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DESIGNING OF A NEW ONLINE TIME DELAY OBSERVER AND ITS APPLICATION IN UNKNOWN TIME VARYING DELAY ESTIMATION ON WIRELESS SENSOR NETWORKS (WSNs)

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Abstract- In this paper, a novel observer has been designed for the online estimation of time delay in SISO-LTI continuous time systems with unknown and time variant delay in the control input. It is obvious that Laplace transfer function of a delayed system includes a time delay factor. In this article, it is assumed that the only unknown and time variant parameter in the system is the very system's time delay parameter. The main idea used in designing the proposed observer is based on the establishment of duality principle between controller and observer, such that a direct adaptive controller structure (MRAS) is indirectly used for designing an estimator. For this, the main sections in an MRAS control system are organized the way that designing the controller will lead to designing the delay estimator in the dual problem. In fact, adaptation law in designing the controller will express the same estimator mechanism in the dual problem. Also, in designing the estimation mechanism, the two methods, one based on Lyapunov Theory and the other based on MIT rule, are used. Finally, simulation results on a Wi-Fi network as a benchmark system, show desirable performance of the proposed estimator in dealing with time varying and uncertain delays.

Keywords: Time Varying Delay, Estimation, Duality Principle, Adaptation Law, Networked Control System (NCS), Wi-Fi Network.

I. INTRODUCTION

Controlling delayed systems is among the issues of the day in the world of Control Engineering. The existence of delay in most real and manmade systems has attracted the attention of many researchers to this issue. The importance of this issue arises from the fact that existence of delay in the control loop is accompanied by the system divergence from the desirable performance, and if the necessary preparations are not considered, it may even lead to system instability. Since inherent delay is an inseparable component of a delayed system, considering delay in the controller design process is the only strategy in encountering this issue. Even if the open loop system could be modeled without any delay, this point should be kept in mind that the closed loop control process, i.e. measuring, decision making and reaction of the controller, causes, by itself, a delay in the plant input; a delay that can also be affected by the varying environment. Time delay systems introduce a class of systems with infinite dimension, which are related to mechanisms such as dispersion, transmission, traffic, exhaustion, flexibility, inertia and other factors that are created after time drop-off.

Generally, delayed systems, from point of time delay certainty and variability, are categorized to four groups:
- Systems with known and time invariant delay,
- Systems with known and time variant delay,
- Systems with unknown and time invariant delay,
- Systems with unknown and time variant delay.

Each of which appears in different systems. In the fourth group, discussing a control algorithm which is capable of fulfilling stability or tracking performance is of great importance. In general, delay may exist in the state vector or in the input, and in this article, time delay means the delay in control input. In most real systems, time delay affects the system performance either inherently or under the impression of environmental conditions. The problems which mainly emerge in the closed loop control process of delayed systems are caused by the following [1]:
- The effect of the disturbances is not felt until a significant time has expired.
- The effect of the control signal takes some time to be felt in the controlled variable.
- The control strategy that is applied based on the actual error tries to improve a behavior that originated sometime before.
- Since system equations are nonlinear in relation to time delay parameters, sensitivity of control characteristics to these parameters is relatively high, therefore, researchers, considering the uncertain nature of time delay, usually look for robust designing.
- Change of open loop transfer function time delay in closed loop control systems leads to phase margin change and gain margin indirect change too; this may lead to closed loop system instability or may decrease relative stability, and hence cause transient response characteristics to become undesirable.

Considering that the system behavior is nonlinear, in relation to the delay factor, by delay change over time, designing technics for making appropriate control reaction in this situation gets more complicated because the designer will also face a time variant system (certain or uncertain). When delay is time varying and unknown, it is often dealt with as a parameter with uncertainty, thus the designing robustness against the change of this parameter should be discussed. Robust control always provides appropriate control strategies for parametric uncertainties [2, 3], but if in particular these uncertainties change slowly, adaptive control would definitely be a more appropriate option.

An important subdivision in indirect adaptive control systems is the plant estimator. In this paper, it is assumed that the only unknown parameter of the system is its time delay. In this research, In the discussion of the estimation of the time delay parameter, a new method is proposed with a relatively high speed and accuracy.

