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# Engineering design method of networked control system with industrial and wireless sensor network

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**Abstract.** Designing a networked control system, which is called NCS, is a common job for a control engineer. The engineering design method of NCS with industrial network and wireless sensor network is presented in this paper. After analyzing the structure and schedules of the NCS, the network induced delays of NCS are simplified as a total delay called bus circle time. While modelling of NCS, the networked induced delay will be presented as a delay element, which is $e^{-\tau}$. The PID controller is also chosen as the algorithm because of its wide use in engineering. The methods to choose bus circle time, sample time of sensor and PID parameters of NCS are illustrated in this paper, which could lead the engineer to design the NCS successfully. Typical example with NCS is formulated to show the validation of the design method.

**Key words.** Engineering design, networked control system, wireless sensor network, PID.

## 1. Introduction

Networked control system is a control system based on industrial network(s). Sensors, actuators and controllers, which possess network interfaces and are linked to the same network, could exchange data with each other. Then every device in the NCS could share the information and overcome the effect called islanding. Also, the NCSs have the advantages of simple device installation, easy maintainability and expansibility [1,2].

In most industrial control areas, fieldbuses and industrial Ethernets are very popular [3]. Also industrial Ethernet has been more and more wildly used in recent years [4,5]. Wireless sensor network has been used in many areas, which is more convenient to install [6,7,8].

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In recent years, many researches are focused on the NCS and wireless sensor network. The design of NCS was discussed comparatively early by Branicky [1]. Many subsequent works on NCS are focused on this topic, which could be referred in the paper about the overview and research trends of NCS [9]. Some subsequent works on NCS are focused on co-design. To compensate for random network-induced delays, Chen [10] proposed a framework of NCS design based on scheduling and control co-design. Dong [11] constructed a delay system model after the analysis of the network transmission delay and then derived the criteria for stability with an H-infinity norm bound and criteria. Wang [12] studied the question about event-triggered error detection filter. When a continuous-time NCS has biased sensor faults, special controller could be designed to coordinate with the faults. In recent years, some works on NCS are focused on wireless networks. Ulusoy [13] studied wireless model-based predictive NCS over cooperative wireless network. Li [14] established a new stochastic switched linear model and presented a sufficient condition for the exponentially mean square stability of the closed-loop. Al-Dabbagh [15] used a fixed structure approach to model and control the wireless NCS. Most of those works pay more attentions to the analysis of NCS in theory rather than in the design method. The latter is more important for the engineer. In the paper, we centre on the engineering design method of NCS with industrial network and wireless sensor network.

## 2. Structure of NCS with industrial and wireless sensor networks

### *2.1. Structure of NCS with industrial and wireless sensor networks*

As illustrated in Fig.1, NCS includes several parts: plant, sensors, actuators, controller and etc., which are connected via networks. From the aspect of network, all those parts are nodes or stations of the network.

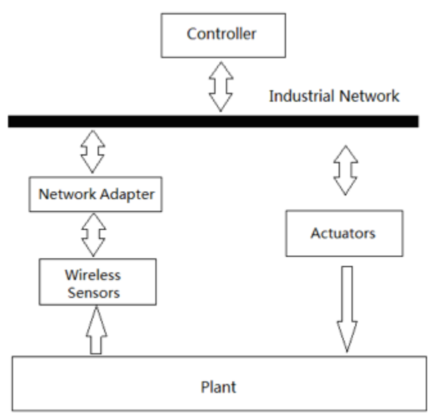


Fig. 1. Structure of a NCS

The wireless sensors are the sensitive cells to measure the states of the plant. Here the sensors are equipped with wireless interferes to send data. There are two types of networks: industrial network and wireless sensor network. The latter is a kind of IoT. Two different kinds of networks need a convertor to link them, and the network adapter just work as the convertor. Sensor nodes are distributed to collect interesting information from the plant. Actually, sensors with wireless network have been used in many fields from natural environment monitoring, industrial line measurement, fire monitoring and temperature monitoring. In a system, the sensor node should have the function of computation, sensing and communication.

