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Design and Analysis of Force/Moment Sensor for a Robot

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Abstract

To safely hold an unidentified object by means of an intelligent hand of robot, the hand has to recognize the weight of it. By attaching six-axis Force/Torque (F/T or Force/Moment) sensor to an intelligent robot's hand the weight can be calculated by measuring forces F_x , F_y and F_z . Forces should be measured in order to precisely pull and push an object. To securely grasp an unidentified object with an intelligent robot's gripper, the forces in the gripping direction and in the gravitational direction needs to be detected, but it also requires to perceive the moments to accurately recognize the position of the object in the grippers. A robot joint can be controlled in better way if three forces and three moments exerted at the joint are measured. The available Force/Torque sensors are bulky, not customized and costly. Therefore, it is essential to customize and develop low cost six axis Force/Torque sensor with new appropriate dimensions for an intelligent robot's joints. Six axis Force/Torque sensor is designed using strain gauge. The strain gauges are selected for Aluminium and its working conditions. The sensor design is based on results of parametric analysis done in ANSYS software to obtain the strain values in the measurable range. The analytical results are compared with Finite Element Analysis (ANSYS) results. The percentage error in deviation is 0.75% maximum.

Keywords: Sensor, Force/Torque sensor, Force measurement, intelligent robot.

1 INTRODUCTION

The intelligent robot hand is required to recognize the weight of the object to be picked safely by it. The weight of object can be calculated by measuring forces F_x , F_y and F_z with the help of six-axis Force/Moment sensor attached to the intelligent robot wrist. The forces in the gripping direction and in the gravitational direction needs to perceive with an intelligent robot gripper to grasp an unidentified object securely. However, griping is also required to perceive the moments about all three axes accurately to identify the position and orientation of the object in the grippers. The force sensing at each joint also helps to control the joint in better way while pushing or pulling the unidentified object. Force and moment perception at each joint of biped system helps to control the joints of biped system while walking. In general, a robot joint can be controlled in better way if forces and moments exerted at the joints are perceived precisely [1].

Numerous multi-dimensional force sensors have been established in the previous decades, which are planned for use at the end effector and/or joints of a robot to observe force and/or moment. Gab-Soon Kim et al have designed and fabricated the structure of three axis Force/Torque sensors using plate-beams [2]. The sensor may be used for sensing the forces along x-axis, y-axis and torque about z-axis. The use of sensor is limited to the joints of industrial robots. The work is extended to develop and fabricate a six-axis Force/Torque sensor [3]. The analytical analysis and FEA analysis of strain is compared with experimental results. It is found that interference error is less than 2%. This sensor is also limited to the joints of industrial robots due to its complexity. A structure of small capacity six-axis Force/Torque sensor is modelled, designed and manufactured by G. Kim [4] to determine the uncertainty of the sensor. The sensor is evaluated for the uncertainty using suggested calibration method. The results confirm the uncertainty of the sensor less than 2.78%.

Multi-fingered robot hands with rigid or soft hemispheric finger ends require intelligent control for grasping and manipulating of an object [5]. It also further reveals that simplified feedback sensors are required without object kinematics and location of the mass center. A strain gauge based gripper for intelligent robot to measure three forces and moments is developed which gives less than 6% maximum error of the rated strain [6]. This sensor gives better control for intelligent task with less than 2.79% maximum interference error. The work is extended to measure forces and torques at finger with less than 9.7% maximum error of rated strain and less than 3.93% maximum interference error [7].

G. Kim has modified model of plate beam six-axis force/torque sensor using rectangular taper beams for an intelligent robot to increase the sensitivity of the sensor without disturbing its rigidity [8]. This sensor can be used to accurately push and pull an object with an intelligent robot’s hand and in order to safely walk with an intelligent robot’s foot. The designed sensor was analyzed by FEM and fabricated similar to size of human being wrist i.e. diameter about 60-80 mm and the thickness about 20-40 mm [9]. The rated outputs from the derived equations and FEM analysis reported well to those from the experiments with interference error of the sensor less than 2.8%. Dan Feng Chen et al have designed and calibrated a six-axis force/torque sensor for large measurement range used in the space manipulator [10].

Many of the above literature have reported analytical analysis and FEM analysis to model the sensor with full bridge strain gauge arrangement. The most of the sensors are not compact and complex in fabrication. In this paper, the compact and simple design of force/torque sensor using full bridge strain gauge sensor is presented for wrist joint of robot hand and knee joint of leg system. The paper follows as: section 2 describes design of the sensor, section 3 presents analytical analysis of the sensor, in section 4 the results are compared and finally section 5 concludes the work.

