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Task-oriented design method and research on force compliant experiment of six-axis wrist force sensor

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ABSTRACT

This paper analyzes the task-oriented design method of six-axis force sensor and proposes the task model of the sensor. The task mathematical model of the sensor is established based on the idea of task ellipsoid. The models of force ellipsoid and moment ellipsoid are also established. The relational expression between the task model and ellipsoid model of sensor is obtained. Then, a fully pre-stressed dual-layer parallel six-axis wrist force sensor is proposed, whose static mathematical model is also established. The sensor task model for assembly work is proposed and the analytical expression between the sensor structure parameters and task model is deduced. According to the assembly work, the sensor structure is designed specifically, and the specific structure sizes of the sensor are obtained. Then the new sensor prototype manufactured for peg-in-hole assembly is processed. The calibration experiment and peg-in-hole assembly experiment on the prototype are completed and each performance index is well examined by the experiment results. The experiment results also lay the foundation for the practical application of six-axis force sensor.

1. Introduction

With the ability of measuring three-component force and three-component torque, six-axis wrist force sensor has been one of the most important sensors in robot force control and force position control. Parallel mechanisms possess the distinguishing advantages of stability, high rigidity, carrying capacity, no error accumulation, accuracy and inverse solution easily [1], and the parallel mechanism ideas are introduced into the design of the force sensitivity element structure of six-axis force sensor by many scholars. Gaillet and Reboulet [2] proposed the six-axis force sensor based on Stewart platform in 1983. Chen [3], Kerr [4], Nguyen et al. [5], Ferraresi et al. [6], Xiong [7] had researched the design problems of Stewart platform-based force sensor. Meanwhile, Romiti [8], Sorli [9], Kerr [10], Kang [11] developed the Stewart platform-based force sensor prototype. Gao et al. [12] designed a miniature six-axis force sensor which is used for the robot wrist and finger based on the design idea of elastic hinge instead of spherical pair. Dwarrakanath [13] designed a Stewart platform based force-torque sensor with a circular sensitive element, and then a Stewart platform-based force sensor [14] was designed based on one-way constraint and point contact. Ranganath et al. [15] designed a force-torque sensor based on a Stewart platform in a near-singular configuration from the angle of the sensor sensitivity. Pacchierotti et al. [16] presented a particular peg-in-hole application that a complex robotic hand using with sensor is considered to return the force of the object to the haptic master. Jia et al. [17] designed a new six-axis heavy force sensor based on the Stewart platform structure.

It's a very complicated problem to do the structure optimization for the parallel structure six-axis force sensor, and many factors need to be considered for its design and applied research. Therefore, a reasonable optimization principle is the basis of the optimization design and performance evaluation. Unfortunately, the optimization principle is still difficult due to the relative complexity of the six-axis force sensor, although the definition of performance index of conventional one-dimensional force sensor is fairly standard. In the past, the researches mainly focused on the sensor itself, rather than associated with the tasks. Actually, the structure, size and performance of sensor should be suitable for the execution of the prescriptive tasks.

Currently, most scholars conducts structural optimization design mainly basing on the isotropic principle, and the isotropic is regarded as an important performance index of six-axis force sensor structural evaluation [7,18–21], such as force isotropy, torque isotropy, sensitivity isotropy, fully isotropic, etc. These indices are

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obtained from the sensor itself without considering the specific and actual situation. Sensor is used to perform a certain task, such as peg-in-hole assembly, planar contour tracking, bolt into the hole and grasping, where sensor does not necessarily need isotropic structure. Actually, those task models are not spherical but ellipsoidal, while the isotropic is not optimal [22]. Therefore, according to the applications of six-axis wrist force sensor, the task model of sensor is established. The sensor elastomeric structure based on the performance evaluation criterion of the task model is also designed. The configuration, structure, size and performance suitable for the specified task are obtained, which have important significance for the design and application of the six-axis wrist force sensor.

