Networked control systems with compensator: Application to Temperature System [*]

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Abstract

The insertion of the communication network in feedback control loop makes the analysis and design of networked control systems (NCS) more complex, and induces some issues that degrade the control system's performance and even cause instability. This paper discusses the analysis of a networked control system whose sensors and actuators exchange information with a remote controller over a shared network. The design of the controller is done in discrete domain without delay. Since the network delay decreases tracking performances, a compensator is used to retrieve the optimal tracking performances achieved by the controller when it is connected point-to-point to the system. To see the effectiveness of this approach, a PID controller with compensator is used to control a temperature system via local network. Good tracking performances are obtained with this control scheme.

Key words: Networked control systems, delay, stability and performance, compensator, temperature system.

1. Introduction

Networked control systems (NCS) are the feedback control loops closed via the serial communication channel. That is, in networked control systems, communication networks are employed to exchange the information and control signals (reference signal, plant response, control signal etc.) between control system components like sensors and actuators.

The main advantages of networked control systems are low cost, reduced system wiring, simple installation and maintenance, and high reliability.

As a result networked control systems have been widely used in many complicated control systems such as manufacturing plants, vehicles, aircraft and spacecraft. However, using communication networks in the control loops make the analysis and design of the networked control system complicated. One main problem is the networked induced delay (sensor-to-controller and controller – to - actuator) that occurs when sensors, actuators and controllers exchange data across the network. The delays may be constant, time varying and in most cases random. The induced delays can easily degrade the performance of the control loop system. Many searchers have study the stability and controller design for stabilization and performance achievement purposes for networked control systems under the existence of network induced delay [3, 4, 5].

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In [8], the problem of stabilization of a linear system subject to communication constraints was considered. In the proposed model, the commands are sent to actuators through a limited shared TDMA bus. At each slot, only one control command can be sent, the remaining commands for the other actuators are held constant. The aims were to optimize off-line both control and bus scheduling.

To ensure the control performance of networked control systems via the Profibus token passing protocol, the network delay should be maintained below the allowable delay level. It is known that the network delay is affected by protocol parameters, such as target rotation time, thus in the work presented in [9], the authors proposed an algorithm for selection of target rotation time using a genetic algorithm to ensure QoS of control information. Liqian *et al* [10] have considered the stabilization problem for a class of networked control systems in discrete domain with random delays. The sensor-to-controller and controller-to-actuator are modeled as two Markov chains, and the resulting closed loops systems are jump linear systems with two modes. They have established the necessary and sufficient condition on the existence of stabilizing controllers.

Recently, there have been significant research efforts on the delay compensation controller design of NCS's. For example, in [17] the authors have modeled the NCS's as discrete-time Markovian jump linear systems with mode-dependent time-delays. Based on this model, the delay compensation controller is constructed and solution of this controller is given through an iterative procedure of a linear matrix inequality minimum problem which is derived from cone complementarily linearization algorithm. Ling *et al* [18] used optimal dropout compensator that can be posed as a constrained generalized regulator. In [19], the authors proposed the compensation of the delay using LMI based delay-dependent optimization method. Yang *et al* [20] study H_∞ control problem for a class of NCS's. An observer-based controller is designed to exponentially stabilize the NCS in the sense of mean square, and also achieve the prescribed H_∞ disturbance attenuation level.

In this paper, first we consider the analysis of the networked control system with the controller designed in discrete-time domain without regard to the delay. From the analysis, we show how to deduce the transmission delay for which the stability of the NCS is guaranteed. In [3], a Lyapunov method has been used to provide the range of the delay to maintain the stability of the closed loop system. In this work, augmented system and Jury test [1] have been used to determine the range of delay that can be tolerated. Afterwards, knowing the range of the tolerated induced delay, a compensator or estimator is used to construct the delayed plant state and make it available for the control calculation. The result is applied on real-time control of a temperature system across local network.

