Development of a Joint Torque Sensor Fully Integrated with an Actuator

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Abstract : This paper suggests the new type of a joint torque sensor which is attached at each joint of a manipulator for making compliance. Previous six axis force/torque sensors are high cost and installed end-effector of the manipulator. However, torque on links of previous an end-effector cannot be measured. We design a joint torque sensor that can be fully integrated with an actuator in order to measure applying torque of the manipulator. The sensor system is designed through the structural analysis. The proposed joint torque sensors are installed to the 6 DOF manipulator of a mobile robot for hazardous works and we implemented experiments of measuring applied torque to the manipulator. By the experiment, we proved that the proposed low-cost joint torque sensor gives acceptable performance when we control a manipulator.

Keywords: joint torque sensor, ROBHAZ, manipulator and compliance control

1. INTRODUCTION

These days, a new application of robotics is appearing, e.g. the areas of field, hazard work and service robot. This robot is used in hazardous works instead of human being, protecting him from danger.

Mostly, hazardous working robots consist of a mobile and a manipulator such as ROBHAZ developed in KIST(Korea Institute Science and Technology) [13]. While a mobile gets to the place with hazardous material, a manipulator is used for treating it. Because it is very dangerous to access and treat it hazardous works, we operate a robot via remote control. When we control manipulator through remote control, it could collide with surroundings because an operator does not know information of the environment and he may make a mistake. This case is very dangerous in hazardous work. Therefore, a proximity sensor can be installed to manipulator not to collide with surroundings or obstacles [12]. However, because proximity sensor should cover the whole manipulator, hardware of robot system becomes very complicated. Also, when manipulator collides with surroundings, we can protect manipulator by force control. However, we must measure external force to enable force control. Previously, the six axis joint force/torque sensor was installed in the end-effector of a manipulator to control force [4]. In this case, the sensor has high cost and it is unable to measure external force exerted on only end-effector of manipulator. To overcome this problem, Hombot in KIST and DLR manipulator were controlled by measured torque of every joint torque sensor [7],[11]. In general control of the manipulator, it is difficult to apply to measure external force except end-effector of manipulator in hazardous works because it is applied in end-effector of the manipulator. Consequently, we must install the joint torque sensors to measure torque in every joint. There are many types of previous joint torque sensors like a type of circular with cross beam [5], hollow hexaform [6] and etc. However, the structure of manipulator should be complicated to install previous joint torque sensors on a manipulator.

In this paper, we suggest a new type of torque sensor which can measure the torque at each joint and can be easily installed on a manipulator. We apply the proposed torque sensor to 6DOF manipulator's each joint of ROBHAZ which is developed at KIST, and implement compliance control. The discussion in this paper focuses on a design of the joint torque sensor and verifies its performance.

This paper is organized as follows section 2 explains the design of a joint torque sensor. Section 3 presents compliance control with the joint torque sensor. Section 4 deals with experiment and result. Finally, the conclusion and future work are made in section 5.

2. DESIGN OF A JOINT TORQUE SENSOR

In this chapter, we describe how our proposed joint torque sensor has been designed, and what are its characteristics compared with the previous joint torque sensors.

2.1 Sensor design

The proposed joint torque sensor is designed as a fully integrated type with actuator compare to the general type of joint torque sensors(Fig. 1(a)). When we design the sensor, we consider followings:

1. The type being capable of fully integrated with actuator.
2. Sensitivity of the sensor.
3. Strength of the sensor.
4. Material of the sensor.

Firstly, the main target of the proposed joint torque sensor is to meet a modular design integrate the actuator. The joint torque sensor must be satisfied with above the other condition. Secondly, the joint torque sensor should be sensitive to the applied torque. The sensitivity is related with the strain of the sensor like Eq. (1) [3].

$$\sigma = \varepsilon E \tag{1}$$

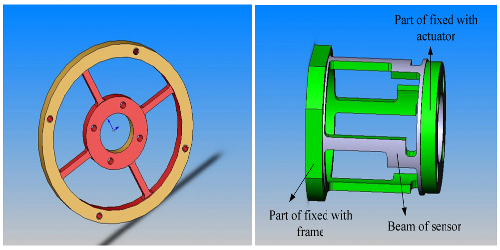
where σ , ε and E are the stress, the strain and the Young's modulus, respectively.