Further in this section, in subsection *I*(*A*), a brief history of what has been done in this regard so far is presented, and in subsection *I*(*B*), wireless networked control systems are focused on. In section II, the structure of the plant is introduced, and then in section III, designing the proposed estimator, for estimating time varying delay, is presented. Finally, in section IV, the simulations results for a sample system are shown, and in section V, performance of the proposed estimator is analyzed and concluded.

A. Research Literature

The main studies made on systems with time-varying delay are divided into three general categories:

- *Category 1* (Identification and Estimation of the Delay): The difficulty of time delay identification comes from the fact that the process model, in relation to delay parameter, is nonlinear.

Based on the articles studied in [4], delay identification methods are divided to four groups: (a) time delay approximation methods, (b) time delay explicit parameter methods, (c) area and moment methods and (d) Higher-order statistics methods.

Several methods of this categorization have been presented in articles [4, 11], such that in case of adaptive control and real time control, methods of groups (a) and (b) are mainly used. Particularly, for time varying delay estimation in LTI systems, many articles have been published [12, 19].

- *Category 2* (Criteria Presented for Stability and Robust Stability): Generally, time delay in open loop systems is a non-minimum phase factor.

It has been proved in many studies that control loops stability, at the presence of delay, is too sensitive to time delay parameters, so this has made researchers to try hard to present reliable criteria for creating a safe stability margin, in the area of designing controllers for such systems [20, 26]. Also, particularly for LTI systems with uncertainty in time delay factor, a lot of effort has been put on presenting criteria for guaranteeing robust stability [27, 30].

- *Category 3* (Control Methods Presented with Goals like Tracking): The importance of controlling systems with time varying delay, provoked researchers to also design, for satisfying the supreme control purposes such as reference input tracking, controllers which are acceptably robust and adaptable against variations of the sensitive time delay parameter. Some of these controllers are as follows: Robust Controllers [30, 33], Fuzzy Controllers [34], Predictive Controllers [34, 39], Sliding Mode Controllers [40, 41], Optimal Controllers [42, 44]. In particular, for LTI systems with unknown and time varying delay, the presented controllers are mostly of adaptive type [45, 50].

B. Networked Control Systems (NCSs) and Wireless Sensor Networks (WSNs)

Networked control systems (NCSs) are spatially distributed systems in which actuators, controllers, and sensors exchange input-output data through a shared some digital communication networks. NCSs have been applied to many engineering systems such as wireless sensor networks (WSNs), remote control problems, internet communications, traffic control systems, and automatic aerial vehicles. Especially, wireless networked control systems (WNCSs) have been increasingly applied in different issues and many applications.

As an alternative solution to wired Networked control systems, wireless networked control systems, are considered as elementary solutions of NCS applications because of their simple structure and portability. However, the reliability and real time performance of WNCSs are lower than for wired NCSs because with wireless networks, the sizes of network delays suddenly change over time owing to the dynamic state variation of wireless networks. It is generally known that even a very small time delay in control loops can make the whole system oscillating or unstable, and it is obvious that fluctuating time-varying delays severely reduce the performance and stability in WNCSs.

In order to deal with the network delays, different control schemes for WNCSs are suggested; These include fuzzy control, model predictive control, robust control, optimal control, smith control and adaptive control. When constructing these control schemes, it is necessary to identify the network unknown delays. And, of course, for identification, it is necessary that the time delay is continuously observed [51]. Figure 1 shows the closed loop structure of WNCS over the Wi-Fi network in the presence of the controller.

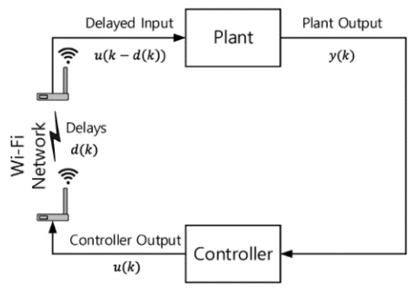


Figure 1. Structure of WNCS over Wi-Fi network [51].

