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Design Study of a Y-shaped Six-Axis Force/Moment Sensor Through Pareto Front and Novel Analytical Model

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Summary:

The Y-shaped sensor structure is optimized by Pareto front with Non-Dominated Sorting Genetic Algorithm II (NSGA-II) and a novel analytical model. Axial strain outputs of force and moments axes are favorable depending on the sensor dimensions. Hence, Pareto front reveals strain-output characteristics of sensor dimensions. Moreover, the novel analytical model permits feasible size optimization in a broad dimension range by respecting equivalent stress and fundamental frequency, unlike previous studies. A prototype of the optimal design is experimentally validated, and sensor properties are characterized.

Keywords: six-axis force/moment sensor, analytical model, pareto front, design, size optimization

Introduction

Strain-based multi-axis force and moment sensors benefit mechanical structure in terms of shape and size. Considering the sensor shape, a Y-shaped structure composed of three sensing beams is statically determinate and produces higher displacements and voltage outputs as opposed to statically indeterminate sensor structures such as a typical cross-beam formed of four beams. In favor of increased flexibility, elastic beams of cross-beams are extended in out-of-plane directions, which expands manufacturing complexity and costs. On the contrary, y-shaped beams allow the required stiffness and strain output in a planar design [1]. In terms of the compliant structure size, different sensor dimensions have significant axial strain outputs. For instance, extending the elastic beam and sensing beam length helps strain outputs, but it also leads to a larger sensor with a lower frequency response. Moreover, minimizing the cross-sectional area of elastic and sensing beams improves strain outputs, yet it reduces the structural safety of the sensor as well. Hence, it creates a design optimization problem with a trade-off between sensor properties [2].

Pareto efficiency is beneficial in optimization problems with competing objectives. In generic design problems, multi-objective pareto optimality can be reduced to a weighted sum single objective optimization. However, strain characteristics against sensor size is a new design optimization problem formulation for y-shaped multi-axis force moment sensors that has not been investigated so far. Previous studies examined strain output either by optimizing beam cross-sectional area or beam length. The main reason for this optimization drawback was modeling incapacities regarding solution times and solution accuracy.

Previous studies that implemented the finite element method for sensor modeling encountered long solution times that were infeasible for large dimension ranges. Other studies that employed analytical models sustained the insufficiency of the preceding approximate models [3]. This study employs a novel analytical model known for its high accuracy and fast solving time, which takes into account the structural safety and fundamental frequency of the mechanical structure. Hence, the large range pareto front optimization process is ultimately feasible for this sensor design problem.

In this study, a population-based genetic algorithm is used. In this way, optimal solutions in the population disclose axial strain-output characteristics depending on sensor dimensions. Moreover, an optimal design is selected considering sensor diameter and strain outputs. A sensor prototype is manufactured, and sensor properties are experimentally characterized. Experimental results are compared with optimization results.

Methodology

This study takes advantage of a new analytical model that involves beam joint reactions and flexibility which significantly increases accuracy and capability compared to prior models. According to this model strain output of sensing beams are formulated in Eq. (1) for F_x force and Eq. (2) for M_x moment.

$$\varepsilon_{F_x} = F_x\left(\zeta\frac{\ell_1 w_1}{2EI_1} - \eta\frac{w_1}{2EI_1}\right) \tag{1}$$

$$\varepsilon_{M_x} = M_x\left(\zeta\frac{\ell_1 h_1}{2EI_4(\ell_1 + r)} - \eta\frac{r h_1}{2EI_4(\ell_1 + r)}\right) \tag{2}$$

As presented in Eq. (1-2), strain outputs are influenced by the sizing of both sensing and elastic beams. In Fig. 1, a sensor prototype is displayed. Strain gauges are placed on sensing beams, and elastic beams form an elastic boundary, increasing the flexibility of the sensor structure.

