COMPENSATOR FOR INTERNET-BASED ADVANCED CONTROL

X Chen and S H Yang*

Computer Science Department, Loughborough University, Loughborough, Leicestershire
LE11 3TU UK
Telephone: 0044 1509 222942, Fax: 0044 1509 211586,
Email: s.h.yang@lboro.ac.uk

Abstract: Internet-based control is becoming next generations of control systems, in which time delay and data loss in Internet transmission are the major obstacles for bringing this control system into a reality. This paper proposes new control architecture in cooperated with two compensators to attack this major difficulty. These two compensators are located in the feedback and feed-forward channels in the architecture in order to compensate the control action and assure the stability of the control system. The novel compensators and control system architecture are illustrated and evaluated through a simulation example by using the DMC control algorithm. *Copyright © 2002 IFAC*

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1. INTRODUCTION

In past years, the success to adopt the Internet to deliver business services has demonstrated a lot of advantages, such as cost reduction, flexibility. In the control area, researchers begin to exploit the advantages of the Internet for control systems, namely Internet-based control system. Such control systems are characterised as globally remote monitoring and adjustment of plants over the Internet. With the prevalence of the Internet, plants stand to benefit from the ways of retrieving data and reacting to plant fluctuations from anywhere around the world at any time. From higher education institutions, researchers have developed web-based virtual control laboratories for distance learning purposes (Shaheen, et al., 1998; Overstreet and Tzes, 1999). Some small-scale demonstrators of Internet-based control have implemented and shown a number of promising results (Yang, et al., 2002a; Halley and Gauld, 1999). Meanwhile, a few companies are more likely to produce Internet-based control systems as a control device (Cushing, 2000). The first systematic design method of Internet-based control systems has been formalised in our recent work (Yang, et al., 2003).

The Internet-based control systems, which have been achieved so far, adopt a discrete control structure, which do not explicitly consider Internet transmission features. For example, Overstreet and Tzes (1999) inserted Internet communication elements between the remote controller and the sampling switches in their Internet-based laboratory control system. They directly adopted a discrete control structure and treated the Internet transmission as a pure lag element. As described in the following section, Internet time delay is determined by the Internet circumstances such as the amount of transmission data, the connection bandwidth, and the distance between the sending and receiving nodes. Therefore Internet time delay cannot be modelled and predicted. Data loss is another significant issue and has a great influence on the performance of control systems.

Therefore, it is essential to study the features of the Internet transmission, and propose a proper measure to overcome the Internet time delay and data loss for Internet-based control systems. This study is organised as follows: Section 2 describes the features of Internet transmission. Section 3 gives out a control structure with a tolerant period of time for sampling. Two compensators located at the feedback and feed-

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*To whom correspondence should be addressed.

forward channels are designed in Section 4 to fully exploit the benefit of the control architecture. A simulation study is used to assess the performance of the compensators in Section 5. Section 6 is the conclusion.

2. INTERNET TRANSMISSION LATENCY

The Internet is a public transmission media, which is fundamentally different from other private transmission medias used by many end-users for different purposes. The exiting studies of the Internet transmission (Luo and Chen, 2000; Acharya and Saltz, 1996) show that the performance associated with time-delay and data-loss possesses large temporal and spatial variation, and uncertain transmitting time-delay and data-loss problems are not avoidable for any Internet-based application.

In detail, the Internet time delay is characterized by the processing speed of nodes, the load of nodes, the connection bandwidth, the amount of data, the transmission speed, etc. The Internet time delay $T_d(k)$ at instant k can be described as follows:

$$\begin{aligned} T_d(k) &= \sum_{i=0}^{n}[\frac{l_i}{C} + t_i^R + t_i^L(k) + \frac{M}{b_i}] \\ &= \sum_{i=0}^{n}(\frac{l_i}{C} + t_i^R + \frac{M}{b_i}) + \sum_{i=0}^{n} t_i^L(k) \\ &= d_N + d_L(k) \qquad (1) \end{aligned}$$

where l_i is the ith length of link, C the speed of light, t_i^R the routing speed of the ith node, $t_i^L(k)$ the delay caused by the ith node's load, M the amount of data, and b_i the bandwidth of the ith link. d_N is a term, which is independent of time, and $d_L(k)$ is a time-dependent term. Because of the time-dependent term $d_L(k)$ it is somewhat unreasonable to model the Internet time delay for accurate prediction at every instant.

