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Overview of Modeling of Delays in Networked Control Systems

Sunil Kumar

M.Tech Scholar National Institute of TechnologyKurukshetra, India
E-mail: sunilkumarabes@gmail.com

Abstract: *Networked control systems (NCSs) are control systems in which the control loop is closed over a real-time network. The advantages of NCS are they have flexible architecture and reduction of installation and maintenance costs. The main drawback of NCSs is the network effects that influence the performance and stability of the control loop, such as time-delays and packet dropouts. Despite these disadvantages, NCSs are applied in a broad range of systems, such as mobile sensor networks, remote surgery, automated highway systems and unmanned aerial vehicles. This paper illustrates the different types of delays taking place in NCS with their modeling.*

Keywords: *Networked control system, Analysis, Time Delay, Packet Dropout*

1. INTRODUCTION

A Networked Control System (NCS) is a control system wherein the control loops are closed through a communication network. The defining feature of an NCS is that control and feedback signals are exchanged among the system's components in the form of information packages through a network. NCS [1] is one type of distributed control systems where sensor nodes, actuator nodes, and controller nodes are interconnected by communications network or by other shared medium.In this, the most important problem is delays due to data packet dropout, a node waiting to send or/and receive a packet via a busy channel, signal processing, and time-delay of controlled plant. A typical structure of NCS can be described as in Fig. 1

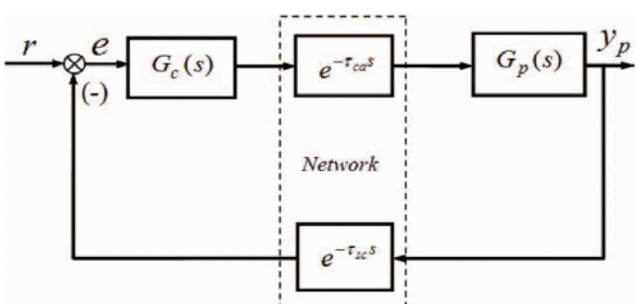
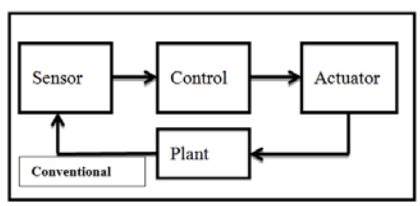


Fig. a.

The most important feature of a NCS is that it connects cyberspace to physical space enabling the execution of different tasks from long distance. In addition, networked control systems eliminate unnecessary wiring and reducing the complexity and the overall cost in designing or implementing the control systems. They can also be easily modified or upgraded by adding sensors, actuators and controllers to them with relatively low cost and no major changes in their structure. Moreover, featuring efficient sharing of data between their controllers, NCS are able to easily fuse global information to make intelligent decisions over large physical spaces.

How do they work?

In conventional digital control systems, there are two major components, the controlled plant and controller. Outputs of the controlled plant are sampled at periodic intervals by the controller, a control algorithm applied to the samples, and then result of the control is produced at the output of the controller generally as a zero order hold signal.



From the theoretical point of view, there is no problem in this approach. From the implementation point, several aspects can be improved:

- This structure depends on a single computer to calculate the control algorithm. According to the complexity of the plant, it may be too complicated. We come across a computational bottleneck.
- The plant can be physically large, it means signals need to travel long distances to the control computer causing noise.

- Due to long connections difficulty in maintenance and troubleshooting.
- The control system is fixed; adding new sensors, actuators to the system and changing the control algorithm would be difficult task.

As a remedy, networked control systems can be used. The idea is to design sensor, control and actuator as separate computer nodes connected by a communication network. The same process as explained above is repeated, except data travels from sensor to control and control to actuator through a communication network instead of dedicated connections.

The remedy to the network delay is to use a dedicated real-time network in the implementation. This network is specially designed to have a guaranteed upper bound on transmission delay, so that stability is not endangered. However this is not a simple solution. Such networks should have carefully tuned parameters for each application, and cannot be readily expanded. Similarly, they are fixed in the amount of data they can transfer. Timed token protocol, master slave type protocols, TDMA type protocols are some examples.

