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Workspace and dynamic performance evaluation of the parallel manipulators in a spray-painting equipment

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ABSTRACT

The paper deals with the workspace and dynamic performance evaluation of the PRR–PRR parallel manipulator in spray-painting equipment. Functional workspace of planar fully parallel robots is often limited because of interference among their mechanical components. The proposed 3-DOF planar parallel manipulator with two kinematic chains connecting the moving platform to the base can reduce interference while still maintaining 3 DOFs. Based on the kinematics, four working modes are analyzed and singularity is studied. The workspace is investigated and the inverse dynamics is formulated using the virtual work principle. The dynamic performance evaluation indices are designed on the basis of maximum and minimum magnitude of acceleration vector of the moving platform produced by a unit actuated force. The index not only can evaluate the accelerating performance of a manipulator, but also can reflect the isotropy of accelerating performance. Workspace and dynamic performances of the four working modes are compared and the optimal working mode for the painting of a large object with conical surface is determined.

1. Introduction

Parallel manipulators have attracted much attention in both industry and academia because of their conceptual potential in high motion dynamics and accuracy combined with high structural rigidity due to their closed kinematic loops [1]. Parallel manipulators have wide application in the industrial world, e.g., flight simulator [2], parallel kinematics machines [3] and conveyor for the pretreatment and electrocoating of vehicle body [4]. Planar parallel manipulators are useful for manipulating an object on a plane. A mechanism is said to be a planar mechanism if all the moving links in the mechanism perform the planar motions that are parallel to one another. As an important branch of parallel manipulators, planar parallel manipulators possessing both outstanding characteristics and simple structure have been widely used in the industry field, e.g., pick-and-place application [5], parallel kinematics machines [6,7], and medical devices [8]. Since planar parallel manipulators are simple and have also the advantages of general parallel manipulators, they are good candidates for developing spray-painting equipments [9].

With the application of parallel manipulators in machine tools and robots, more and more attention is paid to dynamic performance evaluation, which is the fundament of dynamic optimal design. Compared to the kinematic performance measures, the dynamic performance measures are scarce. The generalized inertia ellipsoid [10] and the dynamic manipulability ellipsoid [11] are two conventional conditioning indices for the evaluation of the dynamic performance of a manipulator. As an extension of generalized inertia ellipsoid and dynamic manipulability ellipsoid, Khatib [12] proposed a belted inertia ellipsoid to study the dynamic performance of manipulators, and Tadokoro et al. [13] gave a stochastic dynamic manipulability based on a stochastic interpretation of manipulator motion. Li et al. [14] presented local and global indices when the manipulability in the hardest direction was considered. Mansouri and Ouali [15] proposed a homogeneous manipulability measure of robot manipulators based on power concept. This measure can be used to evaluate the manipulability of a manipulator having both rotational and translational degrees of freedom. Although these indices can evaluate the dynamic performance of a manipulator, most of them do not consider the isotropy of dynamic performance. The spray-painting equipment designed in this paper is to paint a large object with a complex surface. Thus, the spray-painting equipment needs to frequently accelerate or decelerate in all directions to improve the spraying efficiency. Therefore, in addition to the evaluation of

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kinematic performance, the dynamic performance is also necessary, especially the accelerating or decelerating performance in all directions.

In this paper, an index for evaluating the dynamic performance of a 3-DOF parallel manipulator used in a spray-painting robot is proposed. The index not only can evaluate the dynamic performance of a manipulator, but also can reflect the isotropy of dynamic performance. Starting with the structure description and kinematics, four working modes and workspace are determined. The inverse dynamics is formulated using the virtual work principle. The dynamic performance evaluation index is designed on the basis of maximum and minimum magnitude of acceleration vector of the moving platform produced by a unit actuated force. Dynamic performances of four working modes are compared. This paper is organized as follows: Section 2 gives the structure description and kinematics. The singularity and workspace of the parallel manipulator is studied in Section 3. Section 4 derives the inverse dynamic model, which is used to investigate the dynamic performance in Section 5. Section 6 deals with the numerical simulation. Conclusions are presented in Section 7.

2. System architecture and kinematics

2.1. Architecture description

To paint a long object with conical surface, the spray-painting equipment should have at least five degrees of freedom. In the painting process, the painted object can be separated into two parts and each part is separately painted. Based on the painting process, a 5-DOF spray-painting equipment is designed, as shown in Fig. 1. The spray-painting equipment consists of a gantry frame, two serial–parallel mechanisms, and a feed worktable. The feed worktable can move on the base and the painted object is fixed on the feed worktable. The serial–parallel mechanism can move up and down along the gantry frame. The serial–parallel mechanism is composed of a PRR–PRR manipulator and one rotational DOF arm. The rotational arm is attached to the moving platform of the PRR–PRR parallel manipulator. When the serial-parallel mechanism is at a certain position of the frame, the work plane of the parallel manipulator is shown in Fig. 1 and the intersection of work plane and the surface of the painted object is the motion trajectory. Similarly, when the serial-parallel mechanism is at different positions, different trajectories can be obtained and task space of the PRR–PRR manipulator is obtained as well. It can be thought that these trajectories are similar to the trajectory shown in Fig. 1 in shape. The designed PRR–PRR manipulator needs to meet the requirement of the task space. Compared with the fully parallel robot with three legs connecting the moving platform to

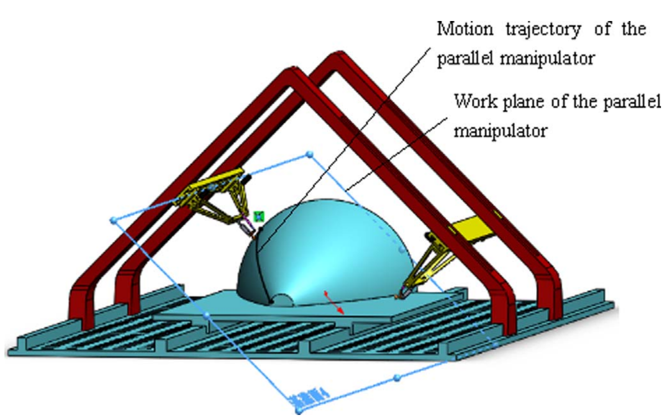

Fig. 1. The spray-painting equipment.

