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Configuration bifurcation and self-motion analysis of 3SPS + 1PS bionic parallel test platform for hip joint simulator

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ABSTRACT

A hip joint simulator with a 3SPS + 1PS spatial parallel manipulator as the core module is proposed. Compared to traditional serial test platform, it brings better performance, as also as its inherent defect—singularity. In order to analyze the motion behavior of the manipulator near singular points, the entire configuration paths corresponding to single input parameter, are traced with the help of the closed-form solution of the forward position. The investigation reveals the reason to cause forward singularity and uncontrolled degree-of-freedom (DOF) of the manipulator, and it is verified by 3-D motion simulation. Then, a Configuration Stability Index is proposed to measure the controllability of DOF and a qualitative and quantitative analysis of self-motion is presented using its equivalent motion. The results indicate that: at all six bifurcation points, the uncontrolled DOFs show a similar direction to *Z*-axis, with slightly offsets to the other two axes. It means that the platform has an unstable rotation around *Z*-axis and a weak load-ability in that direction. Moreover, the direction of uncontrolled DOF almost stays constant under different control precisions. The research provides an analytical basis to achieve the certain motions at singular points and improve the motion stability for parallel manipulator.

1. Introduction

The hip joint simulator is used to evaluate the friction and wear characteristics of hip joint prosthesis biomaterials. It requires the replication of the kinematic and dynamic characteristics of natural human hip joints. To overcome the defects of traditional serial ones on complex motion simulation and large dynamic loading, a hip joint simulator with a 3SPS + 1PS spatial parallel manipulator as the core module is developed [1], but it also has its inherent defect—singularity, which results in uncontrolled motion and poor stiffness at certain poses.

Singularity analysis of mechanisms is a very active research field. A parallel manipulator or a closed-loop mechanism may either lose or gain one or more DOF at a singular configuration, while the Jacobian matrix loses rank, and it loses the ability to counteract external forces in certain directions [2]. One classical way to classify singularities was proposed by Gosselin and Angeles [3]: three types of physical singularities were defined according to the mathematical singularities of two Jacobian matrices, which define the relationship between input and output velocities, and forward singularity was pointed out to be the common type that occurred in parallel manipulators. Different from serial manipulator in which singularities usually occur at the outer boundaries of workspace, parallel manipulator has its singularity distribution on the hypersurfaces inside workspace, which leads to the controllable motion discontinuous [4]. Some researchers have obtained the singularity loci or distributions of parallel manipulator based on the singular conditions of algebra method [5], constraint plane [6], and screw theory [7,8]. Those works generally described the relations among

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the pose parameters of moving platform at singular points, so that they have limited effects on singularity-free design and path planning.

In contrast to serial manipulator, obtaining the singular configurations in parallel manipulators and closed-loop mechanisms is difficult. Some researches solved the singular configurations by using line geometry, looking for possible actuator-line dependencies [5,9]. Kong and Gosselin [10] used the stability condition of an equivalent structure of three-legged robots with spherical joints on the platform to find singular configurations. Innocenti and Parenti-Castelli [11] pointed out that path bifurcation point would occur in singular point, where the configuration would be changed from one kind to another, resulted in uncontrollable motion. Wang and Li [12] introduced the definition of maximum loss control domain to describe the configuration controllable conditions near singular points, but it ignored the case of two asymmetric configuration curves forming the bifurcation points, which may lead to inaccurate prediction.

Self-motion is defined as a finite mobility of a manipulator when all actuators are locked, which is obviously a dangerous effect that must be prevented. A complete classification of the self-motions of the classical Stewart–Gough parallel manipulator was given by Karger and Husty [13]. Bandyopadhyay and Ghosal [14] presented the necessary condition for finite self-motion and finite dwell of the passive links by analyzing second-order properties of constraint equations. Voglewede and Ebert-Uphoff [15] presented two different approaches to analyze the potential for large motion at a singular configuration: the manipulator has perfect precision or finite clearance in joints. It is noteworthy that in recent years, the related studies have pointed out that the possible self-motion is affected by many factors, and it may become determinate or disappear under dynamic inertia forces [16,17].

Up till now, few works have dealt with the relation between singularity and input parameters, as well as the motion behavior near the singular points. However, the direct and effective way to avoid singularity is to detect and control the input parameters. In addition, to approach stable motion, it also needs to predict and control the motion behavior of manipulator near singular points. Based on above overview, the paper is organized as follows: Section 2 builds the analytical model of the forward position analysis. In Section 3, the entire configuration paths under single input parameter are traced. Based on this, the motion behavior near the singular points and the configuration bifurcation characteristics are analyzed and it is verified by 3-D motion simulation. In Section 4, a Configuration Stability Index is proposed to measure the controllability of DOF and the self-motion of the manipulator is analyzed using its equivalent motion. Finally, Section 5 follows with a brief conclusion of the paper.

2. Forward position analysis

2.1. Introduction of the manipulator

The hip joint simulator consists of a moving platform and a base connected by three surrounding SPS-type driving legs and one intermediate PS-type leg, as shown in Fig. 1(a). The driving legs use electric cylinders to drive the moving platform. The intermediate leg is fixed on the base and connected to the center of the moving platform with a thrust bearing. It is used to install the artificial hip joint and balance the loading force of the hydraulic cylinder. The height is determined by the initial adjustments and remains

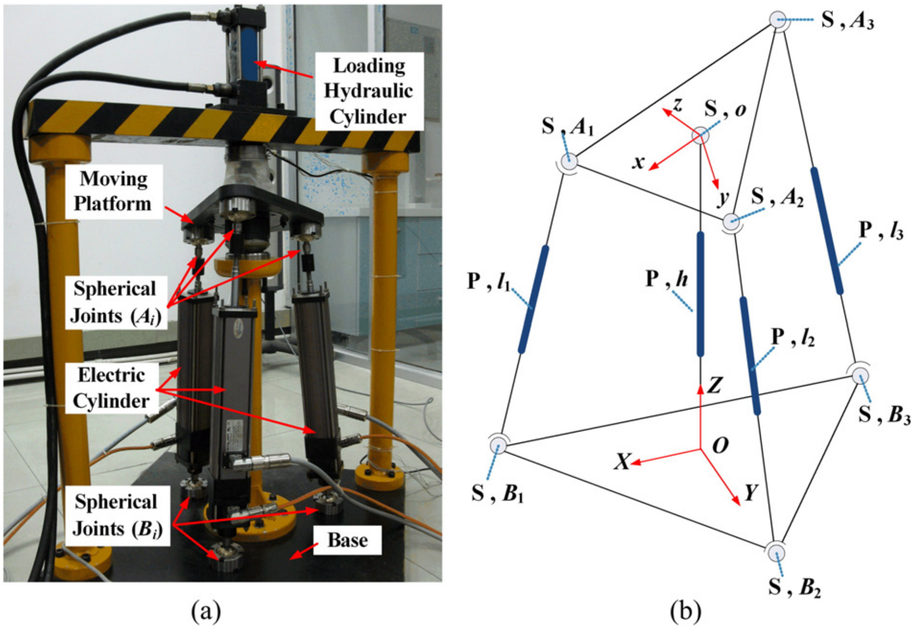

Fig. 1. The parallel hip joint simulator and its topology structure.