Simulation Of Wireless Networked Control System Using TRUETIME And MATLAB

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Abstract: Wireless networked control systems (WNCS) are attracting an increasing research interests in the past decade. Wireless networked control system (WNCS) is composed of a group of distributed sensors and actuators that communicate through wireless link which achieves distributed sensing and executing tasks. This is particularly relevant for the areas of communication, control and computing where successful design of WNCS brings about new challenges to the researchers. The primary motivation of this survey paper is to examine the design issues, and to provide directions for successful simulation and implementation of WNCS. The paper also as well reviews some simulation tools for such systems.

Index Term: Network Control System, Stability Analysis, Industrial Electronics, MATLAB, Time Delay

Introduction

Wireless sensor networks (WSNs) are the promising technology in the future, which is suitable for a lot of applications, such as battle surveillance, environmental monitoring, health care, target tracking, industry, and automation and so on. The primary benefit of wireless technology is essentially the reduced installation cost, both financially and in labor, as a considerable investment is made in the wiring of factories. The use of wireless technology is not only the placement of cables, the benefits go beyond that. With wireless devices, increased flexibility is gained, as sensors can be placed more freely in a plug-and-play fashion, even on rotating machines. Cable failures are eliminated and wireless communication is robust, as it can be done over several paths in a mesh network. Finally, there are the opportunities for new applications that are enabled by wireless control. An important class of networked control systems (NCS) are now being implemented over wireless networks because of the need for node mobility in many applications. These systems are known as wireless networked control systems (WNCS). The simplest WNCS includes a plant and a controller with point to point wireless communication between them. Sensor and actuator in wireless networked control system are composed of a group of distributed sensors and actuators that communicate through wireless link which achieves distributed sensing and executing tasks. Simulation plays an important role at several stages of system design. In order to support the application at hand, co-simulation should simultaneously simulate the computations that take place within the controller nodes, the wireless communication between the nodes, the sensors and actuator dynamics and the dynamics of the controlled plant. The objective of this paper is a real-time simulation model which provides timely reactions to the environment upon detection of sensing data and to establish guidelines for successful implementation of WNCS. The paper also touches on the communication network and co-simulation and focuses on the interactions between the network and the control system.

Related WORK

Two simulation case studies: a simple communication scenario of soccer game and true time are described in [1]. Ngai described about tackle two problems, i.e., minimizing the transmission delay from sensors to actuators and improving the coordination among the actuators for fast reaction and designed areal-time communication framework to support event detection, reporting, and actuator coordination and proposed two self-organized and distributed algorithms for event reporting and actuator coordination [2]. The primary motivation of this survey paper is to examine the design issues, and to provide directions for successful simulation and implementation of WNCS. The paper also as well reviews some simulation tools for such systems.

III COMMUNICATION NETWORK

The following topics are discussed for the design issues from the area of communication network.

A. Wireless communication standards

1) IEEE 802.11

Most WNCS researches are based on mainly IEEE 802.11 standards and support data rates 1, 2, 11, 54 Mbps. IEEE 802.11 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as Medium Access Control (MAC) protocol. However, contention based protocols, e.g., CSMA/CA, are not appropriate for real time communication as they require handshaking among the nodes and do not guarantee bounded packet delay.

2) IEEE 802.15.4/ZigBee

The theme of 802.15 standards is to support short distances (less than 10m). It offers two versions. HighRate-WPAN (802.15.3) supports high data rate and Quality-of-Service (QoS) constraints for multimedia applications and suitable for ad hoc mode. Low Rate-WPAN (802.15.4)
offers low cost and low power consumption in ad hoc mode but low data rate and relaxed performance requirements. Supported datarates are 250, 40 and 20 Kbps.

3) IEEE 802.15.1/Bluetooth

Bluetooth offers low cost and low power requirement with a high degree of versatility. It has been used in some industrial applications such as sensor devices for monitoring, driver hands-free calling etc.

