

# Performance Improvement of a 6-Axis Force-torque Sensor via Novel Electronics and Cross-shaped Double-hole Structure

Chul-Goo Kang

**Abstract:** Performance of a force-torque sensor is affected significantly by an error signal that is included in the sensor signal. The error sources may be classified mainly into two categories: one is a structural error due to inaccuracy of sensor body, and the other is a noise signal existing in sensed information. This paper presents a principle of 6-axis force-torque sensor briefly, a double-hole structure to be able to improve a structural error, and then a signal conditioning to reduce the effect of a noise signal. The validity of the proposed method is investigated through experimental study, which shows that S/N ratio is improved significantly in our experimental setup, and the sensor can be implemented cheaply with reasonable performance.

**Keywords:** Force-torque sensor, noise reduction, microcontroller, LabVIEW, force sensor.

## 1. INTRODUCTION

Performance of a force-torque sensor is affected significantly by an analog noise that is included in a sensor signal, and the noise signal should be reduced appropriately to obtain an adequate performance of the sensor. Generally in 6-axis force-torque sensors, sensed force information always includes some errors. These errors may be classified mainly into two categories: one is a structural error due to the shape of elastic member and inaccuracy of a sensor body. Coupling effect among axes is one example of this kind of error. The other is a noise signal included in a sensor output signal. Generally the sensor output is an analog signal such as voltage and is a low-level small signal, and so is easily contaminated with noise signals due to several noise sources. Most significant examples of noise sources are electromagnetic waves emitted from computers or electronic devices, and 60 Hz periodic noises by AC electric sources.

The structural error can be eliminated to some extent via a good mechanical design and compliance matrix technique that are well investigated in the literatures [1-3]. However, research on noise reduction of force-torque sensors is not sufficiently published.

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processes, particularly in contacting processes of end effector with environment is required for the precise manipulation of robot and the protection of workpiece as well as robot system itself. For this force control purpose, a multi-axis force sensor, usually 6-axis force-torque sensor is utilized in order to measure the magnitude and direction of contacting force. The 6-axis force-torque sensor is usually attached to the robot wrist, that is, between end effector and robot arm. In this case, the sensor size and weight are usually restricted to be small to minimize the dynamic effect of the sensor itself on the robot system. In this viewpoint, a strain gage type sensor is one possible choice for this purpose.

The 6-axis force-torque sensor of the strain gage type usually measures surface strain of elastic members inside the sensor using Wheatstone bridges in the form of analog voltages, and then amplifies the voltage signals and converts them to digital numbers. The linear relationship between external force and measured voltage is satisfied within the prescribed force range.

In the 1990s, systematic design methods of multi-axis force-torque sensors are proposed. For force-torque sensors, Uchiyama et al.[4] and Bayo et al.[5] have proposed the condition number of compliance matrix to be the performance index of the sensor, and have shown that the smaller the condition number, the smaller the force-sensing error from given strain measurement error by using singular value decomposition of the compliance matrix. Nakamura et al.[6] has proposed that three standard design criteria, that is, strain gage sensitivity, force sensitivity, and minimum stiffness should be used instead of the condition number of the compliance matrix for optimum design of the sensor. However Bicchi [7] has

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generalized the condition number of the compliance matrix and again proposed that the condition number could be the performance index of the sensor design. Svinin et al.[8] have shown that the condition number of an elastic structure is able to be derived analytically without resort to FEM analysis.

Similar structures of the elastic member of the sensor were proposed before [9-11], but those have more complex holes or grooves compared to the one in this paper and could be more expensive in manufacturing. The above papers and patent do not consider signal conditioning aspects, but mechanical structural aspects of the sensor.

Recently a novel idea to detect force/moment direction without measuring its magnitude was proposed and demonstrated by Choi and Kim [12], and applied to robot teaching [13]. Also, a new tension-based 7 DOF force feedback device with 6 DOF motion and 1 DOF force (called SPIDAR-G) was proposed and applied successfully to the realization of virtual reality [14].

When three directional force components and torque components acting on a sensor body are obtained from deformations of the elastic member, force-sensing errors are due not only to the measurement errors of surface strains but also to the compliance matrix errors. The compliance matrix is a linear transformation from surface strain vector to force vector, and is of crucial importance for the accuracy of the sensor.

