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Minimizing the influence of revolute joint clearance using the planar redundantly actuated mechanism

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ABSTRACT

Joint clearance is unavoidable in real mechanism, so its effects should be minimized in order to fulfill the designed performances of the mechanism. In this paper, we proposed a method which is based on the redundantly actuated mechanism to minimize the influence of revolute joint clearance. A planar 3DOF redundantly actuated 4-$\underline{R}$RR mechanism with 8 clearance joints is applied as an illustration to show how it works. Firstly, the kinematic and dynamic equations of the 4-$\underline{R}$RR mechanism are established. Secondly, the joint clearance is geometrically described and the contact force models are introduced. After that, the joint clearances are restrained by preloading the passive links of the 4-$\underline{R}$RR mechanism, the two-step Bathe integration method is used to solve these equations. Comparisons are made between the mechanisms with and without clearance restrain. Finally, experiments are carried out to verify the proposed method. Both simulation and experimental results show that the joint clearance can be successfully controlled by the redundantly actuated mechanism.

1. Introduction

Parallel mechanisms are increasingly applied in high speed operation and accuracy positioning, among which the planar 3DOF parallel mechanisms (especially the 3-$\underline{R}$RR mechanism) are more attractive [1], as they have higher stiffness and better dynamical performances. But there is a factor that affects the performances of the mechanism, that is the joint clearance. Joint clearance is unavoidable due to manufacturing tolerances, assembling, wear and material deformation, leading to important deviations between the ideal behavior and real outcomes of the mechanism. The existence of joint clearances also causes vibration, noise and wear, decreasing the service life or even leading to failure of the mechanism [2].

Many researchers have paid their attentions to the influences of the joint clearances on the kinematical and dynamical performances of the mechanism. Venanzi [3] proposed a maximum displacement error method based the principle of virtual work, which is free of external forces and valid for almost any nonoverconstrained mechanism. Meng et al. [4] modified the method and make it feasible to both over-constrained and nonoverconstrained mechanisms. Chen et al. [5] proposed a unified approach to predict the accuracy performance of planar parallel manipulators both with input uncertainties and joint clearance. Wu et al. [6] carried out an experiment to validate the error modeling of a planar 3-PPR parallel manipulator with joint clearances. These are the only the kinematical analysis.

Flores [7–9] is the most representative researcher in the dynamic analysis of the parallel mechanism with joint clearances; he proposed a general calculation method for rigid multibody system with joint clearance, which is easy to integrate the contact force model with the system motion equations. They also studied the influence of different parameters [10], such as the contact force models [11], the friction force models [12], the lubrication [13] and the wear of the joint [14]. Yan et al. [15] proposed a comprehensive model for 3D revolute joints with radial and axial clearances in mechanical systems, which indicate that the initial misalignment of the journal and bearing may lead to the rotation of the bearing. Some researchers [16–18] also take the link flexibility along with the joint clearance into consideration, and indicate that the link flexibility can slightly reduce the high vibrations of the system that caused by joint clearance. Other than the 1DOF mechanism, Xu et al. [19] investigated a planar 2-DOF pick-and-place parallel manipulator with two joint clearances. These are only analysis but not control of the joint clearances.

To maintain a more stable behavior of the mechanism with joint clearances, many methods are proposed by researchers. Erkaya [20]

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optimized the trajectory of a walking mechanism using ANFIS approach, Olyaei [21] presented a control mechanism based on the Pyragas method for stabilizing a slider-crank mechanism with joint clearance. Yaqubi et al. [22] proposed control scheme which can provide continuous contact in joints, but a larger input torque is needed in some cases. Li et al. [23] optimized the performance of a planar slider-crank mechanism considering joint clearance, link flexibility and wear, by using the harmonic drive. Wang et al. [24] investigated the nonlinear dynamics of a flexible multibody system with interval joint clearance size, and a modified extended delayed feedback control is used to stabilize the chaotic system. But they are only focused on the 1DOF mechanism, these methods are invalid for the multi-DOFs mechanism. To reduce the undesirable effects of joint clearance on the behavior of the planar 3-RRR parallel manipulators, Varedi et al. [25] carried out an optimization algorithm for simultaneously kinematic and dynamic synthesis using the PSO method, which only valid for a preset moving trajectory. In Muller's work [26], the internal preload control of redundantly actuated parallel manipulators is applied to avoid backlashes in actuators, in which the 4-RRR mechanism is illustrated. Xu [27] also used the actuation redundancy to reduce backlash in actuators, in which a 3-RRR planar parallel manipulator is illustrated, but both of them did not take the joint clearance into consideration.

Zhang et al. [28] have compared the performances of the fully actuated 3-RRR mechanism and the redundantly actuated 4-RRR mechanism with joint clearances, indicating that the 4-RRR mechanism shows some better performances than the 3-RRR mechanism without any additional control method. In this paper, we do not offer contributions to the fields of contact force model, friction force model or the numerical solution method, but to the new methodology to minimize the influence of joint clearance. We will use the preload control strategy of the redundantly actuated 4-RRR mechanism to minimize the influence of joint clearances, both theoretical analysis and experiments will be carried out.

