Analysis of Noise Effects in Data Acquisition of Multi-Axis Force/Torque Sensors

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Abstract: One of the major factors that effect sensor performance is analog noise that added in a sensor signal such as voltage. In multi-axis force sensors, error sources may be classified mainly in two groups. One is structural error due to inaccuracy of sensor body. The other error source is noise signals existing in the sensed information. This paper presents a brief review about the principle of multi-axis force sensors, and then proposes a method that can reduce the effect of noise signal to sensor performance. The method is to convert analog voltage signal to digital numbers near sensor body and then to read these digital signals and conduct signal processing in the computer. By this way, we can eliminate a bad effect of electromagnetic wave emitted from computer and of 60 Hz noise emitted from AC source. The proposed method is investigated through experimental demonstration. The experimental results show that it improves S/N ratio of the sensor about 40 times in our experimental setup.

Keywords: Multi-axis force sensor, signal processing, noise reduction, microcontroller, electromagnetic wave, LabVIEW

1. INTRODUCTION

The force information sensed in multi-axis force sensors includes always some errors. These errors may be classified mainly into two groups. One group is a structural error due to inaccuracy of a sensor body. Coupling effect among axes is one example of this kind of error. The other group is a noise signal included in a sensor output signal. Generally the sensor output is analog signal such as voltage and is low-level, 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 could be escaped to some extent via good mechanical design and compliance matrix technique which are well investigated in the literatures [1-4]. However, research on noise reduction of force sensors is not well conducted.

Robotic force control in manufacturing automation 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, multi-axis force sensor, usually 6 axis force sensor is utilized in order to measure the magnitude and direction of contacting force. The 6-axis force sensor is usually attached to 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 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 prescribed force range.

In the 1990s, systematic design methods of multi-axis force/torque sensors are proposed. For force-torque sensors, Uchiyama et al.[5] and Bayo and Stubbe [6] 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.[7] has proposed that three standard design criteria, that is, strain gauge 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 [8] has 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 and Uchiyama [9] have shown that the condition number of an elastic structure is able to be derived analytically without resort to FEM analysis.

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 strain measurement error was studied at the references cited above, and force-sensing error due to compliance matrix error was analyzed by Kang [3]. Furthermore, 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 [1].

This paper presents a force-sensing principle of a 6-axis force/torque sensor consisted of cross-shaped elastic members and Wheatstone bridges, and proposes noise-reducible communication method and verifies it through experimental study.

Multi-axis force sensors obtain 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 brought about several sources. In order to improve the sensor performance, we need to find a useful way to reduce the noise signals.

In this paper, we reduce the noise effect by converting the voltage signal to digital signal outside the computer and then by reading the digital signal in the computer. By this way, we can remove the noises due to electromagnetic waves, which contaminate the signal when reading the analog voltage in the computer, and due to AC electric source which generate 60 Hz periodic noise in the sensor output. Outside the computer, PIC microcontroller digitize the analog signals of 6 channels via PIC assembly program. The digital values are read through NI multipurpose I/O board with LabVIEW program, and analyzed and compared with the analog reading case.

2. PRINCIPLE OF MULTI-AXIS FORCE SENSORS

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 [10], inductive displacement transducers [11], and CCD elements [12].

We consider in this paper force-torque sensors using strain gages and Wheatstone bridges that enables to figure out force and torque by detecting its surface strain of elastic structure.

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.

$$\hat{\mathbf{C}}\,\hat{\mathbf{f}} = \hat{\varepsilon} \tag{1}$$

where $\hat{\mathbf{f}}$ is a measured $n \times 1$ force vector whose components are consisted of force components and/or moment components, $\hat{\varepsilon}$ 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 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 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 N_f and N_ε 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 ε as follows:

$$\hat{\mathbf{f}} = \mathbf{N}_f\mathbf{f}, \qquad \mathbf{N}_f = diag\{f_{1M}, f_{2M}, \cdots, f_{nM}\} \tag{2}$$

$$\hat{\varepsilon} = \mathbf{N}_\varepsilon\mathbf{f}, \qquad \mathbf{N}_\varepsilon = diag\{\varepsilon_{1M}, \varepsilon_{2M}, \cdots, \varepsilon_{mM}\} \tag{3}$$

where f_{iM} indicates a maximum force (N) or moment (N·m) of each axis given as design criteria, and ε_{jM} indicates absolute value of maximum strain on the jth strain gage when n f_{iM} acts on the sensor independently. The unit of the strain could be μm/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.

