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Hybrid one-way delay estimation for networked control system

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ABSTRACT

One-way delay estimation in the forward and feedback channels is crucial for a networked control system (NCS) due to its important role in the reliability and availability design. Problems existing in current one-way delay estimation schemes are investigated in this paper. A novel hybrid one-way delay estimation scheme, utilizing the hybrid technique that contains an online monitoring mechanism and an end-to-end estimation method, is proposed to overcome the effects of network asymmetry and delay dynamics in the NCS. Therefore, accurate one-way delay values in the forward and feedback channels can be obtained. In the proposed scheme, only the delay value of the initial packet starting the control loop of the NCS is estimated by the online monitoring mechanism, all the other estimations are performed by the host using the end-to-end method. The experimental results demonstrate that the performance of the proposed novel hybrid one-way delay estimation scheme is better than the other current estimation schemes for the NCS in terms of its high accuracy in tracking delay values as well as requiring lower computation complexity of the system.

1. Introduction

Due to their cost effective and flexibility in practice, network systems in control loops have been widely used in industry, such as in remote industrial controls and factory automations. Networked control systems (NCS) have gained considerable and increasing attention in recent years [1–5]. A NCS is defined as a distributed real-time feedback control system consisting of sensors, controllers, actuators and communication units. It can reduce the system wiring, increase system flexibility, realize resource sharing, coordinate manipulation and simplify the control strategy of large distributed systems. However, the integration of communication networks makes the analysis and design of a control system very complex.

The control sequence of a control system is based on time, thus the data transmission time through network is very important for analysis of a NCS. However, the random network delay induced by the data transmission and traffic congestion is unavoidable in a communication network [6,7]. The delays, in both the forward (from controller to actuator) and feedback (from sensor to controller) channels, can significantly affect the performance of the NCS since the network is embedded in the control system. Designing a NCS without considering the delays will result in instability, and even destabilize the whole control system. Therefore, handling the forward and feedback network delays respectively in the closed-loop control system over networks is the foundation of the analysis and design of a NCS [3,8]. In a real application, one-way delay estimation measuring the individual delays is an efficient solution to the aforementioned problems. Hence, in order to estimate the forward and feedback delays for a NCS, a new scheme, namely, hybrid one-way delay estimation (HOWDE) scheme, is proposed in this paper. The novel scheme cannot only keep track of the changing delay values accurately, but also induce lower computation complexity to the system.

The rest of the paper is organized as follows. Section 2 reviews the related work. The design of the hybrid one-way delay estimation scheme is presented in Section 3. Section 4 shows the simulation results and provides a detailed analysis. Finally, Section 5 gives the conclusion.

2. Related work

Theoretically, in a NCS, the forward and feedback delays can be calculated by subtracting the sender's timestamp in each packet from the receiver's clock, and then compensate for the network transmission delay to achieve a desired control performance. This scheme is under the assumption of clock synchronization. Liu et al. [5,7] carried out works using this method. However, since it is difficult to individually measure the forward and feedback delays unless the clocks at the controller and equipment sides are synchronized, the aforementioned scheme cannot be directly applied in reality. A number of schemes attempted to utilize the physical clock synchronization algorithm to overcome this problem [9,10]. However, the NCS usually works in a heterogeneous

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and large distributed environment, thus it is also very difficult for the clock synchronization to be applied.

The Round Trip Time (RTT) can be used to measure the delays of the end-to-end communication, and it is defined as the time duration for a packet traveling from the sender to the receiver and back. Since the time elapsed between the packet's leaving and return is recorded by the same clock, the scheme using RTT does not need to consider the problem of clock synchronization. Under the assumption that the communication network is symmetric, each of the forward and feedback delays in the NCS can be simply estimated to be 1/2 of the RTT [11]. However, in practice, the NCS usually works within a large-scale distributed environment, thus the forward and feedback channels may have varying bandwidths and the routing paths across the networks are often asymmetric. Furthermore, even if the packet travels across the same route which has the same bandwidth in either direction, it may also experience different queuing levels inside the routers [12,13].

Some researchers have focused on the clock offset and skew and used them for calibration of the timestamps in one-way delay estimation. Paxson [14] addressed this problem and proposed a solution to estimate the relative offset, but the algorithm cannot be applied under the environmental conditions where the network path is asymmetric. To approach the asymmetric problem, Luong and Biro [15] measured the relative offsets of adjacent node pairs on the network path, and added them up to be the relative offset between the end hosts. However, this scheme needs the routers in the path to continuously perform the measurement service, which can result in an overload of the networks. Tsuru et al. [16] focused on the offset and skew estimation of the clock from one-way delay measurement. It reduces estimation errors in the cases where the forward and feedback paths have different bandwidths. However, it operates under the assumptions that both directions have the same propagation delay, transmission delay and error factors, and these assumptions cannot be guaranteed in reality.