In Fig. a, we assume that $G_p(s)$ is the model of controlled plant without delay, $G_c(s)$ is the model of controller,r is input and $y_p$is output of the system. Network induced delays in NCS subsist of sensor-to-controller delay,$\tau_{sc}$and controller-to-actuator delays,τ_{ca}.The closed loop transfer function is given by

$$\frac{y(s)}{r(s)} = \frac{G_c(s)e^{-\tau_{ca}s}G_p(s)}{1+G_c(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_{sc}s}} \quad (1)$$

Equation (1) shows the extant of transmission time delays, $\tau_{sc}$and actuator delayτ_{ca}, generally it has negative consequence on the stability and the control performance of NCS and causes the control system unstable.

The basic problem in Networked control systems (NCS) is network-induced delays, single-packet or multiple- packet transmission and data packet dropout of network. The network-induced delays in NCS occur when sensor nodes, actuator nodes, and controller nodes trade-off data packets across the communication network, these delays can be reduce the performance and stability of designed control systems, even cause the system unstable. Furthermore, the controlled plant with long time-delay or unknown time-delay can have great weightage on the quality of the NCS in terms of stability.

In these days, different control methodologies have been used to overcome the effect of time-delay and packet dropout in process control loop. Smith predictor is aproductive approach used in large time-delay control systems and has been applied to many studies such as [2–5].

2. NCS ANALYSIS USING SMITH PREDICTOR

The Smith predictor is used to control systems with loop delay. In Smith predictor, apart from controlled plant model, a delay model is added to the predict plant model so that delay in the loop can be crushed. Related to such problem, [6], [7], [8] presented a new Smith predictor model for NCS and the other authors in [9] suggest an approach combining predictive control compensation with network scheduling. However, for simplicity, we take into account the basic Smith predictor structure of the NCS as in Fig. b, which is analyzed in the sequel.

According to Fig. b, $G_p(s)$ is the plant model with delay $\tau_P G_{pm}(s)$ with delay $\tau_{pm}$is the predict model of$G_p(s)$. For this structure, y_{fb} can be described as

$$y_s = y_{pm} - G_{pm}(s)u(s) \quad (2)$$

$$y_{pm} = G_{pm}(s)e^{-\tau_{pm}(s)}u(s) \quad (3)$$

$$y_{fb} = G_p(s)e^{-\tau_p s}u(s) - [e^{-\tau_{pm}(s)}\text{-}1]G_{pm}(s)\text{u(s)} \quad (4)$$

And the close loop transfer function $\frac{y_p(s)}{y_r(s)}$

$$\frac{y_p(s)}{y_r(s)} = \frac{G_c(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_p s}}{1+G_c(s)e^{-\tau_{ca}s}[G_p(s)e^{-\tau_p s}-G_{pm}(s)e^{-\tau_{pm}s}+G_{pm}(s)]e^{-\tau_{sc}s}} \quad (5)$$

Assume that the predict model of the controlled plant is chosen exactly, then$\tau_p = \tau_{pm}$and$G_{pm} = G_p$,so (5) can be reduced to

$$\frac{y_p(s)}{y_r(s)} = \frac{G_c(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_p s}}{1+G_c(s)e^{-\tau_{ca}s}G_{pm}(s)e^{-\tau_{sc}s}} \quad (6)$$

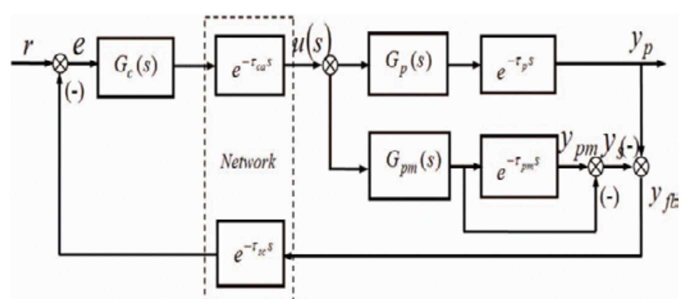


Fig. b: Smith predictor Structure for NCS

Inherently, the transfer function in (6) shows a better stability than in (5). In particular, it is difficult to grasp this result because of two reasons as following:

- The network induced delay is uncertain and the time-delay of the plant is unknown.

- In case the delay of the plant cannot be identified exactly or the different between τ_{pm} and τ_p is considerable, the stability of NCS becomes unacceptable.

Smith predictor is an effective compensator used in large time-delay control systems and has been applied to many studies such as [10] [11] [12]. On the basic structure of the Smith predictor, new Smith predictor models of NCS has been considered in [13–15] assuming that the time-delay of the networked control system plant is predefined and the prediction model is approximately equal to the true model.