II. PROBLEM STATEMENT

The plant in this research is an LTI and stable system (BIBO Stable). State space equations and Laplace transfer function of the assumed system are in the form of following:

$$\begin{cases} \dot{X}(t) = A_g X(t) + B_g u(t - d(t)) \\ y(t) = C_g X(t) \end{cases} \quad (1)$$

$$P(s) = G(s) e^{-d(t)s} \quad (2)$$

which t is the variable of real time domain, $X(t) \in R^n$ is the state vector of the system, scalars $u(t)$, $y(t)$ are control input and plant output, respectively, and A_g, B_g, C_g are the constant matrices with appropriate dimensions. S is the variable of Laplace domain and $P(s)$ is the system transfer function, in which $G(s)$ is obtained from Equation (3);

$$G(s) = C_g (sI - A_g)^{-1} B_g \quad (3)$$

The $e^{-d(t)s}$ factor is the Laplace transfer function of time delay. In Equations (1) and (2), $d(t)$ is the same input time delay of the system, which in this study is assumed to be time variant and unknown, and it is also assumed that the considered system, except the time delay factor, is a linear and time invariant system.

Generally, in control problems related to such systems, the following assumptions for time delay are always in place [52]:

1. $0 \le d_{\min} \le d(t) \le d_{\max} \le \infty$
2. $-\infty < d(t)^{\bullet} < 1$

The main purpose in this research is designing a fast and accurate time delay estimator for an unknown and time varying delay.

III. ESTIMATING UNKNOWN AND TIME VARYING DELAY USING PROPOSED ESTIMATOR

In general, estimator is a dynamical system which, using the real system input and output, estimates one or more unknown parameter(s) of the real system. Particularly, in this study, one of the important goals is designing an estimator system which, using the input and output of a system with Equation (2), the only unknown and time variant parameter of the system is identified in online mode and with an acceptable speed and accuracy. A simple block diagram of the system and delay estimator is shown in Figure 2. As can be seen in Figure 2, estimator inputs are the same input and output of the real system, and the only output of estimator is an estimation of time delay $\hat{d}(t)$.

In this study, indirectly and using a trick, the structure of direct adaptive controller (MRAS) has been used to design an estimator. Figure 3(a) shows the general structure of a direct adaptive controller [53]. This control block diagram, $u_R(t)$ is the same reference input of the desired output. Block diagram of Figure 3(b) is particularly designed for this study.

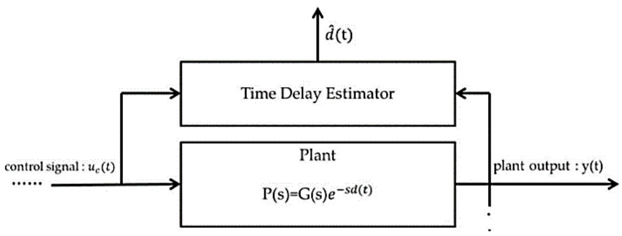


Figure 2. General diagram of the time delay estimator

According to Figure 3(b), considering real system $P(s)$ as the reference model and system $G(s)$ as the controlled system, and considering that the estimation of time delay factor, $e^{-\hat{d}(t)s}$ is an adaptive controller with the adjustable $\hat{d}(t)$ parameter, authors will look for designing an adaptation law, such that by adjusting the only controller parameter (which is an estimation of time delay), system output $G(s)$ converges towards the real system. The purpose of designing this block diagram is just to achieve an estimation of the real system time delay, and Designing controller is a separate process on which the authors have not focused in this study, therefore, the controller existing in block diagram of Figure 3(b) is shown by $C'(s)$ Since the purpose followed in this block diagram is delay estimation, $C'(s)$ will be a semi controller, and its output is also a semi control signal shown by u'_C. In fact, the main output of this block diagram will be the same output of adaptation law block, which is the same time delay estimation. It should be noted that in Figure 3(b), u_C plays the role of reference input, which in fact is the same control input of the real system $P(s)$ in the main control process (signal created by the main controller), and SYS1 is the reference model (in fact the system under control $P(s)$), SYS2 is the adaptation law block (in fact estimator mechanism), SYS3 is the semi plant (in fact the same real system without delay factor or $G(s)$), and SYS4 is a semi controller (In fact, an estimate of the delay factor).

Lyapunov Function and MIT rule are the two common methods for computing adaptation law, presented in [53]. In this study, designing the adaptation law, using both methods, will be focused on. Considering the fact that semi controller $C'(s) = e^{-\hat{d}(t)s}$ could not be directly used in designing and computing adaptation law, alternatively, first (second or higher) order Pade approximations may be used as a semi controller structure.

