Mechanism and Machine Theory 46 (2011) 142–155

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Spatially isotropic configuration of Stewart platform-based force sensor

Jiantao Yao, Yulei Hou, Hang Wang, Tieling Zhou, Yongsheng Zhao *

Robotics Research Center, Yanshan University, Qinhuangdao, Hebei 066004, PR China

ARTICLE INFO

Article history:
Received 13 June 2008
received in revised form 30 September 2010
accepted 2 October 2010
Available online 30 October 2010

Keywords:
Stewart platform
Force sensor
Spatially isotropic
Analytic relation
Jacobian matrix

ABSTRACT

This paper studies isotropic configuration of the Stewart platform-based force sensor using an analytic approach. The conditions leading to spatially isotropic configuration are introduced. The isotropic performance of the classical Stewart platform-based force sensor is studied, the result indicates that it is impossible to realize spatial isotropy in theory. A modified Stewart platform-based force sensor which can achieve spatial isotropy is proposed. In order to obtain spatially isotropic configuration, the analytic relations of key structural parameters leading to spatially isotropic configuration are derived. Classes of spatially isotropic configurations can be easily obtained from the analytic results.

1. Introduction

Stewart platform [1] structure possesses the distinguished advantages of good stiffness, symmetric and compact structure, and straightforward mapping expression between the wrenches applied on the platform and the measured leg forces [2]. These advantages make it particularly suitable for certain applications in six-axis force sensors. The force sensor is applied widely in many research areas such as wind tunnel balances, thrust stand testing of rocket engines, robotics, automobile industry, aeronautics, etc.

Theoretically speaking, each elastic measurement leg of the Stewart platform-based force sensor just sustains tensile strain or compressive strain along its axis regardless of the gravity of the legs and the frictional moment in the spherical pairs, which can realize the measurement of all components of the applied external force without stress coupling. The concise mapping expression between the wrenches applied on the upper platform and the leg reacting forces has attracted numerous researchers to apply Stewart platform as force sensors [3]. Gaillet and Reboulet [4] proposed an isostatic six-axis force sensor based on the octahedral structure of Stewart platform. Kerr [5] suggested that the Stewart platform with instrumented elastic legs be used as a six-axis force sensor and enumerated a few design criteria for the sensor structure. Nguyen et al. [6] developed a Stewart platform-based force sensor with LVDT (linear voltage different transforms) mounted along the legs for force/torque measurement in the presence of passive compliance. Dwarakanath et al. [7] reported the design of a Stewart platform-based force sensor by considering maximization signal to noise ratio and satisfying the dual objective of isotropy and sensitivity. Jin et al. [8] presented a six-axis force sensor with orthogonal parallel architecture based on a variation of Stewart platform, whose three pairs of elastic legs are perpendicular to the three orthogonal surfaces of the basic cube. Ranganath et al. [9] studied the performances of a Stewart platform-based force sensor in the near-singular configuration in order to obtain high sensitivity. Zhao et al. [10] developed a pre-stressed six-axis force sensor based on the Stewart platform. Gao et al. [11] developed a six-axis controller based on the Stewart platform-based force sensor, and introduced the elastic joints to replace the real spherical joints which made the micromation possible.

For the multi-axis force sensor, isotropy is of key importance to the sensor's performance. Isotropy means that the sensor exhibits approximately equal sensitivity for all components of the applied external force, and isotropy also leads to the minimum

* Corresponding author. Tel./fax: +86 335 807 4581.
E-mail addresses: ysuyjt@Gmail.com (J. Yao), yszhao@ysu.edu.cn (Y. Zhao).

0094-114X/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mechmachtheory.2010.10.002

relative error in the force mapping [12]. Isotropic design of multi-axis force sensor is one of the important issues in research. Uchiyama et al. [13–15] proposed an index for the evaluation of structural isotropy of the force sensor and studied a systematic design procedure to minimize the performance index for the force sensor. Xiong [16] presented the concept of isotropy on the basis of Fisher's information matrix. Wang et al. [17] established a model of the solution space for the Stewart platform-based force sensor and conducted an optimal design by using the isotropy performance atlases. Liu and Tzo [18] presented a six-axis force sensor with its force-sensing element in the form of four identical T-shaped bars, which has obtained good results in terms of the measurement isotropy and measurement sensitivity. Hou et al. [19] studied a modified Stewart platform-based force sensor and discussed the performance analysis and comprehensive index optimization of the sensor.

The isotropic performance of the Stewart platform-based force sensor substantially depends on the structure isotropy of the Stewart platform. Pittens and Podhorodeski [20] studied the Stewart Platform's isotropy using the index of condition number. Stoughton and Arai [21] presented a modification of the Stewart platform and optimized the structural design with respect to a weighted sum of dexterity and workspace volume. Zanganeh and Angeles [22] have worked on the Jacobian matrix of Stewart Platform and provided conditions for attaining isotropic parallel manipulators. Fattah and Ghasemi [23] studied the isotropic conditions using a numeric method. Tsai and Huang [24] studied the isotropy conditions in order to get certain isotropy generators. Bandyopadhyay and Ghosal [25] presented an algebraic formulation method to design isotropic spatial parallel manipulators using the concept of combined isotropy.

Few results, however, have been published on the study of spatially isotropic configuration of Stewart platform-based force sensor using the mathematical analytic approach. As far as we know, there is no Stewart platform-based force sensor reported with a spatially isotropic structure except for the force sensor with orthogonal parallel architecture reported in [8]. Studying the isotropic performance of the Stewart platform-based force sensor and finding classes of spatially isotropic configurations of the Stewart platform-based force sensor are the main goals of the paper.

The organization of this paper is as follows. Following the introduction, in Section 2, the mathematical expression of the force mapping matrix for the generalized Stewart platform-based force sensor is built by using the screw theory, and the conditions leading to spatially isotropic configuration are introduced. In Section 3, the isotropic performance of the classical Stewart platform-based force sensor is studied in detail. In Section 4, the isotropy analysis of a modified Stewart platform-based force sensor is presented, and the analytic relations of spatially isotropic configuration are obtained. Finally, the conclusion is presented in Section 5, summarizing the present works.

2. Basic theory

2.1. Mathematical model of the generalized Stewart platform-based force sensor

The drawing of the generalized Stewart platform-based force sensor is shown in Fig. 1, which is composed of an upper platform, a lower platform and six elastic legs connecting the two platforms with spherical joints. The Cartesian coordinates O_g-XYZ, called frame$\{\Omega_g\}$, is set up with its origin located at the geometrical center of the upper platform. $p_i(i=1, 2..., 6)$ is the center of the i-th spherical joint of the upper platform, $P_i(i=1, 2..., 6)$ is the center of the i-th spherical joint of the lower platform. F and M represent the force vector and torque vector acted on the center of the upper platform respectively.

The force and torque applied on the upper platform are distributed to the six legs, for the equilibrium of the upper platform, the following equation can be obtained.

$$F_w = F + \in M = \sum_{i=1}^{6} f_i \$_i \quad (1)$$

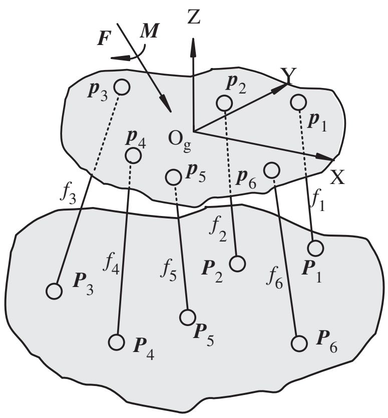

Fig. 1. The generalized Stewart platform-based force sensor.