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Kinematic calibration and investigation of the influence of universal joint errors on accuracy improvement for a 3-DOF parallel manipulator

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ABSTRACT

This paper focuses on the accuracy enhancement of a 3-PRRU parallel manipulator and the influence of imperfect universal joints on calibration result through kinematic calibration. The error model of the PRRU limb that contains all of the identifiable kinematic errors is established based on modified Denavit–Hartenberg method and Hayati convention. By eliminating the motion errors of passive joints and combining all of the limbs' error models, the calibration model of the parallel manipulator is obtained. To verify the effectiveness of the error model and investigate the influence of the imperfect universal joints on positioning accuracy improvement, numerical simulations and experiments of kinematic calibration are respectively conducted and total least squares method is used to identify the kinematic parameters. The results of the simulations and experiments show that the defects of universal joints have smaller effect on the accuracy improvement for this manipulator when compared with the cases that the universal joints are perfectly manufactured and assembled.

1. Introduction

Due to the unavoidable machining tolerances and assembly errors, kinematic parameters of robot manipulators do not exactly match their design goals, which influences the positioning accuracy of the end-effector or moving platform. As an effective and economic method, kinematic calibration plays an important role in improving the absolute positioning accuracy for robot manipulators. In the process of kinematic calibration, the error model has significantly relations with computation stability and calibration result. Therefore, in order to obtain an ideal calibration result, the kinematic models should better satisfy the requirements of completeness, continuity and minimality [1,2].

For conventional serial robots, the calibration models have been intensively studied during the past decades. For example, the Denavit–Hartenberg (D-H) based method and its modified ones [3–5], the zero reference model [6], the single joint method [7], the parametrically continuous model [8] and the models based on product of exponential (POE) formula [9–11].

However, due to the complexity of the forward kinematics, most kinematic calibrations of sensitive analysis of parallel manipulators are conducted based on inverse kinematics or closed form features [12–21]. To simplify the difficulties of kinematic analysis and error modeling, some geometric constraints have to be assumed to be perfect in these processes. For example, the directional errors of revolute (R) joints are not always considered, and the universal (U) and spherical (S) joints are usually regarded as points without considering their defects. As a result, on the one hand, most of the error models cannot meet the requirement of completeness, which limits the manipulators to get higher levels of absolute positioning accuracy. On the other hand, these error models cannot be used to evaluate the effects of the ignored error parameters on positioning accuracy after calibration. To overcome these shortcomings, some researchers established the error models by forward kinematics. To analyze the positioning accuracy of a 6-UPS parallel manipulator, Wang and Masory [22] used D-H method to establish the kinematic model and totally 132 kinematic parameters were included and discussed. Khalil and Besnard [23] analyzed the 6-UPS parallel manipulator by regarding U and S joints as 2R and 3R serial chains. The kinematic parameters were then identified based on self-calibration method by locking U or S joints. Feng et al. [24] used D-H method to build the limb's error model of a 6 degrees of freedom (DOF) parallel manipulator which is used for chromosome dissection. The sensitive of a five-bar linkage was identified by Palpacelli et al. [25] based on D-H method in which 14 kinematic parameters were involved in the error model. Liu et al. [26] proposed an error modeling method for parallel manipulator

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based on screw theory. To investigate the influence of joint backlash on positioning accuracy, Meng et al. [27] established an error model based on POE formula. Furthermore, due to the incompleteness of the error models, the influences of the ignored parameters on the improvement of positioning accuracy after kinematic calibrations are not systematically analyzed. For example, the errors in U joints are usually not considered, which limits the possibilities of discussing the effects of these errors. For parallel manipulators, U and S joints are important components. They can be manufactured as cross axes and spherical shapes or be realized by assembling two and three single revolute joints together. However, no matter what kinds of structures are used to realize the motions of these joints, manufacture and assembly errors will be more or less introduced into the manipulators. These errors will have influences on the positioning accuracy, but they are rarely discussed in kinematic calibrations of parallel manipulators. In the literatures that discussed or mentioned the influence of some particular joints on positioning accuracy, Masory and Wang [22] analyzed the effect of the tolerances of U joints on the positioning accuracy of a 6-UPS parallel manipulator based on D-H method. They found that the defects in U and S joints have minor effects compared with other errors. Thus they ignored the defects of U and S joints in the kinematic calibration [28]. Daney [29] built up a Gough platform by regarding each limb as a 2RP3R serial chain. In the calibration experiment, he found the defects of the U joints cannot be identified correctly because the measurement noises are too large for the U joints' errors. Wu et al. [30] proposed an optimization method to calibrate a 6-UPS parallel machine tool in which the defects in the 3-DOF wrist and 2-DOF shoulder joints were considered as the errors of the kinematic parameters.