In this study, first order Pade approximation is used. It is obvious that for increasing the precision of estimation, higher order approximations may be used. Therefore, Equation (4) will show the structure of $C'(s)$ semi controller.

$$C'(s) = \frac{1 - \frac{\hat{d}}{2}s}{1 + \frac{\hat{d}}{2}s} \quad , \quad \hat{d} = \hat{d}(t) \quad (4)$$

A. First Method: Using Normalized MIT Rule in Designing Time Delay Estimation Mechanism

According to what has been presented in [53], adaptation law in MIT method is expressed using Equation (5).

$$\dot{\theta}(t)=\gamma e(t)\Phi(t) \tag{5}$$

where, $\theta(t)$ is the vector of adjustable parameters of controllers, γ is the adaptation gain, $e(t)$ and $\Phi(t)$ vector are computed respectively through Equations (6) and (7).

$$e(t)=y(t)-y_m(t) \tag{6}$$

$$\Phi(t)=\frac{\varphi(t)}{\alpha+\varphi(t)^T\varphi(t)}\ ,\ \varphi(t)=-\frac{d}{d\theta}\{e(t)\} \tag{7}$$

where, $y(t)$ is the output of $G(s)$ system and $y_m(t)$ is the output of $P(s)$ system, and α is a constant number larger than zero. Considering Figure 3(b), error signal $e(t)$ could be written as Equation (8).

$$e(t)=y(t)-y_m(t)=C'(p).G(p)\ .u_C(t)-y_m(t) \tag{8}$$

Assuming that $\theta=\theta(t)=\hat{d}(t)$ and substituting Equation (4) in Equation (8), error signal will be equal to Equation (9).

$$e(t)=\left(\frac{1-\frac{\theta}{2}p}{1+\frac{\theta}{2}p}\right).G(p)\ .u_C(t)-y_m(t) \tag{9}$$

It should be noted that in the above equations, p is a derivative operator, i.e., $p=\frac{d}{dt}\{.\}$. Using Equation (7), vector $\varphi(t)$ is calculated as follows:

$$\varphi(t)=-\frac{d}{d\theta}\{e(t)\}=-\frac{p}{\left(1+\frac{\theta}{2}p\right)^2}G(p).u_C(t) \tag{10}$$

which could be rewritten as Equation (11).

$$\varphi(t)=-H(p).G(p).u_C(t) \tag{11}$$

where, $H(p)$ is defined according to Equation (12).

$$H(p)=\frac{p}{\left(1+\frac{\theta}{2}p\right)^2} \tag{12}$$

Since θ is unknown, for maximizing the estimation speed, the value of θ parameter in $H(p)$ is assumed to be $\theta_{\min}$ or the same $d_{\min}$. Eventually, considering that $\varphi(t)$ is scalar, $\Phi(t)$ forms according to Equation (13).

$$\Phi(t)=\frac{\varphi(t)}{\alpha+\varphi(t)^T\varphi(t)}=\frac{\varphi(t)}{\alpha+\varphi(t)^2} \tag{13}$$

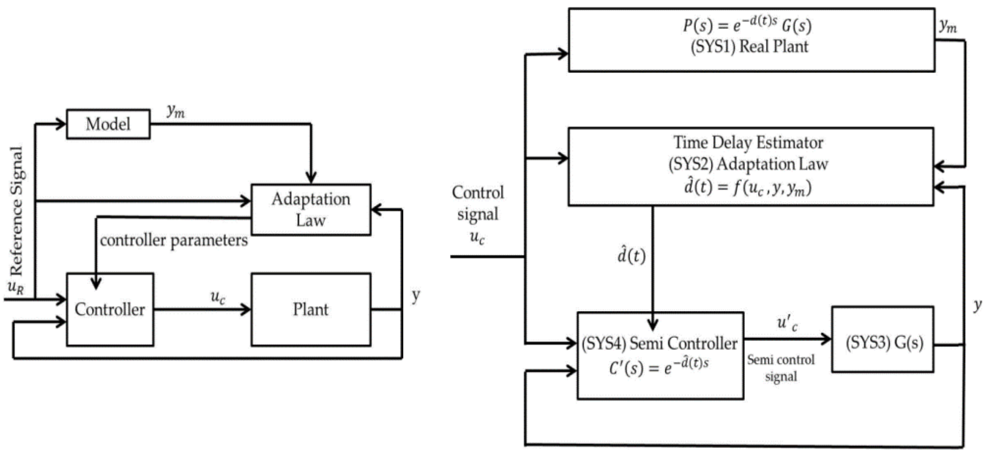
Therefore, according to Equation (5), we have:

$$\dot{\theta}(t)=p.\theta(t)=\gamma e(t)\Phi(t) \tag{14}$$

As a result, adaptation law, for adjusting semi controller parameter, is calculated according to Equation (15).

$$\theta(t)=\frac{\gamma}{p}e(t)\Phi(t)=\frac{\gamma}{p}e(t)\frac{\varphi(t)}{\alpha+\varphi(t)^2} \tag{15}$$

It should be noted that Equation (15) is expressive of the estimator mechanism proposed by MIT method. Assuming that the operator p (in time domain) and the variable s (in Laplace domain) are equivalent, Figure 4 is indicative of the proposed estimator block diagram, using MIT method.



(a) (b)

Figure 3. (a) General structure of MRAS adaptive controller [53], (b) General structure of the estimator used in this study

B. Second Method: Using Lyapunov Stability Theory in Designing Time Delay Estimation Mechanism

According to [53], the general designing process in this method is such that first, the error dynamic equation $\dot{e}(t)$ is calculated, then, defining a suitable Lyabunov function, this equation is tried to become stable, independent of inputs and outputs.

It should be noted that the mentioned Lyapunov function is defined with the purpose of minimizing some extra terms in error differential equations, and adaptation law is also extracted from Lyapunov function derivative, such that building this law should always cause Lyapunov function derivative to be negative (semi) definite.

According to Figure 3-b and by defining $R(s)=G(s).U_c(s)$ Equations (16) and (17) are respectively expressive of $G(s)$ and $P(s)$ system output in Laplace area.

$$Y(s)=e^{-\hat{d}(t)s}.R(s) \tag{16}$$

$$Y_m(s)=e^{-d(t)s}.R(s) \tag{17}$$

where, $U_c(s)$, $Y(s)$ and $Y_m(s)$ are respectively Laplace transfer of $u_C(t)$, $y(t)$ and $y_m(t)$ signals. Assuming that $\hat{d}(t)=\theta(t)=\theta$ is a delay estimation and $d(t)=\theta_r(t)=\theta_r$ is the delay real value at any moment, considering first order Pade approximation for time delay factor, Equations (16) and (17) are respectively rewritten as follows:

$$Y(s)=\frac{1-\frac{\theta}{2}s}{1+\frac{\theta}{2}s}.R(s) \tag{18}$$

$$Y_m(s)=\frac{1-\frac{\theta_r}{2}s}{1+\frac{\theta_r}{2}s}.R(s) \tag{19}$$

Considering the error definition in Equation (6) and using Equations (18) and (19), easily and with a little computation, error dynamic equation will be obtained according to Equation (20):

$$\dot{e}(t)=-\left(\frac{2}{\theta}-\frac{2}{\theta_r}\right)y(t)+\left(\frac{2}{\theta}-\frac{2}{\theta_r}\right)r(t)-\frac{2}{\theta_r}e(t) \tag{20}$$

which $r(t)$ is the inverse Laplace of $R(s)$. Considering what was stated in the second section of the paper, θ_r should always be positive, so a positive definite Lypunov function should be defined such that error differential equation, independent from $r(t)$ and $y(t)$, to be always stable, and

Error tends to zero. Considering these issues, a Lyapunov function is taken into account according to Equation (21).

$$V(e(t),\Delta\theta)=\frac{1}{2}e(t)^2+\frac{1}{2\gamma}\left(\frac{2}{\theta}-\frac{2}{\theta_r}\right)^2 \tag{21}$$

which, γ is the adaptation gain and $\Delta\theta$ is a function of θ and θ_r difference. It is obvious that if this Lyapunov function is minimized, first, error will be minimized and secondly, delay estimation will tend to the real error value. Easily and with a little computation, using Equation (20), the above Lyapunov function derivative, in relation to time, could be written as Equation (22).