2 DESIGN OF THE SENSOR

To measure force and torque simultaneously for typical wrist and knee joints, basic model can be proposed which consist of outer ring, inner transfer ring and four flexible arm (beams) of aluminum. Figure 1 shows the basic drawing of six axis Force/Torque sensor for wrist and knee joint with positions of strain gauges. Different dimensions for wrist and knee joint are tabulated in Table 1.

Type of sensor	Variable dimensions					
	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)	DP1 (mm)	DP2 (mm)
Wrist sensor	85	75	38	20	80	30

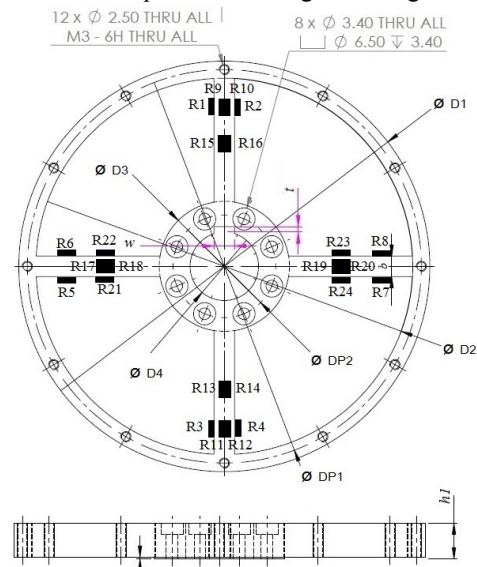


Figure 1: Basic drawing of six axis Force/Torque sensor for wrist and knee with strain gauges

Type of sensor	Variable dimensions					
	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)	DP1 (mm)	DP2 (mm)
Knee sensor	120	110	38	20	115	30

Table 1: Dimensions For Different Sensors

For both the sensors values of w , t , b , h_1 & h_2 are 6mm, 1.6 mm, 6 mm, 10.5 mm & 0.5 mm respectively. For measurement of force F_x , strain gauges R1~R4 are provided. Similarly, for measurement of forces F_y , F_z and moments M_x , M_y and M_z , strain gauges R5~R8, R9~R12, R13~R16, R17~R20 and R21~R24 are provided respectively. The strain gauges are associated into a Wheatstone Bridge circuit with an arrangement of four active gauges to make it full bridge circuit. Strain gauges available now can give the measurable value of output for small strain values, like for strain values of order 10^{-6} can produce measurable output voltages which will make sensor more compact.

3 ANALYTICAL ANALYSIS OF F/T SENSOR

F/T sensor is made up of 4 beams (A, B, C & D) of equal size. Dimensions of beams are length = l , height = h and width = b as in following Figure 1.

On the base of symmetry and the set of equations required for forces and moments, it is observed that the equation of force F_x can also be used for F_y and similarly for moments M_x and M_y .

To determine the values of strains due to forces F_x , F_y and F_z and moments M_x , M_y and M_z analytically the following four cases can be referred:

