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Type synthesis and analysis of rotational parallel mechanisms with a virtual continuous axis

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ABSTRACT

Having virtual continuous axes is an important mechanism performance required by the motion tracking and simulating mechanisms for large-scale heavy-weight apparatus. Mathematical criteria for a virtual continuous axis using virtual coefficient theory is proposed through geometric modeling continuous rotation of the constrained rigid body and a virtual continuous axis. A type of synthesis approach for rotational parallel mechanisms (RPMs) with a virtual continuous axis is given and a type of RPM with arc-rail-slider or cross slipper is constructed. On the basis of screw theory, degree of freedom (DoF) and properties of the axes of a typical RPM with a virtual continuous axis are analyzed, and the inputs selection and arrangement are also discussed. The kinematic and dynamic models of the RPM are established. Finally, a numerical example and a solution to the motion simulation for super-large-scale heavy-weight apparatus are given.

1. Introduction

Motion tracking and simulating platforms with multi-DoF rotational mechanisms (RMs) are widely used for testing the apparatus installed on satellites, planes, ships or vehicles to shorten the development cycle and reduce costs. The traditional multi-DoF RMs [1] mostly, are to employ the serial topology with shafts connected perpendicularly, which have advantages of simple structures and mature techniques. However, with regard to the motion tracking and simulating mechanisms for large-scale heavy-weight apparatus, having virtual continuous axes and the carrying capacity are the important mechanism performances, which are the disadvantages of the traditional multi-DoF RMs. Bearing these disadvantages in mind, multi-DoF rotational parallel mechanisms (RPMs) have drawn more and more attention from both academia and industry in recent years. As to the 3-DoF RPMs, 3-RRR spherical parallel mechanism (SPM) [2,3] is the most famous one, and other different SPMs were proposed in the literatures [4–11]. The 5R SPM [12,13] which has been applied into several fields, is claimed as the simplest topology of the 2-DoF RPMs. The SPMs above have a rotation center which is the intersecting point of more than two revolute joint axes. To avoid the above geometric condition, Huang et al. [14] proposed a 3-DoF RPM without intersecting axes. According to different application requirements, many scholars also proposed and analyzed other architectures of 2-DoF RPM [15–24] such as 3-RSR/US [16], 2-PUS/U [17–19] 3-UPS/U [22] and 2-RUUR [23,24].

In recent years, with the rapid development of the theory of type synthesis of parallel mechanism (PM), plenty of new PMs were

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synthesized [25–30]. However, those work mainly focuses on synthesizing PMs with different numbers and properties of DoF. As to type synthesis of RPMs, many approaches were proposed. Karouia and Hervé [31] enumerated many new non-overconstrained 3-DoF RPMs using equivalencies that stem from the algebraic structure of Lie group of the set of Euclidean displacements. Using the screw theory, Fang and Tsai [32] enumerated a class of 3-DoF RPMs while Kong and Gosselin [33] synthesized 3-DoF SPMs. Chen et al. [34] synthesized a class of 3-DoF RPM with no intersecting axes using the screw theory and the subchain theory. Gogu [35] synthesized a 2-DoF decoupled RPM with fully-isotropy based on the theory of linear transformations. Vertechy and Parenti-Castelli [36,37] adopted US limbs to synthesize 2-DoF RPMs with different constraining properties, and addressed the static and stiffness analyses of this class of mechanisms. Using algebraic properties of rigid-body motion subsets, Hervé [38] introduced an uncoupled actuation of Pan-Tilt wrist. Zeng et al. [39] synthesized a family of decoupled 2-DoF RPM based on screw theory. Based on the graphic approach, Yu et al. [40,41] investigated a type of 2-DoF RPM with equal-diameter spherical pure rotation. All of the above work promote the development of mechanisms and support the engineering applications. Driven by the requirements of the motion simulation mechanism for large-scale heavy-weight apparatus, this paper defined the virtual continuous axis, and proposed its mathematical criteria, and synthesized a class of RPMs with a virtual continuous axis, which are the main contributions of the paper.

The paper is organized as follows. In Section 2, mathematical criteria for a virtual continuous axis using virtual coefficient are proposed through geometric modeling continuous rotation of the constrained rigid body and the virtual continuous axis. Combining the criteria and the constraint screw-based synthesis method, closed-loop kinematic chains with a virtual continuous axis are synthesized in Section 3. In Section 4, a type synthesis approach for RPMs with a virtual continuous axis is given and 2-DoF RPMs with arc-rail-slider or cross slipper are constructed. After that, DoFs and axes properties of a typical 2-DoF RPM with a virtual continuous axis are analyzed on the basis of screw theory, and inputs selection and arrangement are discussed in Section 5. Based on virtual mechanism principle and screw theory, kinematics and dynamics models of the 2-DoF RPM are established in Section 6. A numerical example and a solution to the motion simulation for super-large-scale heavy-weight apparatus are given in Section 7 before the conclusions are drawn in Section 8.

2. Virtual continuous axis and mathematical criteria

2.1. Continuous rotation and virtual axis of rigid body

If a rigid body can purely rotate around an axis, the axis can be denoted by a screw as $S^{\mathrm{m}} = (s^{\mathrm{m}}\ ;\ r^{\mathrm{m}} \times s^{\mathrm{m}})$, where s^{m} is a unit vector indicating the direction of the axis, and r^{m} is a vector from the reference origin to the axis. If s^{m} and $r^{\mathrm{m}} \times s^{\mathrm{m}}$ both stay invariant during the motion, screw motion $\delta\theta S^{\mathrm{m}}$ of the rigid body is a rotation around a constant axis called continuous axis; Otherwise, that is a rotation around a variable axis called instantaneous axis. Herein, $\delta\theta S^{\mathrm{m}}$ is a twist of infinitesimal amplitude $\delta\theta$ around the screw S^{m}.

Assuming a rigid body connects with other bodies or kinematic chains by n revolute joints, as shown in Fig. 1, the revolute joints can be indicated by line vector as $S_i^{\mathrm{J}} = (s_i^{\mathrm{J}}\ ;\ r_i^{\mathrm{J}} \times s_i^{\mathrm{J}})$, where s_i^{J} is the unit vector denoting the direction of the axis of the revolute

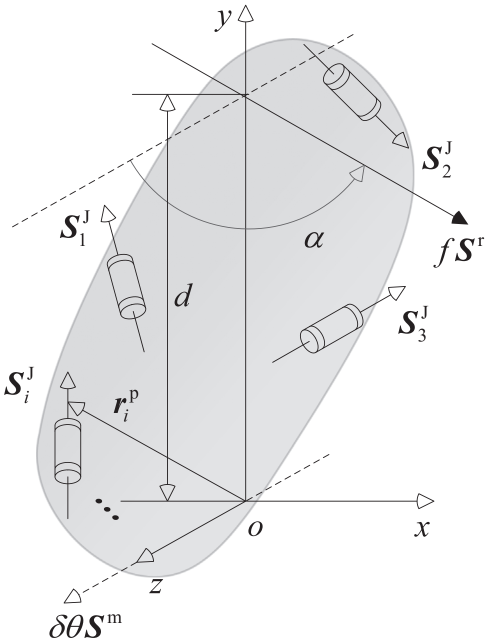

Fig. 1. Rotation of a rigid body constrained by a wrench.