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Dimensional synthesis of a three translational degrees of freedom parallel robot while considering kinematic anisotropic property

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A R T I C L E I N F O

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A B S T R A C T

By taking the Delta robot as the object of study, this paper deals with the methodology of the dimensional synthesis of the three translational degrees of freedom parallel robot while considering the kinematic anisotropic property. The velocity transmission index is employed as the objective function of the optimization design. The physical meaning of the velocity transmission index is the maximum of the input angular velocity when the moving platform translates with an assigned velocity. The determinant of the direct kinematic Jacobian matrix, the ratio of the machine volume to that of the desired workspace and the difference between the radius of the base and the radius of the moving platform are adopted as the constraints for the dimensional synthesis in order to make the Delta robot have a good transmission behavior between the distal links, keep far away from the direct kinematic singular configuration, not to be a very tall and slender configuration, achieve the desired performance without large dimension and big building cost. The example of the dimensional synthesis of the Delta robot is presented in the simulation while considering the maximum velocity requirements for the moving platform along the respective direction parallel to the x axis, y axis and z axis are varied. The conclusions are provided at the end of the paper.

1. Introduction

Parallel mechanism is a closed-loop kinematic chain mechanism whose moving platform is linked to the base by at least two independent kinematic chains. Due to the parallel topology with the base-mounted or near base-mounted actuation arrangement, it is widely recognized that parallel mechanisms usually have potential advantages such as high speed, high rigidity/weight ratio and good dynamic characteristics. Parallel mechanisms have been successfully used in motion simulator, machine tool, robotic moving platform and in circumstances like fast pick-and-place operation. In order to achieve good performance, dimensional synthesis is necessary for the parallel mechanism when the structural synthesis is finished. Dimensional synthesis of the parallel mechanism is a constrained optimization problem with multi-criteria [1–5]. It is usually carried out while considering workspace [5–13], stiffness [14–17], dexterity [5,17–22,29], singularity [9,10,23,24], payload [25,26], balancing [26–30], accuracy [31–34], manipulability [35–37] and so on.

In the existing dimensional synthesis, the parallel mechanisms are often assigned to have isotropic performance in all directions and the anisotropic characteristics are seldom to be considered. However, the anisotropy should also be considered in the dimensional synthesis of the parallel mechanism due to the following facts: (1) Most of the parallel mechanisms have symmetrical structures with symmetrical characteristic while not isotropic characteristic in the whole workspace since they have not the same performance in all directions. For the parallel mechanisms with asymmetrical structures, they have also anisotropic characteristics in the whole workspace [38–40]. (2) In practical application, the performance requirement of the parallel mechanism is usually not isotropic in all directions within the whole desired workspace. For example, the Delta robot should have a higher speed in the horizontal plane than on the direction of the plumb line when it is used for the long-distance pick-and-place operation. Even for the same parallel mechanism, the results of the dimensional synthesis should be different whether the anisotropic characteristic is considered or not. Little work has been done on the dimensional synthesis of the parallel mechanism while considering the anisotropy [41]. So the motivation of the paper is to investigate the methodology of the dimensional synthesis of the three translational degrees of freedom parallel robot while considering the kinematic anisotropic property.

Delta robot is a three translational degrees of freedom parallel robot which had been presented by Clavel [42]. It is usually developed for high-speed operation and it is well known in the electronics, food and pharmaceutical sectors as a reliable system with fast execution of light duty tasks [43]. Many investigations have been done on the kinematics [44–46], dynamics [47–53], performance evaluation [45,53–55], design [1,6,8,13,16,27,56–62],

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singularity [23,47,63] and control [51,52]. This paper presents the dimensional synthesis of the Delta robot while considering the kinematic anisotropic property.

The following sections will concentrate on the dimensional synthesis of the Delta robot. The paper is organized as follows: in Section 2, the description of the Delta is given. Then, Section 3 presents kinematics. Dimensional synthesis of the Delta robot while considering the kinematic anisotropic property is investigated in Section 4. Design example is illustrated in Section 5. Finally, Section 6 gives the conclusions.

2. System description

The Delta robot is shown in Fig. 1. It consists of a moving platform connected to the base platform by three identical kinematic chains. There are two limbs for each kinematic chain: the active proximal link and the distal links which make up of a parallelogram. The distal links are connected to the bar of the driven parallelogram adjacent to the active proximal link and the moving platform by ball joints. Due to the three parallelograms, the rotational motion is restrained and the moving platform possesses three translational degrees of freedom.

For the purpose of analysis, the following coordinate systems are defined: the reference coordinate system $O-xyz$ is attached to the center of the base platform, with its x axis and y axis are on the fixed plane and the z axis points down vertically. Another coordinate system $A_i-x_iy_iz_i$ is attached to the fixed base at the point A_i, such that the x_i axis is in line with the extended line of OA_i and the z_i axis is parallel to the z axis. The constant angle ϕ_i is measured from the x axis to the x_i axis. The pose of the moving platform can be described by the position vector p shown in Fig. 2. For each kinematic chain, θ_{1i}, θ_{2i} and θ_{3i} are employed to describe the pose of the links, where θ_{1i} is the angle from the x_i axis to A_iB_i, θ_{2i} is the angle from the extended line of A_iB_i to the line determined by the intersection of the plane of the parallelogram and the x_iz_i plane, θ_{3i} is measured from the y_i direction to B_iC_i.