The sensitivity of the sensor can be improved by large strain.

Thirdly, the sensor should have enough strength to endure the applied torque on the sensor. Otherwise would occur to plastic deformation. As mentioned above, we should determine material and structure of the sensor to satisfy the condition. Basically, the chosen sensor material must have a linear strain-stress relation. And in the Eq. (1), high strain and low stiffness are occurred as young module is low under the constant stress. Therefore, as the material of sensor, duralumin and steel are chosen to satisfy linear strain-stress relation, high sensitivity and high stiffness. A result of the test experiment shows that strain of duralumin is higher than that of steel but stiffness of duralumin is lower than that of steel. Due to these properties of duralumin, it has hysteresis. On the other hand, strain of steel is lower than that of duralumin but stiffness of steel is higher than that of duralumin. Therefore, it does not have hysteresis.

For this reason, steel is chosen as a material of torque sensor. And we designed the sensor as a structure of fully integrated with a actuator shown as Fig. 1(b).

As a result of design by the structure analysis program, install places of strain gauges are determined to enable maximum strain is occurred as shown in Fig. 2(b). Fig. 2(c) shows the distribution of FOS (Force of safety: limit stress/ apply stress) when torque is applied to the sensor. FOS should be lager than one. In fig. 2(d), the blue area means that FOS is over 1.5 and the red area does FOS below 1.5. And minimum FOS of the red area is 1.1 in the Fig. 2(c). Through this process, we optimized the sensor dimension and the size and place of strain gauges.



(a) (b)

Fig. 1 (a) General type of a joint torque sensor (b) The type of proposed joint torque sensor

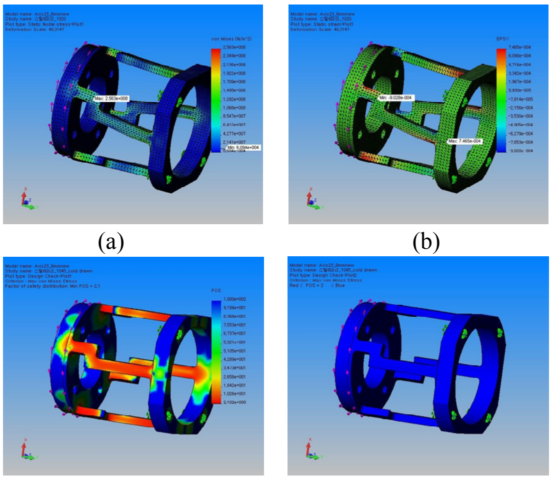


Fig. 2 The result of structure analysis : (a) The stress distribution (b) The strain distribution (c) The FOS of joint torque sensor. (d) The FOS of joint torque sensor

2.2 Sensor characteristic and installation on the manipulator.

The proposed joint torque sensor has characteristics compared with previous joint torque of sensors. Firstly, because the proposed joint torque sensor can be fully integrated with an actuator, complicated structure is not needed to install the sensor. Secondly, because the deformable part of torque sensor is parallel with the axis of applied torque as shown in Fig 1, we can make the radius of the joint torque sensor smaller than previous sensors. Thirdly, due to its structural characteristics it measures only pure toque without disturbance by other components of the torque on the sensor. Fourthly, because the torque sensor is fixed without rotation, it is easy for wiring compared with previous torque sensors.

The proposed torque sensor combined with an actuator is shown in Fig. 3. Adopting the developed sensor, 6 DOF(Degree Of Freedom) manipulator of ROBHAZ is made. It use the sensor at all joints except axis 1 because a harmonic gear is installed into axis 1, a general type torque sensor is used as shown Fig. 1(a). Basically, the torque sensors are installed at axis 2,3,4,5,6 have the same structure and sensor dimension and size are determined by applying torque and the size of an actuator. As a result, three types of sensors are designed and installed. Axis 2 and axis 3 use the same torque sensor, axis 5 and 6 use the same and axis 4 use its own.

