Mechanism and Machine Theory 91 (2015) 135–150

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Isotropy analysis of redundant parallel six-axis force sensor

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ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form 26 March 2015
Accepted 27 March 2015
Available online 29 April 2015

Keywords:
Force sensor
Six-axis
Isotropy analysis
Redundant parallel mechanism
Jacobian matrix

ABSTRACT

The structural model of generalized redundant parallel six-axis force sensor is proposed. Based on the modified Stewart platform, its mathematical model is established with screw theory. The structural models of four typical redundant six-axis force sensors are proposed and their mathematical models are established for the corresponding structures. The isotropy of the four structural models is analyzed. The parameters relation leading to spatially isotropic configuration is conduced and demonstrated by a numerical example. Analytic solutions to the isotropy of the four models are conducted and their valid range of the analytic results leading to isotropic configuration is discussed. The conclusion is drawn that under the condition of force isotropy, two structures with the relatively least thickness are selected when all the legs of different structures are the same.

1. Introduction

The Stewart platform, originally proposed for a flight simulator by Stewart [1] in 1965, has been most widely used among parallel mechanism. It possesses high load capacity as its in-parallel linkages sustain the payload in a distributive manner. Besides, it has some other characteristics including high rigidity, high accuracy and so on. The Stewart platform has been applied to many fields, for example micromanipulators [2], radio telescope orientation [3], motion simulators [4,5] and machine tools [6]. The Stewart platform is one of the optimal structures that are used in parallel six-axis force/torque sensor. Researchers from all over the world have done many researches on the Stewart platform and proposed many kinds of six-axis force sensor possessing good characteristics.

Gaillet and Reboulet [7] firstly applied the Stewart platform to parallel six-axis force sensor. Jin et al. [8] presented the design for a parallel architecture of robot's six-component force/torque sensor based on a variety of the Stewart platform, and defined the translational stiffness and the torsional stiffness of the sensor. Ranganath et al. [9] proposed a Stewart platform based force–torque sensor in a near-singular configuration. Theoretical concepts were demonstrated with a prototype sensor which is sensitive to two components of the externally applied force and one component of the externally applied moment. Zhao et al. [10,11] developed a pre-stressed six-axis force sensor based on the Stewart platform. Dwarakanath and Venkatesh [12] presented a six component parallel mechanism based force/torque sensor without any mechanical joints. It can offer a straightforward and easy method to reconstruct the wrench applied on one of the plates from measured connector forces. Hou et al. [13,14] studied a modified Stewart platform-based force sensor and discussed the performance analysis and comprehensive index optimization of the sensor. A hyperstatic Stewart platform-based force/torque sensor was proposed and the structural parameters of the sensor were optimized based on genetic algorithms. Jia et al. [15] presented a new type of six-axis heavy force sensor which is based on the method of six-axis load sharing. Combination of the deep beam element stiffness matrices and the force Jacobian matrix of the Stewart platform was firstly examined, and the method of six-axis load sharing based on the Stewart platform was deduced. Yao et al. [16,17] concluded that it is impossible for the classical

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http://dx.doi.org/10.1016/j.mechmachtheory.2015.03.018
0094-114X/

Stewart platform-based force sensor to realize spatial isotropy and proposed a modified Stewart platform-based force sensor which can achieve spatial isotropy. He also conducted the theoretical analysis of a statically indeterminate pre-stressed six-axis force sensor and it was demonstrated by experiments on a prototype. Dwarakanath and Bhutani [18] proposed a beam type parallel mechanism based 6-axis force–torque sensor. Wang et al. [19,20] presented a fully pre-stressed dual-layer six-axis force/torque sensor based on a modified Stewart platform architecture, and discussed the hyperstatic analysis of the sensor, then finished the calibration experiment on the fully pre-stressed six-axis force/torque sensor with double layers.

In the force measuring system of deep-sea exploration, aerospace and national defense, the force sensor is required to be highly reliable. If some measuring limbs are out of work, the whole system may trap into breakdown. Besides, it is hard to repair the disabled force sensor in time due to the limitation of special environment, which will lead to the decrease of system function or even the failure of the task. Six-axis force sensors based on Stewart platform with six measuring limbs possess the least number of limbs which can hold the geometrical invariability. However, the Stewart platform-based force sensors which are mentioned in reference [7–9,11–15,17,18] will not measure the applied six-component force accurately if any measuring leg is out of work. If redundant measuring limbs are added, this problem can be improved. Yao et al. [21] also proposed that redundant parallel six-axis forced sensor has the characteristics of heavy load and fault-tolerance. Thanks to the optimization design of parallel six-axis force sensor with redundancy, it can possess better measurement characteristics. More importantly, it can still work if some legs are out of work but the available ones are at least six. Faced with some applications in harsh environment, parallel force sensor with redundancy plays an extraordinary role. Therefore, it is of great importance to do research on redundant parallel six-axis force sensor in order to improve the stability and reliability of measurement.

As can be seen from the literature survey, applying Stewart platform to six-axis force sensor is aimed at achieving an isotropic configuration. Xiong [22] presented the concept of isotropy on the basis of Fisher's information matrix. Isotropy is an important index to reflect the performance of six-axis force sensor. The analysis of isotropic performance is a key component during the structure design of Stewart platform-based parallel six-axis force sensor. The main purpose of this paper is to propose four structures of redundant parallel six-axis force sensor and to analyze isotropy of them.

The organization of this paper is as follows. Following the introduction, in Section 2, the mathematical models of four kinds of redundant parallel six-axis force sensor are established. In Section 3, the isotropy of the structural models is analyzed. In Section 4, the analytic solutions to the isotropy of the four models are conducted and their valid ranges of solutions are obtained by numerical method. In Section 5, the relation among parameters leading to isotropic configuration is given. Finally, conclusions are presented, summarizing the present work, in Section 6.

2. Structures and mathematical models of four kinds of redundant parallel six-axis sensor

2.1. The generalized redundant parallel six-axis force sensor

The drawing of the generalized redundant parallel six-axis force sensor is shown in Fig. 1, to which the redundant legs are added to meet the requirement of reliability. The n-SS parallel structure is composed of an upper platform, a lower platform and n legs connecting the two platforms with spherical joints. There exist r redundant legs where r is equal to n-6. The Cartesian coordinates O-XYZ, called frame $\{\Omega\}$, is set up with its origin located at the geometrical center of the upper platform. $p_i(i = 1,2\ldots,n)$ is the center of the i-th spherical joint of the upper platform and $P_i(i = 1,2\ldots,6)$ is the center of the i-th spherical joint of the lower platform.

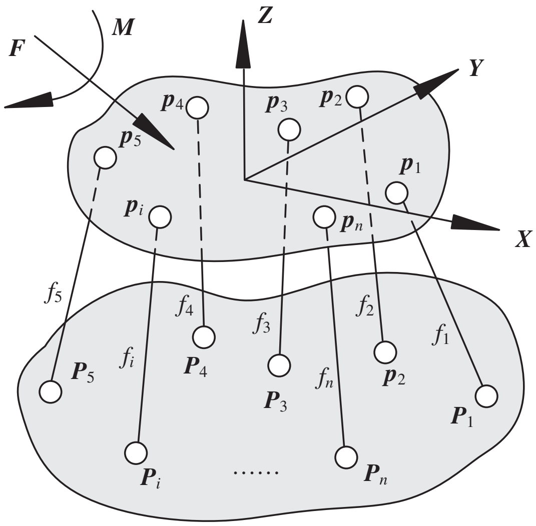

Fig. 1. The generalized redundant parallel six-axis force sensor.