Development and Experiment of Networked Control Systems with Congestion Control

Takehito Azuma and Shinsaku Saijo

Abstract The purpose of this paper is to develop an autonomous vehicle system including communication networks and to demonstrate congestion controllers for networks based on state predictive control via the developed system. In the networked autonomous vehicle, the vehicle has one camera as sensor. Images from camera are sent to a computer via computer networks and are processed to recognize circumstances around the vehicle. Using the processed camera image, the vehicle is controlled over computer networks. By considering that this system uses computer networks, congestion problems are important because congestion causes instability of the whole system. For these problems, congestion controllers are designed based on the systems & control theory. In this paper, new congestion controllers are designed by using state predictive control to assure stability of computer networks. Effectiveness of congestion controllers is verified in experiments using the developed system.

Keywords Networked control systems · congestion control · camera sensor · autonomous vehicle · state predictive control

1 Introduction

Recently communication networks are developed widely [1] and it uses to control many machines from a distant place. For example, a surgery is done between USA and Euro using surgery manipulators. This surgery is called as laparoscope-assisted surgery. In the control engineering research area, this kind of researches are called as NCSs (Networked Control Systems) and many researches have been done [3, 4].

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On the other hand, one of communication networks is computer network and Internet or LAN (Local Area Network) is famous as a computer network [1, 2]. A main problem in the computer network is to transfer data smoothly in the network. If data transfer is not smooth, the network is busy and this status is called as congestion. It is possible to avoid congestion in the computer network by using systems & control theory. Some researches focus on this problem and some methods are proposed [5, 6].

In this paper, NCSs and congestion problems in the computer network are both considered, a NCSs is developed actually and a congestion controller is designed based on state predictive control. Moreover some experiments are done in the developed NCSs and the efficacy of congestion controllers is verified in the real networked system. It seems original to show the efficacy of congestion controllers in the developed NCSs.

Firstly an autonomous vehicle system including computer networks is developed In the system, the vehicle can be controlled via radio transmission and a camera is mounted on the vehicle as sensor to recognize circumstances. Visual images from camera are sent to the developed vehicle control system and the image data is processed at a receiver computer through a simple computer network. Based on the image processing, a reference trajectory is detected and the vehicle is controlled from a distant place.

Secondly considering dynamics of computer networks, congestion controllers are designed. The dynamics of computer networks is nonlinear but it is possible to obtain a linearized model with an information delay, which causes from the round trip time of data transfer. The information delay is called as time-delay in the systems & control theory. For this linear time-delay system, a congestion controller is designed to avoid occurring congestion in the computer network.

Finally applying the designed congestion controller to the developed autonomous vehicle system, efficacy of the designed congestion controller is verified by having experiments without a congestion controller and with the designed congestion controller.

2 Development of Networked Control Systems

2.1 System Configuration

A networked autonomous vehicle system has been developed and the system is shown in Fig. 1. In this figure, a wire-less vehicle is tracking the black cycle line that denotes a reference trajectory for the vehicle. The wire-less vehicle is controlled via visual feedback control. Visual feedback control is a control method by using camera as sensor. The vehicle control system consists of data sending and receiving parts via wire-less radio transmission. The vehicle control system is connected through a RS-232C cable. Sender is a computer that is connected to computer networks. Here LAN (Local Area Network) is considered as the computer network.

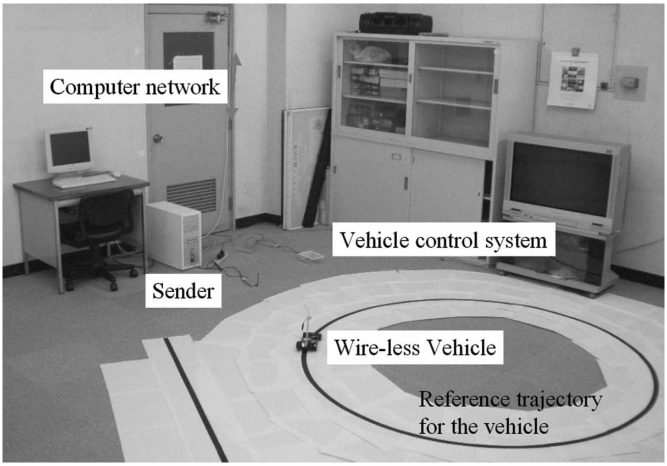


Fig. 1 The developed autonomous vehicle system

A router and a receiver are shown in Fig. 2. The LAN cable from the computer network in Fig. 1 goes to the router in Fig. 2. The receiver is connected to the router via a LAN cable. The room in Fig. 1 is different from the room shown in Fig. 2. The room in Fig. 1 is vacant during some experiments and the wire-less vehicle is controlled from another room through the computer network.

