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A 3-D printed redundant six-component force sensor with eight parallel limbs

Jiantao Yao[a,b], Hongyu Zhang[a], Ximei Xiang[a], Huidong Bai[a], Yongsheng Zhao[a,b,*]

[a] Parallel Robot and Mechatronic System Laboratory of Hebei Province, Yanshan University, Qinhuangdao 066004, China
[b] Key Laboratory of Advanced Forging & Stamping Technology and Science, Ministry of Education of China, Yanshan University, Qinhuangdao 066004, China

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ABSTRACT

In this paper, the design, manufacture and calibration test of a 3-D printed parallel six-component force sensor are presented. Aiming at improving the measuring performances and downsizing the outline of six-component force sensor, a novel redundant parallel six-component force sensor with spoke structure combining parallel mechanisms with flexible mechanisms is proposed. The mathematical model of the proposed sensor is established by screw theory which reveals the force mapping relationship. Considering the structure particularity, three-dimensional printing technology is innovatively applied to manufacture six-component force sensor prototype and main details regarding manufacture are described. Calibration tests for the sensor prototype are also carried out. Based on the data recorded in experiments, the calibration matrix is obtained and its performances such as non-linearity, repeatability and hysteresis are analyzed, which show good results in six-component force measurement.

1. Introduction

Six-component force sensor is superior to single-dimensional force sensor for its ability to measure all the force information in space simultaneously, including three-dimensional force and three-dimensional torque. It has been used in many areas of science and engineering such as robotic assembly [1], robot gripper and foot [2,3], wind tunnel experiments [4,5], automobile industry [6], aerospace industry [7] and so on.

An important class of six-component force sensor is based on the parallel mechanisms. Because of the mechanisms decoupling characteristic of parallel mechanism, parallel mechanism based force sensors overcome the problem of achieving decoupling by placing strain gauges to form the bridge in principle. Some good characteristics make parallel mechanisms suitable for being the structure of six-axis force sensor, such as the compact structure, good symmetry, high stiffness, high load bearing, no accumulative error, easy solution for mapping relation and so on. Researchers have done many theoretical researches on six-component force sensor with parallel structure and developed many different kinds of sensor prototypes [8–21]. However, some disadvantages cannot be ignored, like interval existing in traditional spherical joint, friction in traditional spherical joint and the contradiction between stiffness and boundary dimension. In order to solve these problems, we try introducing flexible mechanism into the design of parallel six-component force sensor.

Flexible mechanism is a novel one which can communicate or transfer movement, force or energy by the deformation of material. However, there is a close relationship between flexible mechanism and parallel mechanism, and both can compensate for some weaknesses each other. Combining flexible mechanism with parallel mechanism, six-axis force sensor will possess the good characteristics of both and perform better measurement properties. Based on this, the flexible-parallel mechanism is incorporated into the structure design of six-component force sensor and a novel parallel six-component force sensor is designed and manufactured in this paper.

The six-component force sensor used for haptic feedback in surgery described in [22] is a good example which uses Stewart platform structure coupled with flexible joints. Compared with this force sensor, the six-component force sensor proposed in this paper uses spoke structure with eight limbs which consists the redundant parallel configuration. The force sensor with spoke structure is more suitable for measuring force in shaft and hole parts and covers less space in height, which benefits the installation at the end of manipulators in limited space. The eight parallel limbs provide extra force information besides six-component force, which realizes the self fault tolerance ability of the force sensor. The

* Corresponding author at: Parallel Robot and Mechatronic System Laboratory of Hebei Province, Yanshan University, Qinhuangdao 066004, China.
E-mail addresses: jtyao@ysu.edu.cn (J. Yao), yszhao@ysu.edu.cn (Y. Zhao).

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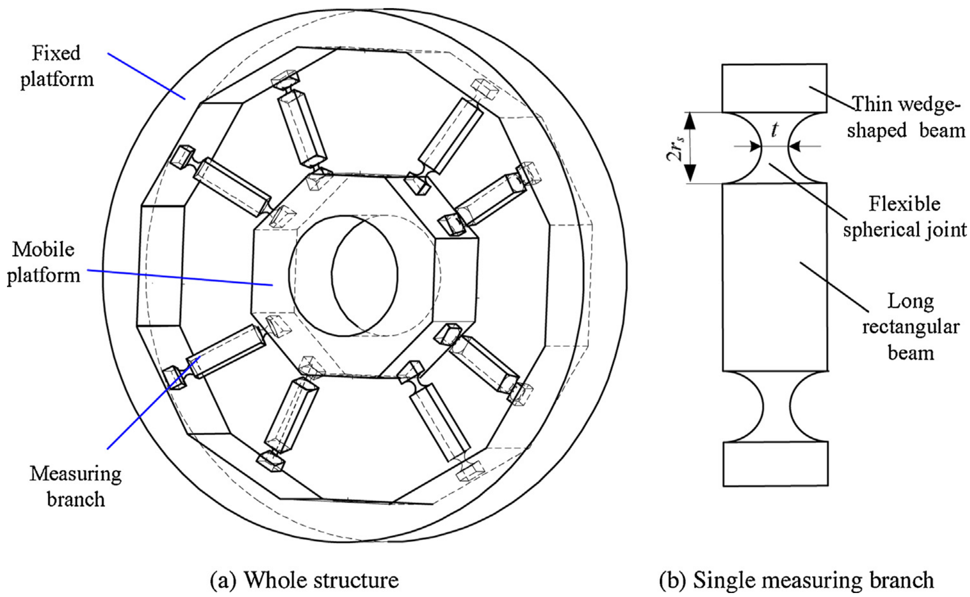