The controller is the key part of the whole control system. It's more than a controller of the plant. It is also the controller of the communications. The main function of the controller is to receive the information from the sensors and to decide the control value for the actuator. The actuators are the executive device to implement the control function. The actuator receives the control value from the controller via network. And then drive the plant work with the proper signals, which are associated with the control data from the controller.

### *2.2. Scheduling analysis of DES with network and nodes*

Schedule of network and nods is a kernel question of NCS. The operation of sending message could be charged by the node. The node could complete their work and then send message to the destination node. For example, the wireless sensor works at time trigger mode. When the sending time arrives, it sends the latest data to the network adapter. The adapter could be event triggered. It will transfer the data the controller right after it receives the data from the wireless sensor. When the controller receives the data, it will compute and then send the result the actuator. The actuator will drive the plant according the data from controller.

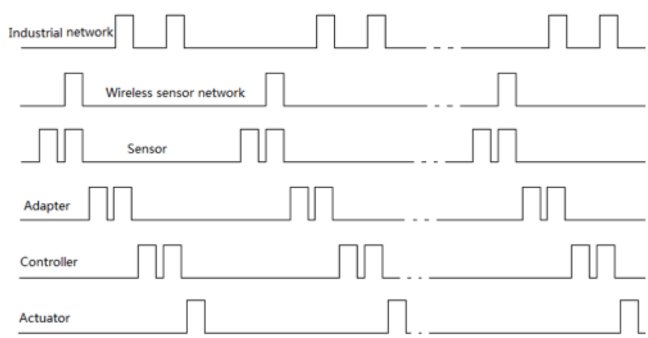


Fig. 2. Schedule of network and nods

In Fig. 2, Sensor has two nearby pulse. The first one means that the sensor collects the signal from the plant and save it as data. The second one means that the sensor sends the message through the wireless sensor network. Of course, the adapter will receive the massage. The first pulse of the adapter means internal data processing of the adapter node, and the second one means the time to transmit the data to the controller.

The first pulse of the controller means the controller node compute the value for control, and the next pulse means the controller transmit the control value to the actuator node. Then the actuator uses the control value to drive the plant and will not use the network to transmit data to other nodes. Whenever the node transmits data, the network will be a high level to illustrate that the network is working. The node could complete their work and then send message to the destination node.

### *2.3. Simplicity of network induced delay*

From the schedule of NCS, the signal from the sensor to the actuator must be delayed by the network transmission. Firstly, let's study a usually situation, in which the system includes a senor, an actuator and a controller, as shown in Fig.3. The delay from sensor to controller is called , and the delay from controller to actuator called $\tau_{sc}$. The delay in controller is called $\tau_{ca}$.The total delay is $\tau_{all}$.

$$\tau_{all} = \tau_{sc} + \tau_{ca} + \tau_c. \tag{1}$$

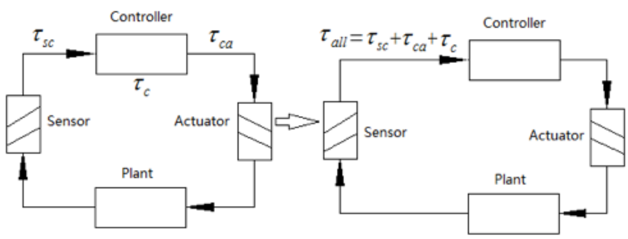


Fig. 3. Network induced delays and their combination

From Fig.3, the separated delays could be combined to a unique delay as an equivalent transformation [1]. When the data from the sensor arrive at the controller, the controller will compute and decide the output to the actuator.

Definition 1: (bus circle time)

The bus circle time of the network, illustrated as $T_{bc}$, is the time spending on the data transmission from the first sensor node to the controller node, and then to the last actuator node.

In engineering, the $T_{bc}$ is regarded as the average value of $\tau_{all}$.

## 3. Modelling of NCS and controller design

### *3.1. Modeling of NCS*

In engineering project, designing a networked control system is complex. In order to simplify the project, a networked control system could be modeled as Fig.4. In Fig.4, $\tau$ is the network induced delay, which is also $T_{bc}$. $G_p(S)$ is the plant, which is the control object of the NCS.