Force-sensing error due to the strain measurement error was studied at the references cited above, and the force-sensing error due to compliance matrix error was analyzed by Kang [2]. Furthermore, the structural force-sensing error, i.e., the measurement error propagation due to elastic structure, is analyzed in a unified way for the case where both strain measurement error and compliance matrix error exist, and the upper bound of the force-sensing error is derived by Kang [1].

This paper presents a force-sensing principle of a 6-axis force-torque sensor consisted of a cross-shaped double-hole elastic member and Wheatstone bridges, and shows noise-reducible communication method and verifies it through experimental study. With the proposed method, we develop a cheap and compact force-torque sensor.

This force-torque sensor acquires force information by amplifying low-level voltage signals in proportion to external force. In this process, several noise signals are added to useful voltage signals and aggravate S/N ratio of the sensor output. These noise signals are originated from several sources. In order to improve the sensor performance, we need to find an appropriate way to reduce the noise signals.

In this paper, we reduce the noise effect by packaging all the analog and digital electronics inside

the sensor body and converting the voltage signal to digital signal inside the sensor body and then by transmitting the digital signal to the computer. By this way, we can remove the noises due to electromagnetic waves, which contaminate the signal when reading analog voltage in the computer, and due to AC electric source that generate 60 Hz periodic noise in the sensor output. Generally, it is difficult to install all digital electronics of the 6-axis force-torque sensor inside sensor body because of physical space limitation. Many commercial products of a multi-axis force-torque sensor use a separate signal amplifier and conditioning module existing outside the sensor body, and so it is vulnerable for the signals to be contaminated by noises easily. In the proposed sensor system, PIC microcontroller and MPASM assembly program are utilized in the sensor body electronics, and NI multipurpose I/O board with LabVIEW program are utilized in the PC side.

The paper is organized as follows. Section 2 presents briefly the principle of the 6-axis force-torque sensor developed in the paper, and Section 3 describes mechanical structure of the proposed sensor with cross-shaped double-hole structure. In Section 4, performance improvement via novel electronics is explained and in Section 5, experimental results of the sensor are discussed. Concluding remarks are given in Section 6.

## 2. PRINCIPLE OF A 6-AXIS FORCE-TORQUE SENSOR

When an external force acts on a sensor body, the force-torque sensor detects elastic deformation of the internal structure of the sensor and transforms the deformation to voltage or digital value and calculates the six components (or parts of them) of the acting force. The elastic deformation is usually detected by means of strain gages, optoelectronics [15], inductive displacement transducers [16], CCD elements [17], or LVDT [18].

We consider in this paper a 6-axis force-torque sensor using strain gages that enable to figure out force and torque by detecting its surface strain of the elastic member.

If the elastic deformation of the internal member in the sensor is within elastic limit, the relationship between maximum surface strain of the internal structure and the applied force on the sensor can be written as follows.

$$\hat{\mathbf{C}} \hat{\mathbf{f}} = \hat{\boldsymbol{\varepsilon}}, \quad (1)$$

where  $\hat{\mathbf{f}}$  is a measured  $n \times 1$  force vector whose components are consisted of force components and/or moment components,  $\hat{\boldsymbol{\varepsilon}}$  is a measured  $m \times 1$  strain vector whose components are consisted of  $m$  strain

measurements of  $m$  points on the internal structure,  $\hat{\mathbf{C}}$  is a measured  $m \times n$  compliance matrix or calibration matrix. We assume that  $m \geq n$  and  $\text{rank}(\hat{\mathbf{C}}) = n$  without losing generality. The condition  $m \geq n$  implies that the number of strain measurement points is equal to or greater than the number of force components we want to seek. Generally  $n$  is equal to or less than 6. The condition  $\text{rank}(\hat{\mathbf{C}}) = n$  can be easily satisfied from the physical point of view.