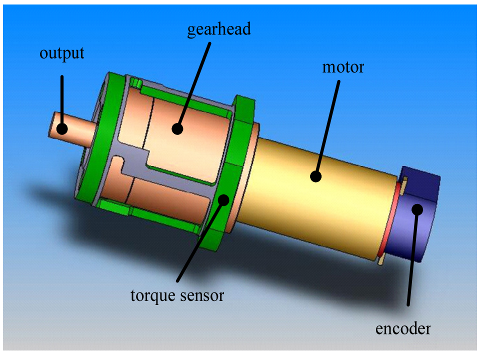


Fig. 3 Combined torque sensor with an actuator

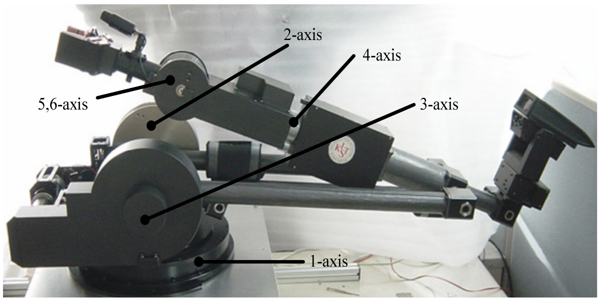


Fig. 4 Installation of joint torque sensors on the manipulator

3. COMPLIANCE CONTROL WITH JOINT TORQUE SENSOR

3.1 Sensor calibration

The four strain gauges are attached at four points where the maximum strain occurs. These four strain gauges constructs a full wheatstone-bridge. The torque is converted to the voltage through the INA amp board and the A/D converter which has 10 bit resolution. Experimental equipment for the sensor calibration is shown Fig. 5. Fig. 6 shows the voltage output versus the applied torque. This experiment result is about the sensor of axis 2 amongst six sensors in the manipulator. As shown in Fig. 6, the torque versus the voltage output becomes linear within 0.2% maximum error by curve-fitting. We have the same results with the other sensor.

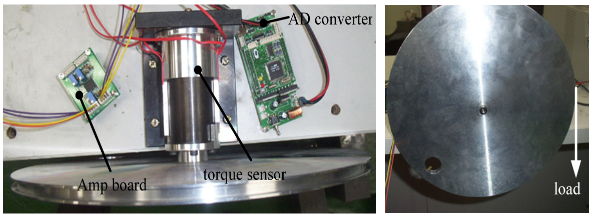


Fig. 5 Experiment for calibration of torque sensor

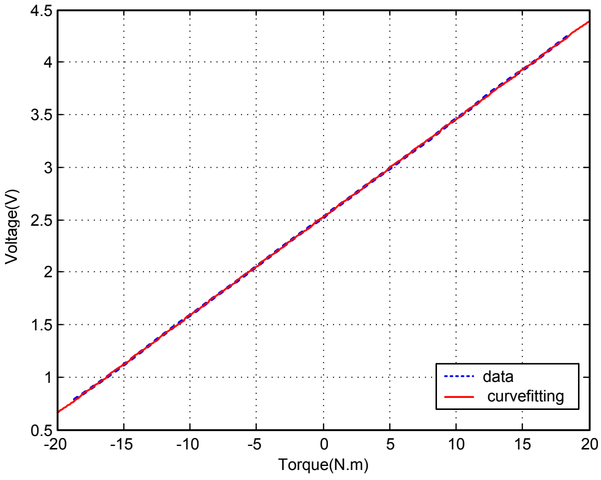


Fig. 6 Sensor output versus applied torque (2,3 axis)

There is a difference between the sensitivity and the resolution from Table. 1. It is because the misplacement during strain gauge installation and the noise from the power source.