On one hand, $\tau$ is a delay element, which will make Bode diagram (logarithmic phase frequency response curve) shift down and weaken the stability. Bode diagram is usually used to analyze the frequency characteristic of the open system. The bigger of the amount of $\tau$, the more badly that the delay element weakens the stability. Considering the stability, the amount of $\tau$ is expected to be small and the smaller, the better. On the other hand, all the network operation, including sending data, receiving data and waiting, cost time, which is just the reason leading to network induced delay $\tau$. It is obviously that the communication will be easy to fulfill if the big amount of $\tau$ is permitted. So, from the need of network, the amount of $\tau$ is expected to be big.

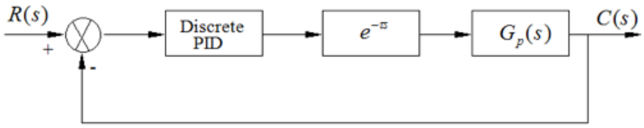


Fig. 4. Control model of NCS

### 3.2. Discrete PID

PID is a popular control algorithm in engineering project. In order to comply with the theme, discrete PID is chosen to use as the controller. In engineering project, to simplify the question is a normal way. To use the PID algorithm in the controller, the equations in Eq. (2) should be followed.

$$u(n) = P(n) + I(n) + D(n), \tag{2}$$

where $P(n) = K_p(r(n) - c(n))$, $I(n) = I(n-1) + \frac{K_p \times h}{T_i}(r(n) - c(n))$ and $D(n) = \frac{K_p T_d}{h}[(r(n) - c(n)) - (r(n-1) - c(n-1))]$.

Remarks: The controller is a discrete PI controller, so the computing of the control is discrete, and the symbol $n = 1, 2, \ldots$. The output of the controller is $\mu n$, which is the sum of $P(n)$, $I(n)$ and $D(n)$. The symbol $r(n)$ means the set value, $c(n)$ means the output value of the system, and $K_p$ is the gain of the Proportion element of PID. $I(n)$ is the integral part of the PID controller. $T_i$ is the integral constant. $h$ is sample time of the controller, which is also the computing interval of the controller. $D(n)$ is the differential part of the PID controller and $T_d$ is the differential constant. The details of the controller could see the reference [16].

## 4. Design of NCS and its parameters

### 4.1. Design and main parameters of networks

Although a rapid and advanced network has less delay, the choice of a network need to think of more things. When we consider the worse situation, what network could satisfy the basic need of the system? The most important principle is that the delay induced from the network will not reduce the properties of the system distinctly. If a system is a rapid process, a rapid network should be chosen, and if the system is a slow process, a slow network may be operable. For example, a temperature control system is a slow process, to control which a slow field bus could be chosen to use. However, if the plant is a high-speed motion control system, Ethernet may be a more suitable choice.

For a low order system, the accommodation time of the system will be 4∼5 times of the characteristic time of the system.

Claim 1: The bus circle of the network, illustrated as $T_{bc}$, is expected to be less than or equal to the characteristic time of the plant.

If the characteristic time of the system is not easy to get, the following rules could be a reference. For a processcontrolsystem, like a temperature system, $T_{bc}$ should be 100∼500ms (millisecond); For a program logic control system, $T_{bc}$ should be 10 100ms; For a motion control system, $T_{bc}$ should be 5∼10ms. After $T_{bc}$ is determined, a fieldbus should be chosen according the manual of the standard fieldbus in IEC61158.

Lemma 1: $T_{bc}$ is associated with the speed of network, the number of nodes and the frame size, which could be formulated as Eq. (3).

$$T_{bc} = \frac{L \times m}{v} \times \frac{1}{(1-\alpha)\beta}, \tag{3}$$

Remarks: (1) $L$ is minimum frame size of the data (bits); (2) $m$ is the number of the nodes. (3) $v$ is the data rate of the network (bits/s); (4) $\alpha$ is the idle rate of the network. If $\alpha$ is 0.2, it means that at 20% time the bus is idle; (5) $\beta$, from 0 to 1, is associated with the quality of network, which is to represent the loss and error code probability. If $\beta$ is 1, it means that the quality of network is very good. For the common fieldbus in IEC61158, $\beta$ is usually above 0.9.