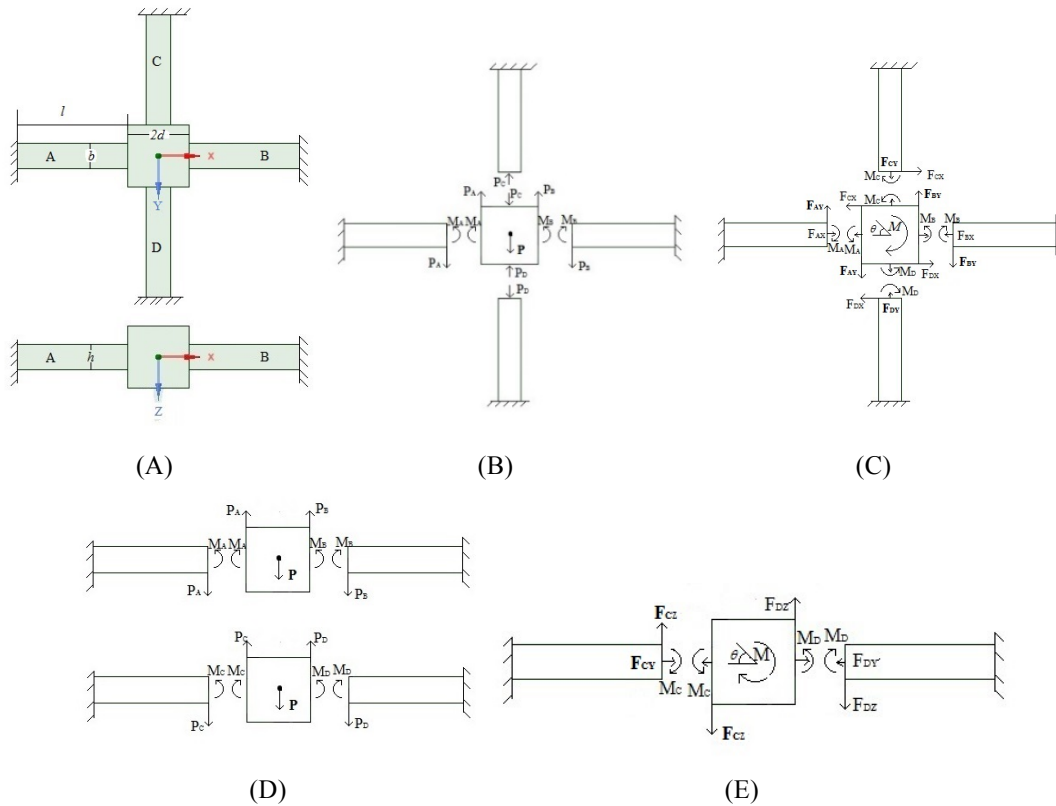


Figure 2: F.B.D when (A) no load (B) $F_x = P$ N, (C) $M_z = M$ Nm (D) $F_z = P$ N and (E) $M_x = M$ Nm

3.1 Calculation for measuring strain due to force F_x (or F_y) = P N.

From Figure 2 (B), it can be seen that beam A and B are under bending and beam C and D are under axial loading. So $P = P_A + P_B + P_C + P_D = \frac{AE\delta}{l} + \frac{AE\delta}{l} + \frac{3EI_y\delta}{l^3} + \frac{3EI_y\delta}{l^3}$

$$\delta = \left[\frac{P}{\frac{2AE}{l} + \frac{6EI_y}{l^3}} \right] \quad (1)$$

Now for beam A, $P_A = \left[\frac{3EI_y\delta}{l^3} \right]$, Put the δ from (1), $P_A = \left[\frac{3PI_y}{2Al^2 + 6I_y} \right]$

Moment M_A at the end of beam A can be written as, $M_A = P_A \times \frac{l}{2} = \left[\frac{3PI_y}{2Al^2 + 6I_y} \right] \times \frac{l}{2}$

Moment at arbitrary point x leads to, $M_A = \left[\frac{3PI_z}{2Al^2 + 6I_y} \right] \times \left(x - \frac{l}{2} \right)$ (2)

From Hook's law, $\sigma = \varepsilon E$ and From Bending equation, $\sigma = \frac{My}{I}$

So, $\varepsilon E = \frac{M_A y}{I_y} = \frac{M_A y}{I_y E} = \frac{M_A}{EZ_{py}} \quad \left(\because Z_{py} = \frac{I_y}{y} \right)$ (3)

From (2) and (3) strain on upper and lower part of beam is given as,

$$\varepsilon_U = \left[\frac{3PI_y}{2Al^2 + 6I_y} \right] \times \left(x - \frac{l}{2} \right) \times \frac{1}{EZ_{py}} \quad \text{and} \quad \varepsilon_L = \left[\frac{-3PI_y}{2Al^2 + 6I_y} \right] \times \left(x - \frac{l}{2} \right) \times \frac{1}{EZ_{py}} \quad (4)$$

3.2 Calculation for measuring strain due to force $F_z = P$ N.

From Figure 2(D), it is observed that beam A, B, C and D are under bending. Under the effect of applied force P , the produced reaction force P_A, P_B, P_C and P_D can be represented as,

$$P = P_A + P_B + P_C + P_D = \frac{3EI_z\delta}{l^3} + \frac{3EI_z\delta}{l^3} + \frac{3EI_z\delta}{l^3} + \frac{3EI_z\delta}{l^3}$$

Similar to previous case for beam C, strain on upper and lower part of beam is given as,

$$\varepsilon_U = \left[\frac{P}{4} \right] \times \left(y - \frac{l}{2} \right) \times \frac{1}{EZ_{pz}} \quad \text{and} \quad \varepsilon_L = \left[\frac{-P}{4} \right] \times \left(y - \frac{l}{2} \right) \times \frac{1}{EZ_{pz}} \quad (5)$$

3.3 Calculation for measuring strain due to moment M_x (or M_y) = M Nm.

Figure 2(C), shows free body diagram when moment M Nm applied about X axis. Reaction generated due to application of moment are represented in the same.

