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Experimental investigation on high-performance coordinated motion control of high-speed biaxial systems for contouring tasks

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ABSTRACT

The recently developed global task coordinate frame (TCF) is utilized to synthesize a high-performance contouring controller with cogging force compensation for a linear-motor-driven biaxial gantry to test the practically achievable high-speed/high-accuracy contouring performance. Specifically, the approach employs the global task coordinate formulation to meet the stringent control performance requirements for high-speed and large-curvature coordinated contouring tasks. Moreover, the approach explicitly takes into account the specific characteristics of cogging forces existed in linear motors for the controller design as model compensation to further improve practical contouring performance. Physically intuitive discontinuous projection modifications are used to ensure all the on-line estimates within their known bounds. Robust control terms are also constructed to effectively attenuate the effect of model compensation errors due to various uncertainties for a theoretically guaranteed transient performance and steady-state tracking accuracy in general. Comparative experiments are carried out on an industrial linear-motor-driven biaxial gantry and the results verify the effectiveness of the proposed cogging force compensations – a contouring tracking accuracy improvement of 30% is achieved. Experimental results also validate the rather excellent contouring performance of the proposed controller for high-speed/high-accuracy contouring tasks in actual implementation in spite of various parametric uncertainties and uncertain disturbances.

1. Introduction

Contouring control is ubiquitous in multi-axes manufacturing applications to meet the increasing demands for higher contouring accuracy at high machine speeds [1–4]. Earlier researches on the coordinated contouring control problem propose the cross-coupled control (CCC) strategy which is also widely utilized in the multi-axes motion control of machine tools [5–7]. As another alternative, the contouring control problem is also formulated in a task coordinate frame (TCF) by using either the concept of generalized curvilinear coordinates introduced in [8] or the locally defined coordinates attached to the desired contour proposed in [9]. After transforming the system dynamics of the Cartesian space into the TCF, control laws could be designed to assign different dynamics to the normal and tangential directions relative to the desired contour, which attracts researchers to synthesize various contouring control schemes based on task coordinate approaches [10,11]. However, all these publications on coordinated control techniques cannot explicitly deal with parametric uncertainties and uncertain nonlinearities.

In [12], the adaptive robust control (ARC) strategy [13,14] was combined with the task coordinate frame [9] to develop a contouring controller for high-speed machines under various parametric uncertainties and uncertain nonlinearities. In addition to good contouring performance, accurate on-line parameter estimations for secondary purposes such as machine component health monitoring and prognosis is also achieved in [15]. However, the task coordinate frames used in all these work are locally defined based on the desired trajectory to be tracked on the desired contour, which is valid only for applications with very small actual tracking errors and small curvatures. They would not be sufficient when large-curvature and high-speed contouring is of main concern or significant tracking errors exhibit due to sudden disturbances. A global task coordinate frame (GTCF) approach was proposed in [16] which is globally defined and has nothing to do with the specific desired trajectory, and the calculation of the contouring error is rather accurate and not affected by the curvature of the desired contour. Consequently, the GTCF approach is able to achieve good contouring performance even when high-speed and large-curvature contouring tasks are required. As the control law is simply synthesized considering the uncertain

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nonlinearities only, the resultant contouring controller could not deal with parametric uncertainties such as the change of payload. In addition, physical characteristic of the actuator, such as the cogging force of linear motors are not explicitly explored for model compensation, which may lead high requirements of the robust control term. For high-speed and high-accuracy contouring tasks, exploration of model compensation can attenuate the potential of input saturation, guarantee the effecter moving rather fluently, and achieve better contouring performance.

To obtain a higher level of contouring motion control performance for multi-axes mechanical systems driven by iron core linear motors [17,18], the existing significant nonlinear cogging forces should be effectively compensated. Once the cogging force can be accurately known, simple feed-forward compensation for each linear motor can be synthesized to achieve good contouring performance. But the cogging force usually cannot be exactly known—practically speaking, the cogging force can be approximately measured and the results can show that cogging forces have significant values at certain frequencies, but it is not easy to determine the accurate value. As the cogging force cannot be exactly known, in [19,20], the cogging force is assumed to be periodic functions with respect to position so that Fourier expansion with a few significant terms could be utilized to represent the cogging force. Non-periodic effect is also considered in a recent publication [21]. Noting all these cogging force compensation researches are done for single axis motion only, the effect of cogging forces and velocity measurement noises have been carefully addressed in a contouring controller design for biaxial systems in [22] with good contouring performance seen in implementation. However, due to the utilization of the local task coordinate frame (LTCF), the proposed scheme cannot achieve good contouring performance when ultra high-speed and large-curvature contouring tasks are of main concern.