The vector  $\hat{\mathbf{f}}$  includes force and moment components together, and so the property of the matrix  $\hat{\mathbf{C}}$  depends on the units of force and moment. In order to remove this inconvenience, we express force and strain vectors in dimensionless vectors using square matrices  $\mathbf{N}_f$  and  $\mathbf{N}_\varepsilon$  in which the diagonal elements are consisted of allowable maximum values of each component. That is, we obtain dimensionless force vector  $\mathbf{f}$  and dimensionless strain vector  $\varepsilon$  as follows:

$$\hat{\mathbf{f}} = \mathbf{N}_f \mathbf{f}, \quad \mathbf{N}_f = \text{diag}\{f_{1M}, f_{2M}, \dots, f_{nM}\}, \quad (2)$$

$$\hat{\varepsilon} = \mathbf{N}_\varepsilon \varepsilon, \quad \mathbf{N}_\varepsilon = \text{diag}\{\varepsilon_{1M}, \varepsilon_{2M}, \dots, \varepsilon_{mM}\}, \quad (3)$$

where  $f_{iM}$  indicates a maximum force (N) or moment (N·m) of each axis given as design criteria, and  $\varepsilon_{jM}$  indicates absolute value of maximum strain on the  $j$ th strain gage when  $n$   $f_{iM}$  acts on the sensor independently. The unit of the strain could be  $\mu\text{m}/\text{m}$  or volt converted by amplifiers. In this way, the condition number of the compliance matrix becomes 1 in an ideal sensor that  $m = n$  and there is no cross coupling among axes.

Dimensionless force and strain vectors have following relationship.

$$\mathbf{C} \mathbf{f} = \varepsilon, \quad (4)$$

where  $\mathbf{C}$  shows dimensionless compliance matrix that can be written as

$$\mathbf{C} = \mathbf{N}_\varepsilon^{-1} \hat{\mathbf{C}} \mathbf{N}_f. \quad (5)$$

The solution of the linear algebraic equation (4) can be considered in two different cases. One is where there are no errors at  $\mathbf{C}$  and  $\varepsilon$ . In this case,  $\text{rank } \mathbf{C} = \text{rank} [\mathbf{C} : \varepsilon]$  is satisfied, i.e.,  $\varepsilon$  is included in the range space of  $\mathbf{C}$ , and so there exists a unique solution  $\mathbf{f}$ . The other case is where  $\text{rank } \mathbf{C} < \text{rank} [\mathbf{C} : \varepsilon]$  is satisfied, i.e.,  $\varepsilon$  is not always included in the range space of  $\mathbf{C}$ , and so a unique solution  $\mathbf{f}$  doesn't necessarily exist. In this case, (4) should be written as

$$\mathbf{C} \mathbf{f} \approx \varepsilon$$

and by this, we can obtain an approximate solution instead of the solution. In other words, we can find an approximate solution  $\mathbf{f}$  which minimizes  $\|\mathbf{C} \mathbf{f} - \varepsilon\|$  by considering this problem as a least square problem of full rank. In this paper,  $\|\cdot\|$  represents Euclid norms of vectors or Euclid induced norms of matrices. Note that the Euclid induced norm of a matrix is equal to the maximum singular value of the matrix.

The above-mentioned solution of the first case and the approximate solution of the second case can be obtained by following normal equation

$$\mathbf{C}^T \mathbf{C} \mathbf{f} = \mathbf{C}^T \varepsilon. \quad (6)$$

From (6), the following solution or approximate solution is obtained.

$$\mathbf{f} = \mathbf{C}^+ \varepsilon, \quad (7)$$

where  $\mathbf{C}^+ = (\mathbf{C}^T \mathbf{C})^{-1} \mathbf{C}^T$ , and  $\mathbf{C}^+$  is the left pseudo-inverse. The left pseudo-inverse is a special case of Moore-Penrose inverse that can be defined in a matrix with non-full rank. Moore-Penrose inverse is derived from the singular value decomposition

$$\mathbf{C} = \mathbf{U} \Sigma \mathbf{V}^T, \quad (8)$$

where  $\mathbf{U}$  is  $m \times m$  orthogonal matrix composed of orthonormal eigenvectors of  $\mathbf{C} \mathbf{C}^T$ ,  $\mathbf{V}$  is  $n \times n$  orthogonal matrix composed of orthonormal eigenvectors of  $\mathbf{C}^T \mathbf{C}$ , and  $\Sigma$  is  $m \times n$  matrix in which  $ij$  elements ( $i \neq j$ ) equal 0 and  $ii$  elements ( $i = 1, \dots, n$ ) equal the singular value  $\sigma_i$  of  $\mathbf{C}$  corresponding to the eigenvectors of  $\mathbf{C}^T \mathbf{C}$ . Then Moore-Penrose inverse  $\mathbf{C}^+$  is given as