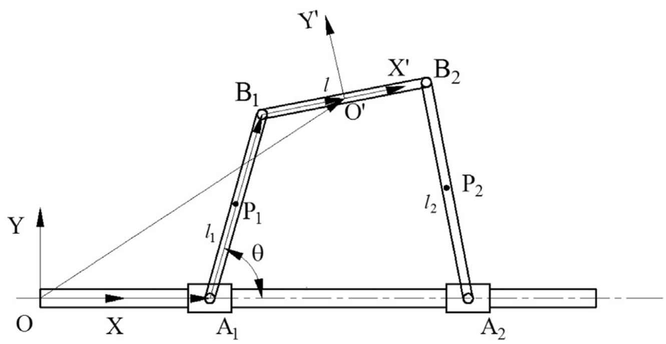

Fig. 2. Kinematic model of one parallel manipulator.

the base, the parallel manipulator has two legs and the PRR leg has a dual function as both a link and an actuator [16,17]. This compromise sacrifices some rigidity by reducing the parallelism in return for increased functional workspace. In this paper, the workspace and dynamic performance of the PRR–PRR manipulator is studied.

2.2. Inverse kinematics

Fig. 2 shows the kinematic model of one parallel manipulator in the painting equipment. The parallel manipulator is composed of a guideway, two sliders A_1 and A_2, links A_1B_1 and A_2B_2, moving platform B_1B_2. Siders A_1 and A_2 are driven by two servomotors via screw mounted on the guideway. Link A_1B_1 is actuated by another servomotor fixed on slider A_1. The whole construction enables the movement of the moving platform B_1B_2 in a plane and a rotation about the axis normal to the motion plane of the manipulator.

A base coordinate $O-XY$ with the Y axis being vertically placed is attached to one end of the guideway. A moving coordinate system $O'-X'Y'$ is attached on the moving platform and X' axis is along the axial axis of moving platform B_1B_2. The constraint equation associated with link A_iB_i can be written as

$$\boldsymbol{r}+\boldsymbol{b}_i=x_{ai}\boldsymbol{e}_1+l_i\boldsymbol{n}_i,\ i=1,2 \tag{1}$$

where x_{ai} is the X coordinate of point A_i in $O-XY$, $\boldsymbol{r}=(x\ \ y)^{\mathrm{T}}$ is the position vector of point O' in $O-XY$, $\boldsymbol{b}_i$ is the position vector of B_i with respect to $O-XY$, $\boldsymbol{b}_i=\boldsymbol{R}\boldsymbol{b}_i'$, $\boldsymbol{b}_i'$ is the position vector of B_i with respect to $O'-X'Y'$, $\boldsymbol{R}$ is the rotation matrix from $O'-X'Y'$ to $O-XY$, $\boldsymbol{R}=\begin{pmatrix}\cos\alpha & -\sin\alpha\\ \sin\alpha & \cos\alpha\end{pmatrix}$, α is the rotational angle of the moving platform, l_i and $\boldsymbol{n}_i$ are the length and unit vector of link A_iB_i, $\boldsymbol{n}_1=(\cos\theta\ \ \sin\theta)^{\mathrm{T}}$, θ is the rotational angle of link A_1B_1, and $\boldsymbol{e}_1=(1\ \ 0)^{\mathrm{T}}$.

Taking the dot product with $\boldsymbol{e}_1^{\mathrm{T}}$ on both sides of Eq. (1) leads to

$$x_{ai}=\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{r}+\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{b}_i-l_i\boldsymbol{e}_1^{\mathrm{T}}\boldsymbol{n}_i,\ i=1,2 \tag{2}$$

Based on Eqs. (1) and (2), $\boldsymbol{n}_i$ can be expressed as

$$\boldsymbol{n}_i=\frac{\boldsymbol{r}+\boldsymbol{b}_i-x_{ai}\boldsymbol{e}_i}{l_i} \tag{3}$$

On the basis of Eq. (3), θ can be written as

$$\theta=\arcsin\frac{\boldsymbol{e}_2^{\mathrm{T}}\boldsymbol{r}-\frac{l}{2}\sin\alpha}{l_1}\ \text{or}\ \theta=\pi-\arcsin\frac{\boldsymbol{e}_2^{\mathrm{T}}\boldsymbol{r}-\frac{l}{2}\sin\alpha}{l_1} \tag{4}$$

where $\boldsymbol{e}_2=(0\ \ 1)^{\mathrm{T}}$ and l is the length of the moving platform.

It is assumed that the mass center is at the center of the geometry, denoted by P_i in Fig. 2. The position vector of the mass center P_i of link A_iB_i in coordinate system $O-XY$ can be expressed as