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Dynamics and contouring control of a 3-DoF parallel kinematics machine

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ABSTRACT

In machining applications, instead of tracking error (the difference between the actual position and the desired position), contouring error (the minimum distance from the actual position to the desired trajectory) characterizes product quality. In this paper, we propose a generalized moving task coordinate frames based contouring control for parallel kinematics machines, whose dynamics is in general coupled and strongly nonlinear. The Orthopod, a 3 degree-of-freedom purely translational parallel kinematics machine, is introduced as a control plant. The Lagrange-D'Alembert formulation is used to model the system dynamics. The developed dynamic model in Cartesian space is transformed and parametrized by tangential error, normal error, and binormal error in moving task coordinate frames. The contouring error is then approximated by the normal error and the binormal error, which is the projection of tracking error to the normal plane at the desired position. By employing the structural properties of the transformed dynamics, a special feedback linearization, the computed torque control is applied. It leads to a stabilization problem for a second-order linear time-invariant system. Coulumb plus viscous friction model is used to compensate friction effects. Friction parameters are identified by least-squares approach. For comparison purpose, the tracking error based computed torque control is also carried out. Experiments demonstrate that the proposed control scheme not only leads to improved contouring accuracy, but also produces smaller and smoother control input torques, which may contribute to smaller vibration.

1. Introduction

Parallel kinematic machines (PKM) possess advantages of high rigidity, large payload-weight ratio and good dynamic performances [1]. They are prudently considered as promising alternatives for high-speed machining and have gained essential attention of a number of companies and researchers. The most famous parallel mechanism is the 6-DoF (degrees of freedom) Gough–Stewart platform [2], which is the crucial structure of many prototypes and commercial parallel kinematics machines. However, the 6-DoF parallel mechanisms suffer from the disadvantages of difficult forward kinematics, complex dynamics, small workspace, coupled position and orientation movements [3]. Those drawbacks can be diminished by designing a *quotient kinematics machine* (QKM) [4], which consists of two fewer DoFs kinematics modules. One or both modules may be parallel mechanisms. In five-axis machining applications, parallel modules with three DoFs are especially popular [5,6] since a QKM with a 3-DoF parallel module may have a good distribution of DoF for the two modules. One module is 3-DoF, and the other is 2-DoF. With short kinematic chains, such a QKM possesses better performance on workspace and stiffness.

Typical representatives for 3-DoF purely translational parallel mechanisms are the Delta robot [7] and its variants, the Orthoglide [8], and the 3-UPU parallel manipulator [9]. In [10], we proposed a novel 3-DoF purely translational parallel mechanism, the Orthopod. It was designed as a three-axis engraving machine or as a parallel module for five-axis machines. In machining, product quality is characterized by the contouring error, which is defined as the minimum distance from the actual position to the desired contour. However, most existing dynamic control techniques were designed based on tracking error, which is the difference between the desired position and the real position. In tracking control, the corresponding contouring error passively decreases as the tracking error decreases. Even there are cases that a real contour with smaller tracking errors may have bigger contouring errors [11].

There have been several effective methods proposed for contouring control.

(1) Feedforward control. Tomizuka [12] introduced a feedforward controller named zero phase error tracking control (ZPETC) that cancels not only all closed-loop poles and

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