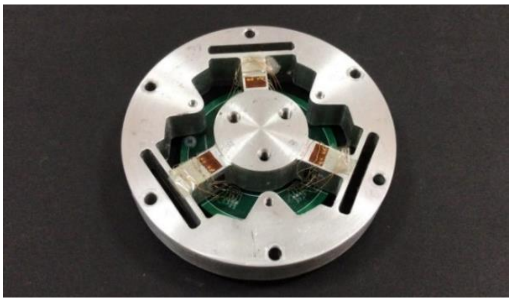

Fig. 1. Illustration of the y-shaped multi-axis force/moment sensor prototype that is composed of sensing and elastic beams.

Pareto front is an optimization process that defines competing objectives in problem formulation. Sensor diameter is expected to be as small as possible, and the strain outputs of all force and moment axes are expected to be increased. The problem formulation is given below.

$$\begin{aligned}
\text{Optimize} \quad & f_1 = \max\left(\varepsilon_{F_x} + \varepsilon_{F_y} + \varepsilon_{M_z}\right) \\
& f_2 = \max\left(\varepsilon_{F_z} + \varepsilon_{M_x} + \varepsilon_{M_y}\right) \\
& f_3 = \min\left(d_{sensor}\right) \\
\text{subject to} \quad & \max\left(\sigma\right) \leq \sigma^* \\
& \min\left(\omega_n\right) \geq \omega_n^* \\
& x_l \leq x_i \leq x_u, \quad i = 1, \cdots, N
\end{aligned}$$

In this study, MATLAB GaMultiObj algorithm is utilized along with the new analytical model for obtaining pareto front. In Fig. 2, pareto-front results are displayed for a generic case. As seen in the figure, population solutions favor different axial strain outputs for varying sensor diameters.

The optimal sensor design is selected from the average of optimal population solutions using the weighting sum method. A sensor prototype is produced and experimentally characterized by the dead-weight test bench given in Fig. 3. This experimental setup is adequate for the required forces and moments. Sensor properties such as nonlinearity, hysteresis, sensitivity, time drift, and crosstalk are obtained. The strain outputs of experimental and analytical results are compared. Fig. 4. illustrates the results of the voltage output vs. dead weight during the calibration process.

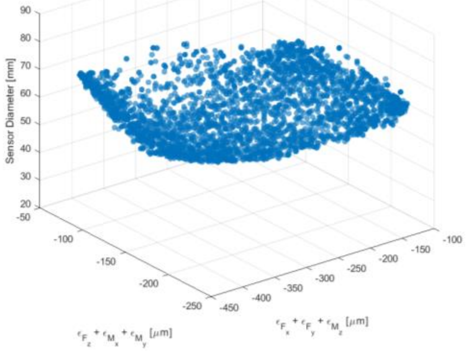

Fig. 2. A typical pareto optimality result for a y-shaped sensor

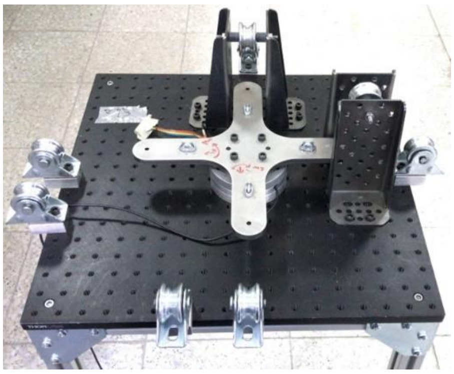

Fig. 3. Experimental dead weight setup for sensor calibration and validation of y-shaped sensor design.

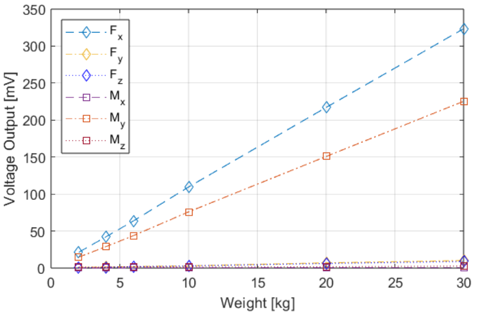

Fig. 4. Voltage output results vs dead weights causing F_x force and M_y moment combination for obtaining calibration matrix.

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