Therefore the performance of the Internet transmission cannot be modelled and predicted, which is necessary to be explicitly handled by control systems.

3. INTERNET-BASED CONTROL ARCHITECTURE

It is arguable that the conventional discrete control structure, which uses a fixed sampling interval, is not suitable for Internet-based control systems. The discrete control structure requires a predictable execution time for closed control loops. Conversely, Internet transmission time delay is unpredictable, which breaks the foundation of the conventional discrete control structure. For example, an actuator may receive a control signal from a controller after the sampling interval passes. As the result, the control system may lose a number of control signals because of the fixed sampling interval. Therefore, a suitable control structure is required to deal with the uncertain execution time, time delay, and data loss for Internet-based control systems.

Conceptually, the architecture should involve several network services and a control functional structure. This paper only addresses the control functional structure. The network services such as global timers and real time control protocols can be referred to our recent work (Chen and Yang, 2002). The evolvement of the Internet-based control functional structure is shown in Fig 1, which maintains the main function of the structure, such as Zero-Order Hold (ZOH). If the discrete control structure (the above part in Fig 1) is considered as a tight coupling structure, the new structure (the lower part in Fig 1) is a loose coupling structure, which introduces a tolerance time Δt to handle the unpredictable Internet communication. The tolerance time chosen must be shorter than the sampling interval, so that the control law can still be maintained. Rather than transmitting control signals at a series of fixed time points, the new structure transmits control signals within a series of time intervals, which theoretically maximises the opportunity for control signals being transmitted on time. In order to implement the new structure, the sampling switches in the conventional discrete control structure is replaced with a pair of sampling switches located in both remote and local sides. The timers synchronised by the network service trigger the sampling switches.

Another significant feature introduced here in the Internet based control structure is that a signal buffer is employed at the feedback channel (see the lower part in Fig 1). The control command becomes useless after an unexpected long time delay, which is treated as a noise. In contrast, the delayed feedback signal is still useful, particularly for updating predictive models for processes. In the Internet based control structure the time-out control command signals are omitted and the delivery of the feedback signal is guaranteed.

4. DEALING WITH TIME DELAY AND DATA LOSS IN CONTROL SYSTEM DESIGN

Although the new control structure is well designed to cope with the Internet features, the traditional controller cannot fully take the advantage of the control structure. It is necessary to add-on some functional elements to efficiently use the new structure. Two compensators for a predictive controller have been designed, which are located at the feedback and feed-forward channels respectively. The widely accepted predictive controller, Dynamic Matrix Controller (DMC), has been chosen to integrate with these two compensators and demonstrate the novel architecture. The concept is shown in Fig 2. The compensator at the feedback channel with a data buffer located at the local side is designed to overcome time delay and data loss occurring in the transmission from the local side to a remote side. The compensator at the feed-forward channel is designed to overcome time delay and data loss occurring in the transmission from a remote side to the local side.

