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Research paper

Error modelling and motion reliability analysis of a planar parallel manipulator with multiple uncertainties

Zhenhui Zhan, Xianmin Zhang*, Zhicong Jian, Haodong Zhang

Guangdong Key Laboratory of Precision Equipment and Manufacturing Technology, School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China

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ABSTRACT

The inherent uncertainties of a manipulator, including manufacturing tolerances, input errors and joint clearances, cause deviations between the actual motion and the expected motion, leading to a motion reliability problem. This paper focuses on the motion reliability of a planar 3-$\underline{R}$RR parallel manipulator with multiple uncertainties. First, the error model of the manipulator is built. Then, an analytical method is presented to verify its validation and accuracy. To address the complexity of the motion in a journal-bearing joint, the joint clearance parameters are modelled as interval variables while other parameters are treated as random variables. A new hybrid approach to motion reliability analysis based on the first order second moment (FOSM) method and the Monte Carlo simulation (MCS) method is developed for the manipulator with both random and interval variables. This method has an easier simulation process than that of the conventional MCS method using direct kinematics. Compared to the probability method with random variables, the proposed hybrid method has a higher confidence estimate of motion reliability for the manipulator with joint clearances.

1. Introduction

In the trend of the development of machines towards high speed and high precision, motion accuracy is increasingly an important factor affecting the quality, life and reliability of products, thus drawing increasingly more attention. An actual manipulator comprises inherent uncertainties, such as manufacturing tolerances, assembly errors, joint clearances, elastic deformations and input errors, leading to deviations between its ideal motion and its actual motion; this is the motion error in whose presence the actual motion may not necessarily be sufficiently accurate for usage [1]. For practical usage of the manipulator, the probability that such a deviation is within an error tolerance limit should be sufficiently large. The term “reliability” is used to describe such performance of the manipulator, and the term “degree of reliability” is applied to denote the value of the probability [2].

When assessing the characteristics of a parameter of a manipulator, its uncertainty can be aleatory (or objective, due to inherent variation) or epistemic (or subjective, due to the lack of information) [3]. The level of epistemic uncertainty is reducible if more knowledge may be gained. If a parameter’s uncertainty is aleatory in nature, it can be modelled as a random variable following a specific probability distribution with sufficient probability information, while if a parameter’s uncertainty is epistemic in nature, it is better to view it as an interval variable with a finite range of values. Both

* Corresponding author.
E-mail address: zhangxm@scut.edu.cn (X. Zhang).

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probabilistic approaches [2,4–10], which treat uncertainties as random variables, and interval approaches [11–14], which treat uncertainties as interval variables, have been used for reliability analysis. Generally, in the literature of motion reliability of the manipulator, the commonly used probability methods include the first order second moment method (FOSM) and Monte Carlo simulation (MCS). MCS is accurate with large sample sizes but may not be efficient. FOSM is efficient but depends on the probability distributions and independence of the random variables [15]. The first order reliability method (FORM), which is more widely used in structural reliability [16], has also been applied in motion reliability analysis [17]. However, FORM is less efficient than FOSM because an iterative search process for the so-called most probable point (MPP) is needed, and it also has the same weakness as FOSM. Probability methods usually involve numerical approximations and assumptions of probability distributions. With an interval arithmetic producing a closed interval in which the true result is guaranteed to lie, the interval analysis method can keep track of all possible solutions simultaneously. The interval method can also be used to assess the time-dependent kinematic reliability for mechanisms over a specific time interval [18].