This paper is organized as follow: In section 2, we discuss network-induced delay on NCS. In section 3, we give the model of NCS and determine the upper bound of transmission delay, which guarantees NCS's stability. In section 4, a compensator is developed. Section 5 deals with the application of a PID controller with the compensator to temperature system. We finish this work by conclusions.

2. Network-induced delay [2,3,7]

The networked-induced delay, that occurs while exchanging data among devices connected to the shared medium, can degrade the performance of the control system designed without considering the delay and can even destabilize the system. The induced delay depends on the medium access control (MAC) protocol of the control network, it can be constant, time varying, or even random.

Figure 1 illustrates various possible situations for *random access networks*. The figure depicts two nodes continually transmitting messages (with respect to a fixed time line). A node on a Carrier Sense Multiple Access (CSMA) network monitors the network before each transmission. When the network is idle, it begins transmission immediately, as shown in case 1 of figure 1. Otherwise it waits until the network is not busy. When two or more nodes try to transmit simultaneously, a collision occurs. The way to resolve the collision is the protocol dependent. DeviceNet, which is a controller area network (CAN), uses CSMA with a bit wise arbitration (CSMA/BA) protocol. Since CAN messages are prioritized, the message with the highest priority is transmitted without interruption when a collision occurs, and transmission of the lower priority message is terminated and will be retried when the network is idle, as shown in case 2 of figure 1. So Ethernet employs a CSMA with collision detection (CSMA/CD) protocol and this mean when there is a collision, all of the affected nodes will back off, wait a random time (usually decided by the *binary exponential back off* algorithm), and retransmit, as shown in case 3 of figure 1. Packets on these types of networks are affected by random delays, and the worst-case transmission time of packets is unbounded. Therefore, CSMA networks are generally considered non deterministic. However, if network messages are prioritized, higher priority messages have a better chance of timely transmission.

Further, the TP protocol appears in token bus (IEEE Standard 802.4), token ring (IEEE Standard 802.5), and the fiber distributed data interface (FDDI) MAC [7] architectures, which use TDMA. Timing diagram for this type of network is shown in figure 2. These protocols eliminate the contention for the shared network medium by allowing each node on the network to transmit according to a predetermined schedule. In a token bus, the token is passed around a logical ring, whereas in a token ring, it is passed around a physical ring. In scheduling networks, it is possible to arrange for periodic transmission of messages.

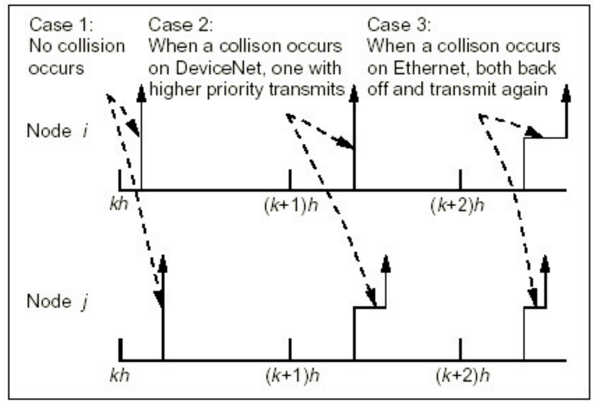

Fig.1 Timing diagram for two nodes on a random access network.

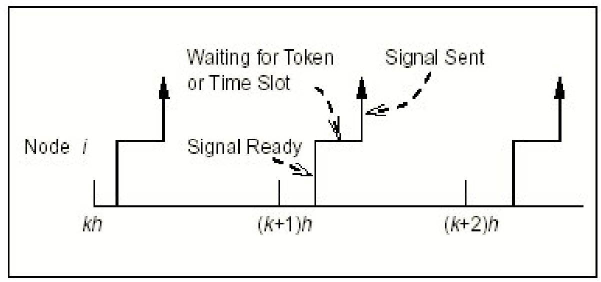

Fig.2 Timing diagram for a scheduling network.