$$\mathbf{C}\,\mathbf{f} = \varepsilon \tag{4}$$

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

$$\mathbf{C} = \mathbf{N}_\varepsilon^{\mathbf{-1}}\,\hat{\mathbf{C}}\,\mathbf{N}_f \tag{5}$$

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 ε. In this case, rank$\,\mathbf{C}$ = rank $[\,\mathbf{C} \vdots \varepsilon\,]$ is satisfied, i.e., ε is included in the range space of $\mathbf{C}$, and so there exists a unique solution $\mathbf{f}$. The other case is where rank $\mathbf{C}$ < rank[$\mathbf{C} \vdots \varepsilon$] is satisfied, i.e., ε 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, the equation (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

$$\mathbf{C}^T\mathbf{C}\,\mathbf{f} = \mathbf{C}^T\varepsilon \tag{6}$$

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

$$\mathbf{f} = \mathbf{C}^{+}\varepsilon \tag{7}$$

where $\mathbf{C}^{+} = (\mathbf{C}^T\mathbf{C})^{-1}\mathbf{C}^T$, and $\mathbf{C}^{+}$ is called 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 [13]

$$\mathbf{C} = \mathbf{U}\,\Sigma\,\mathbf{V}^T \tag{8}$$

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 Σ is $m \times n$ matrix in which *ij* elements ($i \neq j$) equal 0 and *ii* elements ($i = 1, \cdots, n$) equal the singular value σ_i of $\mathbf{C}$ corresponding to the eigenvectors of $\mathbf{C}^T\mathbf{C}$. Then Moore-Penrose inverse $\mathbf{C}^+$ is given as

$$\mathbf{C}^+ = \mathbf{V}\Sigma^+\mathbf{U}^T \tag{9}$$

where Σ^+ is $n \times m$ matrix in which *ij* elements ($i \neq j$) equal 0 and *ii* elements ($i = 1, \cdots, n$) equal $1/\sigma_i$. Note that the matrix $\mathbf{C}$ in this paper have *n* nonzero σ_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.

Fig. 1 shows a schematic functional diagram of force-sensing procedure.

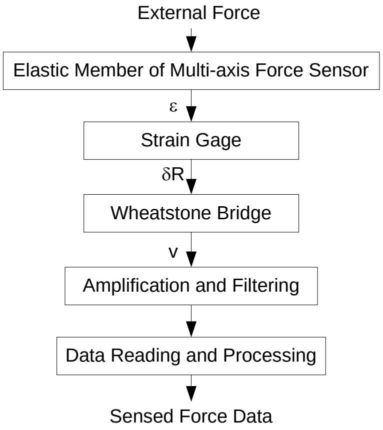


Fig. 1 Force-sensing procedure

3. REDUCTION OF NOISE EFFECTS

In multi-axis force sensors, sensor performance depends significantly on noise signals as well as structural errors existed in useful sensor signals. We focus in this section on the noise signals.

The size of a wrist sensor is restricted according to robotic manipulator, so the space for electronic components of the sensor is not sufficient in general. The 6-axis force sensor having been developed in our laboratory includes 6 Wheatstone bridges and amplifying circuit inside the sensor body. Remaining electronic components were installed on the signal processing board in the computer. In this case, the sensor outputs were contaminated lots of noise signals due to electromagnetic waves and AC electric source (EMI). In order to improve the sensor output signals, we convert the amplified voltage signals to digital values and then read them in the computer through parallel communication. Fig. 2 shows the schematics of the experimental setup of this sensor system.

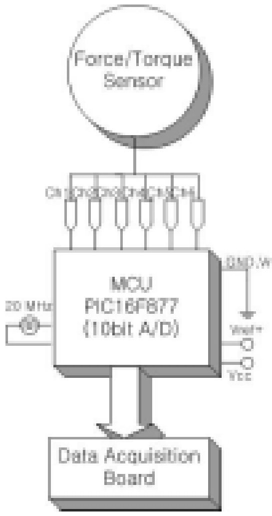


Fig. 2 Schematics of the experimental setup for digital data acquisition

In this research a microcontroller, PIC16F877 of Microchips Technology Inc, and a 10 bit A/D converter are used for generation of digital values with compact size and cheap price [14]. Analog voltage signals coming from 6 channels are converted to digital values in every 200 microsecond that is short time enough for our purpose.

