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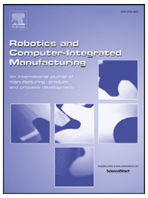

Calibration and decoupling of multi-axis robotic Force/Moment sensors

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ABSTRACT

Multi-axis robotic Force/Moment (F/M) sensors are capable of simultaneously detecting multiple components of force (Fx, Fy, and Fz), as well as the moments (Mx, My and Mz). This enables them to be frequently used in many robotic applications. Accurate, time-effective calibration and decoupling procedures are critical to the implementation of these sensors. This paper compares the effectiveness of decoupling methods based on Least-Squares (LS), BP Neural Network (BPNN), and Extreme Learning Machine (ELM) methods for improving the performance of multi-axis robotic F/M sensors. In order to demonstrate the effectiveness of the decoupling methods, a calibration and decoupling experiment was performed on a five-axis robotic F/M sensor. The experiments demonstrate that the ELM based decoupling method is superior to LS and BPNN based methods. The presented theoretical and experimental demonstrations provide a comprehensive description of the calibration and decoupling procedures of multi-axis robotic F/M sensors. This work reveals that the ELM method is an appropriate and high performing decoupling procedure for multi-axis robotic F/M sensors.

1. Introduction

Multi-axis robotic Force/Moment (F/M) sensing is an important branch of robotic sensing intended to measure the external forces and moments on robotic manipulators. Multi-axis sensing has been widely considered in both industry and academic research and also plays an increasing role in the fields of robotics, haptics, virtual reality, etc. in order to acquire relevant information from physical interactions [1,2]. Recently, researchers have investigated and developed many F/M sensing systems with adequate performance via both direct and indirect approaches [3,4]. A six-axis F/M sensor can measure the tangential force terms along x-, y-, and normal force term along z-axis (Fx, Fy, and Fz) as well as the moment terms about x-, y-, and z-axis (Mx, My, and Mz) simultaneously [5]. Multi-axis F/M sensors refer to sensors that can detect less than the six terms, to which the most commonly used F/M sensors are three-, or six-axis [6–8].

The trend towards flexibility in manipulation and effective control progressively requires high performance multi-axis F/M sensors in robotics and automation. For this purpose, continuous improvement approaches have been attempted. In this process, much of the research has revealed interesting scientific questions and technological challenges in developing high-precision and robust F/M sensing systems. Several researchers have designed a wide variety of multi-axis F/M sensors with novel structures in order to improve the sensing accuracy. For example, Meng et al. presented a novel six-axis accelerometer based on a structure of dual annular membranes [9].

Precise calibration and decoupling of multi-axis F/M sensor is critical and can be challenging. More specifically, the calibration process of multi-axis F/M sensors refers to the relationship between the sensors output voltages and the applied load. This relationship should be accurate and reliable according to the applied standard and maintain a certain accuracy of measurement. Also, the majority of the existing multi-axis F/M sensors have inherent highly coupled interference errors among their components (especially between component F_x and component M_y, component F_y and component M_x respectively), which are influenced by the sensing principle, manufacturing process, EE structure and detection mode [7,10,11]. The coupling effect produces a significant decrease in accuracy of the sensor and requires complicated decoupling algorithms for compensation [12,13]. Therefore, particular emphasis has been given to the decoupling algorithms of multi-axis F/M sensors [15].

Wu and Cai [16] constructed a unique six-axis F/M sensor to measure the interactive force between surgical tools and soft tissue. This can ide-

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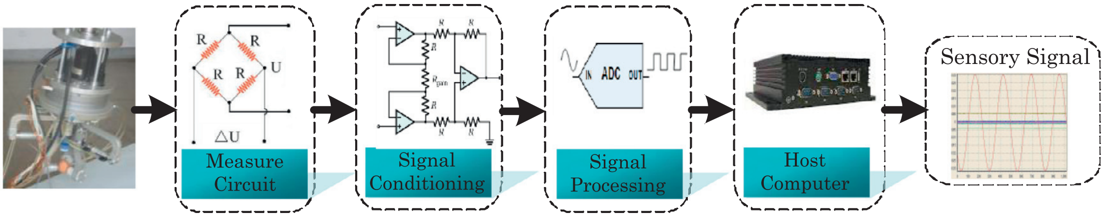

Fig. 1. Schematic illustration of a multi-axis F/M sensor.

ally be used for haptic information acquisition in virtual surgery. The authors proposed a novel Elastic Element (EE) based on a decoupling mechanism with that has a sliding structure. The calculated expanded uncertainty and coupling error of the sensor are 0.1% F.S. and 0.89% F.S, respectively. Yuan et al. [8] constructed a six-axis F/M sensor based on a typical EE with double cross-beam structures for humanoid robot foot. This sensor is capable of over 1000 N of total vertical load, and after linear static decoupling, its repeatability error and interference error are less than 1.88% F.S. and 3.0% F.S., respectively. Dasgupta et al. [17] disclosed a design methodology for the Stewart platform sensor structure based on the optimal conditioning of the force transformation matrix. Unlike the traditional EEs that measure all the F/T components with a single monolithic structure, this kind of sensor employs limbs of the parallel mechanism to detect the F/M components. This uniquely makes it possible to provide de-coupling F/M information with high stiffness and high sensitivity. Recently, a nonlinear static decoupling algorithm based on a coupling error model and six separate Support Vector Regressions (SVRs) for 3-axis force sensors was proposed. In this study, the maximum interference error was claimed to be within 1.6% F.S. [18].