To overcome the problems induced by the delay transmission in NCS, there are two main approaches in NCS design:

1- One way is to design the control system without regard to the packet delay but design a communication protocol that minimizes the likelihood of these events. For example, various congestion control and avoidance algorithms have been proposed to gain better performance when the network traffic is above the limit that the network can handle.
2- The other approach is to treat the network protocol and traffic as given conditions and design control strategies that explicitly take the above-mentioned problems into account.

3. Modeling

The NCS model considering network-induced delay is shown in figure 3. The model consists of a continuous plant:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y = C\,x(t) \end{cases} \tag{1}$$

and the discrete controller is given by:

$$u(kh) = -Kx(kh),\ k = 0,1,2\ldots$$

where h is the sampling period, $x \in R^n$ is state vector, $u \in \Re^m$ is control vector, $y \in \Re^p$ is the output vector and A, B, C, K are of compatible dimensions.

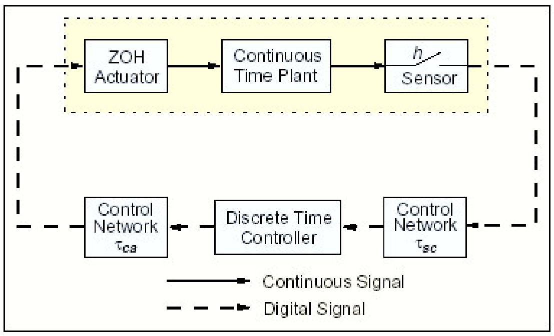

Fig 3 NCS model with network-induced delay.

There are two sources of delays from the network: sensor-to-controller τ_{sc} and controller-to-actuator τ_{ca}. Any controller computational delay can be absorbed into either τ_{sc} or τ_{ca} without loss of generality. For fixed control law (time-invariant controllers), the sensor-to-controller delay and controller-to-actuator delay can be lumped together as $\tau = \tau_{sc} + \tau_{ca}$ for analysis purposes. The timing of signals of the setup with $\tau < h$ is shown in Fig. 4.

3.1 Delay less than one sampling period:

First consider the case where the delay τ_k of each sample is less than one sampling period h. This constraint means that at most two control samples, $u((k-1)h)$ and $u(kh)$ [1], need to be applied during the k^{th} sampling period. The system equations can be written as

$$\dot{x}(t) = A\,x(t) + B\,u(t)\,;\ y(t) = C\,x(t)$$

$$t \in \left(kh + \tau_k,\ (k+1)h + \tau_{k+1}\right)$$

$$u(t^+) = -Kx(t - \tau_k) \tag{2}$$

$$t \in \left(kh + \tau_k\right),\ \text{k=0, 1, 2} \ldots$$

where $u(t^+)$ is piecewise continuous and only changes value at $t = kh + \tau_k$. Sampling the system with period h we obtain:

$$x((k+1)h) = \Phi x(kh) + \Gamma_0(\tau_k)u(kh) + \Gamma_1(\tau_k)u((k-1)h)$$

$$y(kh) = C\,x(kh) \tag{3}$$

where

$$\Phi = e^{Ah}, \quad \Gamma_0(\tau_k) = \int_0^{h-\tau_k} e^{At} B dt,$$

$$\Gamma_1(\tau_k) = \int_{h-\tau_k}^{h} e^{At} B dt.$$

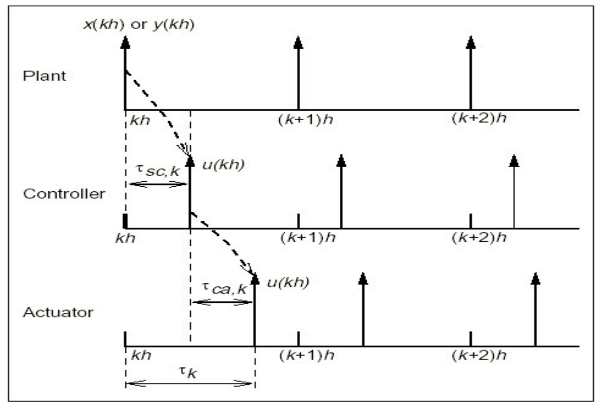

Fig 4 Network-induced delay.