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 PIC microcontroller is shown in Fig. 3, and LabVIEW program for data reading and plotting is shown in Fig. 4. In the LabVIEW program, C language-type programming is conducted [15].

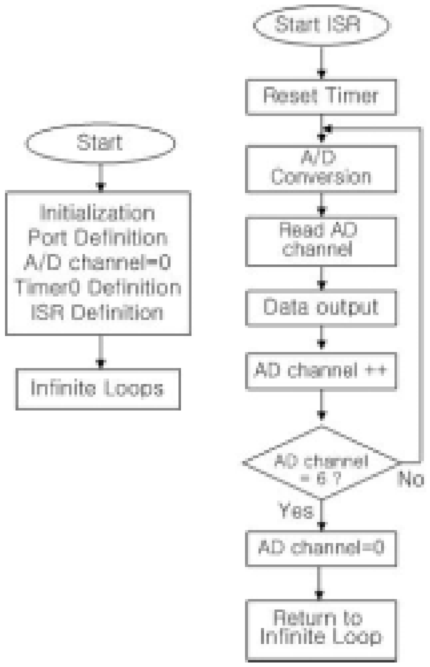
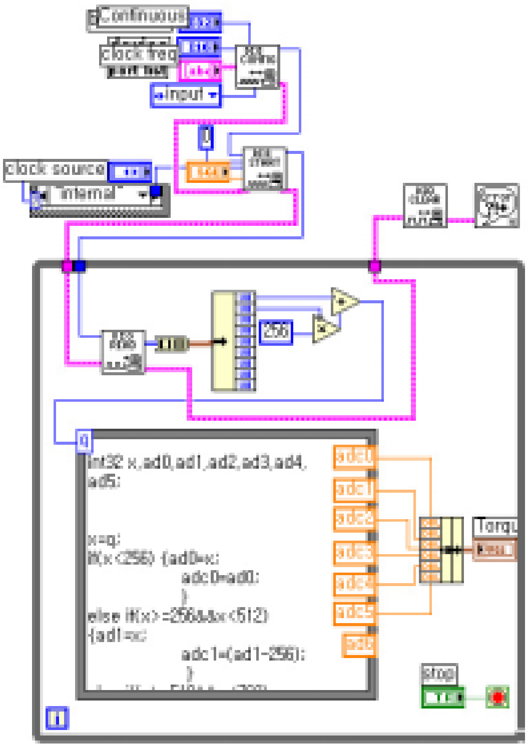


Fig. 3 Flowchart of a PIC microcontroller program



```
int32 x,ad0,ad1,ad2,ad3,ad4,
ad5;

x=q;
if(x<256) {ad0=x;
          adc0=ad0;
          }
else if(x>=256&&x<512)
{ad1=x;
          adc1=(ad1-256);
          }
```

Fig. 4 LabVIEW program for data reading and plotting

4. EXPERIMENTAL RESUTS AND DISCUSSION

In this section, we analyze experimentally how the proposed method improves the 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. 5 shows 6 channels' output values read analog voltages at PC I/O board when 10 kg_f is applied on the sensor in *x* direction. Fig. 6 shows output values read 6 channels' values after converting them digitally outside the PC when 10 kg_f is applied on the sensor in *x* direction. In Fig. 6, 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. 7 shows output values of 6 channels read analog voltages in the PC and Fig. 8 shows output values of 6 channels read after converting to digital values outside the PC. 8.83 Nm came from 10 kg x 9.81 m/s^2 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 S/N ratio is about 2.5 in case 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.

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. 9 shows sensor output values (six components of the sensed force) when the 6 channels' values of Fig. 6 case are processed with 6x6 compliance matrix determined experimentally. Determination of the compliance matrix is another issue related to sensor performance but is not dealt with in this paper.

In Fig. 5 and Fig. 7, data are plotted during 100 ms, and in Fig. 6, Fig. 8, and Fig. 9, data are plotted during 1000 ms. In Fig. 9, the top white line corresponds to F_x component. The other small values existed in Fig. 9, we think, are mainly due to inaccuracy of the external force acting on the sensor body.

