AIP Review of Scientific Instruments

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Citation: Review of Scientific Instruments **84**, 126109 (2013); doi: 10.1063/1.4827683
View online: http://dx.doi.org/10.1063/1.4827683
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/84/12?ver=pdfcov
Published by the AIP Publishing

Note: A compact three-axis optical force/torque sensor using photo-interrupters

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(Received 21 June 2013; accepted 9 October 2013; published online 31 December 2013)

By integrating four photo-interrupters in a cross-shaped structure, we developed a compact three-axis optical force/torque (F/T) sensor. The developed sensor has a diameter of 28 mm and a thickness of 7 mm. Despite simplicity and compactness, the experiments with a prototype of the proposed sensor demonstrate notably high accuracy. The RMS errors are 0.5% ± 0.1% of the maximum vertical force in z-axis, 1.9% ± 0.2% of the maximum torque in x-axis, and 2.0% ± 0.3% of the maximum torque in y-axis. It is expected that the proposed sensor allows cost-effective integration of robot systems requiring compact and multi-axis F/T sensors such as a walking assist robot. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4827683]

Measuring forces or torques in multiple locations may be inevitably needed in various robot systems. Physical reactions either in force or torque are used to ensure safety,[1] estimate human intention,[2,3] or implement force feedback.[4] More recently, as the robot systems are required to have high functionality, compact and multi-axial force/torque (F/T) sensors are required. In our application, as shown in Fig. 1, compact F/T sensors are used to design a ground reaction force (GRF) sensor for walking assist robot. The GRF is the force vector that acts between the foot and the support surface during the walking. The critical requirements of the GRF sensor are compactness and lightness in order not to affect normal walking gait. Therefore, the need for compact, accurate, and multi-axial F/T sensor has drawn much attention for GRF sensing application.

There have been several types of F/T sensors in literature or available commercially. Strain-gauges[5] are attached to an elastic material, and the linear deformation caused by external force is measured. Nevertheless of popularity of strain-gauges in practice, they need accurate installation and large signal amplification, which may lead to high cost and large size of sensing system. Recently, optics-based sensors have also been developed by using photo-detector array,[6] optical fiber.[7] Photo-detector array and optical fiber are used to estimate the relative movement of the light-emitting diode (LED) light source by measuring the difference of light intensity. Meanwhile, some researchers[8,9] have utilized photo-interrupters to measure the light interruption between the emitter and detector. Thanks to the tiny size of photo-interrupters, the developed sensors are compact, but they provide only the single axis measurement in force[8] or torque.[9]

Motivated by the study using photo-interrupters, in this Note, a compact three-axis F/T sensor is newly designed, which detects the force in z-axis (i.e., F_z), and torques around x- and y-axes (i.e., M_x and M_y). In order to enhance the robustness, a cross-shaped structure with four photo-interrupters is devised in a compact size. Also, the calibration method is presented based on the least square method. The accuracy of the proposed sensor is validated by experiments.

A photo-interrupter, or a photo-coupler, is an optically coupled isolator containing a light emitting diode on one side and phototransistor on the other. The photo-interrupter detects the amount of light transmitted as the screen blocks the light beam passing through the slotted path, as shown in Fig. 2. In this study, a cost-effective photo-interrupter is adopted (CNA-1311K, Panasonic Co. Ltd.), which has a miniaturized size ($4\times3\times2.6$ mm^3) and a linearity of output voltage within 50 μm displacement of the screen.[10]

As shown in Fig. 3, a compact 3-axis F/T sensor was designed by using four photo-interrupters. The sensor consists of three parts: a base, an elastic component, and a cover. Photo-interrupters and embedded circuits were located in the base part connected by external wires. The screen is bonded to the cross-shaped elastic component. The elastic component of the F/T sensor was designed to convert each axial force into minute displacement along each axis. The material of the elastic component is aluminium (AL7075) with the yield strength of 5.05×10^2 MPa and Young's modulus of 7.2×10^4 MPa. From the FEM simulation (Solidworks, Solidworks Corp.), the dimension of the elastic part was determined to have 20 μm deformation under 600 N in z-axial force. As a result, the sensor had a working range of maximum ±600 N for z-axis, ±2 Nm for x- and y-axes, respectively.