Table 1. Specification of sensors

	Sensing sensitivity	Sensing resolution	Max. torque
2,3axis	0.054Nm	0.324Nm	20N.m
4 axis	0.028Nm	0.167Nm	13.25N.m
5,6axis	0.014Nm	0.084Nm	6N.m

3.2 Gravity compensation

The dynamic equations of the manipulator can be written as follows :

$$\boldsymbol{\tau}_L = \boldsymbol{\tau}_s + \boldsymbol{F}_L(\dot{\boldsymbol{\theta}}, sign(\dot{\boldsymbol{\theta}})) \qquad (2)$$

$$\boldsymbol{\tau}_s = \boldsymbol{M}_L(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \boldsymbol{V}_L(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \boldsymbol{G}(\boldsymbol{\theta}) + \boldsymbol{\tau}_{ext} \qquad (3)$$

where $\boldsymbol{\tau}_L$ is the 6×1 link driving torque. $\boldsymbol{\tau}_s$ is the 6×1 joint's torque measurement. $\boldsymbol{F}_L(\dot{\boldsymbol{\theta}}, sign(\dot{\boldsymbol{\theta}}))$ is a 6×1 viscous and Coulomb friction. $\boldsymbol{\theta}$ is the 6×1 vector of the joint angles. $\boldsymbol{M}_L(\boldsymbol{\theta})$ is the 6×1 mass matrix. of the manipulator. $\boldsymbol{V}_L(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$ is 6×1 vector of centrifugal and Coriolis terms. $\boldsymbol{G}(\boldsymbol{\theta})$ is a 6×1 vector of gravity terms. $\boldsymbol{\tau}_{ext}$ is the 6×1 external torque on the manipulator.

From the Eq. (2) and Eq (3), The measurement of joint torque include also inertia force, centrifugal, Coriolis force and gravitational force of links. So, the external torque can not be measured directly by joint torque sensors. To measure external torque should compensate above the forces. However, from the Eq. (2) and Eq (3), if the manipulator moves in a very slow speed, the dynamic forces can be set to zero approximately, i.e., $\boldsymbol{M}_L(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} \approx 0$, $\boldsymbol{V}_L(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) \approx 0$ and $\boldsymbol{F}_L(\dot{\boldsymbol{\theta}}, sign(\dot{\boldsymbol{\theta}})) \approx 0$. Therefore, if the gravity force is compensated in the whole workspace. At the equilibrium state the external force can be calculates as:

$$\boldsymbol{\tau}_{ext} = \boldsymbol{\tau}_s - G(\boldsymbol{\theta}) \qquad (4)$$

$$\boldsymbol{G}(\boldsymbol{\theta}) = \left[g_1, g_2, g_3, g_4, g_5, g_6\right]^T \qquad (5)$$

$$\begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \\ g_5 \\ g_6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ c_2 & s_{23} & s_2 & c_{23} & s_{23}c_5 + c_{23}c_4s_5 & 0 \\ 0 & s_{23} & s_2 & c_{23} & s_{23}c_5 + c_{23}c_4s_5 & 0 \\ 0 & 0 & 0 & 0 & -s_{23}s_4s_5 & 0 \\ 0 & 0 & 0 & 0 & c_{23}s_5 + s_{23}c_4c_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \\ k_5 \\ k_6 \end{bmatrix} \qquad (6)$$

where g_i is torque by gravity, k_i is gravitational constants. (i : axis number)

The gravity effect due to the configuration of the manipulator has been compensated by the experimental data.

3.3 Compliance control

Since torque sensors are installed each joint, we can measure external force applying at any location of the manipulator while a six axis force/torque sensor attached at the end-effector of the manipulator. Based on this advantage, the torque can be converted to the angle in Eq. 7.

$$\boldsymbol{\tau}_{ext} = \boldsymbol{C}\Delta\boldsymbol{\theta}_C \qquad (7)$$

where, C is the compliance, $\Delta\theta_C$ is the angle corresponding to applied torque.

We can control the joint level compliance by control the angle as shown Fig. 7.

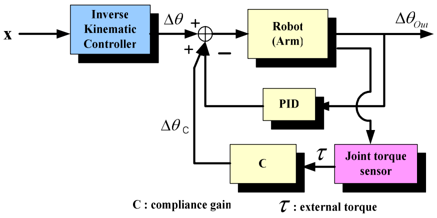


Fig. 7 Joint level compliance control

4. EXPERIMENT AND RESULT

We install the proposed torque sensor on 6DOF manipulator's each joint of ROBHAZ which is developed at KIST such as section 2.2 The manipulator is controlled using DSP2812 and CAMA board which is motor controller [14]. The manipulator is interfaced with motion board via CAN-BUS. Each torque of joint is measured using propose d joint torque sensor. The joint torque sensor is interfaced with the INA amp board and the AD converter. In order to verify performance of the proposed joint torque sensor, we experimented about two cases. The case one is applying force to the end-effector of the manipulator and the other case is applying force to the 2-axis of the manipulator. The results are shown in Figs. 8~9.

