Mechanical Systems and Signal Processing 103 (2018) 413–439

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Dynamic modeling and hierarchical compound control of a novel 2-DOF flexible parallel manipulator with multiple actuation modes

Dong Liang, Yimin Song, Tao Sun *, Xueying Jin

Key Laboratory of Mechanism Theory and Equipment Design of Ministry of Education, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 31 January 2017
Received in revised form 3 June 2017
Accepted 1 October 2017

Keywords:
Parallel manipulator
Redundant actuation
Trajectory tracking
Vibration suppression
Electromechanical coupling dynamic model

ABSTRACT

This paper addresses the problem of rigid-flexible coupling dynamic modeling and active control of a novel flexible parallel manipulator (PM) with multiple actuation modes. Firstly, based on the flexible multi-body dynamics theory, the rigid-flexible coupling dynamic model (RFDM) of system is developed by virtue of the augmented Lagrangian multipliers approach. For completeness, the mathematical models of permanent magnet synchronous motor (PMSM) and piezoelectric transducer (PZT) are further established and integrated with the RFDM of mechanical system to formulate the electromechanical coupling dynamic model (ECDM). To achieve the trajectory tracking and vibration suppression, a hierarchical compound control strategy is presented. Within this control strategy, the proportional-differential (PD) feedback controller is employed to realize the trajectory tracking of end-effector, while the strain and strain rate feedback (SSRF) controller is developed to restrain the vibration of the flexible links using PZT. Furthermore, the stability of the control algorithm is demonstrated based on the Lyapunov stability theory. Finally, two simulation case studies are performed to illustrate the effectiveness of the proposed approach. The results indicate that, under the redundant actuation mode, the hierarchical compound control strategy can guarantee the flexible PM achieves singularity-free motion and vibration attenuation within task workspace simultaneously. The systematic methodology proposed in this study can be conveniently extended for the dynamic modeling and efficient controller design of other flexible PMs, especially the emerging ones with multiple actuation modes.

1. Introduction

Compared with serial manipulators, 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.

* Corresponding author.
E-mail address: stao@tju.edu.cn (T. Sun).

https://doi.org/10.1016/j.ymssp.2017.10.004

Nomenclature

AC	alternating current
AMM	assumed mode method
DAE(s)	differential and algebraic equation(s)
DC	direct current
DOF(s)	degree(s) of freedom
ECDM	electromechanical coupling dynamic model
FEM	finite element method
KED	kineto-elasto dynamics
ODE(s)	ordinary differential equation(s)
PD	proportional-differential
PM	parallel manipulator
PMSM	permanent magnet synchronous motor
PPF	positive position feedback
PZT	piezoelectric transducer
RAParM	Redundantly Actuated Parallel Manipulator
RDM	rigid dynamic model
RFDM	rigid-flexible coupling dynamic model
SRF	strain rate feedback
SSRF	strain and strain rate feedback

To conquer Type II singularities of PMs, the academia proposed some approaches [3–5], amongst which, the actuation redundancy is demonstrated to be a much more feasible strategy for the avoidance of singularities. By using actuation redundancy, no extra degrees of freedom (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.

Motivated by the issue mentioned above, the authors have performed some innovative designs with respect to the traditional planar 2-DOF 5R PM [6] recently, and proposed a novel redundantly actuated PM named RAParM, which can realize multiple potential actuation modes [5,7]. This novel PM may be applied in various scenarios, such as 3D printing, electronic packaging, laser engraving machine and so forth.

As is well known, with the rapid development of advanced manufacturing technology, the requirement for the dynamic performance of manipulators 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 lightweight links. However, in the case of high-speed motion, the deformations of links readily occur owing to the excitation forces arising from inertial and actuation forces. The elastic deformations of links may affect the overall motion of manipulator, even induce the motion instability. Consequently, it is extremely significant to develop an efficient RFDM to investigate the interaction effect between the rigid and elastic motions. One of the main objectives of this paper is to address this critical issue.

To develop a complete dynamic model of a flexible manipulator, many modeling approaches have been presented. Amongst them, some basic formulations, for instance, Newton-Euler formulation, Lagrangian formulation and Kane's formulation, were employed to establish the dynamic models of flexible manipulators. To facilitate computation, some strategies are commonly utilized 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 assumed mode method (AMM) [8–10] and finite element method (FEM) [11–13]. A comparison of the FEM and AMM used to model link flexibility was presented with a detailed review in Ref. [14].

With respect to the dynamic modeling of flexible manipulators, the academia has made great contributions. The comprehensive review of these works can be found in Refs. [15–17]. However, the previous studies primarily concentrated on the modeling of simple serial manipulators with single or double flexible links [8–11]. In contrast, with respect to the flexible PMs containing one or more closed-loop constraints, the associated research is rather fewer in number because of the modeling complexity. Gasparetto et al. [18] 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. [19] 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. Wang et al. [20] presented a FEM model of the flexible planar $3\underline{P}RR$ PM for active vibration control investigation. Kang et al. [21] and Zhang et al. [22] applied the AMM to establish two different dynamic models of the flexible planar $3\underline{P}RR$ PM based on two different boundary conditions, respectively. Based on AMM, Zhang et al. [23] derived a dynamic model of a planar $3\underline{P}RR$ PM with flexible links and performed a trajectory tracking control study. Zhang et al. [24] employed the Hamilton's principle and FEM to establish a dynamic model of a flexible planar $3\underline{R}RR$