

A Survey on Synchronous Control Architectures for Data Transmission Delay in Networked Control Systems

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Abstract. Networked Control Systems (NCS) are widely applied in industrial automation, remote control and other fields. However, data transmission delay has severely affected the stability and real-time performance of systems, becoming a core bottleneck restricting their development. This paper systematically reviews the synchronous control architectures and key technologies for data transmission delay. Firstly, it analyzes the generation mechanism, characteristics of data transmission delay in NCS and its impact on system stability. Secondly, it elaborates the design ideas of current mainstream synchronous control architectures from three aspects: synchronous architecture principle, controller coordination method and delay compensation scheme. Thirdly, it summarizes the typical simulation platforms and performance verification methods, and compares the control effects of different strategies. Finally, it concludes the limitations of existing research and prospects the future development direction in complex network environments. This paper aims to provide a systematic technical reference for the theoretical deepening and engineering application of NCS.

Keywords: Networked Control Systems; Data Transmission Delay; Synchronous Control; Clock Synchronization; Delay Compensation.

1. Introduction

A networked control system is a closed-loop control system where components such as sensors, controllers and actuators in the control loop transmit data packets through a communication network. It has remarkable advantages including simplified wiring, strong scalability and high resource sharing capability. Its development has undergone stages such as pneumatic control, analog signal control and digital computer centralized control. In the early 21st century, with the maturity of industrial Ethernet technology, control networks and information networks have been deeply integrated, and NCS have been widely used in factory automation, rail transit, aerospace and other fields. Nevertheless, the transmission delay of data in the network destroys the timing consistency of the system, resulting in time misalignment of information transmission between the controller and the controlled object, which further leads to performance degradation or even instability of the system. In actual operation, various factors such as network bandwidth limitation, data collision, node scheduling strategy and communication protocol make the delay exhibit complex random fluctuation and asymmetric characteristics. Therefore, designing an effective synchronous control architecture according to the network delay characteristics to improve control accuracy and synchronous response capability has become a core research issue in this field. Focusing on the synchronous control problem under data transmission delay, this paper systematically combs and reviews existing research results to provide theoretical support and technical paths for follow-up research [1].

2. Analysis of Data Transmission Delay Problem

2.1. Generation Mechanism and Characteristics of Delay

Data transmission delay in NCS is complex and uncertain. Its generation mechanism is mainly affected by various factors such as network bandwidth, data collision, node scheduling strategy and communication protocol. The delay shows significant random fluctuation and asymmetric

characteristics under different network topologies and load conditions. Such delay not only causes the delay of output response but also leads to system phase delay and frequency characteristic changes, posing a severe challenge to the robustness of closed-loop systems [2].

2.2. Delay Modeling Methods

To effectively address the delay problem, researchers have proposed various modeling methods, mainly including constant delay model, time-varying delay model and probabilistic delay model. The constant delay model is suitable for scenarios with fixed network load and simple topology, facilitating theoretical analysis. The time-varying delay model is closer to the actual network environment and can describe the trend of delay changing with time. The probabilistic delay model characterizes random delay characteristics based on statistical distribution, which is suitable for robust design of control strategies. Different models have significant differences in descriptive ability and application scope, and selecting an appropriate modeling method is of great significance for the subsequent control strategy design.

3. Design of Synchronous Control Architecture

3.1. Principle of Synchronous Architecture

The uncertainty of data transmission delay in NCS makes it impossible for control nodes to maintain a stable time reference, resulting in information inconsistency and decision deviation. The core of synchronous control architecture is to construct a unified global time reference. A typical scheme is based on the master-slave clock mechanism, where the master clock node periodically broadcasts timestamps to slave nodes, and slave nodes perform deviation estimation and clock calibration according to the received information combined with the local clock state, forming a distributed collaborative clock synchronization system [2].

In view of complex factors such as asymmetric delay, clock drift and noise interference in actual networks, a single synchronization protocol is difficult to meet the requirements of high-precision control. Existing studies generally introduce multi-level synchronization mechanisms and adaptive filtering algorithms to improve clock consistency. Meanwhile, the synchronous architecture should be deeply coupled with the controller execution strategy to ensure that the system can maintain coordination and responsiveness in the presence of transmission delay.

3.2. Controller Coordination Methods

In a networked control environment, coordination between controllers requires not only information sharing, but also unified arrangement of execution rhythm and data processing order to avoid control conflicts and state drift. The core goal of multi-controller coordination is to achieve decision consistency and unified execution timing. Its design needs to consider multiple factors such as network bandwidth limitation, node load capacity and control priority. Common coordination strategies include distributed consensus algorithms, event-triggered synchronization mechanisms and polling scheduling models.

In the distributed consensus algorithm, each control node iteratively updates based on local information and neighbor states and gradually approaches the global optimal control strategy according to the consensus protocol. This method has a strong dependence on the network topology and is suitable for systems with close connection and frequent communication. The event-triggered synchronization mechanism triggers control behavior when key variables change significantly according to the set state threshold, effectively reducing communication overhead and improving real-time response. The polling scheduling model arranges controllers to access communication resources in turn according to the preset timing, which is suitable for systems with balanced control load or clear task priority [4]. In complex scenarios, researchers emphasize the deep integration of clock synchronization mechanism and controller coordination strategy, and the introduction of

conflict detection and avoidance strategies to prevent system instability caused by mutual exclusion of control commands [2], thereby improving the controllability and fault tolerance of the system.

