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Singularity analysis and detection of 6-UCU parallel manipulator

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ABSTRACT

6-UCU kind Gough–Stewart platform (GSP) has been used extensively in practice. The singularity of GSP has been studied by many scholars, but their works mainly focused on finding the methods to divide the cases of singularity or searching the solutions with Jacobian matrices. On the other hand, this paper studies the singularities of 6-UCU parallel manipulator caused by not only the active joints but also passive universal joints. Two types of singularity are derived based on a degree of freedom method by using screw theory. Singularity detection is essential to certify the absence of singularity within a prescribed workspace or a reachable workspace for a practical use of the 6-UCU parallel manipulator. Algorithms are proposed by using evolutionary strategy to detect the singularity in the desired or reachable workspace of the 6-UCU parallel manipulator. Case studies are presented to demonstrate the effectiveness of the proposed singularity detection methods.

1. Introduction

Compared with the spherical joint, the universal joint can bear more tension and rotate in larger angular range, and then 6-UCU kind GSP has been extensively used in practice, such as the tyre test machine designed by Gough in 1955 [1–3] (In the reviewer communication part of Stewart's paper [2], Gough pointed out “In point of fact, the universal joint systems attaching the jacks to the platform are identical to those attaching the jacks to the foundation”.), the first motion simulator patented by Cappel in 1967 [4], the commercial flight simulators [5], the docking test system in China and other over 30 motion simulators produced by our lab, and Moog FCS 5000E motion base [6].

Singularities are critical configurations in which the kinetostatic behavior of a mechanism suddenly changes with respect to a full-cycle condition [7]. The singularity of GSP has been studied by many researchers. Merlet [8] used Grassman geometry to study the singularity of the 3/6 GSP systematically. Gosselin and Angeles [9] studied singularities of GSP on the input–output velocity map. Ma and Angeles [10] studied architecture singularities of GSP. St.-Onge and Gosselin [11] presented a method to determine analytically and represent graphically the singularity loci of the general GSP. Huang et al. [12] analyzed the singularities of 3/6 and 6/6 GSP based on the kinematic status of the machinery and the linear-complex. All the references mentioned above only considered the singularity caused by the Jacobian matrix derived from the input–output velocity map, but they did not considered the singularity caused by the passive joints. The singularity analysis approaches based solely on input–output equations may fail to detect certain singularities in the general closed-loop case as shown in [13–15]. In order to study singularity in a more general framework, Zlatanov et al. [16] proposed a method for finding and classifying all the singularities of arbitrary non-redundant mechanism based on the velocity-equation, but their method may be nonimmediate or ambiguous in some cases due to the deliberate choice of looking at singularities from the standpoint of the device's end user [7]. Zhao and Zhou [17] presented a methodology to analyze the singularity of spatial parallel manipulator with the theory of reciprocal screws, but they did not consider the singularity caused by the actuated joints. Zhao et al. [18] addressed the singularity of spatial parallel manipulator with terminal constraints, but they also did not consider the singularity caused by the actuated joints. In order to identify and interpret the causes of singular events clearly, Conconi and Carricato [7] presented a singularity analysis approach of general parallel kinematic chains on the basis of the physical causes that originate the phenomena. In order to analyze simply and interpret the causes of singular events clearly, the singularity analysis of 6-UCU kind GSP is studied based on a degree of freedom theory by using screw theory in this paper with considering the passive joints and the actuated joints.

In practice, it is crucial during the design phase of a robot to determine whether there are singularities within a given workspace or trajectory or not [19]. A fast straight yes–no answer of the singularity detection is important [19]. Su et al. [20] set the objective function as the square of det ($\boldsymbol{J}$) ($\boldsymbol{J}$ is the Jacobian matrix),

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and used real-coded genetic algorithm to search the minimum value to detect the singularity of GSP for the given workspace, but it is not considered the constraints of leg length limits, and also the six-dimensional workspace is very difficult to obtain. Merlet [21] used interval analysis to detect the singularity of GSP by searching det ($\boldsymbol{J}$), but the main drawbacks of this method is that some expertise in interval analysis is needed to get an efficient implementation [19]. Blaise et al. [6] proposed an algorithm using Matlab to look at the sign of the determinant of the Jacobian matrix for a wide range of constant-orientation workspaces to detect singularity of GSP. Another method is using symbolic language program for the singularity detection: first obtain the analytic expression of det ($\boldsymbol{J}$)=0, and then fixed three mobility variables to draw the singular loci surface and workspace to determine that whether there is or no singularity in the workspace [22–24], but the singularity is only determined at some special postures and not the whole reachable 6D workspaces. In our best knowledge, all the singularity detection methods of the 6-UCU parallel manipulator are not considered the singularity caused by the passive universal joints. The singularity detection algorithms of the 6-UCU parallel manipulator with considering both the passive and active joints are proposed in this paper.

In this paper, the singularities of the 6-UCU parallel manipulator are analyzed in Section 2. The singularity detection algorithms are proposed in Section 3. Some cases are studied in Section 4 to illustrate the use of the singularity detection algorithms proposed in this paper. The conclusions are given in Section 5.

