Sensors and Actuators A 150 (2009) 1–11

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Theoretical analysis and experiment research of a statically indeterminate pre-stressed six-axis force sensor

Jiantao Yao, Yulei Hou, Jie Chen, Ling Lu, Yongsheng Zhao*

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

ARTICLE INFO

Article history:
Received 3 August 2008
Received in revised form 6 October 2008
Accepted 30 November 2008
Available online 11 December 2008

Keywords:
Force sensor
Six-axis
Stewart platform
Pre-stressed
Statically indeterminate
Isotropy

ABSTRACT

This paper presents the theoretical analysis and experiment research of a novel statically indeterminate six-axis force sensor based on a modified Stewart platform architecture. The characteristic of the pre-stressed structure is analyzed in comparison with the traditional Stewart platform-based force sensor. The force-distribution problem of the seven-limb statically indeterminate structure is solved by considering the stiffness properties and compatibility in deformations, and the sensor's force mapping matrix including the effect of the seventh limb is obtained. The isotropy performance of the sensor is studied, and the analytic relations of key structural parameters leading to isotropic configuration are obtained. The pre-tightening force is determined by solving the conditional extremum of the Lagrange function. The sensor prototype and the calibration device are manufactured, and the experiment results prove the superiority of the structure and the correctness of the theoretical analysis.

1. Introduction

With the ability of measuring three force components and three torque components, the six-axis force sensor is one kind of the most important and challenging sensors, and is applied widely in many research areas such as wind tunnel balances, thrust stand testing of rocket engines, and in robotics, automobile industry, aeronautics, etc. 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.

Theoretical and experimental investigations of the behavior of the parallel structure sensor were carried out by many authors. Gaillet and Reboulet [3] proposed an isostatic six-axis force sensor based on the octahedral Stewart structure. Kerr [4] suggested that the Stewart platform with instrumented elastic legs be used as a six-axis force sensor. Nguyen et al. [5] developed a Stewart platform-based force sensor with Linear Variable Differential Transformer (LVDT) mounted along the legs. Dasgupta et al. [6] presented a design methodology based on the optimal conditioning of the force transformation matrix. Svinin and Uchiyama [7] have considered the optimality of the condition number of the force transformation matrix. Sorli and Pastorelli [8] marked anisotropy with greater stiffness in the preferred direction. Xiong [9] presented the concept of isotropy on the basis of Fisher's information matrix. Kang [10] derived the closed-form solution of the forward kinematics of a Stewart platform-based force sensor. Jin et al. [11] 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. Nicholas et al. [12] described the development of a mechanically coupled six-dimension load sensor and derived out the decoupling matrix through finite element analysis. Dwarakanath et al. [13] reported the usage of ring-shaped sensing element in the Stewart Platform sensor, and presented a simply supported, 'joint less' six-component parallel mechanism-based force/torque sensor [14]. Gao et al. [15,16] developed a six-axis controller based on Stewart platform-based force sensor, and introduced the elastic joints to replace the real spherical joints which made the micromation possible.

As can be seen from the literature survey, the reported Stewart force sensor mostly adopted traditional sphere pair, elastic joint or 'joint less' structure. However, there are some intrinsic disadvantages for the sensor with the traditional sphere pair. For example, the structure becomes more complex; there are 12 sphere pairs required to be adjusted and pre-stressed separately which is an arduous task, and it is

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

0924-4247/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2008.11.030

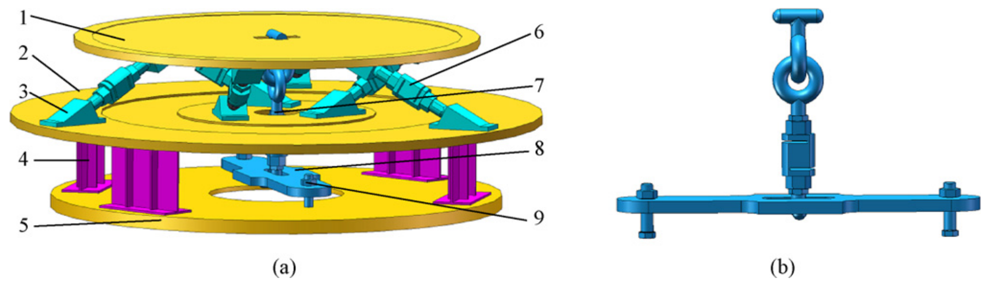

Fig. 1. The pre-stressed six-axis force sensor based on the 6-1/3-3-1 Stewart platform: (1) upper platform; (2) lower platform; (3) ball socket; (4) supporting plate; (5) base platform; (6) measuring limb; (7) pre-stressing limb; (8) pre-stressing plate; (9) pre-stressing screw.