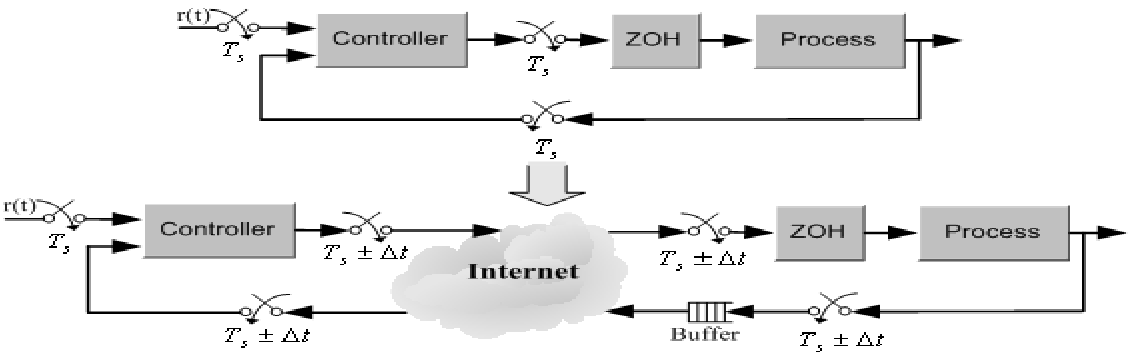


Fig. 1. Evolvement of the control structure

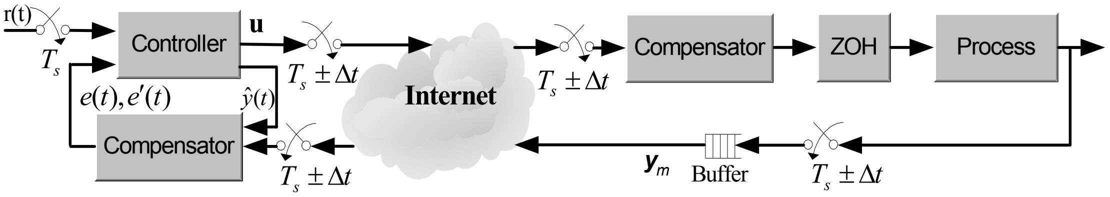


Fig. 2. Predictive controller with data loss and time delay compensators.

4.1 Dynamic Matrix Controller (DMC)

DMC was developed at the end of the seventies by Cutler and Ramaker (1980) of Shell Oil Co. and has been widely accepted in the industrial world, mainly by petrochemical industries. DMC can be divided into prediction and control law two parts.

The process model employed in the DMC formulation is a step response of the plant as shown in Equation 2, while the disturbance is considered to keep constant along the horizon. The procedure of obtaining the predictions is reviewed from Equations 2 to 5 as follows:

$$y(t) = \sum_{i=1}^{\infty} g_i \Delta u(t-i) \qquad (2)$$

where *y(t)* is the output of the process, g_i is the sampled output value for the step input, Δu is the control action. Denote *f(t+k)* as the free response of the system, that is, the part of the response that does not depend on the future control actions. For the asymptotically stable process, the coefficients g_i of the step response tends to be a constant value after N sampling periods. The free response can be given as:

$$f(t+k) = y_m(t) + \sum_{i=1}^{N} (g_{k+i} - g_i) \Delta u(t-i) \qquad (3)$$

Now the predictions can be computed along the prediction horizon (k=1,…,p), considering m control actions.
defining the input vector composed of the future control increments **Δu** as:

$$\mathbf{\Delta u} = [\Delta u(t) \quad \Delta u(t+1) \quad \cdots \quad \Delta u(t+m-2) \quad \Delta u(t+m-1)]^T$$

defining the estimates of output vector **y** as:

$$\hat{\mathbf{y}} = [\hat{y}(t+1|t) \quad \hat{y}(t+2|t) \quad \cdots \quad \hat{y}(t+p-1|t) \quad \hat{y}(t+p|t)]^T$$

defining the system's dynamic matrix **G** as:

$$\mathbf{G} = \begin{bmatrix} g_1 & 0 & \cdots & & 0 \\ g_2 & g_1 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & & \vdots \\ g_m & g_{m-1} & \cdots & g_2 & g_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ g_p & g_{p-1} & \cdots & g_{p-m+2} & g_{p-m+1} \end{bmatrix}_{p\times m} \qquad (4)$$

defining the free response vector **f** as:

$$\mathbf{f} = [f(t+1) \quad f(t+2) \quad \cdots \quad f(t+p-1) \quad f(t+p)]^T$$

^{T} means the transfer of the vector. Then the prediction equation can be written as:

$$\hat{\mathbf{y}} = \mathbf{G\Delta u} + \mathbf{f} \qquad (5)$$

The objective of a DMC controller is to drive the output as close to the setpoint as possible in a least-squares sense with the possibility of the inclusion of a penalty term on the input moves. Therefore, the general results of the control law can be given as:

$$\mathbf{\Delta u} = \mathbf{(G^T G + \lambda I)^{-1} G^T (w - f)} \qquad (6)$$

w is reference trajectory vector. The elements of **w** are represented as:

$$\begin{cases} w(t) = y_m(t) \\ w(t+k) = \alpha w(t+k-1) + (1-\alpha) r(t+k) \\ k = 1, \ldots, N \end{cases} \qquad (7)$$

α is a parameter between 0 and 1.

4.2 Compensator at the feedback channel

The objective of the compensator at the feedback channel is to reduce the effect of time delay and data loss occurring in the feedback channel, i.e. the feedback signal compression, by means of the history data stored at the buffer. It is required to separate the feedback signal from the control action in order to compensate the influence purely at the feedback channel.