3. Kinematics

3.1. Position analysis

As shown in Fig. 2, the closed-loop position equation associated with the ith kinematic chain can be written as

$$\boldsymbol{R}_i + l_1\mathbf{u}_i + l_2\mathbf{w}_i - \boldsymbol{r}_i = \mathbf{p}_{i=1,2,3} \tag{1}$$

where $\boldsymbol{R}_i$ is the vector from the point O to the point A_i, $\boldsymbol{u}_i$ is the unit vector along A_iB_i, $\boldsymbol{w}_i$ denotes the unit vector along B_iC_i and $\boldsymbol{r}_i$ is the vector from the point P to the point C_i. All the vectors in Eq. (1) are expressed in the reference coordinate system $O-xyz$.

The inverse position solution can be achieved when considering the assembly mode

$$\theta_{1i} = 2\arctan\frac{-A_i + \sqrt{A_i^2 - C_i^2 + B_i^2}}{C_i - B_i} \tag{2}$$

where

$$A_i = -2l_1 z \tag{3}$$

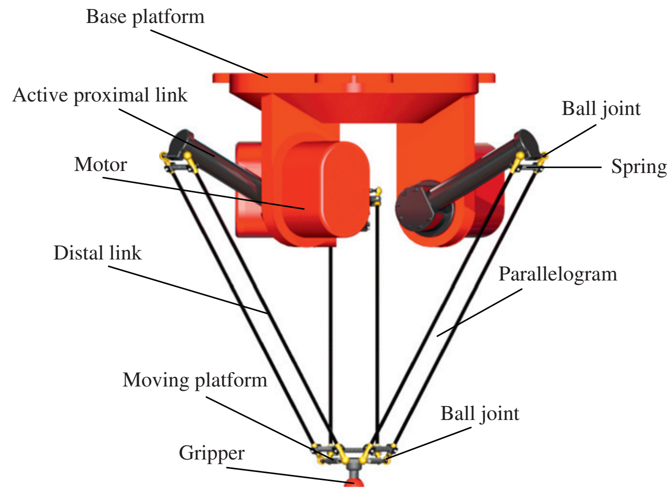

Fig. 1. Delta robot.

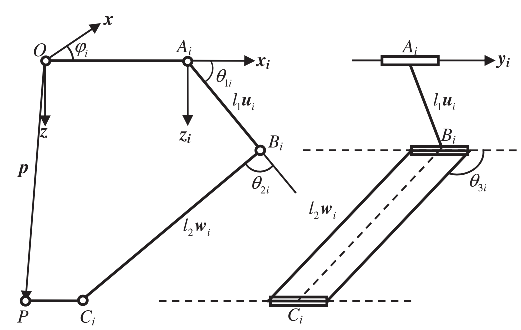

Fig. 2. Description of the kinematic chain.

$$B_i = -2l_1(x\cos\varphi_i + y\sin\varphi_i - e) \tag{4}$$

$$C_i = x^2 + y^2 + z^2 + e^2 + {l_1}^2 - {l_2}^2 - 2e(x\cos\varphi_i + y\sin\varphi_i) \tag{5}$$

$$e = \sqrt{(\mathbf{R}_i - \mathbf{r}_i)^T(\mathbf{R}_i - \mathbf{r}_i)} \tag{6}$$

3.2. Velocity analysis

Taking the derivative of Eq. (1) with respect to time yields

$$\mathbf{v}_p = \boldsymbol{\omega}_{1i} \times l_1\mathbf{u}_i + \boldsymbol{\omega}_{2i} \times l_2\mathbf{w}_i \tag{7}$$

where $\boldsymbol{\omega}_{1i}$ is the angular velocity of the ith actuated joint, $\boldsymbol{v}_p$ is the velocity of the moving platform.

Taking dot product of both sides of Eq. (7) with $\boldsymbol{w}_i$ and simplifying yields

$$\dot{\boldsymbol{q}} = \mathbf{J}_q^{-1}\mathbf{J}_x\boldsymbol{v}_p = \mathbf{J}\boldsymbol{v}_p \tag{8}$$

where $\boldsymbol{J}_x$ is the direct kinematic Jacobian matrix and $\boldsymbol{J}_q$ is the inverse kinematic Jacobian matrix [55], and

$$\mathbf{J}_x = [{}^o\boldsymbol{w}_1\,{}^o\boldsymbol{w}_2\,{}^o\boldsymbol{w}_3]^T = \begin{bmatrix} \cos(\theta_{11}+\theta_{21})\sin\theta_{31}\cos\varphi_1 - \cos\theta_{31}\sin\varphi_1 & \cos(\theta_{11}+\theta_{21})\sin\theta_{31}\sin\varphi_1 + \cos\theta_{31}\cos\varphi_1 & \sin(\theta_{11}+\theta_{21})\sin\theta_{31} \\ \cos(\theta_{12}+\theta_{22})\sin\theta_{32}\cos\varphi_2 - \cos\theta_{32}\sin\varphi_2 & \cos(\theta_{12}+\theta_{22})\sin\theta_{32}\sin\varphi_2 + \cos\theta_{32}\cos\varphi_2 & \sin(\theta_{12}+\theta_{22})\sin\theta_{32} \\ \cos(\theta_{13}+\theta_{23})\sin\theta_{33}\cos\varphi_3 - \cos\theta_{33}\sin\varphi_3 & \cos(\theta_{13}+\theta_{23})\sin\theta_{33}\sin\varphi_3 + \cos\theta_{33}\cos\varphi_3 & \sin(\theta_{13}+\theta_{23})\sin\theta_{33} \end{bmatrix} \tag{9}$$