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Research paper

Coupled kinematic and dynamic analysis of parallel mechanism flying in space

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ABSTRACT

Parallel mechanism with two rotational degree-of-freedoms (DoFs) has been widely applied in driving antenna to track moving targets in space, where its base is moveable and its kinematic performances including position, velocity and acceleration are involved with its dynamic properties. This leads an unsolved coupled kinematic and dynamic problem. In light of this, this paper proposes a novel approach to solve this problem. Firstly, the position, velocity and acceleration of the base are modeled by employing the laws of centroid conservation and momentum conservation. Then, these kinematic properties of the other parts of the mechanism are derived by using superposition principle. For the convenience of dynamic analysis, velocity relationships between the moving platform and the other parts are expressed as Jacobian matrixes. Secondly, the inertial forces of all parts of the mechanism are calculated, and the corresponding virtual displacements are expressed by the displacements of the actuated joints. Finally, the actuated torques of mechanism are solved in a theoretical form by applying virtual work principle for the first time and the validity of this approach is verified by numerical simulation.

1. Introduction

Parallel mechanism with two rotational degree-of-freedoms (DoFs) has been widely applied in actuating antenna to track moving targets in space [1–3]. This mechanism is made up of a base, a moving platform and several closed-loop limbs [4,5]. Commonly, the base of parallel mechanism is fixed on the ground and the moving platform moves under the control of the closed-loop limbs. Then kinematic performances of the moving platform and limbs, including position, velocity and acceleration, are totally determined by their kinematic properties [6,7]. The kinematic and dynamic problem of parallel mechanism in this working environment has been successfully solved by traditional methods [8–12]. When applying the parallel mechanism in space, its base is always attached to a flying vehicle, which position is not controlled during its flying procedure. This means that the attitude of the base of parallel mechanism is constant, but its position is varied. This makes the kinematic problem of parallel mechanism flying in space difficult to solve. Fortunately, the movement of the base is not random in this flying procedure. It follows two rules in terms of the laws of centroid conservation and momentum conservation [13,14]. Under their influence, the positions, velocities and accelerations of the base, the moving platform and limbs are related to their mass properties. In this way, the kinematic problem of parallel mechanism flying in space is coupled with its dynamic property. Hence, a coupled kinematic and dynamic problem of parallel mechanism flying in space is raised.

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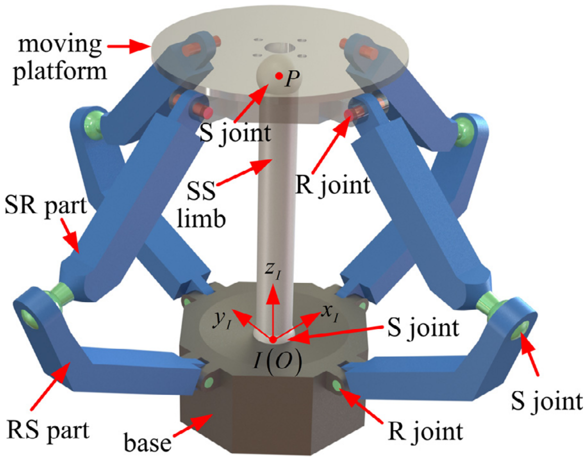

Fig. 1. Structure of 4-RSR&SS parallel mechanism.

It can been seen from the literature review that the existing researches of parallel mechanism flying in space are rare, and the main attention of researches has been paid on serial planar mechanisms till now [15–17]. By employing barycentric method, Papadopoulos and Dubowsky studied kinematics and dynamics of a single-arm flying aerial mechanism [18]. And Moosavian and Papadopoulos figured out dynamics of a flying serial mechanism and employed its dynamic model to control strategy on the basis of Lagrangian formulation [19–21]. It should be noticed that the dynamic problems of the serial mechanism are all carried out by Lagrangian formulation. This formulation needs large amounts of calculation and is hard to be applied on parallel mechanism, since the structure of parallel mechanism is more complicated [22–24]. Compared with Lagrangian formulation, it is more convenient for virtual work principle to reveal the relationship between the actuated torques and the motion of moving platform. Virtual work principle can avoid complicated derivative calculation which is simplified by virtue of Jacobian matrix derived in the kinematic analysis of parallel mechanism. Consequently, virtual work principle is much more applicable for parallel mechanism flying in space.

As stated above, the coupled kinematic and dynamic problem of parallel mechanism flying in space has not drawn enough attention. Until now, software simulation is the common method for this mechanism. By using SolidWorks software, Feng simulated the influence of gravity to 3-RPS and 4-UPU parallel mechanisms [25]. Herein, R, P, U and S denote revolute, prismatic, universal and spherical joints, respectively. Li studied the kinematics and payload capacity of Stewart mechanism in space [26]. As is well known, the simulation results are easily to be gotten but the kinematic and dynamic principles of mechanism cannot be revealed merely by software. Without these theoretical relationships, lots of further researches, including structure optimization, trajectory planning and control strategy, are unachievable. Therefore, to solve the coupled kinematic and dynamic problem of parallel mechanism flying in space in theoretical form is a significant and challenging subject.

Aiming to solve this problem, this paper proposes a novel approach to the coupled kinematic and dynamic problem of parallel mechanism flying in space. The remainder of this paper is organized as follows. In Section 2, structure of parallel mechanism is depicted and its working motion is demonstrated. Then position and velocity of this mechanism are derived in detail in Sections 3 and 4. Followed with Section 5, it carries out acceleration analysis of all parts of mechanism. And Section 6 applies virtual work principle to parallel mechanism flying in space and formulates the actuated torques in theoretical form. Section 7 verifies the validity of this approach by comparing theoretical torques with simulation result before conclusions are drawn in Section 8.

2. Mechanism structure and working mode description

As shown in Fig. 1, 4-RSR&SS parallel mechanism is made up of a base, a moving platform, four identical RSR limbs and one SS limb. The four RSR limbs connect the moving platform and the base by R joints respectively and the SS limb connects centers of the base and the moving platform. Centers of moving platform and base are concentric with centers of S joints. These centers are denoted by points O and P respectively. Axes of R joints in each RSR limb parallel with each other when the moving platform parallel with the base. This configuration is called as initial configuration of 4-RSR&SS mechanism.

In order to describe the motion of 4-RSR&SS mechanism, an inertial coordinate frame $I-x_Iy_Iz_I$ is assigned at the center of the base. It should be noticed that $I-x_Iy_Iz_I$ frame is fixed in space and does not move even the base of mechanism moves. Working mode of 4-RSR&SS mechanism fixed on the ground is shown in Fig. 2(a). The base of this mechanism is fixed on the ground and its moving platform realizes 2-DoF rotations with respect to $I-x_Iy_Iz_I$ frame. When applying 4-RSR&SS mechanism in space, its base is rigidly connected to a flying vehicle, which attitude is controlled to keep its initial status for fulfilling high-precision tracking task. But their position is uncontrolled. The base of mechanism is able to move