$$\mathbf{C}^+ = \mathbf{V} \Sigma^+ \mathbf{U}^T, \quad (9)$$

where  $\Sigma^+$  is  $n \times m$  matrix in which  $ij$  elements ( $i \neq j$ ) equal 0 and  $ii$  elements ( $i = 1, \dots, n$ ) equal  $1/\sigma_i$ . Note that the matrix  $\mathbf{C}$  in this paper have  $n$  nonzero  $\sigma_i$ 's since  $\mathbf{C}$  has full rank. The Moore-Penrose inverse  $\mathbf{C}^+$  gets equal to the inverse  $\mathbf{C}^{-1}$  if  $m = n$  and  $\mathbf{C}$  has full rank. Finding  $\mathbf{f}$  in (7) and substituting it into (2), we can obtain the actual force  $\hat{\mathbf{f}}$  acting on the sensor.

Using the Moore-Penrose inverse and formulating as a least square problem of full rank, Kang [1] showed that the structural error  $\|\Delta \mathbf{f}\|/\|\mathbf{f}_o\|$  in force-sensing amount roughly to the sum of two relative

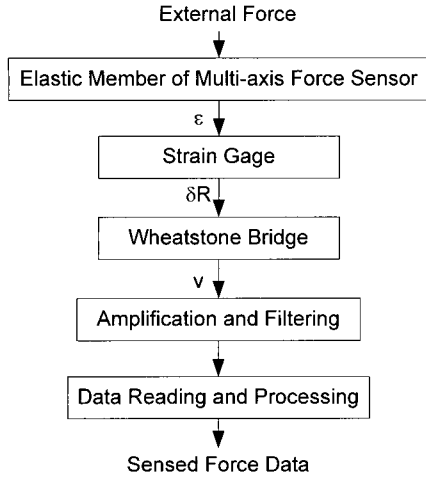


Fig. 1. Functional steps of force-sensing procedure.

errors multiplied by the condition number  $c(\mathbf{C})$  of the compliance matrix and the upper bound is the sum of two relative errors multiplied by  $c(\mathbf{C}) (1 + \alpha)$  where a positive  $\alpha$  is generally much less than 1, if there is a relative error  $\|\Delta\varepsilon\|/\|\varepsilon_o\|$  in strain measurement, and if there is a relative error  $\|\Delta\mathbf{C}\|/\|\mathbf{C}_o\|$  in compliance matrix where  $\mathbf{f} = \mathbf{f}_o + \Delta\mathbf{f}$ ,  $\varepsilon = \varepsilon_o + \Delta\varepsilon$ ,  $\mathbf{C} = \mathbf{C}_o + \Delta\mathbf{C}$  and subscript  $o$  implies nominal values, that is [1],

$$\frac{\|\Delta\mathbf{f}\|}{\|\mathbf{f}_o\|} \leq c(\mathbf{C}) (1 + \alpha) \left( \frac{\|\Delta\varepsilon\|}{\|\varepsilon_o\|} + \frac{\|\Delta\mathbf{C}\|}{\|\mathbf{C}_o\|} \right).$$

Fig. 1 shows functional steps of force-sensing procedure graphically.

### 3. MECHANICAL STRUCTURE OF THE SENSOR

In multi-axis force sensors, sensing performance depends significantly on structural error that are mainly due to the shape of elastic member and inaccuracy of dimensions of sensor body. Inevitable coupling signals among axes can be decoupled using compliance matrix to 100% theoretically (or to most extent practically). In this section, the mechanical structure of the developed sensor is presented, which is a revision of our previous prototype [3]. Our previous model had eight circular holes in the elastic member that had a merit to easily manufacture it but had a disadvantage to have less sensitive to deformation. Our revised model presented in this paper is modified to improve sensitivity to deformation and reliability to environmental disturbances.