difficult to make the pre-stressed force to be uniform; the relatively bigger contact area in the sphere pair leads to the bigger frictional moment which results in the bigger stress coupling in measuring limb; the inherent clearance that exists in the traditional sphere pair causes the mechanical hysteresis and the damage of the linearity of the sensor. Assuming that the elastic joints are used instead of the real spherical joints, it is difficult to realize the measurement of large forces since fragile elastic joints. In addition, the 'joint less' Stewart platform-based force sensor in [14] simplifies the manufacturing complexities by doing away with traditional sphere pair, but its sensing range would be influenced greatly owing to the limitation of deadweight pre-loading.

For overcoming the above shortcomings, this paper proposes a novel pre-stressed six-axis force sensor based on a modified Stewart platform and conducts theoretical analysis and experimental research of the sensor.

2. Structure characteristic

In order to overcome the disadvantages of traditional sphere pair and improve isotropy performance, a pre-stressed six-axis force sensor based on 6-1/3-3-1 Stewart platform is proposed, which is shown in Fig. 1. For the pre-stressed sensor, the centers of six joints on the upper platform are placed on the same circle; the centers of six joints on the lower platform are placed on two concentric circles. Fig. 1a illustrates the pre-stressed six-axis force sensor based on the 6-1/3-3-1 Stewart platform, which mainly consists of an upper platform and a lower platform coupled together with six measuring limbs and a pre-stressing limb. The measuring limb contains a single-axis force transducer and two link rods, which is connected with the two platforms using the cone-shaped spherical pairs with unilateral constraint [17,18] instead of the traditional sphere pairs. Due to the application of the unilateral constraint, a central pre-stressing limb is needed to ensure that all the measuring limbs are always in compression when subjected to the expected range of external loads. Fig. 1b illustrates the pre-stressing limb, which is composed of two revolute pairs and a ring pair in order to ensure that the single-axis force transducer just sustains the axial force, the single-axis force transducer on the pre-stressing limb is used to measure the magnitude of the pre-tightening force. The pre-tightening force is achieved by tightening the two pre-stressing screws connected the base platform and the pre-stressing plate.

The pre-stressed design has several advantages over current designs based on the Stewart platform-based force sensor with traditional sphere pairs. Due to the application of the modified spherical pairs of unilateral constraint, the effect of joint frictional moment can be greatly reduced. Provided that sufficient pre-tightening force act on the sensor, each limb will just sustain compressive force within the measurement range of the sensor; consequently, the error resulted from the nonlinearity and the mechanical hysteresis will be reduced significantly. As a statically indeterminate structure, the dynamic stiffness of the sensor will be improved greatly with the action of the pre-tightening force. Furthermore, as this sensor is assembled by separated elements, it is convenient to realize series products from microsensors to large measuring instruments compared with the sensor of monolithic structure. Meanwhile, it can be seen that the magnitude of the pre-tightening force affects the sensing range of the force sensor, then the magnitude of the pre-load is need to be determined based on the expected range of external force and moment.

3. Force analysis of the statically indeterminate force sensor with seven limbs

The schematic drawing of the pre-stressed Stewart platform-based force sensor is shown in Fig. 2. The Cartesian coordinate O-XYZ, called frame $\{\Omega\}$, is set up with its origin located at the geometrical center of the upper platform. R_{u} denotes the radius of the circle on

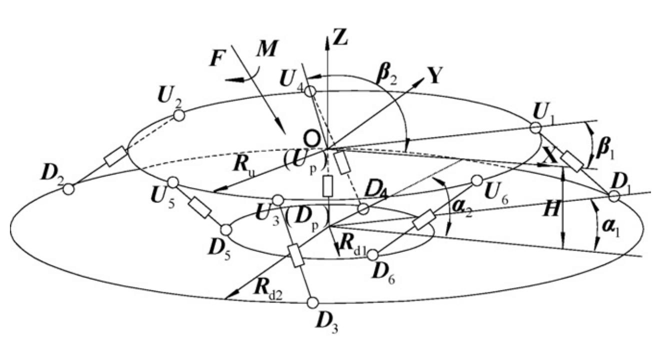

Fig. 2. Schematic drawing of the statically indeterminate pre-stressed six-axis force sensor based on the 6-1/3-3-1 Stewart platform.