Figure 3 shows whole system configuration of our developed autonomous vehicle systems combined with computer networks. In this figure, one more sender is added and the sender is used to cause congestion in the computer network. The purpose of this paper is to verify effectiveness of the designed congestion controller that is implemented in the router. The design problem of congestion controllers is discussed in the next section. Congestion controllers stabilize queue sizes of routers in computer networks.

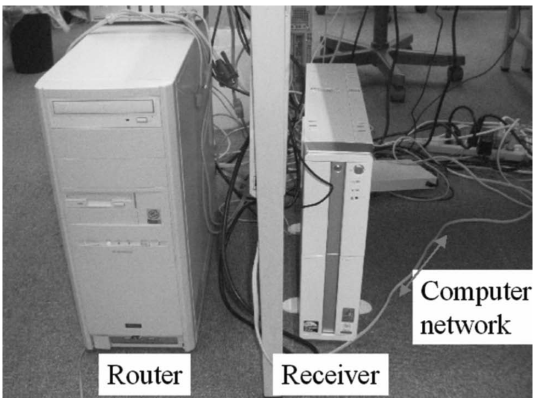


Fig. 2 System configuration for computer networks

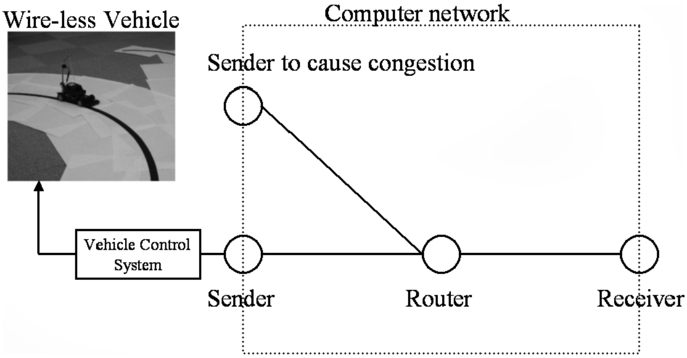


Fig. 3 Network topology and autonomous vehicle system

2.2 Dynamics of the Wire-Less Vehicle and Automatic Control

In the Fig. 4, the wire-less vehicle is shown and it can be seen that a wire-less camera is mounted on the vehicle. The dynamical model of this vehicle can be derived from a two-wheel model that can be obtained as an approximated model of a four-wheel model (the Fig. 4). The dynamics of the vehicle is given as follows,

$$\begin{aligned} \dot{x} &= Ax + B\delta, \\ y &= Cx, \end{aligned} \tag{1}$$

where

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \dfrac{2(K_f + K_r)}{m} & -\dfrac{2(K_f + K_r)}{mV} & -\dfrac{2(l_f K_f + l_r K_r)}{mV} \\ 0 & \dfrac{2(l_f K_f - l_r K_r)}{I} & -\dfrac{2(l_f K_f - l_r K_r)}{IV} & -\dfrac{2(l_f^2 K_f - l_r^2 K_r)}{IV} \end{bmatrix},$$

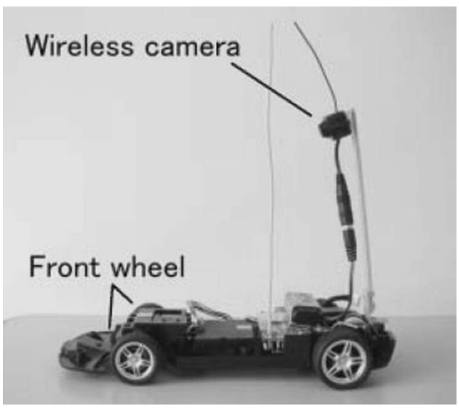


Fig. 4 Wire-less vehicle with a wire-less camera

$$B = \begin{bmatrix} 0 \\ 0 \\ \frac{2K_f}{m} \\ \frac{2l_f K_f}{I} \end{bmatrix}, \quad C = [\,1 \quad l_s \quad 0 \quad 0\,].$$

In the state equation (1), the state variable $x(t) \in R^4$ denotes errors for vehicle center of gravity in Fig. 4 and it can be observed by using the camera image. The input vector $\delta(t) \in R$ denotes the steering angle of the vehicle and it can be applied to the vehicle as a voltage of an electrical motor. The other parameters are constant and it can be determined by measuring the vehicle.