In this paper, a global task coordinate frame based adaptive robust contouring controller with cogging force compensations is synthesized for linear-motor-driven biaxial systems to test the practically achievable contouring performance under large-curvature and high-speed contouring tasks. Specifically, the proposed approach explicitly takes into account the specific characteristics of cogging forces in the controller designs and employs the global task coordinate formulation for coordinated motion controls. Physically intuitive discontinuous projection modifications are used to ensure all the on-line estimates within their known bounds. Robust control terms are also constructed to effectively attenuate the effect of model compensation errors due to various uncertainties for a theoretically guaranteed transient performance and steady-state tracking accuracy in general. In addition, the controller also achieves asymptotic output tracking when there are parametric uncertainties only. Experimental investigations are carried out on a high-speed Anorad industrial biaxial gantry driven by LC-50-200 linear motors with axis position sensing resolution of 0.5 μm by linear optical encoders. Experimental results show that, when the gantry is commanded to track an ellipse with long-axis of 0.2 m and short-axis of 0.1 m at an angular speed of $\omega = 3$ rad/s, the RMS value of the contouring error is 1.57 μm, and the maximum contouring error is 6.88 μm. When the gantry is commanded to track an ellipse with long-axis of 0.2 m and short-axis of 0.1 m at an angular speed of $\omega = 7$ rad/s and a velocity of $v_{max} = 1.4$ m/s, the RMS value of the contouring error is 2.70 μm and the maximum contouring error is 8.85 μm. Comparative experimental results also validate the effectiveness of the proposed cogging force compensation – a contouring tracking accuracy improvement of 30% is achieved. The experimental results additionally show that the proposed controller achieves excellent high-speed/high-accuracy contouring performance even there are different payloads and external disturbances, which illustrates that the proposed controller possesses both strong performance robustness and good steady-state tracking accuracy in practical applications.

2. Problem formulation

In this section, the recently developed global task coordinate frame (GTCF) is first briefly introduced as a basis for the contouring controller design.

2.1. A globally defined task coordinate frame

The definition of the task coordinate frame is introduced from a new perspective as follows. Traditionally, the task coordinate frame for a biaxial system is locally defined at the desired position $P_d(x_d(t),y_d(t))$ based on the desired trajectory on the desired contour given by

$$\mathbf{q_d}(t) = [x_d(t), y_d(t)]^T \tag{1}$$

Such a definition depend on not only the geometry of the desired contour (e.g., a circle or an ellipsoidal) but also the desired motion to be tracked on the contour (e.g., the parametrization of the desired trajectory by the time t). As such, when the actual tracking error is large or the actual position differs from the desired point $\mathbf{q_d}(t)$ significantly, the calculated contouring error could be far different from the actual one as illustrated in Fig. 1 by the coordinate frame in yellow color. For example, for the actual position at P_a and the desired position at P_d shown in Fig. 1, traditional local TCF (LTCF) would be the coordinate frame represented by the dashed lines at P_d and the calculated contour error would be the projection of the position tracking error vector $\mathbf{e}_q = \mathbf{q} - \mathbf{q_d}$ along the normal direction the desired contour at P_d, i.e., $\mathbf{n}_d$ of LTCF. Such a calculated contour error is totally different from the actual contour error ε_c, the distance between the actual position $P_a(x(t),y(t))$ and $P_c(x_c(t),y_c(t))$, in which P_c represents the projection of $P_a(x(t),y(t))$ onto the desired contour along its normal direction as illustrated in Fig. 1. Intuitively, the actual contouring error ε_c depends on the geometry of the desired contour and the actual path of the system only. It has nothing to do with the desired trajectory to be tracked on the contour,

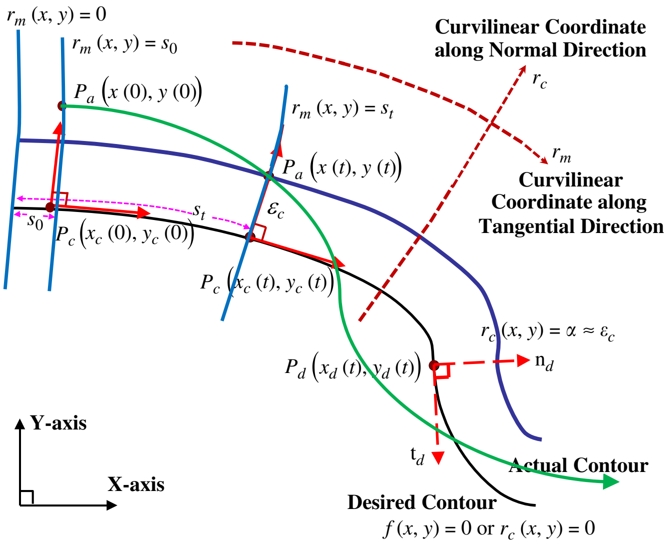

Fig. 1. A globally defined orthogonal task coordinate frame. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)