The external appearance of the prototype sensor developed in this paper is shown in Fig. 2. The size of

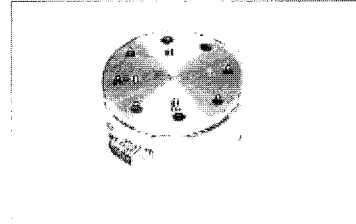


Fig. 2. External appearance of the prototype.

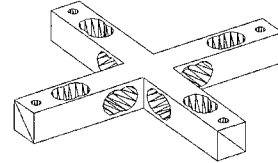


Fig. 3. Cross-shaped elastic member with eight double-holes.

the sensor is  $\phi 76\text{mm} \times 47\text{mm}$ . Inside sensor body, there is a cross-shaped elastic member with eight double-holes as shown in Fig. 3. Two circular holes are drilled and finished adjacently (roughly two centers apart a radius) in the elastic member and total 8 sets of double holes are placed as shown in Fig. 3 in order to increase signal sensitivity. With this double-hole structure, force sensitivity (defined by Nakamura et al.[6]) is improved to 49 compared to 0.24 of our previous single-hole structure even if condition number of the 6x6 compliance matrix is aggravated to 23 from 9.5. This is mainly due to the capability of enough output signal generations in all directions by large surface strains of double-hole structure. Another advantage of this structure is easy machinability, which contributes to cost reduction of the sensor. The compliance matrix of the sensor is shown as follows

$$\mathbf{C} = \begin{bmatrix} 1125 & 7.52 & -0.505 & -4.47 & 13.7 & -18.8 \\ -2.74 & 122 & -3.54 & 7.21 & 5.88 & 10.9 \\ 4.93 & 3.62 & -159 & 14.4 & -9.0 & 1.96 \\ -5.48 & 36.4 & 7.58 & -54.7 & -12.9 & 0.382 \\ 24.2 & -1.61 & 6.12 & -5.31 & -71.9 & -8.78 \\ 2.16 & -0.694 & -2.27 & 3.38 & -3.06 & 60.6 \end{bmatrix}.$$

Fig. 4 shows all the disassembled parts of the sensor, in which design concept is to have high sensitivity to elastic deformation, to have overload protection function, to structurally have reliable electronics, and to be easily manufactured and maintained. In Fig. 4, member 200 is PCBs for electronics, number 110 and 190 are cover plates, and number 130 is a part for bolting cover plates, cross-shaped member and PCBs. 115 and 250 show connector part, and 135 and 175 show supporters of cross-shaped member 150. On each cover plate, there are four metric thread holes for bolting outside objects.

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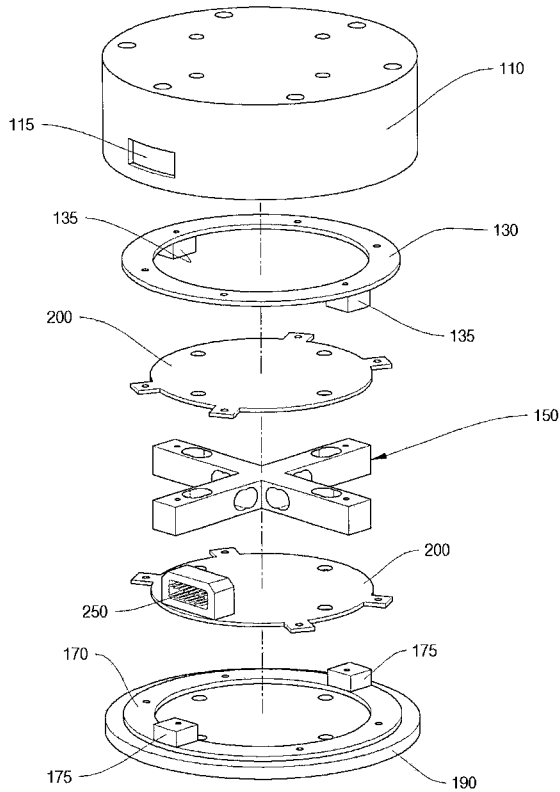


Fig. 4. Disassembled parts of the 6-axis force-torque sensor.