### *4.2. Design of sensor and actuator*

In this paper, we consider the situation that sensors send data to the adapter via the wireless network, which is shown in Fig.1. In engineering, it's an easy way to set the sensors working in time trigger mode.

Claim 2: The sample time of the sensor is expected to be 10%∼30% of $T_{bc}$.

The interval of the collection, which is also called the sample time of the sensor, must be less than the bus circle of the field bus. And new data from the sensors are expected to transfer to the adapter in time to ensure that the controller could get the sensor data lately. If the sample time accords with Claim 2, the delay of collection and transmission in wireless network could be neglected for the time delay in wireless sensor network is far less than in the fieldbus network. And in every bus circle, the controller could get the latest data from the sensor. The actuator could work in time trigger mode or event trigger mode. Although event trigger mode is easy to understand, both modes are same for the design of system.

### *4.3. Parameters of the discrete PID*

The parameters of PID controller involve $K$, $T_i$, and $h$. $K_p$ is used to illustrate the current value of the error. When the error is positive and large, for instance, the control output will be positive and large accordingly. $T_i$ is used to illustrate the past value of the error. If the present output is not strong enough, for instance, the integral of the error will gather over time, which will lead a stronger action to the controller output.

Claim 3: The sample time of the controller, which is presented as $h$, is expected to be 10%∼30% of $T_{bc}$.

## 5. Example: A DC-servo process

The model of the plant is provided as $G_p(S) = \frac{1000}{S(S+1)}$, which is a servo control plant. The characteristic time of this plant is 0.03162 seconds, which is also 31.5 ms. To illustrate the design process, we use MATLAB to simulate the system. The toolbox TRUETIME is used to simulate the networked environment [17].

Both the wireless sensor and data transmission are implemented in a TRUETIME kernel block, which is renamed as wireless transmission. And the TRUETIME Send is used as the fieldbus adapter.

The plant is a middle speed process control system. According to Claim 2, the network induced delay should be less than 31.5ms, which most fieldbus based on EIA485 could satisfy.

Then the NCS is designed as follow:

(1) $T_{bc}$ is 30 ms preliminary; And according to Eq.(3), $v = \frac{L\times m}{T_{bc}} \times \frac{1}{(1-\alpha)\beta} = \frac{80\times 3}{0.03} \times \frac{1}{(1-0.3)\times 0.95} \approx 12kbit/s$; (2) The sample time of the sensor is set as 10ms, which is about 30% of $T_{bc}$; (3) The sample time of the controller, $h$=0.01s; (4) The parameters of PID controller are chosen as $K_p = 1$, $T_i$=inf, $T_d = 0.05$s . And the response curve is shown in Fig.5.

## 6. Conclusions

To design a NCS is a difficult work for an engineer. However, designing a control system based on a network is a common job for a control engineer. In this paper, we centered on the engineering design method of NCS with industrial network and wireless sensor network. Following the method, an engineer could design a NCS in an easier way.

From the schedules of the NCS, the bus circle is the key fact of the network. And the bus circle is used to represent the degree of network induced delay. An engineer should decide the range of the bus circle approximately according to the design method illustrated in section 4.1. Then choose the network and configure the network. When the network, the number of nodes and the transmission rate are determined, the bus circle will be determined accordingly. Other parameters of the system are mainly decided according to the bus circle. In section 5, an example with

NCS is formulated to show the validation of design method.

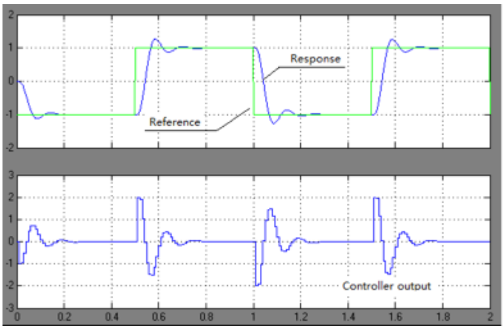


Fig. 5. MATLAB simulation of the DC-servo process

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