In this paper, the mathematical model and task model of six-axis force sensor are established, and the analytical expression between the task ellipsoid and the force ellipsoid is deduced. Besides, the sensor's whole structure is designed based on the task model of the peg-in-hole assembly. Then the structure parameters of sensor are calculated. Furthermore, the sensor prototype is manufactured and the experiment of the peg-in-hole assembly is carried out.

2. The method of establishing the sensor's task model

2.1. The establishment of the task model

Sensor task model can be regarded as a set of generalized force which meets the task requirement. Sensor task model is divided into two cases: the known task and unknown task. The known task model is corresponding to the case that the requirement of measuring task is clear, and it can be described particularly with a set of force wrench. Whereas, the unknown task model is corresponding to the case that the requirement of measurement task is unknown and it can't be described with the set of force wrench.

2.1.1. The establishment of the known task model

For grasping planning, Li and Sastry [22] used task ellipsoid to model the known grasp task and the similar way also can be used to describe mathematical model of the known task [7]. Task model built in the reference [7] is a hyper-ellipsoid of combining force with moment. However, in this paper, the task model is divided into task force ellipsoid model and task moment ellipsoid model, respectively.

The general expression of the task force ellipsoid in sensor task coordinate system can be obtained as

$$\begin{aligned} &a_1F_{Gtx}^2+a_2F_{Gty}^2+a_3F_{Gtz}^2+a_4F_{Gtx}F_{Gty}+a_5F_{Gty}F_{Gtz}+a_6F_{Gtz}F_{Gtx}+a_7F_{Gtx}\\ &\quad+a_8F_{Gty}+a_9F_{Gtz}+a_{10}\le 0 \end{aligned} \tag{1}$$

where F_{Gtx}, F_{Gty} and F_{Gtz} represent three orthogonal force components, and a_i ($i=1, 2,\ldots,10$) represents real coefficient.

Eq. (1) can be rewritten as

$$\begin{aligned} &a_1(F_{Gtx}-u_{FGt})^2+a_2(F_{Gty}-v_{FGt})^2+a_3(F_{Gtz}-w_{FGt})^2\\ &\quad+a_4(F_{Gtx}-u_{FGt})(F_{Gty}-v_{FGt})+a_5(F_{Gty}-v_{FGt})(F_{Gtz}-w_{FGt})\\ &\quad+a_6(F_{Gtz}-w_{FGt})(F_{Gtx}-u_{FGt})+a_{11}\le 0 \end{aligned} \tag{2}$$

where (u_{FGt}, v_{FGt}, w_{FGt}) represents the center of task force ellipsoid,

$$u_{FGt}=-\left(2a_2a_6a_9-4a_2a_7a_3-a_6a_5a_8-a_4a_5a_9+2a_4a_8a_3+a_7a_5^2\right)\big/(2\lambda_{FGt}),$$

$$v_{FGt}=(-2a_1a_5a_9+4a_1a_8a_3+a_6a_4a_9+a_6a_5a_7-a_6^2a_8-2a_7a_4a_3)/(2\lambda_{FGt}),$$

$$a_{11}=\begin{pmatrix} 4a_6^2a_{10}a_2-a_6^2a_8^2-4a_6a_9a_7a_2+2a_6a_5a_7a_8-4a_6a_{10}a_4a_5\\ +2a_6a_4a_9a_8-16a_2a_{10}a_1a_3+4a_2a_3a_7^2+4a_2a_1a_9^2-a_4^2a_9^2+4a_1a_8^2a_3\\ -4a_1a_9a_5a_8+4a_{10}a_5^2a_1-4a_8a_7a_4a_3+2a_4a_9a_5a_7+4a_{10}a_4^2a_3-a_5^2a_7^2 \end{pmatrix}\Bigg/ (4\lambda_{FGt}),$$