$$\dot{V}(e(t),\Delta\theta)=-\frac{2}{\theta_r}e(t)^2+ +\left(\frac{2}{\theta}-\frac{2}{\theta_r}\right)\left(e(t).(r(t)-y(t))\text{-}2\dot{\theta}\frac{1}{\gamma.\theta^2}\right) \tag{22}$$

Considering that θ_r is positive, for $\dot{V}(e(t),\Delta\theta)$ to become a negative (semi) definite function, Equation (23) should be established:

$$\dot{\theta}=\frac{\gamma}{2}\theta^2.e(t).(r(t)-y(t)) \tag{23}$$

By establishing Equation (23), $\dot{V}$ will be the equivalent of Equation (24) and thus, as seen, $\dot{V}$ will be a negative (semi) definite function.

$$\dot{V}(e(t),\Delta\theta)=-\frac{2}{\theta_r}e(t)^2 \tag{24}$$

Considering $\frac{\gamma}{2}=\gamma'$ as a new adaptation gain and using Equation (23), adaptation law for adjusting semi controller could be written as Equation (25). It should be noted that this equation also presents the same delay estimator mechanism.

$$\theta(t)=\int\gamma'.\theta(t)^2.e(t).(r(t)-y(t))dt \tag{25}$$

Assuming that the integrator operator $\int$ (in time domain) and the transfer function $\frac{1}{s}$ (in Laplace domain) are equivalent, Figure 5 is indicative of the proposed estimator block diagram in terms of Lyapunov method. It should be noted that for both block diagrams 3 and 4, the output of the estimator is the $\theta(t)$ signal.

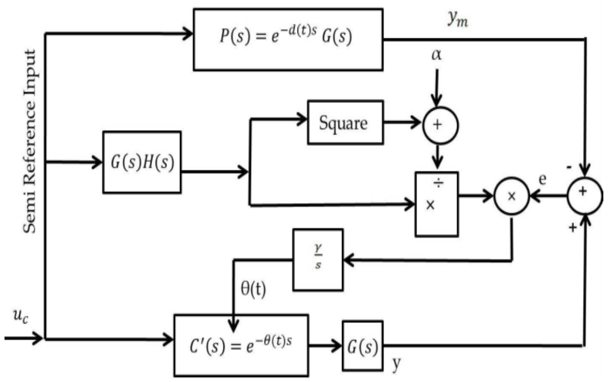


Figure 4. The proposed delay estimator block diagram using MIT method

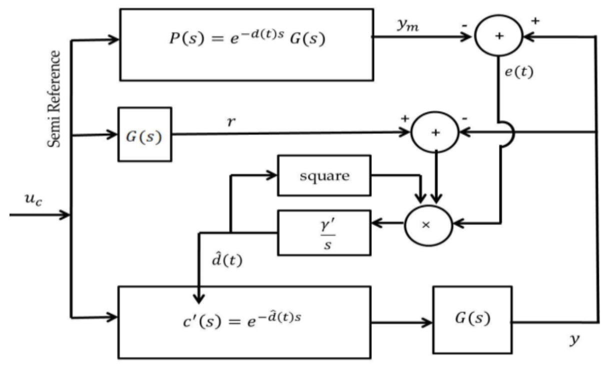


Figure 5. The proposed delay estimator block diagram using Lyapunov Method

IV. SIMULATION RESULTS

In this section, for implementing different simulations and assessing the proposed estimator, a first order system with the following transfer function is selected:

$$P(s)=\frac{1}{1+s}e^{-s.d} \tag{26}$$

where $d=d(t)$ is an unknown and time variant delay. In order to design the delay estimator, the bound of delay variations should be specified, so it is assumed that $d_{\min}=0[\sec]\le d\le d_{\max}=1[\sec]$.

For example, in Figure 6, the effect of sinusoidal time variant delay and periodic pulse are shown on a sinusoidal input.

As can be seen, the input sinusoidal signal undergoes a sever change and loses its standard form after passing through the delayed block. In such condition, also some challenges will definitely appear in the control issues such as reference signal tracking issues.