3. MODELING OF NCS WITH TIME DELAY

The system shown in Fig.c, the controller and the actuator are at the same point. The signals of sensor are transmitted through the network but the signal of controller is not.

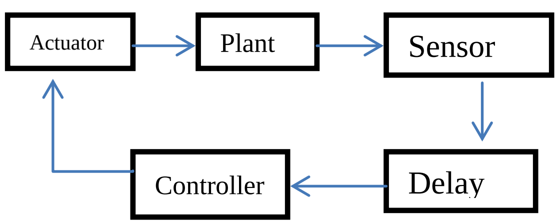


Fig. c

For simplicity of investigation, we make the following balanced assumptions:

The dropout of data packet in the network is not considered.

Sensor, controller and actuator are all time driven.

On the fact that the advanced data is the best data in a Networked control system, we urged the following control method: A time stamp is placed on every data packet that is to be sent at the sending node. Adjacent to the receiving buffer, a second buffer is placed at the receiving node. When receiving node samples the receiving data for the first time, the sampled data packet is used to control on the one hand, the sampled data packet is saved in the second buffer on the other hand. Sub sequential, the receiving node checks the time stamp of every data packet sampled. If it is the advanced data, that is to say the time of time stamp of the receiving data packet is latest than that of the data packet in the second buffer. The collecting data packet is used to control on the one hand, the sampled data packet is preserved in the second buffer to replace the old data packet on the other hand. If it isn't the latest data packet, then the collecting data packet is neglected. The data packet in the second buffer is used to control and hold the line. The process is copied like this. Then the data packet that is used to control at the receiving node is ensured to the latest data packet. For convenience of depiction, we called this control method as the second buffer method.

Probably, when the second buffer method is used in an NCS, the network-induced delay still satisfies the following relations.

$$0 \le \tau_{sc}^k \le T_1, 0 \le \tau_{ca}^k \le T_2 \qquad (7)$$

It is pretended that the controlled process is a linear time-invariant system. The controlled process can be expressed as

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) \qquad (8)$$

X (t)$\in R^n$, u (t)$\in R^p$, y (t)$\in R^q$, A, B and C are matrices of appropriate sizes. The discrete version of system (8) is

$$\begin{cases} x_{k+1} = A_s x_k + B_s u_k \\ \quad y_k = C x_k \end{cases} \qquad (9)$$

The discrete controller of an NCS can be expressed as [11]

$$\begin{cases} w_{k+1} = L w_k + M s_k \\ O_k = N w_k + P s_k \end{cases} \qquad (10)$$

Where $w_k \in R^n, s_k \in R^q, O_k \in R^p$,L, M, P and N are matrices of appropriate sizes. The following section is similar to the method proposed in [11]. From equation (7), we know

$$s_k = y_{k-\tau_{sc}^k = y_{k-i} = \sum_{i=0}^{T1} \alpha_{k,i} y_{k-i}, \alpha_{k,i} \epsilon \{0,1\}} \qquad (11)$$

$$u_k = O_{k-\tau_{ca}^k = O_{k-i} = \sum_{i=o}^{T2} \beta_{k,i} O_{k-i}, \beta_{k,i} \epsilon \{0,1\}} \qquad (12)$$

And

$$\sum_{i=1}^{T_1} \alpha_{k,i} = 1 \ , \sum_{i=1}^{T_2} \beta_{k,i} = 1 \qquad (13)$$

We introduce a new state variable,

$\widetilde{x_k} = [x_k^T x_{k-1}^T \ldots\ldots.. x_{k-T_1}^T] \in R^{n \times T_1}$ then fromequation (10) and (11), we get

$$\widetilde{x_{k+1}} = \widetilde{A}\widetilde{x_k} + \widetilde{B}u_k, \ s_k = C\widetilde{C_{\tau_{sc}^k} x_k} \qquad (14)$$

The closed loop model of a Networked Control System can be expressed as

$$\overline{x}_{k+1} = \overline{A}_{\tau^k} \overline{x}_k$$

4. DIFFERENT DELAYS IN NCS

Since a Networked Control System operates over a network, data transfers between the controller and the remote system will induce network delays in addition to the controller processing delay. Most of networked control methodologies use the discrete-time formulation.