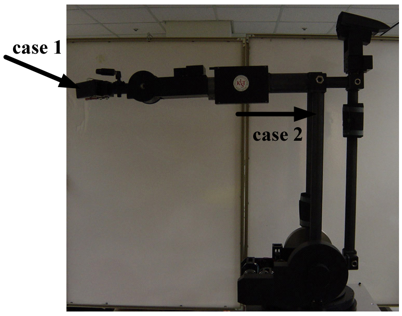


Fig. 8 The environment of experiment.

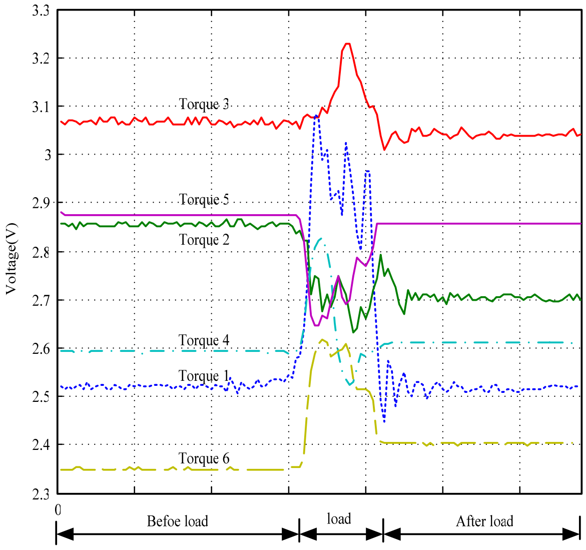


Fig. 9 The result of the case 1.

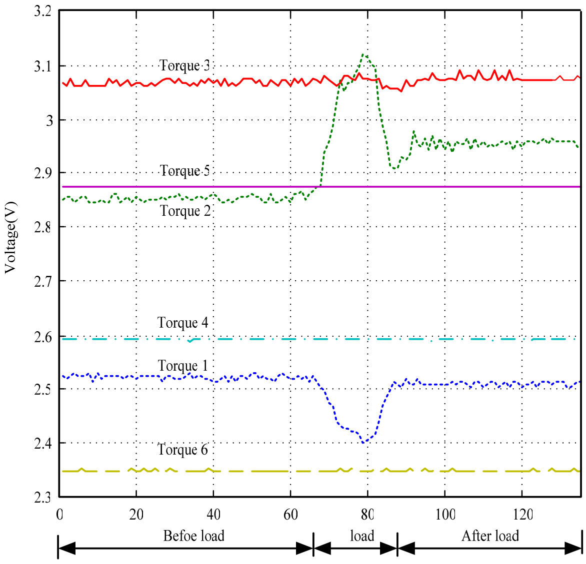


Fig 10 The result of the case 2.

In the above result, we can see that our system measures torque at not only end-effector but also a previous link.

5. CONCLUSION AND FUTURE WORK

In this paper, we designed a new type of a joint torque sensor to measure the joint torque of the manipulator and described about the performance of the sensor. The proposed joint torque sensor has the linearity about the applied torque. By the experiment, when we applied the proposed joint torque sensor to manipulator, the proposed joint torque sensor is verified better performance than previous six axis joint force/torque sensor. Consequently, we develop the low cost joint torque sensor and can control the joint level compliance through measuring every joint torque. Using this advantage, when we remotely control the manipulator, it can be protected from unexpected collision in everywhere of the manipulator. In future, we will implement not only control of joint level compliance but also control of cartesian level compliance. Then, we will develop the integration system interfaced the manipulator and remote controller, the haptic device. We can transfer the measured torque of the manipulator to the haptic device in the integration system.

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