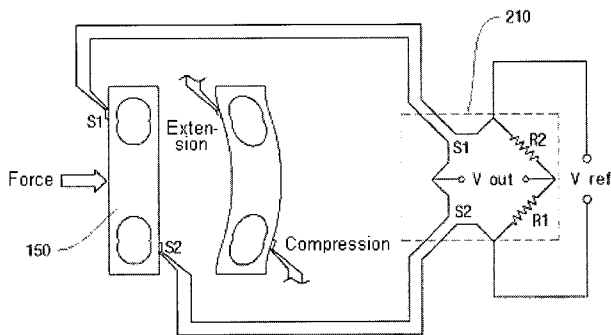


Fig. 5. Strain measurement using Wheatstone bridge.

When an external force is applied to the sensor, the cross-shaped elastic member is elastically deformed and surface strains outside double-holes are measured using Wheatstone bridges as shown in Fig. 5. In order to maximize strain variation, to save economically and to compensate drift signals due to temperature changes, half bridges are adopted. Strain gages are attached as pairs to the points where maximum compressive strain and maximum tensile strain occur. From strains measured at 12 points (using 6 Wheatstone bridges), three directional force and moment components are derived using compliance matrix.

#### 4. NEW ELECTRONICS FOR NOISE REDUCTION

Since the size of a wrist sensor is usually restricted according to the application space limitation of robotic manipulator, the space for electronic components of the sensor is not sufficient in general. Our previous model of the 6-axis force sensor having been developed had compact electronics inside the sensor body that includes 6 Wheatstone bridges and amplifying circuits. Remaining electronic components were installed on the signal processing board in the computer. In this case, the sensor outputs could be contaminated by noise signals such as electromagnetic waves and AC electric source (EMI). In order to improve the sensor output signals, in this paper, we convert the amplified voltage signals to digital values using a microcontroller inside the sensor body and then read them in the computer through parallel communication. Fig. 6 shows an artwork result of the embedded electronics developed in our laboratory, and Fig. 7 shows the signal flow of the improved sensor system using the microcontroller.

In this research, PIC16F877 microcontroller from Microchips Technology, Inc, and a 10 bit A/D converter are used for generation of digital values with compact size and cheap price. Analog voltage signals coming from 6 channels are converted to digital values in every 200 microsecond that is short time enough for our purpose. This 5 kHz speed is a little lower compared to the present leading-edge commercial product, JR3 sensor (expensive) that has 8 kHz data rate. This speed can be improved by using more expensive microcontroller and peripheral chips, but we tried to develop the sensor as cheap as possible with maintaining acceptable necessary performance.

The converted digital values are read via PCI I/O board in every 6 millisecond by using software timer in LabVIEW software. The flowchart of assembly program of the PIC microcontroller is shown in Fig. 8.

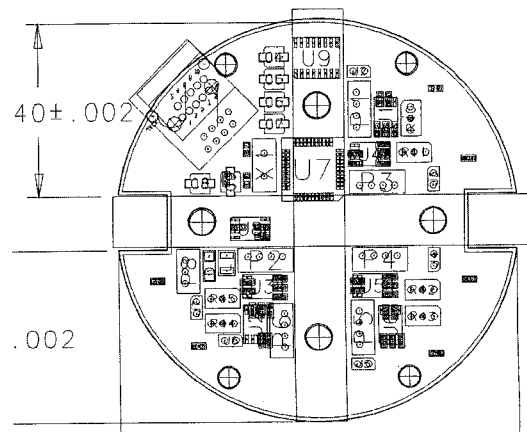


Fig. 6. Artwork of the embedded electronics.

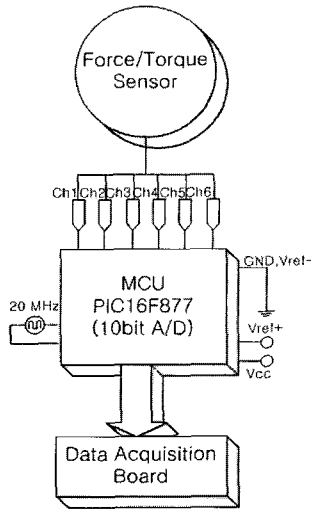


Fig. 7. Signal flow of the improved sensor system using the microcontroller.

