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Rigid-flexible coupling dynamic modeling and investigation of a redundantly actuated parallel manipulator with multiple actuation modes

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ABSTRACT

A systematic dynamic modeling methodology is presented to develop the rigid-flexible coupling dynamic model (RFDM) of an emerging flexible parallel manipulator with multiple actuation modes. By virtue of assumed mode method, the general dynamic model of an arbitrary flexible body with any number of lumped parameters is derived in an explicit closed form, which possesses the modular characteristic. Then the completely dynamic model of system is formulated based on the flexible multi-body dynamics (FMD) theory and the augmented Lagrangian multipliers method. An approach of combining the Udwadia-Kalaba formulation with the hybrid TR-BDF2 numerical algorithm is proposed to address the nonlinear RFDM. Two simulation cases are performed to investigate the dynamic performance of the manipulator with different actuation modes. The results indicate that the redundant actuation modes can effectively attenuate vibration and guarantee higher dynamic performance compared to the traditional non-redundant actuation modes. Finally, a virtual prototype model is developed to demonstrate the validity of the presented RFDM. The systematic methodology proposed in this study can be conveniently extended for the dynamic modeling and controller design of other planar flexible parallel manipulators, especially the emerging ones with multiple actuation modes.

1. Introduction

It is well known that parallel manipulators (PMs) have some advantages in terms of higher stiffness, higher loading capacity, higher precision, less error accumulation, and excellent dynamic performance, *etc.* [1]. Therefore, the application of PMs has increased in various manufacturing industries, such as motion simulator, aviation manufacturing, high-speed machining, electronic packaging and so forth. However, the PMs have some complex singularities (mainly Type II singularities [2]) inside their workspaces so that the potential performance of PMs cannot be exploited adequately.

To conquer Type II singularities of PMs, the academia proposed some approaches [3–5], amongst which, the redundancy approach is demonstrated to be a much more effective strategy for the avoidance of singularities. Basically, there are two

Abbreviations: AMM, Assumed mode method; DOF(s), Degree(s) of freedom; FEM, Finite element method; FMD, Flexible multi-body dynamics; FSM, Finite segment method; KED, Kineto-elasto dynamics; ODE(s), Ordinary differential equation(s); PM(s), Parallel manipulator(s); PSB(s), Parallelogram structure branch(es); RDM, Rigid dynamic model; RFDM, Rigid-flexible coupling dynamic model; VPM, Virtual prototype model.

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types of redundancy strategies included in this approach, i.e., kinematic redundancy [4] and actuation redundancy [5]. Owing to the extra degrees of freedom (DOFs) introduced by kinematic redundancy, the complexity of control for the nonlinear dynamic system may increase in some extent. In contrast, by using actuation redundancy, no extra DOFs are introduced into the PM, and the manipulability as well as dynamic performance of system can be enhanced with the elimination of Type II singularities.

Inspired by the issue mentioned above, the authors have performed some innovative designs with respect to the traditional planar 2-DOF 5R PM recently, and proposed a novel redundantly actuated PM named RAParM, which can realize multiple potential actuation modes [6]. This novel PM has some promising application prospects, such as 3D printing, electronic packaging, laser engraving machine and so forth.

With the rapid development of advanced manufacturing technology, the demand for the dynamic performance of manipulators in industry field is higher and higher. Under this circumstance, the manipulators should possess the capabilities of high speed and high precision. To achieve high speed, more and more manipulators are typically designed with light-weight links. However, in the case of high-speed motion, the elastic vibrations of links readily occur owing to the excitation forces arising from inertial and actuation forces. The elastic vibrations of links may affect the overall motion of manipulator, even induce the motion instability. Consequently, it is extremely significant to develop an effective RFDM to investigate the interaction effect between the rigid and elastic motions.