Currently, some works estimate the individual delays by monitoring the traffic across the networks. These works can be divided into those using the online traffic monitoring mechanism and the ones using end-to-end measurement mechanism. The online traffic monitoring mechanism [8,17] can be introduced to monitor various network performance metrics, including packet loss, delay and delay variance. Shao et al. [8] proposed a scheme that estimated the network induced delay of the NCS using automatic route trace technology. It is a router-based online measurement mechanism. However, this mechanism enables every node along the path to contribute in monitoring the packet delay all the time. As the scale of the network grows, the system processing load and network overhead will increase dramatically. On the other hand, the end-to-end measurement mechanism [11,13,18] using only the ingress and egress nodes for performance monitoring, can also be used to estimate the one-way delay. Gu and Yu [11] measured the time interval between the two packets in each probe pair at the end host, and estimated the distribution of end-to-end one-way delay by a Fourier-to-Time reconstruction algorithm. However, this scheme is not designed for the NCS applications, and it cannot show the exact delay value in practical networks. The scheme proposed by Joo et al. [18] needs a reference delay value measured under the network environment with no traffic congestion, but it is difficult to obtain the reference value in large-scale distributed networks such as the NCS. Choi and Yo [13] proposed a scheme that can individually estimate the forward and reverse delays in asymmetric networks. However, the algorithm accuracy is mainly determined by the first forward delay estimation, and this work used a heuristic method to predict the first forward delay which might lead to a bottleneck of the individual delay estimation accuracy. Furthermore, this also is a scheme which is not designed for NCS applications.

3. Hybrid one-way delay estimation

As mentioned above, most of the existing works have their own shortcomings. To overcome these problems, a novel hybrid one-way delay estimation scheme, namely, HOWDE, is proposed for NCS applications which integrates the online monitoring mechanism and the end-to-end estimation method.

This work mainly builds upon the techniques of [8,13,19]. In this section, the concept and design of the proposed scheme are explained and analyzed theoretically.

3.1. One-way delay estimation for NCS

Fig. 1 depicts the structure of the NCS and the network induced delays. The structure can be divided into three parts: the controller side, the equipment side and the network. In this system, a set of control sequences and measurements can be transmitted from one side to another by packing them into one packet under the distributed environment. However, due to the randomness of the induced delays in the forward and feedback channels in the NCS, it is very difficult to perform the control design and stability analysis [5]. Here the RTT is used to measure the total time delay of a control cycle in the NCS. The total delay consists of three parts and can be written as [20]:

$$\mathrm{RTT} = t_{sc} + t_p + t_{ca} \tag{1}$$

where t_{sc} is the delay at the feedback channel, t_{ca} is the delay at the forward channel, and t_p is the processing delay at the end sides. Since the processing delay, t_p, can be determined by the local clock at the host and the major RTT dynamics is purely dependent on the time delay at the forward and feedback channels, we mainly focus on the estimation of t_{ca} and t_{sc}.

Similar to [13], to estimate the one-way delay one packet per RTT is used. However, in contrast to the works presented in [13], the proposed scheme initially sends the packet from the receive side (equipment side) rather than the sender side (controller side), and the control mechanism initiated by the equipment side is the one described in [20]. Since the control cycle is started at the equipment side, an initial packet will firstly be sent from the equipment side to the controller side. Subsequently, multiple packets are started from the controller side. In addition, the sensor data is encapsulated into the acknowledgement packet sent from the equipment side, and then the packet containing the sensor data is delivered to the controller side. The packet exchange between the controller side and equipment side in the proposed scheme is illustrated in Fig. 2, where:

S_n the sending time of the nth packet at the controller side
R_n the arrival time of the nth packet at the equipment side
t_n the forward delay of the nth packet
k_n the feedback delay of the nth packet
$\mathrm{RTT}(s,n)$ the Round Trip Time of the nth packet at the controller side
$\mathrm{RTT}(r,n)$ the Round Trip Time of the acknowledgement packet for the nth packet at the equipment side

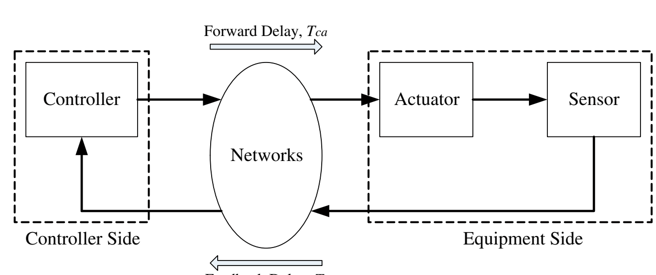

Fig. 1. The NCS structure and the network induced delays.