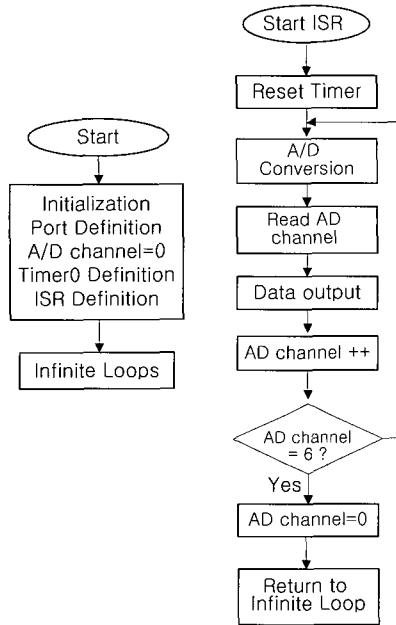


Fig. 8. Flowchart of a PIC microcontroller program.

LabVIEW program is used for data reading and plotting. In the LabVIEW program, C language-type programming is conducted.

### 5. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, we analyze experimentally how the proposed method improves sensor output signals, and how much the noise effects are reduced. By the proposed method, noise signals are significantly reduced in data transportation and reading processes.

Fig. 9 shows 6 channels' output values read analog voltages at PC I/O board when 98.2 N (10 kg) is applied on the sensor in x direction. Fig. 10 shows

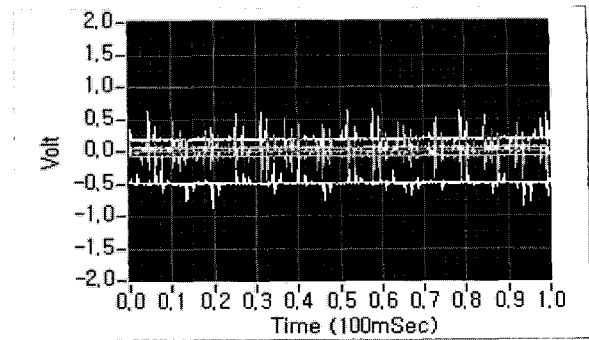


Fig. 9. Experimental 6 channel values when a force (98.2 N) is applied in x direction (analog data acquisition).

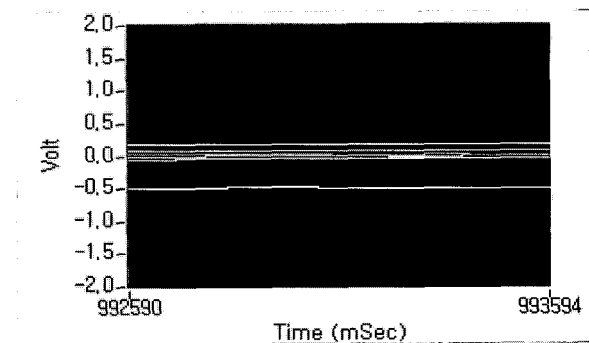


Fig. 10. Experimental 6 channel values when a force (98.2 N) is applied in x direction (digital data acquisition).

output values read 6 channels' values after converting them digitally outside the PC when 98.2 N (10 kg) is applied on the sensor in x direction. In Fig. 10, ordinate voltages are ones corresponding to digital values read. When a moment of 8.83 Nm is applied on the sensor in y direction, Fig. 11 shows output values of 6 channels read analog voltages in the PC and Fig. 12 shows output values of 6 channels read after converting to digital values outside the PC. The magnitude of the moment, 8.83 Nm came from 10 kg x 9.81 m/s<sup>2</sup> x 0.09 m. Figures shown are screen-captured ones of LabVIEW windows generated automatically.

From the experimental results shown in the above figures and other results not shown in the paper, the magnitudes of the useful signals and noise signals for the worst case are summarized in Table 1 for the previous analog method (denoted by analog data acquisition) and for the proposed method (denoted by digital data acquisition) in this paper. Therefore the S/N ratio is about 2.5 in case that analog voltages of 6 channels are read in the computer. However, the S/N ratio is about 100 in case digital values are read in the computer after analog voltages are converted to digital values outside the computer. Here the S/N ratio is not the value expressed in dB but the value expressed by direct division of voltage levels.

Table 1. Summary of experimental data for the magnitudes of signals.