2. Modeling the 4-RRR mechanism

The planar redundantly actuated 4-RRR mechanism is a symmetry structure that has four chains, as shown in Fig. 1. It is composed by ten components: the fixed platform $A_1A_2A_3A_4$, the moving platform $C_1C_2C_3C_4$, the driving link A_iB_i and the following link B_iC_i (i=1~4). $A_1A_2A_3A_4$ are actuating joints that are attached to actuators, while $B_1B_2B_3B_4$ and $C_1C_2C_3C_4$ are passive joints that have clearance. The global coordinate system XOY is defined, the original point is at the center of fixed platform, with the axis-x is along A_1A_2 and the axis-y is along A_1A_4. Fig. 1 shows the planar redundantly actuated 4-RRR parallel mechanism without and with joint clearance respectively, the only difference between them is at the passive joints B_i and C_i.

The reference point coordinates [29] are utilized to describe the system; the local coordinate system is established at the center of mass of each component. Particularly, the local coordinate system of moving platform is labeled in Fig. 1. Thus each component can be described by three parameters

$$\boldsymbol{q}_{ij} = [x_{ij}, y_{ij}, \theta_{ij}]^T \tag{1}$$

in which i=1~4 represents the index of each chain, while j represents the driving link (j=1) or following link (j=2). x_{ij} and y_{ij} is the coordinates of the center of mass of component ij in the global coordinate system, θ_{ij} is the angle between the local coordinate system and global coordinate system. Particularly, for the moving platform, the coordinates are $\boldsymbol{q}_o = [x_o, y_o, \theta_o]^T$.

The generalized coordinates of the system can be expressed as

$$\boldsymbol{q} = [x_{11}, y_{11}, \theta_{11}, \ldots, x_{42}, y_{42}, \theta_{42}, x_o, y_o, \theta_o]^T \tag{2}$$

There only exists the planar revolute joints in the mechanism, each ideal revolute joint introduces two constraint equations. The system constraint equations can be expressed as

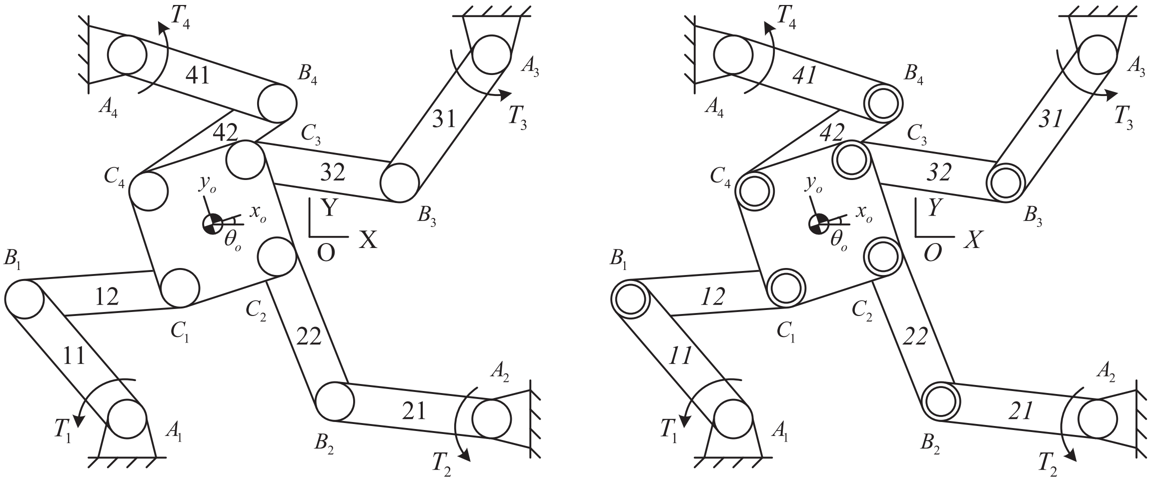
$$\boldsymbol{\Phi}(\boldsymbol{q}) = \begin{bmatrix} \boldsymbol{\Phi}_1 \\ \boldsymbol{\Phi}_2 \\ \boldsymbol{\Phi}_3 \\ \boldsymbol{\Phi}_4 \end{bmatrix} = \boldsymbol{0} \tag{3}$$

In which $\boldsymbol{\Phi}_i$ is the constraint equations for chain i, where i=1~4.

For the system without considering joint clearance, each chain introduces six constraint equations, that is

$$\boldsymbol{\Phi}_i = \begin{bmatrix} x_{i1} - 0.5l_{i1}\cos\theta_{i1} - x_{Ai} \\ y_{i1} - 0.5l_{i1}\sin\theta_{i1} - y_{Ai} \\ (x_{i1} + 0.5l_{i1}\cos\theta_{i1}) - (x_{i2} - 0.5l_{i2}\cos\theta_{i2}) \\ (y_{i1} + 0.5l_{i1}\sin\theta_{i1}) - (y_{i2} - 0.5l_{i2}\sin\theta_{i2}) \\ (x_{i2} + 0.5l_{i2}\cos\theta_{i2}) - (x_o + 0.5l_{i3}\cos(\theta_o + 3\pi/4 + i\pi/2)) \\ (x_{i2} + 0.5l_{i2}\sin\theta_{i2}) - (y_o + 0.5l_{i3}\sin(\theta_o + 3\pi/4 + i\pi/2)) \end{bmatrix} = \boldsymbol{0} \tag{4}$$

While for the system considering the clearances in passive joints, only joint A_i has constraint, thus each chain only introduces two constraint equations, that is



(a) (b)

Fig. 1. Planar redundantly actuated 4-RRR parallel mechanism: (a) Without joint clearance; (b) With joint clearance.