The cross-shape arrangement of four photo-interrupters provides a geometrically symmetric structure, which significantly enhances the robustness in measurement. Since a single photo-interrupter may be affected by not only vertical load but also moment, paired photo-interrupters in x- and y-axes compensate the undesired moment for each other. Thus, each photo-interrupter below the elastic component measures only the vertical load at each location independently.

The manufactured sensor is thin and compact, and lightweight (diameter: 28 mm, thickness: 7 mm, mass: 11 g). A 5 V electric power source is needed to operate. Moreover,

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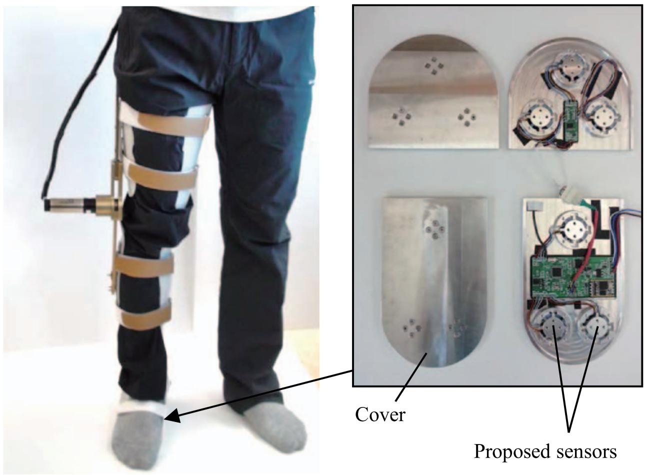

FIG. 1. Walking assist robot(left) with GRF sensor(right).

the sensor does not require any additional device for amplifying or filtering.

In order to detect the force and torques, the force input and the signal outputs from photo-interrupters should be related with a linear transformation. Using the function of photo-interrupter and kinematic geometry, let us consider the relationships as follows:

$$\underbrace{[F_z\ M_x\ M_y]^T}_{F} = C\ \underbrace{[v_1\ \ v_2\ \ v_3\ \ v_4\ \ 1]^T}_{S}\quad (C \in R^{3X5}), \qquad (1)$$

where v_i, F_z, M_x, M_y are the voltage signal of the ith photo-interrupter, the z-axial force, the x-axial torque, and the y-axial torque, respectively. C is the constant calibration matrix unknown. According to Eq. (1), the resultant relation of the input force corresponding to F with the output signal corresponding S can be found by the calibration matrix. The elements of matrix C can be determined by the least square method (LSM) for several sets of known F and S (obtained by experimental tests). In order to acquire the calibration data

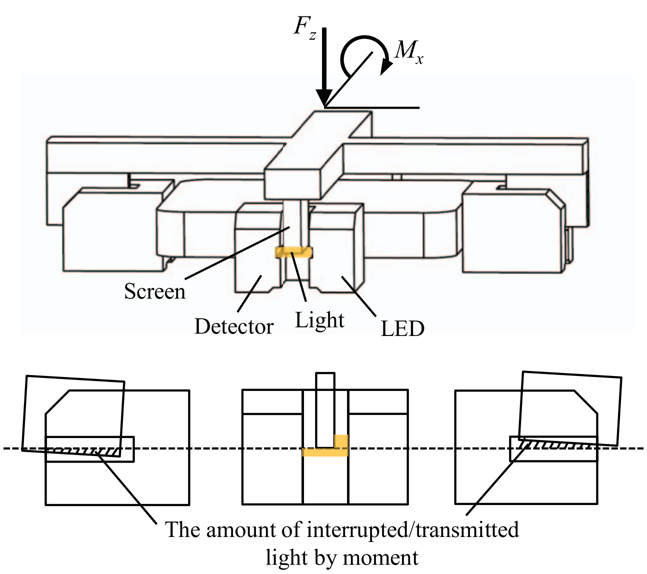

FIG. 2. Operation mechanism of the structure.