B. Packet delay

Network packet delay can degrade the NCS performances significantly and even destabilize the entire system. The total closed loop delay \( \tau_{\text{total}} \) is given in (1) where \( \tau_{\text{sc}} \) is sensor-to-controller, \( \tau_{c} \) is controller computation and \( \tau_{ca} \) is controller-to-actuator delay, respectively.

\[
\tau = \tau_{\text{sc}} + \tau_{c} + \tau_{ca}
\]

For simplicity, the controller delay \( \tau_{c} \) is ignored or treated as a part of the controller-to-actuator delay since it is negligible and almost constant compared to the delays \( \tau_{sc} \) and \( \tau_{ca} \). Therefore the total delay can be obtained by (2):

\[
\tau = \tau_{sc} + \tau_{ca}
\]

Control mechanisms based on constant time delay are not suitable for NCS, since network delay is usually time varying. When this is less than the sampling period \( T_{s} \), the stability condition of the NCS can be found by computing the upper bound of delay between any two successive sensor messages. On the other hand, when it is larger than the sampling period, some delay compensation technique must be employed. Various delay compensation techniques can be found in [34]. Networks with constant and independent delays have been developed and controller design with constant and random time delay have been discussed in [7]–[10].

C. Packet drop/loss

Wireless networks can suffer from packet drop/loss that can cause instability of the NCS. Re-transmission will generate obsolete packets and it will simply produce more traffic in the network. As NCS carries real-time traffic, it might be beneficial to drop a packet that cannot be transmitted immediately. The tolerable packet drop rate must be analyzed to maintain guaranteed desired system stability. NCS with packet drop can be modeled as two-state switch, where \( \theta \in \{0,1\} \) is the sequence which indicates reception (\( \theta = 1 \)) or loss (\( \theta = 0 \)). If the current state of the packet is missing because of the packet drop, the previous state buffered at the controller is used. Therefore, the dynamical model can be expressed by (3) . Modern NCS can tolerate packet drop up to some extent as can still maintain stability [10]. Modelling NCS with random communication delays, where the sensor is clock driven and the controller and the actuator are event driven. The discrete-time linear time-invariant plant model is as follows:

\[
x_{p}(k+1) = Ax_{p} + Bo_{p}, \quad y_{p}(k) = Cx_{p}(k),
\]

Where \( x_{p}(k) \in \mathbb{R}^{n} \) is the plant’s state vector and \( \omega_{p}(k) \in \mathbb{R}^{m} \), \( z_{p}(k) \in \mathbb{R}^{m} \) and \( y_{p}(k) \in \mathbb{R}^{p} \) are the plant’s disturbance input and output vectors, respectively. A, B, and C are known as real matrices with appropriate dimensions with C being of full row rank. A more general case that the measurement with a randomly varying communication delay is described by

\[
y_{c}(k) = \begin{cases} y_{p}(k-\tau_{m}^{c}), & \delta(k)=1 \\ y_{p}(k), & \delta(k)=0 \end{cases}
\]

Where \( \tau_{m}^{c} \) stands for measurement delay, the occurrence of which satisfies the Bernoulli distribution, and \( \delta(k) \) is Bernoulli distributed white sequence. An approach for a remote PID controller design for multivariable NCSs has been addressed in [11].

D. End to end connection type

Communication over wireless network can be performed using either Transmission Control Protocol (TCP) or User Datagram Protocol (UDP). TCP/IP is not suitable for MANETs as it uses connection oriented packet transfer. On the other hand, UDP offers low overheads as it does not maintain connections and discards obsolete or lost packets. Therefore, it is preferable for networked control applications.

E. Delay jitter

In general, jitter is defined as deviation of an instant the signal from its actual position in time or standard deviation of the measured delays of network packet. This problem can be caused by some or all of the following: clockdrift of a transmitter-receiver, congestion, routing algorithm communication systems, scheduling of real time tasks in computer systems, number of hops on the path. It can be expressed by

\[
E_{j} = V_{j} - U_{j}
\]

Where \( U_{j} \) is the time between \( j \)-th and \((j+1)\)-th packet arrival and \( V_{j} \) is the time between \( j \)-th and \((j+1)\)-th packet departure. In this case, negative jitter represents clustering of packets that can cause buffer overflow and positive jitter correspond to dispersion of packets that can cause excessive delay.