Network delays[12] in an NCS can be categorized from the direction of data transfers as the sensor-to-controller delay τ_{sc} and the controller-to-actuator delay τ_{ca} . The delays are computed as $\tau_{sc} = t_{cs} - t_{sc}$, $\tau_{ca} = t_{rs}$-t_{ce} where t_{sc} is the time instant that the remote system encapsulates the measurement to a frame or a packet to be sent, t_{cs} is the time instant that the controller starts processing the measurement in the delivered frame or packet,t_{ce} is the time instant that the main controller encapsulates the control signal to a packet to be sent, and t_{rs} is the time instant that the remote system starts processing the control signal. In fact, both network delays can be longer or shorter than the sampling time T. The controller processing delay τ_c and both network delays can be lumped together as the control delay t for ease of analysis. This approach has been used in some networked control methodologies. Although the controller processing delay τ_c always exists, it could be neglected as it is small compared to the network delays.

Waiting delay (τ_w): The waiting time delay is the delay, of which a source (the main controller or the remote system) has to wait for queuing and network availability before actually sending a frame or a packet out.
Frame time delay (τ_f): The frame time delay is the delay during the moment that the source is placing a frame or a packet on the network.
Propagation delay (τ_p): The propagation delay is the delay for a frame or a packet traveling through a physical media.
Generally, the controlled plant in Networked Control System is assumed to be continuous-time, and thus the actuator implements zero-order hold (ZOH) holding the last control until the next one arrives or until the next sample time. Since networks are used for transmitting the measurements from the plant output to the controller, the plant has to be sampled (sample time T), which motivates the use of discrete-time controllers.

5. TIME DELAY COMPENSATION

The time delays in the NCS may degrade the system performance and cause the system instability. Therefore, it is necessary to design a controller which can reimburse for the time delays and improve the control performance of the Networked Control system.

Different mathematical, interested and statistical-based approaches are taken for delay compensation in NCSs. Several advanced techniques have been presented in literature [13] that compensate network delays and potentially enough to be used in critical real-time applications.

The sensor to controller delay can be known when the sensors data is used by the controller to generate a control signal. In case of controller-actuator delay, the controller does not know how long it will take the control signal to reach actuator. So no exact correction can be made at the time of control calculation.

An estimator can be used to conclude an un-delayed plant state and make it available for control calculation. The estimator must estimate all state of the plant using partial state measurements and also compensate for sensor delay. This can be implemented by either full state feedback or output feedback.

In the NCS environment the main intention of the control system is to maintain Quality of Performance (QoP) of the control system regardless of the delays in the network. The system should be robust and be able to compensate the delay induced by the network.

6. DIFFERENT TYPES OF TIME DELAY CONTROL STRATGIES

The time delay compensation techniques are used to compensate the time delays causes in the feedback loop. Different types of time delay compensation schemes are given below.
1. Model Predictive Controller
2. Smith predictor
3. PID controller
4. Optimal controller
5. Fuzzy controller
6. Robust control
7. Sliding mode controller
8. Adaptive controller

In addition to the above methods there are different network control approaches, different software, different platforms and systems are used to control the Networked Control system.These are given below-

- **Easy Java Simulations**: In 2010, a new method to create collective networked control labs [3] is described. This is described by two main software tools that are MATLAB and Easy Java Simulations. MATLAB is a generally used tool in the control community, whereas Easy Java Simulations is a robust tool, which is used to build interactive applications in Java without special programming skills. The remote labs created by this approach give to students the opportunity to face the effects of network delays on the controlled system and also to specify on the fly their own control algorithm.
- Easy Java Simulations is a platform to control NCS with externally connecting MATLAB/Simulink. EJS is a free software tool for rapid creation of applications in Java with high-level graphical potential and with an increased degree of interactivity. The applications created by EJS can be standalone Java applications or applets. The source files of the EJS applications are saved in a customized xml format. EJS is different from most other authoring tools in that EJS is not designed to make life easier for professional programmers but also has been conceived for science students and teachers.
- EJS structures the application in two main parts, the model and the view. The model can be described by means of pages of Java code and ordinary differential

equations or by connecting to external applications (such as MATLAB). The view provides the judgment of the application and also the user interface elements required for user interaction. These view elements can be chosen from a set of predefined components to build a treelike structure. Model and view can be easily interconnected so that any change in the model state is automatically reflected by the view, and vice versa.