$$w_{FGt}=(-2a_6a_2a_7-a_4^2a_9+a_4a_5a_7+a_4a_6a_8+4a_2a_1a_9-2a_5a_1a_8)/(2\lambda_{FGt}),$$

$$\lambda_{FGt}=a_4^2a_3-4a_2a_1a_3+a_6^2a_2-a_4a_5a_6+a_5^2a_1.$$

Similarly, the general expression of the task moment ellipsoid in sensor task coordinate system can be obtained as

$$\begin{aligned} &b_1M_{Gtx}^2+b_2M_{Gty}^2+b_3M_{Gtz}^2+b_4M_{Gtx}M_{Gty}+b_5M_{Gty}M_{Gtz}\\ &\quad+b_6M_{Gtz}M_{Gtx}+b_7M_{Gtx}+b_8M_{Gty}+b_9M_{Gtz}+b_{10}\le 0 \end{aligned} \tag{3}$$

where M_{Gtx}, M_{Gty} and M_{Gtz} represent the three orthogonal moment components, and b_i ($i=1, 2,\ldots,10$) represents real coefficient.

Eq. (3) can be rewritten as:

$$\begin{aligned} &b_1(M_{Gtx}-u_{MGt})^2+b_2(M_{Gty}-v_{MGt})^2+b_3(M_{Gtz}-w_{MGt})^2\\ &\quad+b_4(M_{Gtx}-u_{MGt})(M_{Gty}-v_{MGt})+b_5(M_{Gty}-v_{MGt})(M_{Gtz}-w_{MGt})\\ &\quad+b_6(M_{Gtz}-w_{MGt})(M_{Gtx}-u_{MGt})+b_{11}\le 0 \end{aligned} \tag{4}$$

where (u_{MGt}, v_{MGt}, w_{MGt}) represents the center of task moment ellipsoid;

$$u_{MGt}=-\left(2b_2b_6b_9-4b_2b_7b_3-b_6b_5b_8-b_4b_5b_9+2b_4b_8b_3+b_7b_5^2\right)\big/(2\lambda_{MGt}),$$

$$v_{MGt}=(-2b_1b_5b_9+4b_1b_8b_3+b_6b_4b_9+b_6b_5b_7-b_6^2b_8-2b_7b_4b_3)/(2\lambda_{MGt}),$$

$$w_{MGt}=\left(-2b_6b_2b_7-b_4^2b_9+b_4b_5b_7+b_4b_6b_8+4b_2b_1b_9-2b_5b_1b_8\right)\big/(2\lambda_{MGt}),$$

$$b_{11}=\begin{pmatrix} 4b_6^2b_{10}b_2-b_6^2b_8^2-4b_6b_9b_7b_2+2b_6b_5b_7b_8-4b_6b_{10}b_4b_5\\ +2b_6b_4b_9b_8-16b_2b_{10}b_1b_3+4b_2b_3b_7^2+4b_2b_1b_9^2-b_4^2b_9^2+4b_1b_8^2b_3\\ -4b_1b_9b_5b_8+4b_{10}b_5^2b_1-4b_8b_7b_4b_3+2b_4b_9b_5b_7+4b_{10}b_4^2b_3-b_5^2b_7^2 \end{pmatrix}\Bigg/ (4\lambda_{MGt}),$$

$$\lambda_{MGt}=b_4^2b_3-b_4b_2b_1b_3+b_6^2b_2-b_4b_5b_6+b_5^2b_1.$$

Eqs. (2) and (4) can be written in matrix form as:

$$\mathbf{F}_{Gt}^{\mathrm{T}}\mathbf{C}_{FGt}^{\mathrm{T}}\mathbf{C}_{FGt}\mathbf{F}_{Gt}\le 1 \tag{5}$$

$$\mathbf{M}_{Gt}^{\mathrm{T}}\mathbf{C}_{MGt}^{\mathrm{T}}\mathbf{C}_{MGt}\mathbf{M}_{Gt}\le 1 \tag{6}$$