F. Network design

In order to achieve a wider acceptance of wireless technology in industrial control, various networking challenges are to be addressed. One main network design issue in WCSSs is the medium access (MAC) protocol, as it determines the communication opportunities. The distribution and length of consecutive packet drops are significant from the controller point of view, because of the real-time requirements of control. MAC protocols can be categorized into deterministic and random access. In random access MACs, no guarantees to acquire access to the medium in a given time can, in general, be given. In deterministic MACs, a communication slot (either in frequency, time, with code division, or a combination of them) is assigned to each node or node pair. This

\[ z_{p}(k) = Gx_{p}(k) \]
assignment has the advantage that the access to the medium can be guaranteed in a predetermined time. Deterministic MAC protocols are thus more desired in WCS, where real-time operation is required. A network using a random access MAC protocol is obviously non-deterministic, but actually even a deterministic MAC protocol is somewhat stochastic due to interference or fading. In the case of packet loss, retransmission is needed, which results in variable response times, to avoid information loss. The use of frequency hopping and spread spectrum techniques makes the wireless network less vulnerable to these threats.

G. Control design
The controller design in WNCSs introduces the requirement of robustness against packet loss and delay jitter, which the network inherently induces. Single control loop systems can be analyzed analytically and existing stability proofs take the network delay jitter into account. The case becomes difficult in large control systems with many control loops, or when specific network protocols are considered. In these cases, simulations are needed to investigate the effect of the network and the various protocols on the control system. There are three main control system design architectures in NCS, depicted in Figs. 1–3. All architectures consider only wireless measurements, as the controller can in most cases be placed at the actuator, removing an unnecessary communication link between the controller and actuator. These cases can naturally be extended also to the case of wireless communication between the controller and actuator, but in those cases the design becomes more difficult.

Figure 1. Optimal state feedback architecture for WNCS

Figure 2. State estimator and regular PID controller for WNCS

Figure 3. Jitter margin tuned PID controller for WNCS

H. Co-design of wireless control systems
With random access MAC there is a trade-off between the network quality of service (QoS) and control performance as a function of network traffic, that is, sampling time of the control system. If the available network bandwidth is too low, this can be compensated by load balancing, changing the network topology, or adding a high-speed back bone network, quantization or increase in sampling interval of the controllers. In the case of packet drop, the physical layer need to be improved or acknowledgment and retransmissions can be utilized. On the control side a state estimator or a network delay jitter aware controller can be used. If packet drops are due to collisions or if communication delay jitter occurs due to retransmission, a deterministic MAC protocol is the solution, or the previously mentioned control side techniques can also be used to compensate for the packet drop.

IV Implementation of WNCS

TrueTime Simulator
TrueTime is the Matlab/Simulink-based simulator which facilitates co-simulation of controller task execution in real-time kernels, network transmissions, and continuous plant dynamics, and the latest version is 2.0 beta 7. It consists of kernel (computer) and network blocks as shown in Figure 4. The TrueTime blocks are connected with ordinary Simulink blocks to form a real-time control system. The important feature of TrueTime is the possibility of co-simulation of the interaction between the real-world continuous dynamics and the computer architecture in the form of task execution and network communication [12]. It is available at http://www.control.lth.se/truetime. TRUETIME network block simulates Medium Access and Packet Transmission in a Local Area Network (LAN) environment. A node uses ttSendMsg primitive function to transmit a message over network. This causes a triggering signal to the network block on the corresponding channel of node on the network. Version 1.5 of TRUETIME supports simple models of networks including: CSMA/CD (e.g., Ethernet), CSMA/AMP (e.g., CAN), Round Robin (e.g., Token Bus), FDMA, TDMA (e.g., TTP), and Switched Ethernet. The models ignore propagation delay since it is very small in LAN. Models support packet level simulation. Network parameters the can be configured according to experiment include number of nodes connected to network, data rate in bits/s (i.e., speed of network), minimum frame size (bits), and loss probability from 0-1 (i.e., probability that message loss during transmission).
Proposed Block Diagram of WNCS

