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Kinematic optimal design of a 2-degree-of-freedom 3-parallelogram planar parallel manipulator

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ABSTRACT

A 2-degree-of-freedom (2-DOF) 3-parallelogram planar parallel manipulator (PPM) can follow an arbitrary planar curve and keep the end-effector in a definite posture. Such features are valuable for spray-painting robots. Considering these advantages, authors proposed a new spray-painting robot containing a 2-DOF 3-parallelogram PPM. In order to obtain a spray-painting robot with the best performance, the 2-DOF 3-parallelogram PPM should possess the largest workspace and most stable transmissibility. This study addresses the performance evaluation and kinematic optimization of this manipulator. First, the kinematics of the manipulator is analyzed, and performance indices that consider desirable workspace and transmissibility are proposed. Then, the process to determine optimal geometry parameters by using performance atlases is presented. Finally, a 2-DOF 3-parallelogram PPM with desirable workspace and transmissibility is identified.

1. Introduction

Parallel mechanisms (PMs) exhibit excellent characteristics, such as higher rigidity, better positioning accuracy, and higher load capacity, compared with serial mechanisms [1]. As an important branch of PMs, the 2-DOF PPMs possessing both outstanding characteristics and simple structure have been widely used in the industry field. PMs have been intensively studied since the 1980s and still attract much attention up to the present [2–6]. For PMs one of the most important and challenging problems is kinematic optimization in which two issues are concerned: performance evaluation and dimensional synthesis [7,8].

The 2-DOF 3-parallelogram PPM, actuated by two coaxial revolute joints, is a typical 2-DOF PPM. It has a non-symmetrical structure composed of three parallelogram mechanisms. This PPM has a prominent function that does not only follow an arbitrary planar curve precisely within the workspace but also keep the end-effector in a definite posture at all times. Given its outstanding advantages and simple structure, this PPM has been widely applied in palletizing robots [9].

Regardless of how simple a 2-DOF PPM is, the optimal design is challenging. Many researchers have devoted themselves to this issue for many years. Gao et al. [10] presented a physical model of the solution space of 2-DOF PPMs and systematically discussed the comprehensive classification of this kind of manipulators. Huang et al. [11] presented a hybrid method for the kinematic optimal design of 2-DOF PPMs with a mirror symmetrical geometry. Liu et al. [12] addressed the graphical representation of performance and the optimum design issue of planar 5R symmetrical PPMs. However, all 2-DOF PPMs discussed in these articles have a mirror symmetrical structure. The 2-DOF 3-parallelogram PPM is another type of 2-DOF PPM with a non-symmetrical structure. Although many

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articles have investigated its application in palletizing robots, including structural optimization [13], optimum motion control [14] and layout analysis [15], articles about the kinematic optimal design of this manipulator in spray-painting robots are seldom found.

The traditional kinematic optimization method for PMs is the objective function method that involves establishing an objective function and obtaining a result via algorithms [16–18]. Three unavoidable difficulties are encountered in this method. (a) The highly non-linear objective function is difficult to establish, and some simplification are inevitably involved in objective function. Thus, the iterative solving process is not only time consuming, but the optimal result based on objective function method is sometimes unreliable. (b) This method may provide an optimal result, but users cannot know how optimal the result is because the relationship between design parameters and performance indices is unknown. (c) If the design conditions vary, then users have no choice but to restart their work from the beginning [19]. Compared with the traditional objective function method, the performance atlases method exhibits several obvious advantages. It not only graphically and globally shows the relationship between performance indices and design parameters but also provides all possible solutions to users [20]. Users can obtain the optimal results by comparing all possible solutions in the same chart, which is convincing and convenient.

Performance evaluation and dimensional synthesis are two important issues in kinematic optimization. To conduct kinematic optimal design for a 2-DOF 3-parallelogram PPM, performance indices are required. The local conditioning index (LCI) [21] and the global conditioning index (GCI) [2] have been widely used by numerous researchers. However, a recent study [22] found serious inconsistencies when these indices were applied to the kinematic optimal design of mixed-DOF PMs. Furthermore, the LCI cannot provide a mathematical distance between current position and singularity [7], which also limits the application of this index. Wu et al. [7] proposed two simple but useful frame-free indices, namely, the local transmission index (LTI) and the global transmission index (GTI). The LTI can judge the effectiveness of transmissibility in a single pose, whereas the GTI represents the average effectiveness of a series of poses in the good transmission workspace (GTW). Although the GTI can provide a PM with good average transmissibility, how the effectiveness of transmissibility in each pose varies around the average transmissibility remains unclear. This variation demonstrates the fluctuation of the LTI around the GTI, which is particularly important for the optimal design of driving motors. According to the application requirements in the spray-painting robots, new indices that consider desirable workspace and transmissibility are introduced to comprehensively solve the kinematic optimization problems of the 2-DOF 3-parallelogram PPM. Then based on these performance indices, the kinematic optimization is achieved by using performance atlas method. Finally, a 2-DOF 3-parallelogram PPM with desirable workspace and transmissibility is identified.

This paper is organized as follows. The kinematics of a 2-DOF 3-parallelogram PPM is analyzed in Section 2. Section 3 investigates the design space of the manipulator, including its length and angular design parameters. The GTW of the manipulator is discussed in Section 4. According to the application requirements in the spray-painting robots, performance indices based on desirable workspace and transmissibility are proposed in Section 5. Performance atlases based on these performance indices are also illustrated in this section. Section 6 introduces the use of performance atlases to determine the optimum parameters and provides an optimal manipulator. Conclusions are presented in Section 7.

2. Kinematics of a 2-DOF 3-parallelogram PPM

2.1. Architecture

Fig. 1(a) shows a 2-DOF 3-parallelogram PPM. Fig. 1(b) presents the physical model of a spray-painting robot proposed by authors which contains a 2-DOF 3-parallelogram PPM. The 2-DOF 3-parallelogram PPM is widely used in palletizing robots, but seldom applied in the spray-painting robots. As shown in Fig. 1(a), the 2-DOF 3-parallelogram manipulator consists of three parallelogram mechanisms, and each parallelogram mechanism can be configured as a parallelogram form or an anti-parallelogram form. Thus, there can be several configuration modes for the end-effector. However, the anti-parallelogram mechanisms are easy to cause

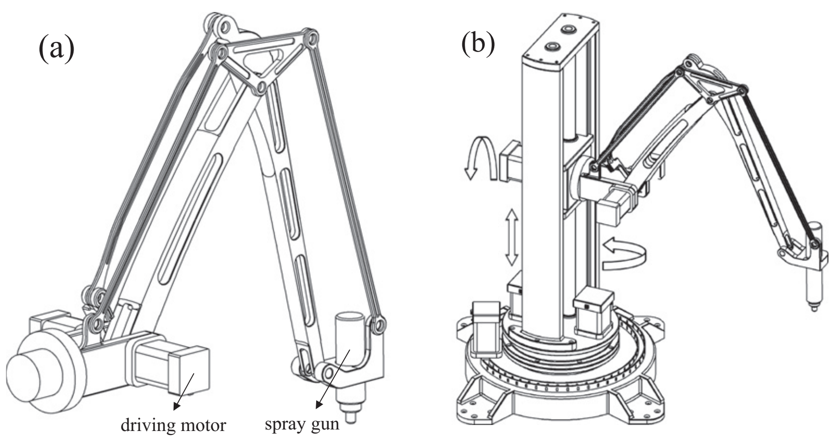

Fig. 1. The 2-DOF 3-parallelogram PPM: (a) kinematic structure and (b) application in a spray-painting robot.