ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

Development of a decentralized multi-axis synchronous control approach for real-time networks☆

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ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form
23 January 2017
Accepted 17 March 2017

Keywords:
Networked control system
Multi-axis motion
Decentralized control
Position synchronization
Cross-coupled control
Real-time network

ABSTRACT

The message scheduling and the network-induced delays of real-time networks, together with the different inertias and disturbances in different axes, make the synchronous control of the real-time network-based systems quite challenging. To address this challenge, a decentralized multi-axis synchronous control approach is developed in this paper. Due to the limitations of message scheduling and network bandwidth, error of the position synchronization is firstly defined in the proposed control approach as a subset of preceding-axis pairs. Then, a motion message estimator is designed to reduce the effect of network delays. It is proven that position and synchronization errors asymptotically converge to zero in the proposed controller with the delay compensation. Finally, simulation and experimental results show that the developed control approach can achieve the good position synchronization performance for the multi-axis motion over the real-time network.

1. Introduction

The distributed control systems with a real-time network is becoming promising in modern industrial and commercial applications equipped with a number of actuators and sensors [1], for instance, humanoid robots, printing machines, automobiles, computer numerical control (CNC) machining centers, and so on. Such kind of systems is generally known as the networked motion control systems (NMCSs), where functional modules such as actuators, sensors, and controllers are spatially interconnected and distributed with a communication network [2]. Compared with traditional centralized control systems with directly wiring devices together, NMCSs provide several advantages in terms of remote-control capability, scalability and reliability. Besides, NMCSs reduce the problems of transmit-length limitation and wiring connection, and decrease reconfiguration, installation, and maintenance costs [3].

In a networked motion control system, a large number of feedback and command messages should be periodically communicated among distributed nodes with a high speed [3]. To address such challenges, a lot of efforts have been made in recent years, which can be categorized into the following two parts: networking technologies and control over network [4]. In order to develop the network appropriate for real-time applications, the main concern in networking technologies is to improve the network quality of service (QoS) [5] such as routing control, congestion reduction and communication protocol. On the other hand, control over network focuses on controller design over the network to maintain the control quality of performance (QoP) by compensating for the network-induced delay or packet dropout. At the same time, synchronous errors among axes are important aspects that significantly affect the motion accuracy in a multi-axis motion control system [6]. Different from the traditional centralized control systems, besides the inertias and disturbances factors, the message scheduling and the network-induced delays also influence the synchronous performance in network-based systems.

However, literatures focusing on NMCSs study combined with the synchronous control are few reported. It remains a challenging problem how to design a decentralized multi-axis synchronous controller with considering the network-induced factors and prove the asymptotic stability of the global system. To this end, we present a decentralized multi-axis synchronous control approach in this paper to realize the accurate position tracking and synchronizing motion, dealing with the factors such as the different inertias, different disturbances, the message scheduling and the network-induced delays of the real-time network together. Based on the detailed analysis of the problems of the message scheduling in the real-time network, we choose a subset of preceding-axis pairs as the position synchronization error. And a motion message

☆This research was supported in part by Shanghai Sailing Program under Grant 14YF1414200, the Science and Technology Commission of Shanghai Municipality under Grant 16JC1401000, and State Key Laboratory of Robotics and System (HIT).
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http://dx.doi.org/10.1016/j.isatra.2017.03.012
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estimator is introduced in the synchronous controller to estimate the current position errors of preceding axes to reduce the effect of network-induced delays. Simulations and experiments are conducted on networked multi-axis motion control systems to verify the effectiveness of the developed approach. The networked simulation system is designed through the Matlab/Simulink and the TrueTime toolbox [7], while the experimental set-up is built based on smart networked motion control nodes, a four-axis table and the real-time Ethernet communication. It should be also noted that compared with our previous developed system [8], the time synchronization scheme is added to the real-time communication cycle and the time synchronization performance is also validated in the test system. Both simulation and experimental results demonstrate that the proposed synchronous control approach achieves good position synchronization performance in the networked system for multi-axis motion control.

The remainder of this paper is organized as follows. In Section 2, we survey existing results on networked motion control systems. and the problem formulation is devoted in Section 3. In Section 4, we design a decentralized synchronous controller for networked motion control systems. In Section 5 and Section 6, simulations and experiments are performed to verify the proposed synchronization control approach. Conclusions are given in the last section.