3.3. Delay Compensation Schemes

Faced with the inevitable random delay in the network, constructing an effective delay compensation scheme is the key to improving the stability and accuracy of the control system. The basic idea of delay compensation is to predict the future output by using the current and historical states of the system, so as to estimate the future system state when the controller issues commands, realizing advanced control and error suppression.

This method usually establishes a state observer or predictor based on the system model to perform feedforward correction on the control error caused by delay. Under accurate modeling conditions, the delay compensation scheme based on Smith predictor can effectively improve the closed-loop response speed of the system. Its core is to construct a collaborative operation structure of delay-free model and delay compensation link, enabling the controller to respond in advance according to the predicted state.

When there is uncertainty in the system model, adaptive control technology can be combined to modify model parameters or fuzzy control strategy can be introduced to improve compensation robustness. In nonlinear systems or large-delay systems, time-varying delay difference method can be used to construct a dynamic compensation mechanism. This method adjusts the control output according to the real-time change of network delay, making the compensation strategy flexible and adaptable.

Some systems also adopt a hierarchical compensation structure, which handles part of static delay at the communication protocol layer and dynamically adjusts compensation parameters at the control logic layer, thereby improving compensation efficiency and control accuracy [3]. In practical applications, delay compensation must be closely coupled with the synchronous control architecture. The packet arrival time and execution command delay are determined on the basis of clock synchronization to avoid system oscillation or response overshoot caused by compensation error, ensuring the stability and consistency of the overall control system operation.

4. Experimental Verification and Performance Evaluation

4.1. Typical Simulation Platforms

In existing studies, Matlab/Simulink combined with the TrueTime toolbox is the most commonly used simulation platform for NCS, which supports network protocol configuration, control strategy programming and communication delay simulation. The experimental objects often select systems with typical time-delay characteristics and nonlinear disturbances such as double-tank water level control [4].

In simulations, parameters such as master-slave clock synchronization frequency (e.g., 10 Hz), network protocol (UDP), topology (star) and bandwidth (e.g., 1 Mbps) are usually set, and comparative tests are conducted for different delay levels (e.g., 5 ms, 20 ms, 50 ms). Evaluation indicators include overshoot, settling time, steady-state error and network load [2] [4].

4.2. Comparison of Control Effects

A large number of simulation results show that the synchronous control architecture is significantly superior to the traditional control strategy without compensation in terms of overshoot, settling time and steady-state error under low-delay conditions. In medium and high-delay scenarios, although the performance of the synchronous architecture decreases, the deterioration trend of control indicators is gentle, showing strong robustness; while the performance of the uncompensated control strategy deteriorates rapidly, the overshoot exceeds the safety boundary, and the system suffers from severe oscillation [2] [3].

In terms of network load, synchronous control is slightly higher than traditional control due to the increase of clock synchronization messages and state feedback frequency, but it is still within the typical communication capacity of industrial Ethernet.

4.3. Comprehensive Review

On the whole, the synchronous control architecture shows good anti-interference ability and stability under different network delay conditions. Its advantages are not only reflected in the improvement of error indicators, but also in the smoothness and regularity of the system output curve. Although the synchronous strategy increases a small amount of communication overhead, this cost is acceptable in control scenarios with high real-time requirements. Existing studies have verified that architecture is suitable for distributed systems with medium and high-frequency feedback control requirements.

5. Research Prospect

5.1. Limitations of Current Research

Although the existing synchronous control architectures have made remarkable progress in suppressing delay in NCS, there are still the following shortcomings: most studies are based on relatively ideal network assumptions, with insufficient consideration of extreme scenarios such as sudden high delay, packet loss and network attacks [1]; existing delay compensation methods rely heavily on accurate system models [3], and their performance decreases significantly in highly nonlinear or model-unavailable scenarios; the integration depth of synchronization mechanism and control strategy still needs to be strengthened.

5.2. Future Development Directions

Future research can be carried out in the following directions: combining artificial intelligence methods such as deep reinforcement learning to realize self-perception of network state and adaptive adjustment of synchronization parameters; designing hierarchical and cross-domain synchronous control mechanisms for industrial Internet of Things and edge computing scenarios [3]; studying resilient synchronous control architectures under network attacks (e.g. delay attacks, timestamp tampering); promoting the deep integration of synchronous control protocols and industrial network standards, and carrying out large-scale actual system verification [2] [4].

6. Summary

This paper systematically reviews the research progress of synchronous control architectures for data transmission delay in NCS. Research shows that the synchronous control architecture integrating clock synchronization and delay compensation can effectively alleviate the control error caused by delay and improve the response speed and robustness of the system. The research results in this field provide important theoretical basis and technical support for networked control systems in complex industrial scenarios, with significant engineering promotion value.

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