For the vehicle dynamics (1), a LQG (Linear Quadratic Gaussian) controller can be designed. The LQG controller is general and useful as a basic method to construct automatic control systems based on systems and control theory. The LQG controller design is given as follows,

1. Solve the matrix $P > 0$ which satisfies the following matrix equation (Riccati equation).
$$PA + A'P - PBR^{-1}B'P + C'QP = 0 \tag{2}$$
where matrices R, Q are weighting matrix for LQG control.
2. Solve the matrix $M > 0$ which satisfies the following matrix equation.
$$MA' + AM - MC'CM + BGG'B' = 0 \tag{3}$$
where G denotes a system matrix for the state equation (1) in case of considering disturbances.
3. By using the above matrices $P > 0, M > 0$, the LQG controller is given as follows,
$$\begin{aligned} \dot{x}_K &= A_K x_K + B_K y, \\ \delta &= C_K x_K, \end{aligned} \tag{4}$$
where
$$\begin{aligned} A_K &= A - HC - BF, \\ B_K &= H, C_K = -F, \\ F &= R^{-1}B'P, H = CM. \end{aligned}$$

Here note that LQG control minimizes the following cost function.

$$J = \int_0^\infty \{x'(t)QPx(t) + u'(t)Ru(t)\}dt$$

Moreover this designed controller is implemented as a program in the receiver shown in Fig. 2.

3 Congestion Controller Design Using the State Predictive Control

3.1 Dynamics of Computer Networks

In this paper, the network topology is given in Fig. 3 as a computer network. This kind of network topology can be considered as The network consists of n nodes (Sender) , 1 node (Receiver) and 1 bottleneck router which sends packets form the Sender to the Receiver. This network topology denotes 1 server machine to multiple client machines in a computer network. Large scale networks can be simplified as this network topology in case of designing congestion controllers if only one router is bottleneck in the large-scale computer network.

From the paper [5], the following nonlinear models describe behaviors of the average window size in senders and the queue size in the bottleneck router in the network.

$$\begin{aligned} \dot{w}_s(t) &= \frac{1}{R(t)} - \frac{w_s(t)}{2}\frac{w_s(t-R_r(t))}{R(t-R(t))}p(t-R(t)), \\ \dot{q}(t) &= N(t)\frac{w_s(t)}{R(t)} - C(t), \end{aligned} \tag{5}$$

where $w_s \in [0, w_{s\max}]$ is the average TCP windows size, $w_{s\max}$ is the maximum window size, $q \in [0, q_{\max}]$ is the queue length at the bottleneck router, $q_{\max}$ is the maximum queue size, N is a number of TCP sessions, $p \in [0,1]$ is probability of packets loss at the bottleneck router, C is a link capacity from the router to the receiver and R is an information delay. The information delay R is called as the round trip time and can be described as

$$R = \frac{q}{C} + T_p,$$

where T_p is a propagation delay on links of the computer networks. The nonlinear model with a time delay has a property that the time delay R is linearly dependent on the queue size which is one of the state variables of the nonlinear model given. This property makes it difficult to design congestion controllers. Introducing an equilibrium point, the nonlinear model is linearized.

To obtain the linearized model of the nonlinear model, it is assumed that the number of TCP sessions N and the propagation delay T_p are constant. The equilibrium point is defined as (w_{so}, q_o, p_o) and new variables are defined as follows,

$$\delta w_s(t) = w_s(t) - w_{so}, \quad \delta q(t) = q(t) - q_o, \quad \delta p(t) = p(t) - p_o.$$

Then the linearized model is given as follows,

$$\begin{aligned} \dot{x}_p(t) &= A_p x_p + B_p u(t-R_0), \\ y_p(t) &= C_p x_p(t), \end{aligned} \tag{6}$$

where

$$A_p = \begin{bmatrix} -\frac{2N}{R_0^2 C} & 0 \\ \frac{N}{R_0} & -\frac{1}{R_0} \end{bmatrix}, \quad B_p = \begin{bmatrix} -\frac{R_0 C^2}{2N^2} \\ 0 \end{bmatrix}, \quad C_p = \begin{bmatrix} 0 & 1 \end{bmatrix},$$

and $x_p(t) = \left[\delta w_s(t)\ \delta q(t)\right]^T$, $y_p(t) = \delta q(t)$ and $u(t) = \delta p(t)$.