Defining $z(kh) = \left| x^T(kh) \quad u^T((k-1)h \right|^T$ as the augmented state vector, the augmented closed-loop system is:

$$z((k+1)h) = \tilde{\Phi}(k)z(kh) \tag{4}$$

where:

$$\tilde{\Phi}(\tau_k, k) = \begin{bmatrix} \Phi - \Gamma_0(\tau_k)K & \Gamma_1(\tau_k) \\ -K & 0 \end{bmatrix}$$

If the delay is constant (i.e. $\tau_k = \tau$ for $k = 0, 1, 2\ldots$), the system is still time invariant, which simplifies the system analysis. Thus, we can use static scheduling network protocols, such as token ring or token bus, which can provide constant delay. Even in this simplified setup, the problem is to determine the range of the delay that the system in closed loop via a network can tolerate. We have to analyze the stability of the matrix $\tilde{\Phi}(\tau_k)$ and find the range where the performance and stability are maintained [16].

3.2 Longer delays:

When the delay is longer than one sampling period ($0 < \tau_k < lh$, l > 1), one may receive zero, one, or more than one (up to l) control sample(s) in a single sampling period.

In the special case where:

$$(l\text{-}1)h < \tau_k < lh \quad \text{for all } k,$$

one control sample is received every sample period for k > l. In this case, the analysis resulting in:

$$\tilde{\Phi}(k) = \begin{bmatrix} \Phi & \Gamma_1(\tau'_k) & \Gamma_0(\tau'_k) & 0 & 0 \\ 0 & 0 & I & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & I \\ -K & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{5}$$

where $\tau'_k = \tau_k - (l\text{-}1)$.

The augmented state vector is given by: $z(kh) = \left| x^T(kh) \quad u^T((k-1)h) \quad \ldots \quad u^T((k-l)h) \right|^T$

Here also, to determine the range of the tolerated delay, we have to analyze the stability matrix $\tilde{\Phi}(\tau_k)$. Note that, by using Jury test one can determine the range of tolerated induced delay [16].

4. Compensation for networked - induced delay

Sensor-to-controller delay, τ_{sc}, and controller-to-actuator delay, τ_{ca}, have different natures. Sensor-to-controller delay can be known when the controller uses the sensor's data to generate the control signal, provided the sensor and controller clocks are synchronized and the message is time stamped. Thus an estimator can be used to reconstruct an approximation to the delayed plant state and make it available for the control calculation. Controller-to-actuator delay is different, however, the controller does not know how long it will take the control signal to reach the actuator; therefore, no exact correction can be made at the time of control calculation.

The estimation of the plant state $x(kh + \tau_{sc})$ is based on the sensor measurement at time $t = kh$ and the sensor-to-controller delay τ_{sc}.

It is assumed that a single-packet transmission and delay less than one sampling period ($\tau_{sc} < h$) are used.

The compensation scheme is illustrated in figure 5, where $\tau_{sc,k}$, denotes the sensor-to-controller delay for plant state $x(kh)$, and $\hat{x}(kh + \tau_{sc,k})$ denotes the plant state estimate at the time $t = kh + \tau_{sc,k}$ when $x(kh)$ is received. Assuming there is no measurement noise, $\hat{x}(kh + \tau_{sc,k})$ can be calculated as:

$$\hat{x}(kh + \tau_{sc,k}) = e^{A\tau_{sc,k}} x(kh) + \int_{kh}^{kh+\tau_{sc,k}} e^{A(kh+\tau_{sc,k}-s)} B\, u(s)\, ds \tag{6}$$

and the control law is computed as:

$$u(kh + \tau_{sc,k}) = -K\, \hat{x}(kh + \tau_{sc,k}) \tag{7}$$

where the gain K represents the control parameters vector.