In Figure 6(a), the input signal equals $u(t)=5\sin(\pi t)$, as shown in Figure 6(a). The time delay signal exerted for forming Figure 6(b) equals $d(t)=0.5+0.45\sin(2\pi t)$, and in forming Figure 6(c), time delay signal consists of a two-level periodic pulse wave (a level with the value of 0.05 and a level with the value of 0.95, respectively) with a period of 1 second and a pulse width of half a second.

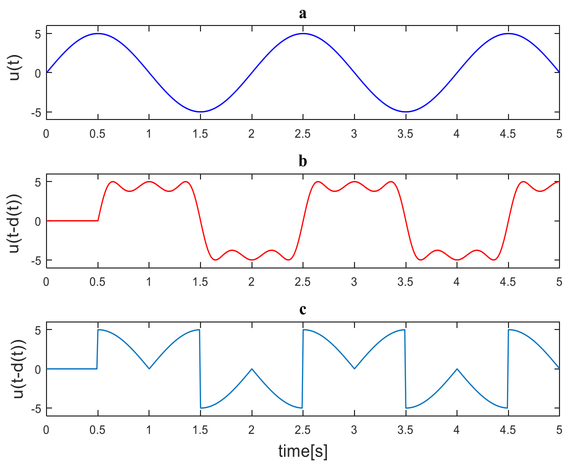


Figure 6. Comparing the input signal before delay exertion and after passing through the delayed block
(a) delay-free input signal, (b) input signal with sinusoidal delay
(c) input signal with periodic pulse delay

Continue, the simulation, with respect to estimation of the two different time delay results, are presented for a system with equations presented in (26). It should be noted that, for identification, the system input signal is considered to be sinusoidal with equation $u(t)=5\sin(\pi t)$. In all figures and tables, the two proposed methods (method 1 and method 2) and an efficient method (presented in [18]) are compared with each other.

Figure 7 indicates the performance of the proposed estimators (1) and (2) and also the performance of the method of presented in [18], in the sinusoidal time delay estimation. In this figure, the real delay of the system equals $d(t)=0.5+0.45\sin(2\pi t)a$. In sections a, b, c of Figure 7, the performance of the second proposed estimator, the first proposed estimator and the estimator presented in [18] are observed, respectively. To accurately compare performance of these estimators, the mean of squares of estimation error (MSE) for all three estimators are calculated, which are shown in Table 1.

Figure 8 also indicates the performance of these estimators in estimating periodic pulse time delay. In this figure, the real system delay equals a two-level periodic pulse wave (a level with the value of 0.05 and a level with the value of 0.95, respectively) with a period of 1 second and a pulse width of half a second. In sections a, b, c of Figure 8, the performance of the second proposed estimator, the first proposed estimator and the estimator proposed in [18] are respectively observed. For this type of delay also, to accurately compare the performance of the estimators, the mean of squares of estimation error (MSE) for all three estimators was calculated, the results of which are presented in Table 2. According to what presented in figures and Tables, it could be said that the accuracy of the second proposed estimator is higher than that of the two others.

It should be noted that if the uncertainty bound for delay parameter is considered larger, the accuracy of the second proposed estimator (Based on Lyapunov theory) would be, by a lot of difference, higher than that of the two others, because this estimator, contrary to the two others, is designed independent of time delay changes average; that is the second estimator is somehow designed to be more robust.

This is completely observable in Figure 9. Performance of all three estimators, for a Multi-level stepping time delay, could be observed in this figure. As can be seen, as the uncertainty bound for time delay gets larger, the performance supremacy of the second proposed estimator, in comparison to the two others, becomes clearer and more prominent. Also, accuracies of these three estimators for this type of time delay are compared in Table 3.

