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Adaptive thrust allocation based synchronization control of a dual drive gantry stage☆

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ABSTRACT

In order to take full advantage of the hardware benefits by using redundant drive mechanisms, both synchronizing motions of the two actuators and avoiding excessive internal forces are vital to the smooth operations of dual drive gantry systems. However, almost all existing control schemes focus on pure motion synchronization only and the latter has been essentially ignored. Thus, even if the synchronization errors are kept within a small enough range, “pull and drag” phenomena could still exhibit due to the near-rigid physical coupling crossbeam and the consequent large internal forces. In this paper, a three-level synchronization control scheme based on adaptive thrust allocation is proposed to achieve not only better synchronized motion performance but also simultaneous regulation of internal forces. The overall control algorithm is composed of the motion tracking (Level I), the adjustable thrust allocation (Level II) and the on-line recursive least squares estimation (Level III), which is capable of achieving excellent internal force regulation and synchronization performance even when the distribution of system load cannot be priori known exactly in implementation or suffers from variations. Simulation and experimental results verify the effectiveness of the proposed synchronization control scheme based on adaptive thrust allocation in practical applications.

1. Introduction

Precision dual drive gantry stages have been widely applied in automation processes including printed circuit board manufacturing, precision metrology, and circuit assembly. As studied in this paper, two redundant linear motors [1–5] moving along two parallel linear guides are connected through a crossbeam to provide joint thrust for higher acceleration/speed movement. Along with the advantages by the coupling mechanism, “pull and drag” problem might also arise due to the physical constraint, i.e., the two actuators interfere with each other leading to excessive wear in sliding parts [6] and performance deterioration. Hence, it is necessary to guarantee synchronized motions of the two motors without excessive internal forces for the smooth operations of these systems.

For the synchronization control of dual actuators to follow one same motion, asymmetry characteristics of different axes, various parameter uncertainties, uncertain nonlinearities and disturbances including unbalanced load distribution need to be addressed. Traditional synchronization control [7–10] schemes can be classified into three categories [7]: (i) synchronized master motion command generation, in which each motor has its own individual control loop but receives the synchronized motion commands, (ii) master-slave motion control, in which the commands to the slave motor control loop are to follow the master motor motion, and (iii) relative dynamic stiffness motion control [8,11], in which a synchronization compensator is constructed based on the relative position and velocity of the two machine axes to be synchronized. The first two are intuitive but have inherent performance limitations due to non-sharing of certain feedback information (e.g., feedback information of the slave axis is not shared with the master in the second one), while the third one can be thought as a special case of the cross-coupled coordinated motion control [12,13] by simply defining the contour error [14,15] to be the relative position of the two machine axes in this case. As is done in the coordinated motion controls [16–18], latest synchronization motion controls mainly focus on the use of feedback information of all axes and/or more refined control design methodologies to achieve better motion synchronization under

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different drive characteristics and loading conditions of individual axis [8,9,19,20].

It should be noted that the existence of physical constraints between the two motors—the mechanical mechanism of coupling bridge between the two motors in the dual-motor drives—restricts the relative motion of the two actuators, or, in another words, physically tries to synchronize motions of the two actuators. This causes large internal force when the motion control of the two motors are not well synchronized, leading to performance deterioration, control chattering/saturation, and even damage of mechanical components. Recognizing these potential detrimental effects of rigid mechanical coupling when controls of two motors are not well synchronized, compliance mechanisms are actively introduced in [6] to avoid excessive wear in sliding parts and to provide certain hardware safety but also compromising the mechanical accuracy that can be achieved by these dual drive systems.

In fact, near-rigid crossbeam is essential for the configuration of these precision H-type gantry stages. Inevitably, dynamics of individual drive axes are completely coupled, which forms the subtle but fundamental differences with the decoupled axial dynamics in coordinated motion control. Thus, for smooth operations of these systems, an excellent synchronization control approach should not only achieve synchronizing motions of the two actuators, but also avoid excessive internal forces between the drive axes. However, the problem of internal force regulation has been essentially ignored in existing synchronization control schemes. Part of the reasons might be due to the complexity of having a good knowledge of the completely coupled dynamics of the two actuators by the mechanical coupling bridge. Lagrangian equations are used to model the gantry systems in Teo et al. [21] and Lin et al. [22] by choosing the displacements of the two motors and the rotational angle of the crossbar as the generalized coordinates. However, such handling of motion constraints directly contradicts with the rigid crossbar connection of the two motors implicitly assumed in these papers. Later on, a lumped-parameter model is presented [23] by treating the connections between the crossbar and the two parallel linear guides of the two motors of the X-axis as pure rotational flexible joints with lumped rotational spring stiffness. Again, such a modeling directly contradicts with the rigid cross-bar assumption made in the paper. Namely, when the rigid cross-bar has a rotational motion as assumed in the paper, there must be lateral displacements between the bar and the two fixed parallel linear guides along the Y-axis. Therefore, the connections between the bar and the two linear guides cannot be assumed to be pure rotational flexible joints.