The designed congestion controller, which is an AQM mechanism, is given as a state feedback controller whose input signal is $x_p(t) = \left[\delta w_s(t)\ \delta q(t)\right]^T$ and whose output signal is $u(t) = \delta p(t)$. The controller is implemented as a program in the bottleneck router of the Fig. 2. Now define the object of the design as stabilizing the queue size at the equilibrium point q_0 for the TCP/AQM network consisting of a TCP network and the designed AQM mechanism. In this paper, the equilibrium point q_0 is given as half of the maximum value of the queue size to achieve no congestion and effective utility of the queue size. Moreover the time delay $R(t)$ become constant if the queue size is stable near the equilibrium point $q_0 = 0.5q_{\max}$.

3.2 Congestion Controller Design

In this section, congestion controllers are designed by using state predictive control to satisfy the control object defined in the end of the previous section. Figure 5 shows the block diagram of the closed loop system designed finally in this paper though it is needed that this block diagram is same one for the closed loop system of the error system.

The procedure of the controller design is as follows,

1. Designing an observer for the input time delay system given by equation (6).
2. Constructing an augmented system from the designed observer and an integrator. The integrator is introducing to improve the steady state characteristic.

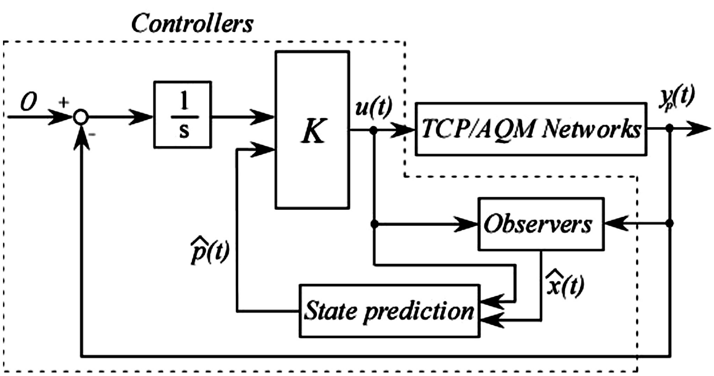


Fig. 5 The block diagram of the closed loop system using state predictive control

3. Transforming the augmented system into a linear time invariant system by using state predictive control because the augmented system is expressed as an input time delay system.
4. Designed a LQI (Linear Quadratic with Integrators) controller for the derived linear time invariant system.

The dotted line area is the designed congestion controller from the above procedure and the controller is embedded as a program in the bottleneck router that is equivalent to an AQM mechanism. Here note that this is a controller for the error system and it is of no meaning for the controller to be implemented directly as Fig. 2.

Design of the observer gain L_p: It is impossible to obtain the state of equations (6) directly because the controller is embedded in the bottleneck router and the TCP window size is not available on-line. The state $x_p(t)$ is estimated by using the following observer.

$$\dot{\hat{x}}_p(t) = A_p\hat{x}_p(t) + B_p u(t-R_0) - L_p(y_p(t) - C_p\hat{x}_p(t)),$$

where L_p is an observer gain which is designed as $A_p + L_pC_p$ becomes stable. Considering an estimated error of the state $e_p(t) = x_p(t) - \hat{x}_p(t)$, the error system is given as follows,

$$\begin{aligned}\dot{e}_p(t) &= \dot{x}_p(t) - \dot{\hat{x}}_p(t),\\ &= A_p(x_p(t) - \hat{x}_p(t)) + L_pC_p(x_p(t) - \hat{x}_p(t)),\\ &= (A_p + L_pC_p)(x_p(t) - \hat{x}_p(t)),\\ &= (A_p + C_pL_p)e_p(t).\end{aligned}$$

Thus it is possible to design observers if (C_p, A_p) is observable.

Now it is assumed that (C_p, A_p) is observable and the observer gain L_p is designed as a synthesis problems of a Kalman filter in case of considering that the small change of the input time delay is a white noise. The general description of linear systems with white noises is given as follows,

$$\begin{aligned}\dot{x}(t) &= Ax(t) + B_1u(t) + B_2\xi(t),\\ y(t) &= Cx(t) + D_1u(t) + D_2\xi(t) + \eta(t),\end{aligned}$$

where $A = A_p$, $B_1 = B_p$, $B_2 = \left[\, w_{s0}{}^{*}2 \; q_0/2 \,\right]^T$, $C = C_p$, $D_1 = 0$, $D_2 = 0$, $E\left[\xi(t)\xi(t)^T\right] = 1$ and $E\left[\eta(t)\eta(t)^T\right] = 1$. B_2 denotes the small change of the input time delay. Finally the observer gain L_p is easily designed as a synthesis problem of a Kalman filter for this system by using MATLAB if (C_p, A_p) is observable.