2. Related work

2.1. Networking technologies

While choosing the communication network for the multi-axis motion control system, the main issues include time-synchronized actions between field devices, time-deterministic communication, reliability and availability. In the literature, a number of real-time control networks, such as Profibus, control area network (CAN), FIP, serial real-time communication specification (SERCOS), have been developed for NMCSs during the past decade [9–12]. As an alternative, due to the advantages of high transmission speed, deterministic communication, and low price, the real-time Ethernet (RTE) has recently been developed for information exchanges in real-time motion control systems [13,14]. Besides, we can adopt a double-ring topology architecture or optical fiber as the transmission medium to improve the reliability of the RTE, which indicates the effect of the packet dropout can be neglected in these real-time networks. This is also the reason why the packet dropout will not be considered in this work.

2.2. Control over network

After using a proper real-time communication protocol to guarantee the network QoS, we also need an advanced controller to guarantee the control QoP. In terms of the controller design, the current research in NMCSs focuses on control system design and control strategies when a traditional feedback control system is closed through a network. This control system can also be denoted as a networked control system (NCS). For example, NCS models with network-induced delay were developed by Zhang and Branicky [15]. A theoretical framework was presented by Yook et al. [16] to develop an optimal network architecture. The modelling and optimal controller design of NCSs with multiple communication delays were investigated by Lian et al. [17]. A controller gain adaptation was proposed in [5] to handle the changes in QoS requirements. Besides, there are many algorithms in networked control systems to compensate the network-induced delays, such as Smith predictor [18], model-based control [19], networked predictive control [20] and communication disturbance observer [21]. But these delay compensation algorithms were complicated and required extensive on-line calculations.

2.3. Traditional multi-axis synchronous control

The reported works were only contributed to the stability analysis and controller development of single closed-loop in network environments. In traditional centralized control systems, different inertias and disturbances in different axes are the main factors which cause synchronous problem. To improve the synchronization performance for centralized systems, many efforts have been devoted. Koren [22] proposed a cross-coupled control (CCC) for biaxial motion systems. Various improved contour controllers were later presented to further reduce synchronous errors of different axes [23–29].

2.4. Multi-axis synchronous control over network

As aforementioned, it remains a challenging and open problem how to design a decentralized multi-axis synchronous controller over a network. Recently, Nuño [30] proposed an adaptive synchronous controller to achieve the networks' synchronization in nonidentical Euler–Lagrange systems. But noted that constant network delays were assumed and delay compensation was not considered in their controller design. Besides, we made some attempts on this issue in [31] and have proposed a time-stamped cross-coupled controller in networked CNC systems. But this controller was based on biaxial motion systems and was verified only by numerical simulation. In order to validate the synchronous controller in applications, a networked multi-agent system based on real-time Ethernet was developed in our previous work [8]. This paper furthers these research and investigates a decentralized multi-axis synchronous control over real-time networks.

3. Problem formulation

Generally speaking, the multi-axis motion control system over real-time networks includes a set of smart networked motion control nodes, which are spatially interconnected and distributed by one real-time network. And its typical network architecture is the ring topology due to the low cabling cost. As shown in Fig. 1, the master node manages the whole digital communication and achieves the key functions of a reference position generator, for instance, trajectory interpolation, velocity planning, code interpretation, etc. Simultaneously, position-loop control and cross-coupled control are implemented in the distributed motion control nodes to realize the parallel computing and fast response. There are some applications, like soft-CNC systems [32,33], which integrate position-loop control, velocity-loop control, and even current-loop control in the master node. However, the main difficulty in these applications arises from the tradeoff between the extensive real-time calculations of the centralized multi-axis controller and the constrained computation capability in the master node. This has been the motivation of this work to design a decentralized synchronous controller for real-time network-based systems. Compared to the traditional centralized architecture, the decentralized architecture can improve the response speed and the modularity of the system through combining the merits of the distributed computing and the real-time network. Finally, we can summarize our problem as:

Problem: Consider that a networked multi-axis system with n axes requires position synchronization of all distributed axes. As in [24], this task requirement can be transformed to a relationship that the position errors of all axes must be regulated, namely