated in humanoid robot foot system," *Meas. J. Int. Meas. Confed.*, vol. 44, no. 9, pp. 1651–1660, 2011.

[3] S. A. Liu and H. L. Tzo, "A novel six-component force sensor of good measurement isotropy and sensitivities," *Sensors Actuators, A Phys.*, vol. 100, no. 2–3, pp. 223–230, 2002.

[4] J. J. Park and G. S. Kim, "Development of the 6-axis force/moment sensor for an intelligent robot's gripper," *Sensors Actuators, A Phys.*, vol. 118, no. 1, pp. 127–134, 2005.

[5] G. S. Kim, "Design of a six-axis wrist force/moment sensor using FEM and its fabrication for an intelligent robot," *Sensors Actuators, A Phys.*, vol. 133, no. 1, pp. 27–34, 2007.

[6] G. Kim, H. Shin, and J. Yoon, "Development of 6-axis force / moment sensor for a humanoid robot's foot," *Sensors Actuators A Phys.*, vol. 20070019, no. May 2007, pp. 276–281, 2008.

[7] Q. Liang, D. Zhang, Q. Song, Y. Ge, H. Cao, and Y. Ge, "Design and fabrication of a six-dimensional wrist force/torque sensor based on E-type membranes compared to cross beams," *Meas. J. Int. Meas. Confed.*, vol. 43, no. 10, pp. 1702–1719, 2010.

[8] Z. Y. Jia, S. Lin, and W. Liu, "Measurement method of six-axis load sharing based on the Stewart platform," *Meas. J. Int. Meas. Confed.*, vol. 43, no. 3, pp. 329–335, 2010.

[9] Z. Wang, Z. Li, J. He, J. Yao, and Y. Zhao, "Optimal design and experiment research of a fully pre-stressed six-axis force/torque sensor," *Meas. J. Int. Meas. Confed.*, vol. 46, no. 6, pp. 2013–2021, 2013.

[10] D. Chen, A. Song, and A. Li, "Design and Calibration of a Six-axis Force/torque Sensor with Large Measurement Range Used for the Space Manipulator," *Procedia Eng.*, vol. 99, pp. 1164–1170, 2015.

[11] E. Moreira, L. F. L. F. Rocha, A. M. Pinto, A. P. Moreira, and G. Veiga, "Assessment of Robotic Picking Operations Using a 6 Axis Force / Torque Sensor," *IEEE Robot. Autom. Lett.*, vol. 1, no. 2, pp. 768–775, 2016.

[12] Y. Sun, Y. Liu, T. Zou, M. Jin, and H. Liu, "Design and optimization of a novel six-axis force/torque sensor for space robot," *Meas. J. Int. Meas. Confed.*, vol. 65, no. January, pp. 135–148, 2015.

[13] F. Beyeler, S. Muntwyler, and B. J. Nelson, "Design and calibration of a microfabricated 6-axis force-torque sensor for microrobotic applications," *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 520–525, 2009.

[14] R. M. Voyles, J. D. Morrow, and P. K. Khosla, "The Shape From Motion Approach to Rapid and Precise Force/Torque Sensor Calibration," *J. Dyn. Syst. Meas. Control*, vol. 119, no. 2, p. 229, 1997.

[15] K. Kim, Y. Sun, R. M. Voyles, and B. J. Nelson, "Calibration of multi-axis MEMS force sensors using the shape-from-motion method," *IEEE Sens. J.*, vol. 7, no. 3, pp. 344–351, 2007.

[16] C. Yuan *et al.*, "Development and evaluation of a compact 6-axis force/moment sensor with a serial structure for the humanoid robot foot," *Meas. J. Int. Meas. Confed.*, vol. 70, pp. 110–122, 2015.