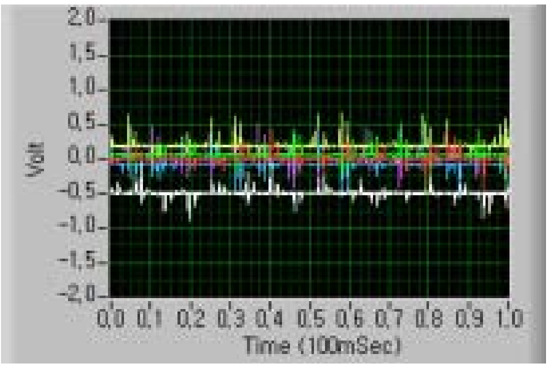


Fig. 5 Experimental 6 channel values when 10kg_f is applied in *x* direction (analog data acquisition)

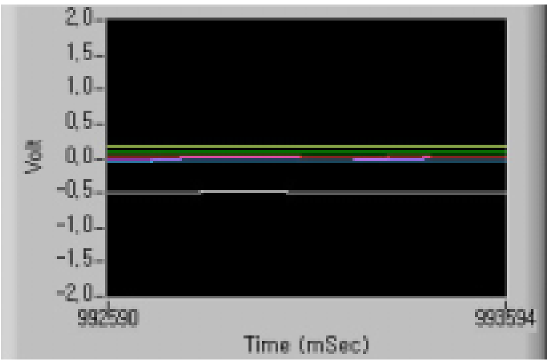


Fig. 6 Experimental 6 channel values when 10kg_f is applied in *x* direction (digital data acquisition)

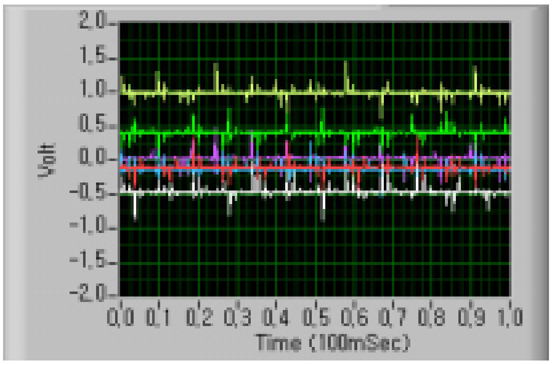


Fig. 7 Experimental 6 channel values when 8.83 Nm is applied in *y* direction (analog data acquisition)

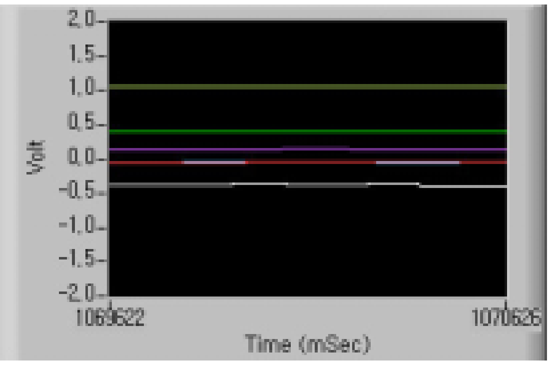


Fig. 8 Experimental 6 channel values when 8.83 Nm is applied in *y* direction (digital data acquisition)

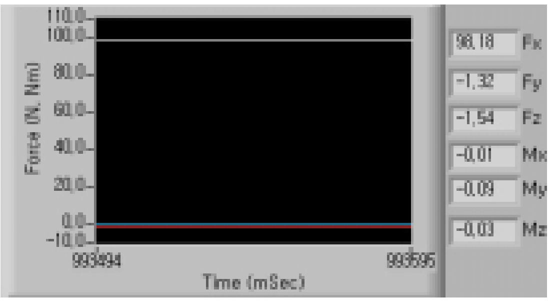


Fig. 9 Force sensor output when 10kg$_f$ is applied in *x* direction (digital data acquisition)

4. CONCLUSION

In this paper the principle of multi-axis force sensors was presented briefly, and it is shown that the Moore-Penrose inverse is required mathematically in order to get the proper solution from strain measurements in the sensor. Then a method that can reduce the effect of noise signal to sensor performance was proposed and evaluated the validity of it experimentally. The method is to convert analog voltage signal to digital numbers near sensor body (outside the computer) and then to read these digital signal and conduct signal processing in the computer.

By this way, we could eliminate significantly the bad effect of electromagnetic wave emitted from computer and of 60 Hz noise 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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