	Signal level	Noise level
Analog data acquisition	2 V	0.8 V
Digital data acquisition	2 V	0.02 V

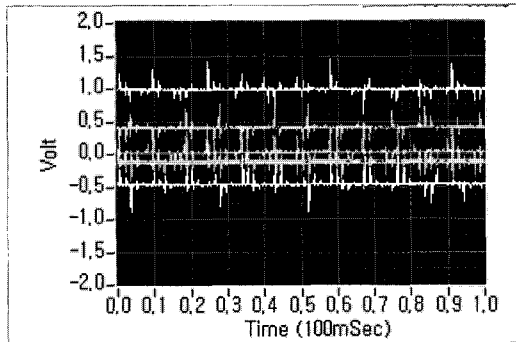


Fig. 11. Experimental 6 channel values when a moment (8.83 Nm) is applied in y direction (analog data acquisition).

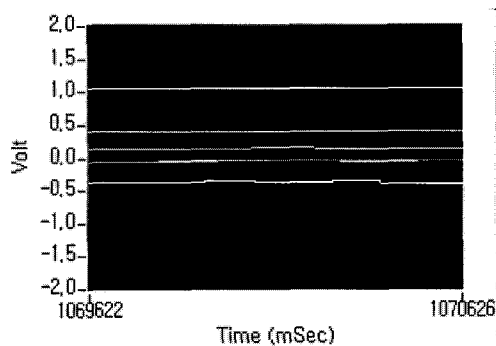


Fig. 12. Experimental 6 channel values when a moment (8.83 Nm) is applied in y direction (digital data acquisition).

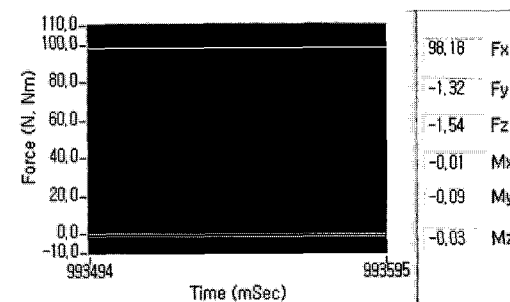


Fig. 13. Force sensor output when a force (98.2 N) is applied in x direction (digital data acquisition).

Therefore we obtained about 40 times improved S/N ratio of sensor output signals by the proposed method in the experimental setup presented in the previous section.

Fig. 13 shows sensor output values (six components of the sensed force) when the 6 channels' values of

Fig. 10 case are processed with 6x6 compliance matrix determined experimentally. In Fig. 9 and Fig. 11, data are plotted during 100 ms, and in Fig. 10, Fig. 12, and Fig. 13, data are plotted during 1000 ms. In Fig. 13, the top white line corresponds to  $F_x$  component. The other small values existed in Fig. 13, we think, are mainly due to inaccuracy of the external force acting on the sensor body.

## 6. CONCLUSIONS

Performance of the force-torque sensor is affected significantly by an error signal that is included in the sensor signal, and the error signal should be reduced appropriately to obtain an adequate performance of the sensor. Generally in 6-axis force-torque sensors, these errors may be classified mainly into two categories: one is a structural error due to the shape of elastic member and inaccuracy of a sensor body, and the other is a noise signal existing in sensed information.

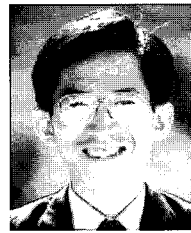
This paper has presented a principle of 6-axis force-torque sensor briefly, and then has shown a mechanical structure including cross-shaped double-hole elastic member that has improved structural errors. In order to reduce the effect of the noise signal to sensor performance, all the electronics are packaged inside the sensor body and the analog voltage signal is converted to digital numbers inside it and then these digital signals are transmitted to PC and digital signal processing is conducted in the computer. The validity of the proposed method has been evaluated experimentally using a 6 axes force-torque sensor based on an embedded microprocessor.

By this way, we have developed a cheap and compact sensor that could eliminate significantly from the computer and of 60 Hz noises emitted from AC source. The experimental results show that it improves S/N ratio of the sensor output signals about 40 times in our experimental setup. In the experimental setup, analog-processed voltage signals are converted to digital values through A/D converters inside the PIC microcontroller in every 200 microsecond, and then the digital values are read through I/O board inside the computer using LabVIEW in every 6 ms.

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