Design of the state feedback gain *K* based on state predictive control : The system consisting of the observer and the error dynamics is given as follows,

$$\begin{aligned}\dot{\hat{x}}_p(t) &= A_p\hat{x}_p(t) + B_p u(t-R_0) - L_pC_pe_p(t),\\ \dot{e}_p(t) &= (A_p + C_pL_p)e_p(t).\end{aligned}$$

Considering the integrator

$$\dot{x}_i(t) = r(t) - y_p(t) = -y_p(t),$$

the augmented system is obtained such as

$$\begin{aligned}\dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t-R_0) - \begin{bmatrix} L_pC_p \\ 0 \end{bmatrix} e_p(t),\\ \dot{e}_p(t) &= (A_p + C_pL_p)e_p(t),\\ \hat{x}(t) &= \begin{bmatrix} \hat{x}_p(t) \\ x_i(t) \end{bmatrix},\ A = \begin{bmatrix} A_p & 0 \\ -C_p & 0 \end{bmatrix},\ B = \begin{bmatrix} B_p \\ 0 \end{bmatrix}.\end{aligned}$$

Here note that the integrator is used to improve the steady state characteristic because steady state errors appear and the control object cannot be achieved in case of no integrators on SIMULINK simulations and *ns-2* simulations. Moreover the dynamics of the augmented system is divided into the above two equations to reduce the dimension of the augmented system and to make it easy to apply state predictive control.

Now introduce the following auxiliary variable.

$$\hat{p}(t) = \hat{x}(t) + \int_{-R_0}^{0} e^{-A(\beta+R_0)}Bu(t+\beta)d\beta.$$

Differentiating the auxiliary variable $\hat{p}(t)$ and considering the input time delay system, the following linear time invariant system is derived.

$$\dot{\hat{p}}(t) = A\hat{p}(t) + e^{-AR_0}Bu(t) - \begin{bmatrix} L_pC_p \\ 0 \end{bmatrix} e_p(t).$$

The linear system with no time delays can be described as the next equation by considering a state feedback controller $u(t) = K\hat{p}(t)$.

$$\dot{\hat{p}}(t) = (A + e^{-AR_0}BK)\hat{p}(t) - \begin{bmatrix} L_pC_p \\ 0 \end{bmatrix} e_p(t).$$

If $(A, e^{-AR_0}B)$ is controllable, the state feedback gain K exists and it can be given as a solution of linear quadratic control problems. For example, defining Q_{aug}, R_{aug} as weighting matrices, the state feedback gain K is decided as follows,

$$K = -R_{aug}^{-1}B^T e^{-A^T R_0}P,$$

where the matrix P is a solution of the following Riccati equation.

$$PA + A^T P - PBe^{-AR_0}R_{aug}^{-1}B^T e^{-A^T R_0}P + Q_{aug} = 0.$$

Thus the next equation is the control input which stabilizes the input time delay system with the state feedback gain.

$$u(t) = K\hat{p}(t) = K\left\{\hat{x}(t) + \int_{-R_0}^{0} e^{-A(\beta+R_0)}Bu(t+\beta)d\beta\right\}.$$

4 Experimental Results

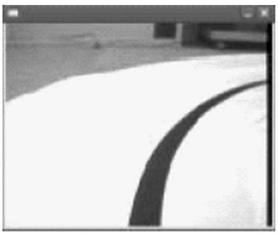
In this section, a networked autonomous vehicle system is developed and effectiveness of congestion controllers is verified by using the developed vehicle system.

4.1 Results without Congestion Control

The networked autonomous vehicle system is actually constructed such as Figs. 1 and 2. The designed LQG controller is embedded in the receiver of Fig. 2. Here note that parameters are omitted to show in this paper.

The image from camera is shown in Fig. 5. The receiver processes camera images and provides a line for LQG control (See the Fig. 6(c)). The LQG controller can make a voltage for the electrical motor for the wire-less vehicle to track the detected line. In this experiment, the reference trajectory is given as a circle.