In the prediction (Equation 5) only **f** involves the feedback signal. Equation 3 is rewritten as:

$$f(t+k) = \hat{y}(t\,|\,t) + e(t) + \sum_{i=1}^{N} (g_{k+i} - g_i)\Delta u(t-i) \quad (8)$$

where e(t) is the adjustment value of the prediction model associated with the feedback, and is defined as:

$$e(t) = \beta\big(y_m(t) - \hat{y}(t\,|\,t)\big) \quad (9)$$

β is a parameter between 0 and 1 to adjust the effect of the feedback value. If β is 1, Equations 3 and 8 become identical.

In the control law (Equations 6 and 7), *w(t)* includes the feedback signals and can be rewritten as:

$$w(t) = \hat{y}(t\,|\,t) + e'(t) \quad (10)$$

where $e'(t) = y_m(t) - \hat{y}(t\,|\,t)$

When the data loss occurs and/or the feedback signals do not arrive on time because of the time delay, it is assumed that the prediction value is equal to the measured value, then e(t) and e'(t) in Equations 8 and 10 can be set to zero. The control actions purely rely on the model prediction. Therefore, Equations 8 and 10 become:

$$f'(t+k) = \hat{y}(t\,|\,t) + \sum_{i=1}^{N} (g_{k+i} - g_i)\Delta u(t-i)$$

$$w'(t) = \hat{y}(t\,|\,t) \quad (11)$$

Assuming the period of the data loss is *D* (number of discrete time steps), consequently, the data buffer at the feedback channel preserves the history data, and the accumulated error can be expressed as:

$$\sum_{i=1}^{D} e(t-i) \quad (12)$$

When the transmission is back to normal, e(t) in Equation 8 can be re-calculated as:

$$e(t) = \beta(y_m(t) - \hat{y}(t/t)) + \beta\sum_{i=1}^{D} e(t-i)$$

or

$$e(t) = \beta\sum_{i=0}^{D}\left[y_m(t-i) - \hat{y}(t-i\,|\,t-i)\right] \quad (13)$$

The compensation has been added in Equation 13. There is no compensation for e'(t) and for the reference trajectory.

4.3 Compensator at the feed-forward channel

The objective of the compensator at the feed-forward channel intends to reduce the effect of the control signals blank caused by the Internet transmission. Equation 6 shows that **Δu** is a vector composed of the future control increments, whose size is equal to the control horizon. Actually, only the first control increment, however, is taken into action, the rest of them are not in use. Therefore, it is possible to use the rest of the control signals to deal with the transmission data loss and time delay.

Defining the control increments vector as:

$$\mathbf{\Delta u} = \left[\Delta u(t) \quad \Delta u(t+1) \quad \cdots \quad \Delta u(t+m-2) \quad \Delta u(t+m-1)\right]^T \quad (14)$$

When the data loss and time delay occur, the previous control vector will be used to control the process by shifting the vector one step forward, which can be written as:

$$\mathbf{\Delta u} = \left[\Delta u(t+1) \quad \Delta u(t+2) \quad \cdots \quad \Delta u(t+m-1) \quad 0\right]^T \quad (15)$$

The control increment taken into action will be *u(t+1)* and the last element of the vector is filled with zero. In the remote side the controller will adopt the latest available signals for its calculation, and keep sending the latest control action to the local side. Once the transmission recovers all the control actions will be received by the local side and those, which are out of date, will be simply omitted.

Ideally, the control action pushes the process to the right direction so that the effect of the control signal blank can be reduced. However, it may lead toward serious problems such as process unstable because of the mismatch between the prediction model and the process and/or the heavy process noise. This problem can be solved through the tuning of the control horizon. In the worse case, the control horizon can be set as one, so that the control signal will be maintained at a fixed value. The control system is degraded into an open control or manual control operation.

5. SIMULATION STUDY

The objectives of the simulation study are to investigate the effect of the Internet time delay and data loss on the control system and to evaluate the performance of the two compensators at the feedback and feed-forward channels. The major benefit of this simulation study includes: (1) isolating the control issues from the Internet communication; (2) amplifying the frequency of the Internet time delay and data loss; (3) providing an identical circumstance for the evaluation. The set-point step change and the step disturbance have been introduced in the simulation in order to assess the control system performance.