An actual manipulator is a complex engineering system subject to complicated factors. Tolerances on manufacturing are inevitable and commonly assumed in the literature to follow a normal distribution. The central limit theorem justifies this assumption for any quantity with randomness caused by several unknown sources. Therefore, the geometric variables of the linkages that are due to manufacturing tolerances can be modelled as random variables following normal distributions. In addition, a joint clearance is also unavoidable and often necessary due to the machining tolerance, wear and permission of assembling or relative motion between the connected bodies. However, it causes uncertainties that degrade the accuracy and motion reliability; these cannot be ignored and require special consideration for high-precision operations. Lin and Chen [19] used homogeneous error transformation matrices to account for the effects of error motions due to joint clearances. Jawale and Thorat [20] proposed a general scheme to quantify the positional error due to joint clearance in a five-bar planar mechanism with two DoF (Degree of Freedom). Cammarata [21] performed an elastostatic analysis and employed the Virtual Work Principle to determine displacement/orientation errors in over-constrained mechanisms with clearance-affected joints. Wu et al. [22] performed error modelling with experimental validation of a planar manipulator subjected to joint clearances. Binaud et al. [23] stuied the kinematic sensitivity of manipulators to joint clearances by using two nonconvex quadratically constrained quadratic programs. Tsai and Lai [24] presented an effective method to analyse the kinematic sensitivity with joint clearance based on transmission quality. Erkaya and Uzmay [25,26] proposed neural-genetic algorithms and optimization methods for modelling the characteristics of joints with clearance to improve the mechanism precision. Probabilistic methods have also been adopted to study the uncertainty performance due to joint clearances [6,15,27,28]. Lee and Gilmore [27] applied the “effective link length” to determine the probabilistic properties of the velocity and acceleration within stochastically defined planar-pin-jointed kinematic chains. Du et al. [6,15] presented a hybrid dimension reduction method (HDRM) to address the dependent joint clearance variables. In general, the probability density function (PDF) is commonly used to describe the random behaviuor of a joint clearance variable with the assumption of a uniform or normal distribution. Nevertheless, the motion in a journal-bearing joint is of great complexity (and even chaotic) for an actual manipulator. Tian et al. made a comprehensive survey of the literature of research works related to the dynamics of multibody mechanical systems with clearance or imperfect joints [29]. Erkaya [30] investigated the joint clearance effects on a welding robot manipulator with a revolute joint with clearance. The trajectories of robots with joint clearance, also, have been studied and design variables optimized to minimize the trajectory errors [31,32]. Marques et al. [33,34] focused on modelling spatial joints with clearance, indicating that the clearances in mechanical joints play a crucial role in the analysis, design and control of multibody systems. Akhadkar et al. [35] presented a nonsmooth contact dynamics method to address the robustness of a circuit breaker mechanism, taking into account spatial revolute joints with both radial and axial clearances. Flores et al. [36–41] presented computational and experimental studies on the dynamic responses of multi-body systems with clearance joints; the studies show the influences of the clearance variables and the complex trajectories of the journals relative to the bearings. In fact, it is difficult to identify the probability distributions of clearance variables in these mechanisms despite some assumptions.

It is also notable that many reliability studies focus on simpler mechanisms such as planar four-bar mechanisms, whereas only few researchers have studied the manipulators with more than one DoF [4], especially for planar parallel manipulators (PPMs) with multiple closed-loop linkages. PPMs now play an important role in industrial applications, for which their reliability study is necessary and valuable. For the PPM with joint clearances, compared to that of a planar four-bar mechanism, the behaviour in a clearance joint will be more complicated with a parallel topology configuration [42–44]. In addition, due to its characteristic of multiple close-loop legs, it creates a coupling effect of joint clearances (as well as errors in other geometric variables) on the motion error, causing significant deviation between the analysis result and the actual one when using an improper probability distribution assumption. Hence, the variable of joint clearance is recommended being modelled as an interval variable with upper and lower limits. Wang et al. [45] investigated the dynamics of a planar slider-crank mechanism with interval clearance size in a revolute joint between the flexible connecting rod and rigid slider. In practical engineering applications, both aleatory and epistemic uncertainties often occur simultaneously [46]. Therefore, the uncertainties of a manipulator with joint clearances can be treated as a mixture of random and interval variables [47–49].

The objective of this paper is to investigate the effect of uncertainties, including manufacturing tolerances, input errors and joint clearances, on the motion reliability performance of PPMs. The 3-$\underline{R}$RR PPM is typical and is widely used in industrial applications and laboratory research for its advantages of high speed, high stiffness and precise positioning capability [42,50–52]. Hence, we chose it as the specific study object. Considering the complexity of the actual manipulator, the uncertainties of clearance joints are considered epistemic and modelled by interval variables. It will help to achieve a more