Recognizing the fact that rotations of the cross-bar are actually caused by the linear spring stiffness effect of the ball bearings between the rotors and the linear guides of the two motors, a physics based lumped parameter modeling approach is proposed in our previous works [24,25], which can be taken to properly address the complex dynamic couplings issue mentioned above. On the basis of the appropriate coupled dynamic model, the control objective can then be specified as guaranteeing motion tracking performance through suitable control design methodology and simultaneous regulating internal forces through appropriate synchronization strategy. An approach is explored in our previous publication [26] to avoid large internal forces by simple thrust allocation where the allocation factor needs to be prior determined. However, this static allocation algorithm is quite rough and the unknown or variable load distributions could lead to degradation of the force regulation and synchronization performance.

In this paper, the synchronization control strategy based on thrust allocation is elaborated systematically, and a novel three-level synchronization control scheme with adaptive thrust allocation will be proposed to achieve not only better synchronized motion performance but also simultaneous regulation of internal forces. Specifically, the adaptive robust control (ARC) theory [27–29], which has been applied in high performance motion control for a variety of mechatronic systems [30–33], is used in Level I to synthesize motion tracking law to address the issues of significant parametric uncertainties and uncertain nonlinearities existing in practical systems, An adjustable thrust allocation algorithm is designed in Level II to avoid excessive internal forces in practice. In Level III, an adaptive allocation factor is introduced via a physical model based recursive least squares estimation algorithm to assure an appropriate allocation, which helps achieving excellent internal force regulation and synchronization performance even when the distribution of system load cannot be priori known exactly in implementation or suffers from variations. The effectiveness of the proposed synchronization controller will be verified by comparative simulations and then experiments carried out on a dual drive industrial gantry stage.

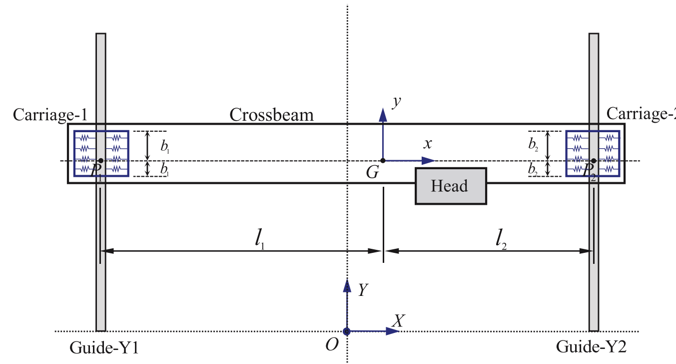

Fig. 1. Dual drive gantry with ball bearings at two parallel linear guides.

2. Physical modeling and problem formulation

2.1. Configuration and kinematics

The schematic vertical view of a dual drive gantry is shown in Fig. 1, in which two linear guides Y1 and Y2 are aligned parallel to each other and a crossbeam is mounted cross them. The crossbeam is driven along the direction of the linear guides by two linear motors Y1 and Y2 with their rotors rigidly attached to the crossbeam at the two ends while their stators mounted on the bases of the two linear guides respectively. The gantry stage head is either rigidly attached to the crossbeam or driven along the crossbeam by another linear motor for an additional X-axis directional motion. As this paper focuses on the synchronized control of the two motors Y1 and Y2 for Y-axis motion of the head only, for simplicity, it is assumed that the head is rigidly attached to the crossbeam.

Linear motion guides using recirculating ball bearing [34] as shown in Fig. 2, which have many advantages such as high stiffness, good reliability and low cost, are widely used in precise positioning systems

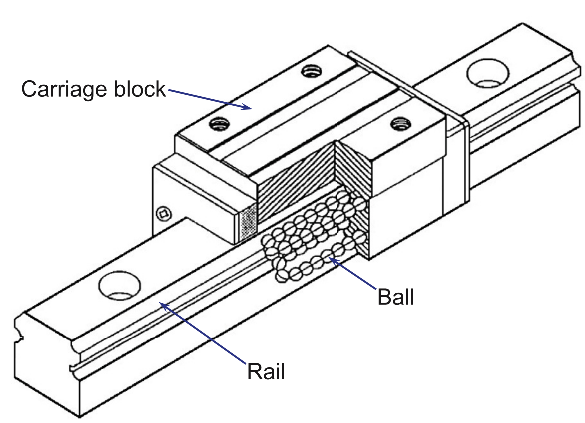

Fig. 2. Linear guideway type linear ball bearing.