- Gain Scheduler Middleware: A gain scheduler middleware (GSM) is developed by Tipsuwan and Chow to mitigate the network time delay effect on the NCS. Conventionally, in order to control an application over a data network, a specific networked control or tele-operation algorithm is used to compensate network delay effects for controller design. So the existing controller has to be improved or replaced by a new controller system. The replacement process is generally costly, inconvenient, and time consuming. Gain Scheduler Middleware [14] is a novel methodology to enable existing controllers for networked control and tele-operation.
  The proposed methodology uses middleware to customize the output of an existing controller based on a gain scheduling algorithm with respect to the current network traffic conditions. This approach can save much time and investment cost by utilizing existing controller.

7. AN ILLUSTRATIVE EXAMPLE

Now the theoretical results derived in the preceding sections will be validated by an illustrative example.

Example 1: Consider the following system controlled over a network:

$$\omega_p(s)e^{-\tau s}=\frac{3}{5s+1}e^{-4s} \quad (1)$$

And the system with Smith predictor and the system without Smith predictor are compared in Figure d which PI controller used in the simulation.
Parameters of PI controller are selected to get the best results which are shown in Figure d. The blue line represents the step response of system with Smith predictor while green

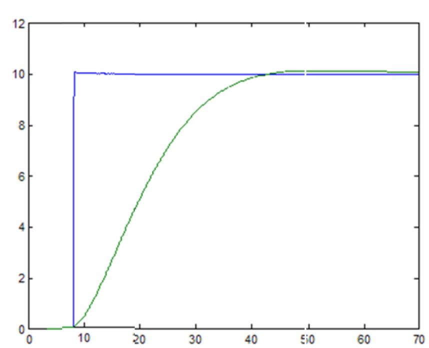
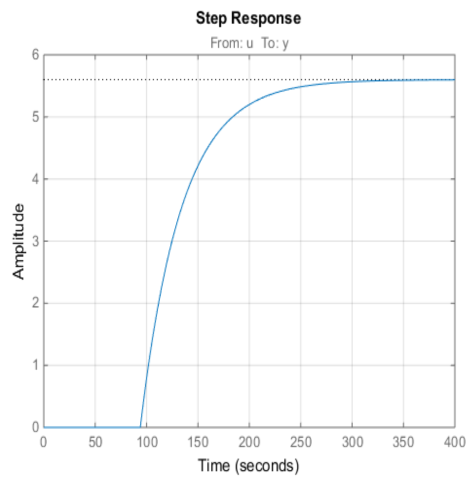


Fig.d

Example 2: The process open-loop response is modeled as a first-order plus dead time with a 50.2 second time constant and 92.7 second time delay:

$$\omega_p(s)e^{-\tau s}=\frac{7.6}{50.2s+1}e^{-92.7s} \quad (2)$$

Note that the delay is more than twice the time constant. This model is representative of many chemical processes. Its step response is shown below



To compare the performance of the two designs, first derive the closed-loop transfer function from ysp,dto y for the Smith Predictor architecture. To facilitate the task of connecting all the blocks involved, name all their input and output channels and let CONNECT do the wiring:

Use STEP to compare the Smith Predictor (blue) with the PI controller (red) in Fig. e:

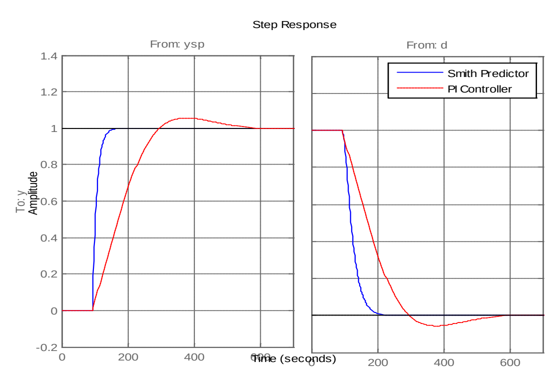


Fig. e

8. CONCLUSION

In this paper, we have discussed different types of delays induced in Networked Control system and their impact on the performance of NCS. We also discussed different methods or techniques to mitigate the time delay in NCS. Here we discussed one method in details i.e. Smith Predictor by taking numerical example also and compare the performance specification with and without smith predictor and observe that system performance increase by using smith predictor in the system.

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