5.1 Design of the simulation

The simulation study is conducted in the Matlab/Simulink environment. The system structure is shown in Fig 3, including two compensators, two delay elements, a DMC, and a process model. The process model is stable. The sampling interval Ts is chosen as 1 second, the process variable was collected at the same rate. In order to provide an identical simulation circumstance for various simulation tasks, an identical time delay pattern was employed at both the feedback and feed-forward channels, which was randomly generated. Fig 4(a) illustrates the feedback delay pattern; Fig 4(b) shows the feed-forward delay pattern. In the simulation study, the prediction horizon p is chosen as 10; the control horizon m 5; the reference trajectory parameter, α, 0.7; the parameter β 1. The set-point step change is 1, and the step disturbance is 0.5.

There are four proposed scenarios: the time delay and data loss do not exist, only exist at the feedback channel, only exist at the feed-forward channel, and exist at both channels. Corresponding to the real world, the first scenario refers the ideal situation, the second one refers Asymmetrical Digital Subscriber Lines (ASDL) communication and the feed-forward channel obtains a high bandwidth; the third one refers ASDL communication and the feedback channel obtains a high bandwidth; the last one refers to the symmetrical communication.

5.2 Simulation Result

Fig 5 shows the simulation results for the scenario, in which the time delay and data loss only exist at the feedback channel. The first disturbance is caused by the set-point step change, the second by the step disturbance. Since the simulation circumstance is identical to various simulation tasks, it is assumed that the differences in the responses are purely produced by the feedback delay and data loss, and the employment of the compensator. As the result, the feedback compensator can significantly reduce the influence caused by the set-point step change and the step disturbance. The difference between the one with a compensator and the one with no delay is still obvious.

Fig 6 gives the simulation results for the case, in which the time delay and data loss only exist at the feed-forward channel. The time delay and data loss causes the process variable oscillation, which potentially leads the process towards unstable. The effect in the response with the compensator has been dramatically reduced in the set-point step change and the step disturbance. However, the effect has not been fully compensated.

Fig 7 represents the simulation results for the case in which the time delay and data loss exists at both channels. As expected, outputs become worse (more oscillation and overshoot), although they finally reach a stable point. The response with the compensators maintains the performance at an accepted level.

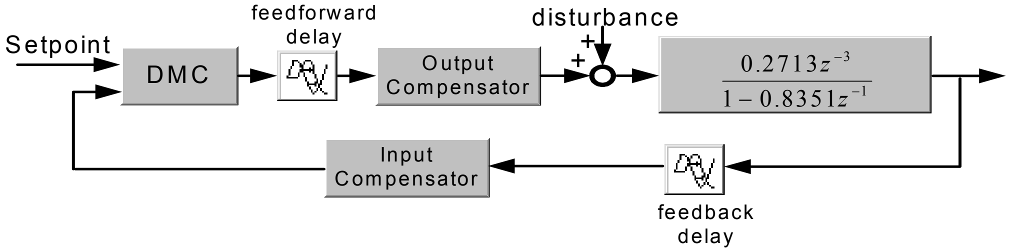
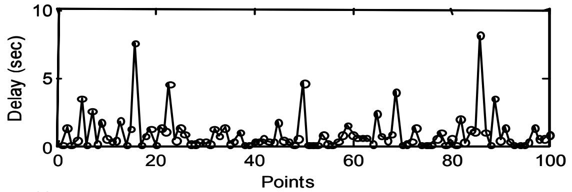
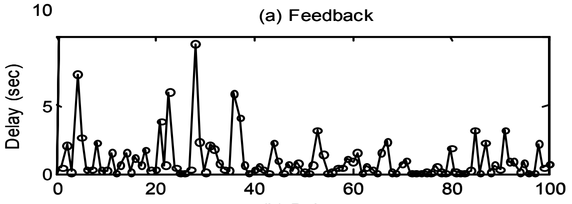


Fig. 3. Simulation structure.



(a) Feedback



(b) Feedforward

Fig. 4. Input and Output delay pattern.