Moment M_C at the end of beam C can be written as, $M_C = \frac{M_x}{2}$

The forces F_{CY} , F_{CZ} and moment M_C as referred in [3] can be written as, $F_{CY} = \frac{AE d \theta^2}{l}$,

$$F_{CZ} = \frac{12EI_z \theta}{l^3} \left(d + \frac{l}{2} \right) \text{ and } M_C = \frac{12EI_z \theta}{l^2} \left(\frac{d}{2} + \frac{l}{3} \right) \quad (6)$$

By using moment equilibrium condition, $\frac{M_x}{2} = dF_{CZ} + M_C$ (7)

From (6) and (7) $\theta = \frac{M_x/2}{\left[\frac{12EI_z d}{l^3} \left(d + \frac{l}{2} \right) + \frac{12EI_z}{l^2} \left(\frac{d}{2} + \frac{l}{3} \right) \right]}$ (8)

Moment at arbitrary point y leads to, $M_{C'} = M_C - yF_{CZ} = \frac{12EI_z \theta}{l^2} \left[d \left(\frac{1}{2} - \frac{y}{l} \right) + l \left(\frac{1}{3} - \frac{y}{2l} \right) \right]$ (9)

The equations for analysing the strains on the upper and lower part of plate-beam C can be developed by uniting the strain developed due to tension and bending, can be expressed as,

$$\varepsilon_U = \frac{6h\theta}{l^2} \left[d \left(\frac{1}{2} - \frac{y}{l} \right) + l \left(\frac{1}{3} - \frac{y}{2l} \right) \right] + \frac{d\theta^2}{l} \text{ and } \varepsilon_L = \frac{-6h\theta}{l^2} \left[d \left(\frac{1}{2} - \frac{y}{l} \right) + l \left(\frac{1}{3} - \frac{y}{2l} \right) \right] + \frac{d\theta^2}{l} \quad (10)$$

3.4 Calculation for measuring strain due to moment $M_Z = M \text{ Nm}$.

Figure 2(E), indicates reaction forces and moments generated at the end of beams A, B, C and D due to moment $M \text{ Nm}$ applied about Z axis.

Moment M_A at the end of beam A can be written as, $M_A = \frac{M_Z}{4}$

As in previous case we can find $\theta = \frac{M_Z/4}{\left[\frac{12EI_y d}{l^3} \left(d + \frac{l}{2} \right) + \frac{12EI_y}{l^2} \left(\frac{d}{2} + \frac{l}{3} \right) \right]}$ and equation for analysing

the strains on the upper and lower part of plate-beam A can be developed by uniting the tension strain and the bending strain, which are written as,

$$\varepsilon_U = \frac{6b\theta}{l^2} \left[d \left(\frac{1}{2} - \frac{x}{l} \right) + l \left(\frac{1}{3} - \frac{x}{2l} \right) \right] + \frac{d\theta^2}{l} \text{ and } \varepsilon_L = \frac{-6b\theta}{l^2} \left[d \left(\frac{1}{2} - \frac{x}{l} \right) + l \left(\frac{1}{3} - \frac{x}{2l} \right) \right] + \frac{d\theta^2}{l} \quad (11)$$

Equations (4), (5), (9), (10) and (11) can be used to estimate strain in the beams at particular point from inner ring end on beam when Force and/or Moment is apply on transfer ring, where $A = b \times h$, $I_y = \frac{hb^3}{12}$, $Z_{py} = \frac{hb^2}{6}$, $I_z = \frac{bh^3}{12}$ and $Z_{pz} = \frac{bh^2}{6}$. These set of equations also can be used to estimate force and/or torque produced for a known values of strain applied.

4 COMPARISON BETWEEN STRAIN MEASURED BY ANALYTICAL AND ANSYS

By applying different forces and moments, strain values are found out using analytical equations derived in section III and using ANSYS. Strain values found out by both methods are compared and % error is calculated. Results of calculation are tabulated in Table 2.

Parameters	Strain calculation methods		Error %
	Strain in ANSYS	Strain by equations	
$F_y = 120\text{N}$ $x = 12\text{mm}$	9.8644×10^{-7}	9.9243×10^{-7}	0.60%
$F_z = 120\text{N}$ $y = 12\text{mm}$	1.1679×10^{-5}	1.1620×10^{-5}	0.51%
$M_x = 48\text{Nmm}$ $y = (-12)\text{mm}$	1.6627×10^{-7}	1.6755×10^{-7}	0.75%
$M_z = 48\text{Nmm}$ $x = (-12)\text{mm}$	1.0250×10^{-7}	1.0193×10^{-7}	0.56%

Table 2: Comparison Between ANSYS And Analytical

5 CONCLUSION

The sensor design is based on results of parametric analysis done in ANSYS software to obtain the strain values in the measurable range. The FEA (ANSYS) results are compared with analytical results. The percentage error in deviation is 0.73% maximum. So it allows to use derived analytical equations for further optimization of design and if strain generated due to Force/Torque in beam can be found out by any means (using strain gauges) these equations can also be used for finding the force and/or torque value. The six-axis Force/Torque sensor can also be optimized with the help of analytical equations derived for six axis F/T sensor. These equations can also be verified by performing experimental strain analysis of six-axis Force/Torque and can be compared with the analytical analysis and FEM analysis.

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