where

$$\mathbf{F}_{Gt}=[F_{Gtx}-u_{FGt}F_{Gty}-v_{FGt}F_{Gtz}-w_{FGt}]^{\mathrm{T}},$$

$$\mathbf{C}_{FGt}^{\mathrm{T}}\mathbf{C}_{FGt}=-\frac{1}{a_{11}}\begin{bmatrix} a_1 & a_4/2 & a_6/2\\ a_4/2 & a_2 & a_5/2\\ a_6/2 & a_5/2 & a_3 \end{bmatrix},$$

$$\mathbf{M}_{Gt}=\left[M_{Gtx}-u_{MGt}M_{Gty}-v_{MGt}M_{Gtz}-w_{MGt}\right]^{\mathrm{T}},$$

$$\mathbf{C}_{MGt}^{\mathrm{T}}\mathbf{C}_{MGt}=-\frac{1}{b_{11}}\begin{bmatrix} b_1 & b_4/2 & b_6/2\\ b_4/2 & b_2 & b_5/2\\ b_6/2 & b_5/2 & b_3 \end{bmatrix}.$$

As matrix $\mathbf{C}_{FGt}^{\mathrm{T}}\mathbf{C}_{FGt}$ is a real symmetric matrix, we have (1)–(7) with the orthogonal diagonal factorization of the matrix.

$$\begin{aligned} \mathbf{C}_{FGt}^{\mathrm{T}}\mathbf{C}_{FGt}&=\mathbf{Q}_{FGt}diag(\lambda_{FGtx},\lambda_{FGty},\lambda_{FGtz})\mathbf{Q}_{FGt}^{\mathrm{T}}\\ &=[Q_{FGtx}Q_{FGty}Q_{FGtz}]diag(\lambda_{FGtx},\lambda_{FGty},\lambda_{FGtz})[Q_{FGtx}Q_{FGty}Q_{FGtz}]^{\mathrm{T}} \end{aligned} \tag{7}$$

where λ_{FGtx}, λ_{FGty} and λ_{FGtz} represent the eigenvalues of matrix $\mathbf{C}_{FGt}^{\mathrm{T}}\mathbf{C}_{FGt}$, and the square roots of their reciprocal are half the length of the sensor's task force ellipsoid spindles, respectively. The three column vectors of matrix Q_{FGt} constitute a complete orthonormal feature vector system of matrix $\mathbf{C}_{FGt}^{\mathrm{T}}\mathbf{C}_{FGt}$, which represent the direction of the task force ellipsoid's three spindles, respectively.

Similarly, we have Eq. (8) with the orthogonal diagonal factorization of the matrix:

$$\begin{aligned} \mathbf{C}_{MGt}^{\mathrm{T}}\mathbf{C}_{MGt}&=\mathbf{Q}_{MGt}diag(\lambda_{MGtx},\lambda_{MGty},\lambda_{MGtz})\mathbf{Q}_{MGt}^{\mathrm{T}}\\ &=[Q_{MGtx}Q_{MGty}Q_{MGtz}]diag(\lambda_{MGtx},\lambda_{MGty},\lambda_{MGtz})[Q_{MGtx}Q_{MGty}Q_{MGtz}]^{\mathrm{T}} \end{aligned} \tag{8}$$

where λ_{MGtx}, λ_{MGty} and λ_{MGtz} represent the eigenvalues of matrix $\mathbf{C}_{MGt}^{\mathrm{T}}\mathbf{C}_{MGt}$, and the square roots of their reciprocal are half-length of the sensor's task moment ellipsoid spindles, respectively. The three column vectors of matrix Q_{MGt} constitute a complete orthonormal feature vector system of matrix $\mathbf{C}_{MGt}^{\mathrm{T}}\mathbf{C}_{MGt}$, which represent the direction of the task moment ellipsoid's three spindles, respectively.