In the developed system, it is possible to occur congestion in the computer network by using another sender in Fig. 3. To show the efficacy of congestion



(a) Original image

(b) 2-bit image after first image processing

(c) Detecting a reference trajectory for autonomous vehicle after second image processing

Fig. 6 Image processing based on visual information from camera

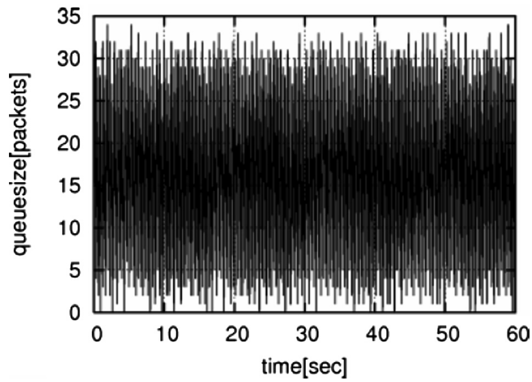


Fig. 7 Queue size in the router (Congestion case)

controllers, we make congestion occur in the computer network. The Fig. 7 shows the queue size in the router of the Fig. 3. It is known that the queue size is largely changing and many congestions occurs in the computer network. In this case, the autonomous vehicle system becomes unstable and the wire-less vehicle is out of control. The Fig. 8 shows the error between the detected reference trajectory and vehicle center of gravity. After 15[s], the vehicle is out of control.

4.2 Results with Congestion Control

The designed congestion controller is applied to the router and congestion is avoided in the computer network.

Figure 9 shows the queue size in the router. It is easy seen that congestion does not appear in the computer network and the amplitude of oscillation is made small in comparison from Fig. 7. It also known that the designed congestion controller works well and can avoid to occur congestion in the computer network.

Figure 10 shows the error between the detected reference trajectory and vehicle center of gravity. At 9 [s] and 15 [s], the error become large but the designed LQG

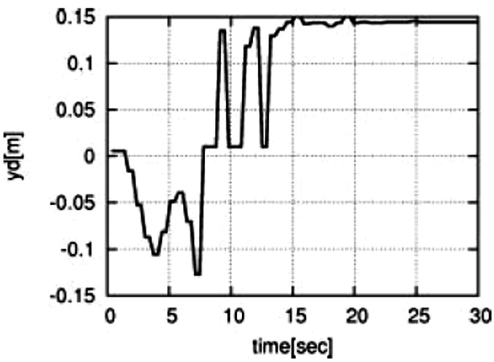


Fig. 8 Error from a reference trajectory (Congestion case)

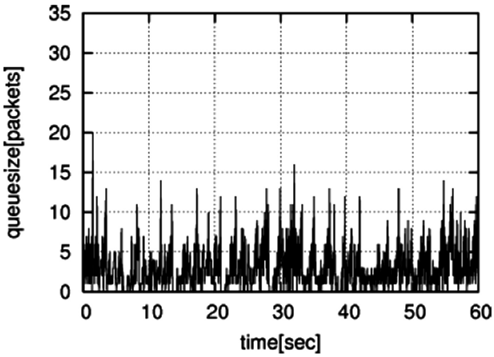


Fig. 9 Queue size in the router

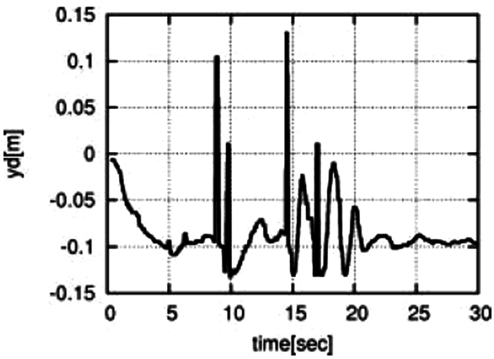


Fig. 10 Error from a reference trajectory

controller makes the system stable. The wire-less vehicle can drive automatically on the near reference trajectory. Thus the networked autonomous vehicle system can be developed. It is also seen that the designed congestion controller have important role in the networked autonomous vehicle system.

5 Conclusion

In this paper, a networked autonomous vehicle system has been developed. Especially dynamical models of the computer network are considered and congestion problems have been discussed. To avoid congestion in the computer network, a congestion controller has been designed based on state predictive control. Some experiments have been done in the developed vehicle system and effectiveness of the designed congestion controller has been verified from a experiment for tracking control of a circle trajectory. The result of this paper is located between researches about NCSs (Networked Control Systems) and Control of Networks. There are few researches to discuss about both topics of NCSs and control of networks. Moreover almost no researches are available to develop NCSs actually and design congestion controllers for computer networks.

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