Fig. 1. Structure drawing of flexible parallel six-component force sensor.

other highlighted innovation is the way of 3-D printing technology used for manufacturing mental prototype. This technology is more effective in mass production and modularized production of six-component force sensor.

Manufacturing method for the sensor proposed is also a key component in this paper. Considering the particular structure of the sensor proposed, it will be rather costly to manufacture the sensor by traditional machining method and 3D printing rapid prototyping technology is used to produce the metal sensor prototype in this paper. 3D printing technology is a new manufacturing method which has been widely used in many areas [23,24]. It is also used in the three-axis force sensor reported in [25–27] which are made of ABS plastic. However, the material used in this paper is Ti alloy and it is true that six-component force sensors made of metal by 3D printing technology are rarely seen. With the new idea of manufacturing metal-made force sensor by 3D-printing technology, the fabrication of some force sensors with complex structure is no more a difficulty and more and more novel configurations of six-axis force sensor will be proposed regardless of structure complexity. Using 3-D printing technology may bring a revolution in the area of six-component force sensor.

2. Sensor structure

The structure drawing of the redundant six-component force sensor with eight parallel limbs is drawn in Fig. 1(a). As can be seen from the drawing, there exist one outside ring called fixed platform, one inside ring called mobile platform and flexible measuring branches between the two platforms. Eight branches are divided into two groups whose outer joints are respectively placed on the two circles of outside ring and all the inner joints are on the middle surface of inside ring.

The flexible measuring branches connect the fixed ring and the mobile ring by spherical joints at two ends of each branch. Details about flexible branch are shown in Fig. 1(b). There exist two right-circular flexible spherical joints in each measuring branch whose truncation shape of elastic part is right-circular. Besides, there are two beams with different shapes including a thin wedge-shaped beam and a long rectangular beam. Main parameters of this spherical joint are the diameter of minimum circular truncation t and arc radius r_s. Strain gauges are designed to be attached to the middle of each measuring branch. The flexible spherical joint which is used in each measuring branch effectively avoids the friction torque existing in traditional spherical and lubrication is no longer needed here. Therefore, the influences of interval and torque existing in joints on measurement accuracy are eliminated by mechanism structure.

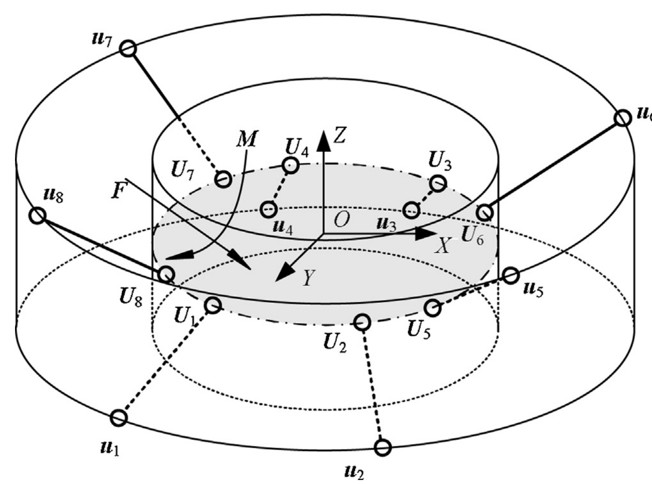

Fig. 2. Configuration of parallel six-component force sensor with flexible structure.

3. Measuring theory

The drawing of the configuration of parallel six-component force sensor with flexible structure is shown in Fig. 2. The Cartesian coordinates O-XYZ called frame $\{\Omega\}$ is set up with its origin located at the geometrical center of the inner platform. $u_i(i = 1,2\ldots,n)$ is the center of the i-th spherical joint of the outer ring and $U_i(i = 1,2\ldots,6)$ is the center of the i-th spherical joint of the inner ring.

According to screw theory, the force and toque applied on the inner platform are distributed on all branches. For the equilibrium of the inner platform, the following equation can be obtained.

$$\mathbf{F} + \in \mathbf{M} = \sum_{i=1}^{8} f_i \$_i \quad (1)$$