The proposed block diagram of WNCS is shown in Figure 5. The controller gets the output of the system through wireless communication such as IEEE 802.11b or IEEE802.15.4 (ZigBee) from the sensor(s). Then the controller sends the control output to the actuator by wireless link which is different from the traditional wired control system.

![Proposed Block Diagram of WNCS](image)

**Figure 5. The proposed block diagram of WNCS**

The figure 5 shows the simulation model of WNCS. In this model, it has two nodes and communication network which is constructed by TRUETIME wireless network block. The three nodes are the controller node, the node 2 is the sensor/actuator node. Each node is represented by TrueTime kernel block. A time-driven sensor/actuator node samples the process periodically and sends the samples over the wireless network to the controller node. The control task in this node calculates the control signal and sends the result back to the sensor/actuator node which is subsequently actuated. The calculation of the mathematical model of servo motor is used in simulation in [13]. The transfer function of servo motor which is used as plant in NCS are

\[ G_p(s) = \frac{1000}{s(s+1)} \]  

(6)

A. Calculation of PD Gain

PD Controller is used as control algorithm for controller node in this simulation. So controller parameter is required to calculate. The transfer function of controller is

\[ G_c = K_p + K_d s \]  

(6)

In this paper, servo motor acts as plant in the Simulink model. The transfer function of motor is shown in (5). First, P controller's gain Kp is first considered by:

\[ G(s) = \frac{1000}{s(s+1)} K \]  

(7)

The equation is changed into characteristic equation and solved by root criteria. So the value of gain kp for the controller p must be greater than zero (kp>0). And next calculation is PD controller gain by

\[ G(s) = \frac{1000}{s(s+1)} \times (K_p + K_d s) \]  

(8)

By using Routh-Hurwitz, the value of Kd must be greater than 0.001. So the values of gain of KP and KD are 1 and 0.035 [13]. The reference input signal is generated by the pulse generator.

**The table 1 shows the simulation parameter for wireless network block.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network type</td>
<td>802.11b (WLAN)</td>
</tr>
<tr>
<td>Data rate</td>
<td>80kps</td>
</tr>
<tr>
<td>Minimum frame size</td>
<td>272 bits</td>
</tr>
<tr>
<td>Transmit power</td>
<td>20 dbm</td>
</tr>
<tr>
<td>Receiver signal threshold</td>
<td>-48 dbm</td>
</tr>
<tr>
<td>Path loss exponent</td>
<td>3.5</td>
</tr>
<tr>
<td>Retry limit</td>
<td>5</td>
</tr>
</tbody>
</table>

**Figure 6. Simulink Model of Wireless Networked Control System**

Simulation Results of Wireless NCS

The simulation is carried out using PD controller in WNCS. As discussed above PD controller consists of two tuning parameters Kp and Kd. Figs. 7 show the normal simulation result with sampling period is 10ms. As increase the sampling period to 20ms, the simulation results of model is more overshoot than the earlier result. From these results, sampling rate can degrade the system performance.

**Figure 7. The simulation results of WNCS with 10ms sampling rate**
Conclusion

Wireless sensor networks introduced into the control systems communication media thereby initiating an interesting class of control systems termed wireless networked control systems (WNCS). This paper presents a wireless sensor and actuator networked control system (WNCS) based on TrueTime and Matlab. Then control effects over the PD control algorithm are applied. The simulation results indicate that for WNCS architecture, the influences of sampling time. This paper provides a simulation model of WNCS which is cost-effective, easily deployable.

Reference