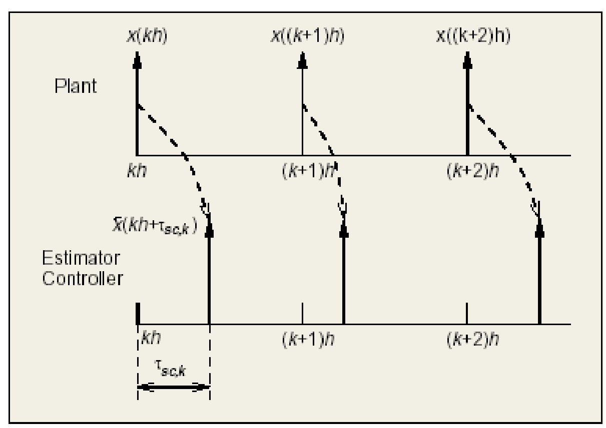

Fig. 5 Plant and estimator timing diagram.

5. Real-time application to temperature system

5.1 Description of the temperature control system

The temperature control system is an important component in many industrial processes. In this work, the used temperature control system, which is from Leybold-Didactic Company [14], consists of a glass channel that can be viewed as an oven. A picture of this system is shown in figure 6.

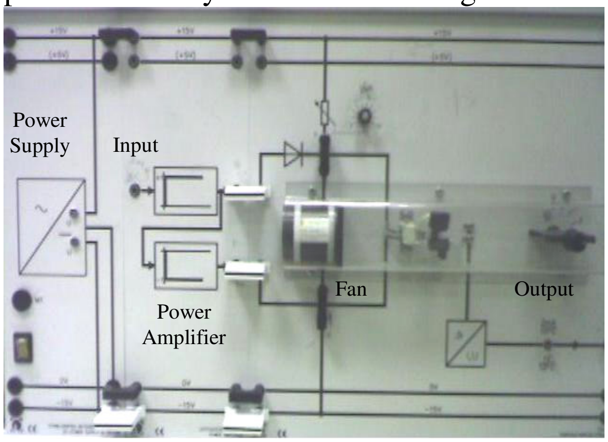

Fig. 6. Picture of the temperature control system.

The system consists of main components:

- A power supply ($\pm$ 15v),
- Power amplifier,
- Temperature system which includes: Fan, heater (halogen lamp) and flap. All these components are inside the glass channel.

Note that in all experiences, the flap and fan are set to 2 div. The sensor module is used to measure the temperature over the range 0^{o}C - 100^{o} C and the corresponding voltage range is 0V - 10V.

Data acquisition board CE122 from ***TQ*** Company [15] is used as interface between PC and the controlled system.

The main control program, which calculates the control signal to be sent to the temperature system through the interface CE122, is written in C++ language.

5.2 PID Controller with a compensator:

The PID controller used in this work to control the temperature system is given by:

$$\begin{aligned} u(kh) &= u\big((k-1)h\big) + K_p\big(e(kh) - e((k-1)h)\big) \\ &+ K_d\big(e(kh) - 2e\big((k-1)h\big) + e\big((k-2)h\big)\big) \\ &+ K_i\, e(kh). \end{aligned} \tag{8}$$

where K_p, K_d and K_i are the PID control parameters.

The structure of the networked control system is shown in figure 7. The temperature system is in one side and the PID controller in another side (client). The temperature system is controlled via a local network which is constituted by three PC's (Cen-2, Cen-2 and Cen-3). All these PC's are connected to the local network via Hub (10Mbps).