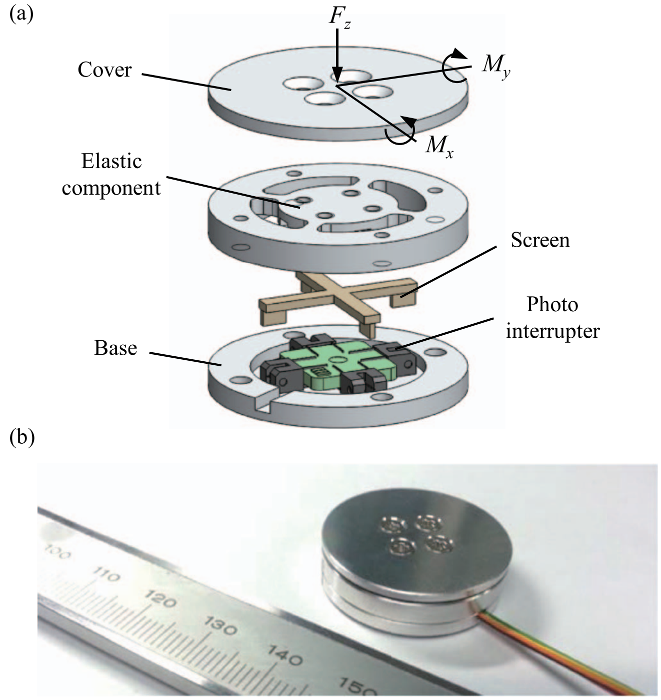

FIG. 3. (a) Components of the proposed optical F/T sensor and (b) the manufactured F/T sensor.

of F and S, the proposed sensor was mounted on a reference F/T sensor (Mini40, ATI Corp.). The data from Mini40 and the proposed sensor were collected by a data acquisition system (PCI-6221, NI Co. Ltd) with the sampling frequency of 1 kHz. External force and torque were exerted to the proposed sensor along with each axis manually. After collecting a number of sets of (F, S), the calibration matrix was obtained by

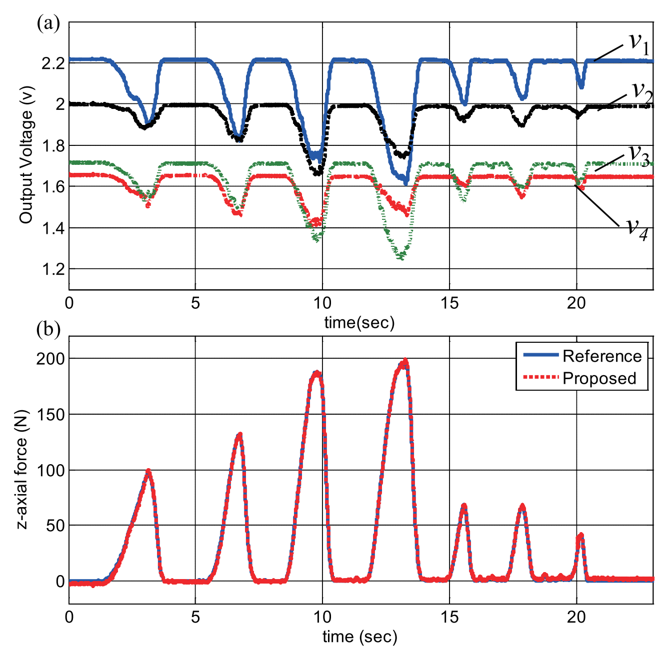

FIG. 4. (a) Voltage signals of photo-interrupters before calibrating and (b) the estimated z-axial force after calibration.