2. Singularity analysis of the 6-UCU parallel manipulator

The 6-UCU parallel manipulator consists of a moving platform, a fixed base and six identical legs. Each leg consists of two universal joint at both ends of the leg and a cylindrical joint in the middle. The piston of the ith (i=1–6) leg is attached to the platform with a universal joint at point P_i, and the cylinder is attached to the base with a universal joint at point B_i. In practice, the piston and piston rod of the cylinder not only retract (or extend) along the axis of the cylinder actively, but also rotate along the axis passively. As shown in Fig. 1, the world frame $O-xyz$ is fixed on the base at origin O, and the body frame $O-x_1y_1z_1$ is fixed on the moving platform at origin O_1.

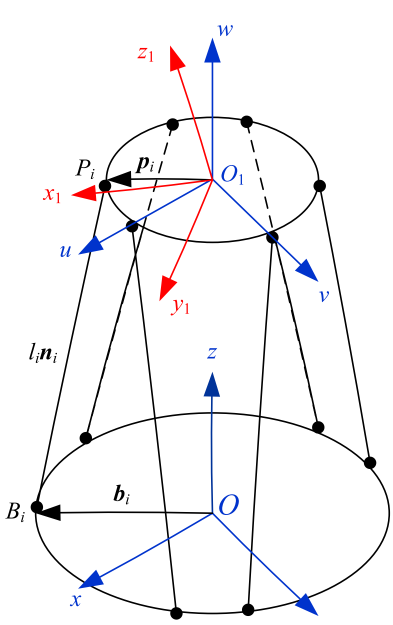

Fig. 1. Coordinate systems of 6-UCU parallel manipulator.

From the causes of physical phenomena, the singularities of 6-UCU parallel manipulator can be divided into two types: leg singularity and actuator singularity. If the connective of the moving platform is changed to less than 6 at an instantaneous pose, this type singularity is defined as leg singularity. If the actuated joints cannot drive the whole 6-UCU parallel manipulator effectively at an instantaneous pose, this type singularity is defined as actuator singularity.

In order to analyze the singularities of the 6-UCU parallel manipulator completely, we define an instantaneous reference frame with its origin located at point O_1 and the axes u, v, and w parallel to the axes x, y, and z of frame $O-xyz$. Then we express all the joint screws with respect to this instantaneous reference frame. Fig. 2 depicts the equivalent kinematic chain of a UCU leg, where the lower universal joint is replaced by two intersecting unit screws, $\hat{\$}_{01}^i$ (subscript 0 stands for zero pitch) and $\hat{\$}_{02}^i$, and the upper universal joint is replaced by two intersecting unit screws, $\hat{\$}_{05}^i$ and $\hat{\$}_{06}^i$. The cylinder joint is replaced by two colinear unit screws, $\hat{\$}_{\infty 3}^i$ (subscript ∞ stands for infinite pitch) and $\hat{\$}_{04}^i$.

There are six joint screws associated with each leg. The third joint is the only actuated joint, and the remaining five are passive. The actuated joint screw is an infinite pitch screw, and the remaining five are zero pitch screws. Let $\mathbf{s}_{j,i}$ be a unit vector along the jth joint axis of the ith leg. Then the six unit joint screws of a leg can be written as

$$\hat{\$}_{01}^i = \begin{bmatrix} \mathbf{s}_{1,i} \\ (\mathbf{p}_i - l_i\mathbf{n}_i) \times \mathbf{s}_{1,i} \end{bmatrix}$$

$$\hat{\$}_{02}^i = \begin{bmatrix} \mathbf{s}_{2,i} \\ (\mathbf{p}_i - l_i\mathbf{n}_i) \times \mathbf{s}_{2,i} \end{bmatrix}$$

$$\hat{\$}_{\infty 3}^i = \begin{bmatrix} \mathbf{0} \\ \mathbf{s}_{3,i} \end{bmatrix}$$

$$\hat{\$}_{04}^i = \begin{bmatrix} \mathbf{s}_{4,i} \\ \mathbf{p}_i \times \mathbf{s}_{4,i} \end{bmatrix}$$

$$\hat{\$}_{05}^i = \begin{bmatrix} \mathbf{s}_{5,i} \\ \mathbf{p}_i \times \mathbf{s}_{5,i} \end{bmatrix}$$

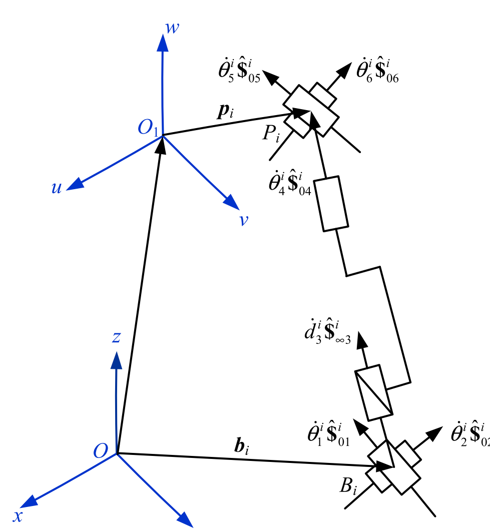

Fig. 2. Equivalent kinematic structure of a UCU leg.