To design a compensator, we have to find the transfer function of the temperature system. It is known that the temperature system is a first order system with transfer function:

$$G(s) = \frac{K}{\kappa s + 1} = \frac{\frac{K}{\kappa}}{s + \frac{1}{\kappa}} = \frac{b}{s + a} \tag{9}$$

To find the parameters value of this transfer function, the reaction curve based method is used and we got: $K = 0.35$ and $\kappa = 53$, i.e: $a = -\frac{1}{53}$, $b = 66\ 10^{-4}$.

The equation (6) leads to the estimator that can be written as follows:

$$\begin{aligned} \hat{x}(kh + \tau_{sc,k}) &= e^{\frac{-\tau}{53}} x(kh) \\ &+ 0.35\,(1 - e^{\frac{-\tau}{53}})\, u((k-1)h) \end{aligned} \tag{10}$$

Thus, the tracking error used by the controller is given by:

$$e(kh + \tau_{sc}) = x_{ref}(kh + \tau_{sc}) - \hat{x}(kh + \tau_{sc}) \tag{11}$$

In this experiment, the PID controller is used with control parameters values: K_p= 4, K_d= 3 and K_i =0.25. The reference signal or a desired value is T_d= 80 C^o (which is equivalent to 8 volts), and the calculated sampling period is h =*0.2* (sec).

First, we will investigate the output of the temperature system without delay, i.e the controller is directly connected to the system (point-to-point connection). Afterwards, the controller is connected to the network as it is shown in figure 7. The delay which is less than the sampling period and approximated by τ= 0.19 (sec).

Figure 8 depicts experimental results and we can conclude that:

- The red curve represents the dynamic response of the temperature system without delay. The achieved tracking performances are: %OS (overshoot) = 1% and Ts (settling time) = 130 sec (2.2 min). Note that the desired value T_d = 80 C^o is well tracked without steady state error.
- The blue curve represents the dynamic response of the temperature system with network (high load) and without compensator. The achieved tracking performances are: %OS = 2.5% and the Ts = 160 sec (2.7 min). It is clear that the induced delay has decreased the tracking performances.
- The green curve represents the dynamic response of the temperature system controlled via network with high load and with compensator. The tracking performances have been retrieved since the %OS = 1% and the Ts = 130 sec (2.2 min).

6. Conclusion

In this paper, the linear networked control system is analyzed. First, the digital controller is designed by ignoring the delay induced by the information exchange in the network.

It is shown that the range of the induced delay, that maintains the stability, can be provided by using Jury test. The problem is that the induced delay decreases the tracking performances. To overcome this problem and to retrieve the tracking performances achieved by the controller without network connection, a compensator or estimator is added to the closed loop system. This approach is applied on real-time experiment to temperature system. Experiments results showed that tracking performances have been retrieved.

The future work is to estimate the induced delay exactly and use it in the controller. Moreover, this approach will be tested on an unstable nonlinear system (inverted pendulum).

References:

[1] Franklin, G. F., Powel, J. D. and Workman, M. L., *Digital control of dynamic systems*, Addison-Wesley, 1989, USA.

[2] Lian, F. L., Moyne, J. R. and Tilbury, D. M., “ Performance evaluation of control networks: Ethernet, ControlNet and DeviceNet”, *IEEE control systems Magazine*, 2001, pp.66-83.

[3] Walsh, G. C., Ye H. and Bushnell, L., “Stability analysis of networked control systems”, Proceedings of the American control conference, San-Diago, 1999, USA.

[4] Walsh, G. C., Ye H., “ Scheduling of networked control systems” IEEE Control systems magazine, 2001, pp.57-65.

[5] Anderson, M. Henriksson, D., Cervin A. and Arzen K. E., “Simulation of wireless networked control system”, 44th IEEE conference on Decision and control and ECC European control conference, Seville, 2005, Spain.

[6] Nilsson J. “Real time control systems with delays” *PhD thesis*, Lund Institute of Technology, Sweden, 1996.