In this paper, we study the theoretical and experimental demonstrations of several proposed decoupling methods such as LS, BPNN, and ELM. Calibration and decoupling experiments with the proposed methods are carried out on a five-axis F/T sensor, and the results are compared and discussed.

2. Multi-axis F/M sensor system and its fundamental principle

Configurations adopted in multi-axis F/M sensors originate from various measurement principles such as resistive, capacitive, inductive, piezoelectric, magnetic and optical methods [19]. The most commonly used approaches out of these principles relies on resistive or piezoresistive measuring. The most well-known resistive transducers utilized on multi-axis F/M sensors are strain gauges. The measurement chain of the multi-axis F/M sensor system that uses the resistive method consists of several blocks, which can be observed in Fig. 1.

When bonded onto the EE of the sensor, the strain gauges will undergo changes of resistance that correspond to the deformation of the EE. This relationship is given by

$$\Delta R_i = G\varepsilon_i R_i \tag{1}$$

where R_i is the original resistance of the ith strain gauge, G and ε_i are the gauge factor and the strain, respectively. Provided that the EE behaves within the elastic range of the material, the occurred strain, ε_i, and the applied load, L, are related by the following equation:

$$\varepsilon_i = f_i(L) \tag{2}$$

Full-bridge measure circuits are always used to detect the small resistive changes with high sensitivity and inherent linearity. The output voltage of the jth bridge can be expressed as

$$\Delta U_j = \frac{1}{4}U_e G(\varepsilon_{j1} - \varepsilon_{j2} + \varepsilon_{j3} - \varepsilon_{j4}) \tag{3}$$

where U_e denotes the voltage excitation source, and ε_{jk} represent the strain in the kth gauge of the jth full-bridge circuit.

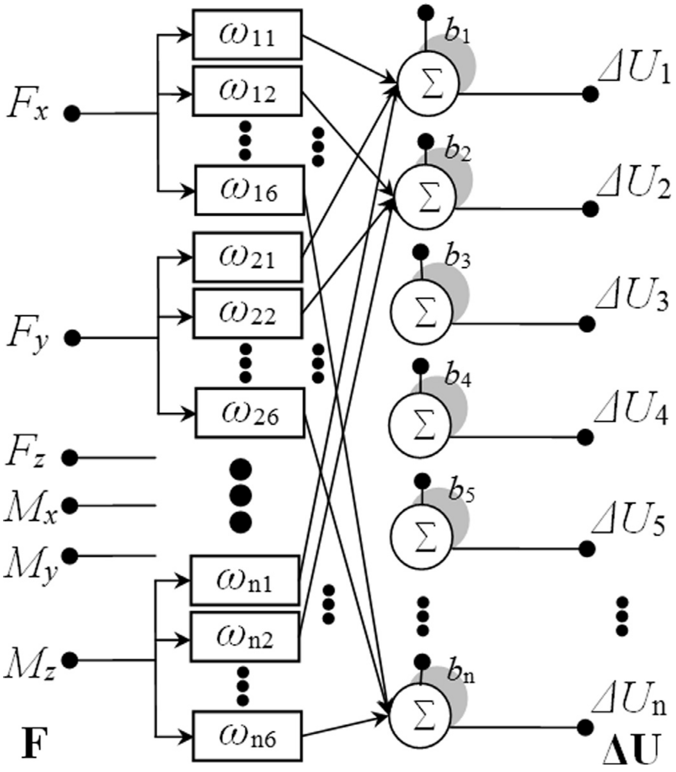

Fig. 2. Coupling model of multi-component F/M sensor.

Regarding multiple axis F/M sensors, several components will simultaneously generate output signals when a single F/M component is applied onto the sensor. This is mainly caused by the monolithic structure of the EE and the inherent manufacturing error. The coupling model of the multi-component F/M sensor is illustrated in Fig. 2.

Therefore, the output of the sensor composed of n full-bridge circuits $\mathbf{\Delta U} \in \Re^n$ can be expressed as

$$\mathbf{\Delta U} = \mathbf{wF} + \mathbf{b} \tag{4}$$

where $\mathbf{w} \in \Re^{n\times m}$ and $\mathbf{b} \in \Re^n$ represent the coupling coefficient and bias matrices, respectively, and $\mathbf{F} \in \Re^m$ represents the applied load vector that contains three force components and three moment components applied to the center of the sensor. The output can also be expressed as

$$\mathbf{\Delta U} = \mathbf{TF} \tag{5}$$

where $\mathbf{T} \in \Re^{n\times m}$ is the transformation matrix, which depend on the structure and geometrical dimensions of the EE, the particular locations, and the configuration of the strain gauges bonded on the EE.

Signal conditioning of the F/M sensor includes amplification, isolation, thermal compensation, filtering, and range matching to qualify and enhance the sensor output $\triangle\mathbf{U}$ to be suitable for processing.

The main challenge in processing the signals from the F/M measurement is related to the methods used to extract useful information from