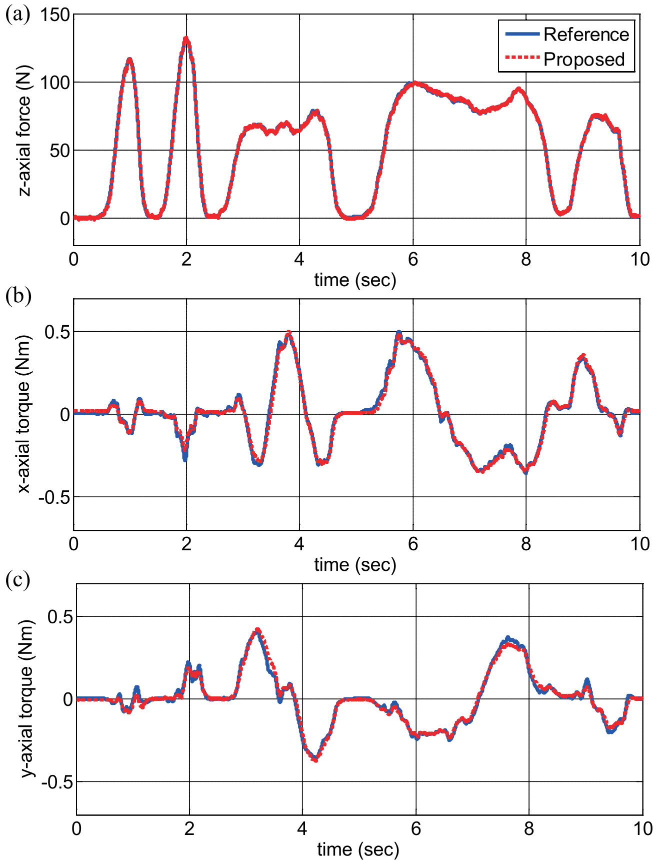

FIG. 5. (a) Experiment result of z-axial force, (b) x-axial torque, and (c) y-axial torque.

$$C = FS^T(SS^T)^{-1}. \tag{2}$$

Figure 4 shows the result of calibration. When z-axial force was loaded and unloaded repeatedly, the deformation of elastic component made the voltage drop by interrupting the light path. After calibration, the proposed sensor shows high measurement accuracy of less than 1 N RMS error about z-axis. We repeated the experiment 10 times and averaged the elements of C. Finally, the obtained calibration matrix of the manufactured sensor was given by

$$C_{obt} = \begin{bmatrix} -122 & -143 & -125 & -147 & 1024 \\ 0.04 & 0.67 & 0.08 & -1.26 & 0.85 \\ -0.94 & -0.21 & 0.86 & -0.22 & 0.99 \end{bmatrix}. \tag{3}$$

Several experiments for measurement were repeatedly conducted at a room temperature to validate the performance of the proposed sensor. Manual force and torque were applied to the sensor assembly (i.e., the proposed sensor and the reference sensor). One of the measured samples is shown in Fig. 5. It is noted that the estimated force and torques (by Eq. (3)) in red do match to those of reference sensor with negligible error. Based on several sets of measurements, the characteristics of the proposed sensor are summarized in Table I. It clearly shows the feasibility of the proposed sensor system which is of compact size and low cost, compared with the reference sensor.

TABLE I. Characteristics of the proposed sensor.

Item		Parameters	Units
Dimension (ϕ,h)		(28, 7)	mm
	Mass	11	g
F_z	Min./Max.	0/201	N
	RMS error	1.0±0.2	N
M_x	Min./Max.	−0.95/+0.96	Nm
	RMS error	18.0 ± 2.1	mNm
M_y	Min./Max.	−0.90/+0.95	Nm
	RMS error	19.1±2.5	mNm
Resolution(F/T)		0.018/0.061 (16 bit DA)	N/mNm

As a remark, all the experiments in this Note were conducted at a room temperature since the sensor was devised to be primarily used for a walking assist robot (which is used at normal environment). One may implement a simple electrical feedback loop for maintaining the constant photo intensity level regardless of temperature variation, if necessary. In addition, by a precise alignment of the components, the errors in x- and y-axial moments could be reduced and be symmetric.

In this Note, a novel F/T sensor was presented to measure the z-axial load and the torques in x- and y-axes. Using four photo-interrupters installed in a cross-shaped structure, robust and accurate measurement was obtained by simple but effective calibration method. Also, the proposed F/T sensor has a small and compact size without any electric amplifier, and is cost-effective due to the simple architecture and low-cost components. In a case of GRF application, six proposed F/T sensors satisfy all performance requirements by providing a compact size of multi-axial sensing system with high cost performance. Thus, the proposed F/T sensor is expected to be very useful to robot researchers in practice, who have to integrate multiple F/T sensors.

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