[7] Tanenbaum A. S., *Computer Networks*, 4th edition, Prentice Hall, New Jersey, 2003, USA.

[8] Rehbinder H. and Sanfridson M., “Scheduling of a limited communication channelfor optimal control”, Automatica, Vol.30, No.3, 2004, pp.491-500.

[9] Kyung C. L., Suk L. and Man H. L, “QoS-based remote control of networked control systems via Profibus token passing protocol”, IEEE Trans on Industrial Informatics, Vol.1, N.3, 2005, pp.183-193.

[10] Liqian Z., Yang S., Tongwen C. and Biao H., “A new method for stabilization

of networked control systems with random delays", IEEE Trans. On Automatic Control, Vol.50, No.8, 2005, pp.1177-1181.
[11] Silvia M. and Abdullah C. T., "Networked control system and communication networks: Integrated model and stability analysis", IFAC World Congress, 2005, Prague.
[12] Liu G. P. and Rees D., "Stability criteria networked predictive control systems with random network delay", 44th IEEE conference on Decision and control and ECC European control conference, Seville, 2005, Spain.
[13] Babak T. and Parviz J. M., "Robust design of networked control systems with random varying delays and packet losses", 44th IEEE conference on Decision and control and ECC European control conference, Seville, 2005, Spain.
[14] www.leybold-didactic.de
[15] www.tq.com
[16] R. Hedjar, A. Al-Qahtani and A. Al-Goblan, "Asymptotic behavior of linear networked control system", National Computer Conference (NCC18), Riyadh, March 26-29, 2006.
[17] C. Wang, Y. Wang and G. Ma, "Compensation time-varying delays in networked control systems via jump linear system approach" Proc. of the 5th World Congress on intelligent control and automation, Hangzhou, 2004, China.
[18] Ling Q. and Lemmon M. D., "Optimal dropout compensation in networked control systems", Proc. of the 42nd IEEE conference on decision and control, Hawaii, 2003, USA.
[19] Yoo, H. J., Ryu, H. S., Yoo K. S. and O. K. Kwon, "Compensation of NCS using LMI – based - dependent optimization method" Proc. Of the SICE conference, Osaka, 2002, Japan.
[20] F. Yang, Z. Wang, Y. S. Hung and M. Gani, "H_∞ control for networked systems with random communication delays" IEEE Transaction On Automatic Control, vol.51, No.3, 2006, pp. 511-518.