In this paper, kinematic calibrations are conducted for a 3-degree-of-freedom (DOF) parallel manipulator with the type of 3-PRRU. In order to establish the error model which contains all of the potential error parameters, the error model of the limb that satisfies the requirement of completeness, continuity and minimality is established based on D-H method by regarding each PRRU chain as a PRRRR serial robot. Then, by projecting the left null space of the passive joints' twist space onto the deviation of the end-effector (or moving platform) , the positioning error caused by the motion errors of the passive joints can be eliminated. After assembling the limbs' error models together, the calibration model of the parallel manipulator can then be obtained. For U joints, if their defects are ignored, the inverse kinematics, error modeling and control strategies of parallel manipulators will be simpler. But on the contrary, the error models cannot satisfy the requirement of completeness, which will reduce the effect of kinematic calibration. Therefore, in order to investigate the effect of the U joints' errors on the improvement of positioning accuracy after kinematic calibration, both the error models that consider and ignore the defects of U joints are used to identify the error parameters in the numerical simulations and calibration experiments.

This paper is organized as follows. In Section 2, the 3-PRRU parallel manipulator is introduced and inverse kinematics is briefly given. In Section 3, the error models of the manipulator are established based on modified D-H method and the Hayati model. Numerical simulations and experiments are then carried out in Section 4 to verify the effectiveness of the error model and investigate the effect of the U joint's errors on calibration results. Finally, some conclusions are drawn in Section 5.

2. Kinematics of 3-PRRU parallel manipulator

In this section, the studied 3-DOF parallel manipulator is firstly introduced. Since the PRRU limbs are regarded as PRRRR serial robots, the displacements of all joints should be obtained. Therefore, a brief inverse kinematic analysis is then given in the second part.

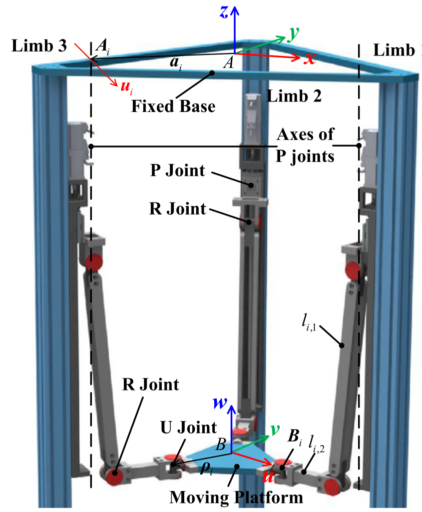

Fig. 1. The structure of the 3-PRRU parallel manipulator.

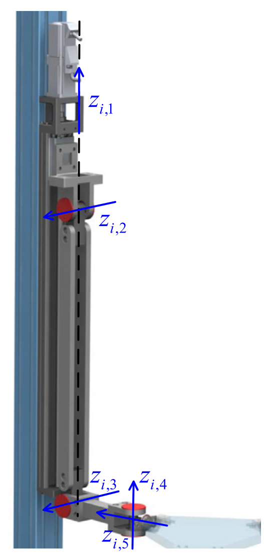

Fig. 2. The structure of the PRRU limb.

2.1. Introduction of the 3-PRRU parallel manipulator

The structures of the symmetrical 3-PRRU parallel manipulator and the limb are shown in Figs. 1 and 2, respectively. The fixed base and the moving platform of this manipulator is connected by three identical limbs, denoted by PRRU, which consists of a prismatic (P) joint, two parallel R joints and a U joint in a successive manner. Thereinto, the underlined P implies that only the P joints in these limbs are actuated. The axes of the P joints are perpendicular to the plane of the fixed base and intersect the plane at point $A_i (i = 1, 2, 3)$. The center of the U joint is represented by point B_i. For this manipulator, points A_i and B_i form two equilateral triangles whose circumcircle radii are denoted by $r1$ and $r2$, respectively. Since the limbs are arranged symmetrically, the angle between each adjacent limb is 120°.

In order to describe the position and orientation (pose) of the manipulator, two reference frames, denoted by {A} and {B}, are attached at the centers of the fixed base and the moving platform, respectively. In frame {A}, x axis points from A to A_1, z axis is perpendicular to plane $A_1A_2A_3$ and y axis satisfies right hand rule. Similarly, in frame {B}, u axis points from B to B_1, w axis is perpendicular to the plane of the moving platform and v axis satisfies right hand rule.