For modeling of flexible multi-body system, the derived dynamic model based on some boundary conditions is generally a group of partial differential equations which are nonlinear, time-varying and strongly coupled [7]. The analytical solution for the complex flexible system is almost impossible. A common method to address this problem is to discretize the flexible system from an infinite degrees-of-freedom system to a finite degrees-of-freedom system. The common discretization strategies mainly include lumped parameter method [8], assumed mode method (AMM) [9], finite element method (FEM) [10] and finite segment method (FSM) [11], *etc*. Amongst them, the FEM and AMM are two most commonly used ones in practice. A comparison of the FEM and AMM used to model link flexibility is presented with a detailed review in Ref. [12]. For convenience of dynamic controller design, the AMM can be resorted to as the proper discretization method.

With respect to the research about the flexible mechanisms, the academia has made great contributions. The comprehensive review of these works can be found in Ref. [13]. However, the previous studies primarily concentrated on the modeling of simple open-loop serial manipulators [7,9,10] and some four-bar mechanisms [8,11,14]. In contrast, with respect to the flexible PMs containing one or more closed-loop constraints, the associated research is rather fewer in number. Some research contributions are summarized as follows. Gasparetto et al. [15] developed a dynamic model of a flexible planar 5R PM using FEM, and carried out an experiment to verify the effectiveness of the model presented. Piras et al. [16] implemented elastic dynamic modeling with respect to a planar $3\underline{P}RR$ PM with flexible links by virtue of kineto-elasto dynamics (KED) method, and obtained a set of linear ordinary differential equations (ODEs) of motion. Then, Wang *et al.* [17] presented a FEM model of the flexible planar $3\underline{P}RR$ PM and made a strain rate feedback control simulation based on a simplified model. Yu et al. [18] developed an elastic dynamic model of a planar $3\underline{R}RR$ PM with flexible links by virtue of KED method, and implemented experiments to verify the effectiveness of the presented model. Subsequently, Zhang et al. [19] employed the Hamilton's principle and FEM to establish a dynamic model of the flexible planar $3\underline{R}RR$ PM, and solved the dynamic equations based on the assumption of KED. Cammarata et al. [20] established a linearly dynamic stiffness model for a spherical parallel robot based on FEM and analyed its natural frequence. Mukherjee et al. [21] employed Newton-Euler formulation to derive a dynamic model of the Stewart platform. However, each supporting leg is merely modeled as a spring-damper system whose axial stiffness is considered merely in the dynamic model. Sun et al. [22] implemented the elastic dynamic modeling with respect to a Delta-string manipulator based on KED method. Song et al. [23] applied KED method and spatial beam elements to establish an elastic dynamic model of a PM with two DOFs of rotation, and implemented natural characteristic analysis based on the dynamic model deduced.

The aforementioned review reveals that, the majority of publications, which referred to the dynamic modeling of flexible PMs, mainly concentrated on the KED method, but few involved the nonlinearly rigid-flexible coupling dynamic modeling. Moreover, the influence of different actuation numbers and modes on the dynamic performance of flexible PMs was not investigated in former works. Therefore, it is extremely significant and challenging to solve this problem.

To this end, based on the FMD theory, we will propose a systematic modeling methodology to develop the nonlinear RFDM of the novel PM with multiple actuation modes. Based upon the nonlinear RFDM, the dynamic performance of the PM, such as the driving torques, the elastic deformations of links and the trajectory tracking precision will be comprehensively investigated under different actuation modes.

In summary, the main contributions of this paper can be listed as below:

- Firstly, a systematic modeling approach is developed to formulate the RFDM of planar flexible PMs. This approach endows the RFDM with the modular characteristic, which can be implemented efficiently by programing.
- Secondly, a hybrid calculation approach is presented to address the RFDM of system. This approach blends the advantages of Udwadia-Kalaba formulation [24,25], Baumgarte stabilization technology [26] and TR-BDF2 algorithm [27], which can avoid solving the Lagrangian multipliers and balance the solving efficiency and stability.
- Thirdly, the influence of different actuation numbers and modes on the dynamic performance of a novel PM is comprehensively discussed. The superior redundant actuation mode can be introduced to attenuate the vibration and enhance the dynamic performance of system. Owing to easy operation, the presented scheme can be extended conveniently for other planar flexible PMs.