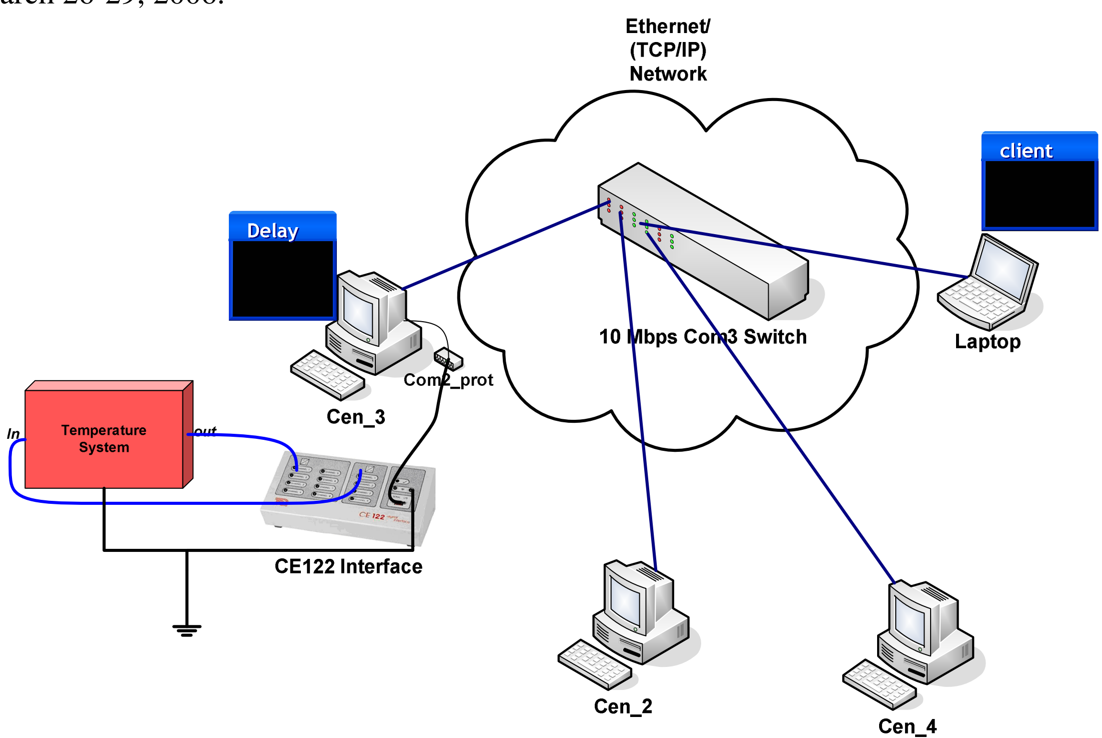

Fig7. Temperature system with network.

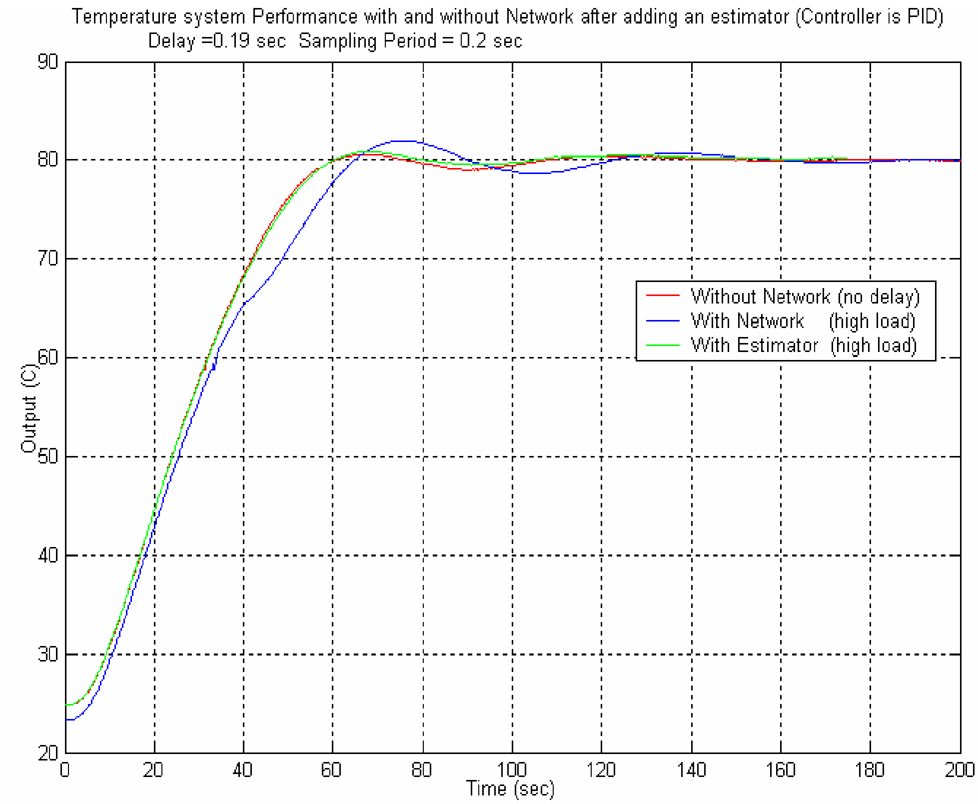

Fig 8: Tracking performances with and without network.