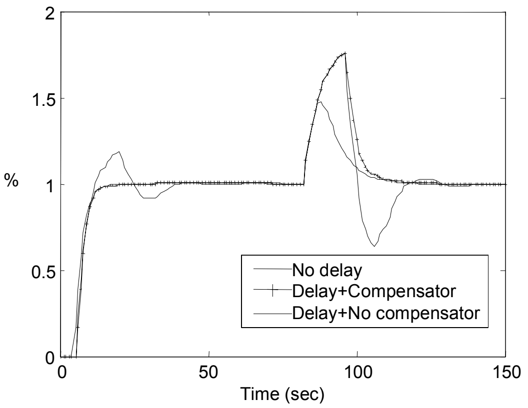


Fig. 6. Comparison of feed-forward delay effect.

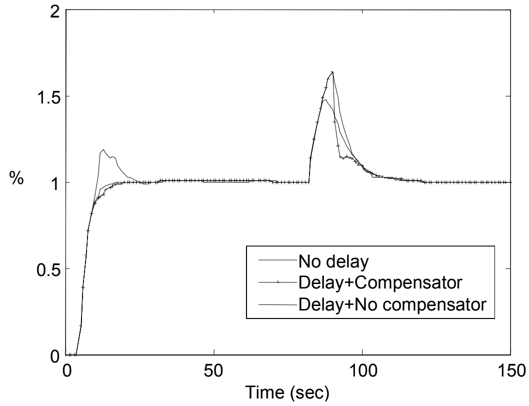


Fig. 5. Comparison of feedback delay effect.

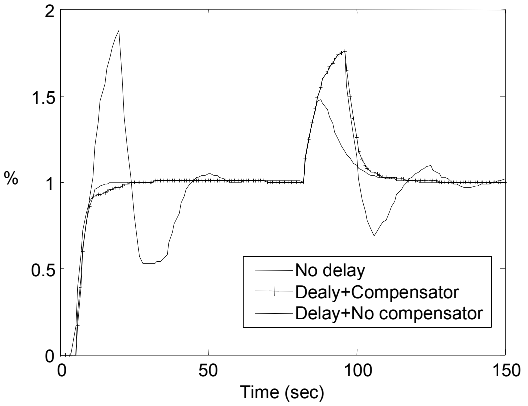


Fig. 7. Comparison of feedback plus feed-forward delay effect.

6. CONCLUSIONS

The conventional discrete control structure is not suitable for Internet-based control systems since it does not consider the Internet transmission features such as uncertain time delay and data loss. In order to handle the Internet transmission features, a novel control structure has been proposed to offer a solution for Internet-based control systems. Taking advantage of the new control architecture, two compensators have been designed to compensate the effect of the Internet time-delay and data loss at the feedback and feed-forward channels. A simulation study has been conducted to evaluate the control architecture and two compensators. The simulation results show that the compensators in the new architecture can significantly reduce the effect of the Internet time-delay and data loss. Another interesting finding is that the feed-forward time delay and data loss seem to cause more serious influence to the control performance, and is more difficult to be compensated in the controller design. Therefore, the feed-forward channel is desired to give a high bandwidth if possible.

NOMENCLATURE

b_i.	bandwidth of the ith link
C	speed of light
D	period of data loss
$d_L(k)$	a time-dependent term in the Internet time delay
d_N	a time-independent term in the Internet time delay
$e(t)$	adjustment value of the prediction model
$e'(t)$	adjustment value of the reference trajectory
f	system free response without the time delay and data loss
f'	system free response with the time delay and data loss
$\boldsymbol{f}$	vector of f
$g_i(i=1,\ldots,N)$	process output for a step input
$\boldsymbol{G}$	system dynamic matrix
I	identity matrix
k	instant
l_i	the ith length of link
m	control horizon
n	number of nodes
N	process horizon
p	prediction horizon
r	set-point
$T_d(k)$	Internet time delay at instant k
$t_i^L(k)$	delay caused by the ith node's load
t_i^R	routing speed of the ith node
T_s	sampling interval
Δt	Tolerant period of sampling time
Δu	increment of input variable
$\boldsymbol{\Delta u}$	vector of Δu
w	reference trajectory values
$\boldsymbol{w}$	vector of reference trajectory
y	output variable
$\hat{y}$	estimated output variable
y_m	measured output variable
$\boldsymbol{\hat{y}}$	vector of $\hat{y}$
α	parameter between 0 to 1
β	parameter between 0 to 1
Superscripts T	transposition of matrix

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