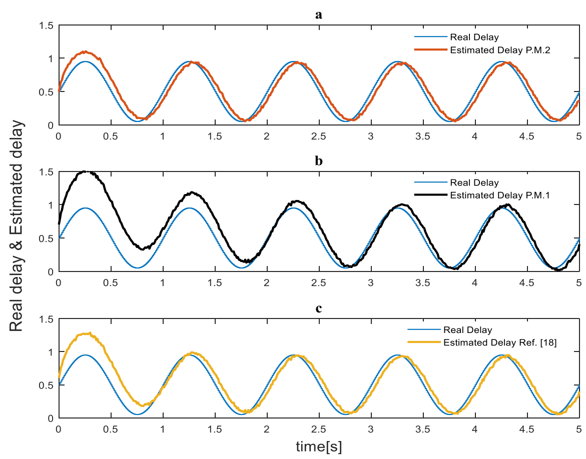


Figure 7. Comparing the two proposed estimators and the estimator presented in [18] in sinusoidal time delay estimation problem

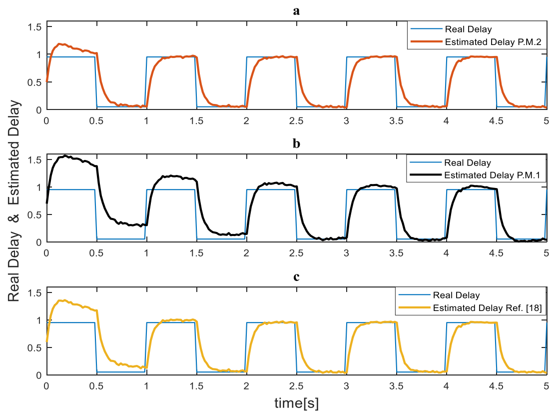


Figure 8. Comparing the two proposed estimators and the one presented in [18] in the periodic pulse time delay estimation problem

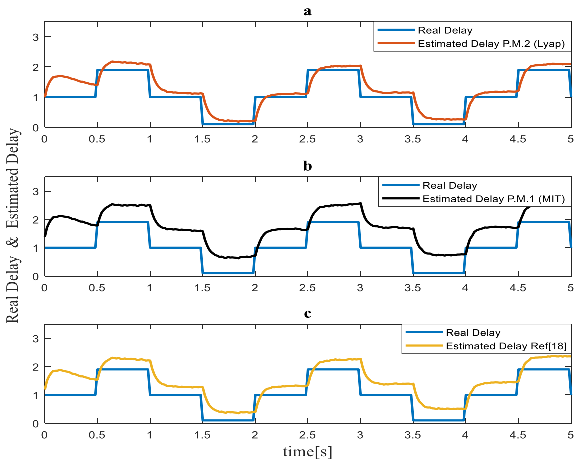


Figure 9. Comparing the two proposed estimators and the one presented in [18] in multi-level stair-shaped time delay estimation

Table 1. Comparing the accuracy of the proposed estimators and the one presented in [18] in sinusoidal time delay estimation problem

Delay Estimator	Mean of Squares of Estimation Error (MSE)
Proposed Method 1 (P.M.1)	0.0540
Proposed Method 2 (P.M.2)	0.0113
The Method Presented in Ref. [18]	0.0222

Table 2. Comparing the accuracy of the proposed estimators and the one presented in [18] in periodic pulse time delay estimation problem

Delay Estimator	Mean of Squares of Estimation Error (MSE)
Proposed Method 1 (P.M.1)	0.1041
Proposed Method 2 (P.M.2)	0.0607
The Method Presented in Ref. [18]	0.0721

Table 3. Comparing the accuracy of proposed estimators and estimator presented in [18] in multi-level stair-shaped time delay estimation

Delay Estimator	Mean of Squares of Estimation Error (MSE)
Proposed Method 1 (P.M.1)	0.4009
Proposed Method 2 (P.M.2)	0.0952
The Method Presented in Ref. [18]	0.1987

V. CONCLUSIONS

A time delay estimator, for a specific class of LLTI systems with varying and uncertain time delay, was presented in this study. It is obvious that in the process of designing indirect adaptive controllers, the plant parameter estimation mechanism is a fundamental element. In this paper, a novel method has been presented for designing a rather fast and accurate estimator. The main idea behind this method is based on the establishment of duality principle between controller and observer. In this study, the structure of the direct adaptive controller (MRAS) has been indirectly used for designing an estimator. Briefly, the main parts in an MRAS control system (including reference model, plant, adjustable controller and adaptation law) are organized the way that designing the controller leads to designing the delay estimator in dual problem.

In fact, adaptation law in designing the controller expresses the same estimator mechanism in dual problem. It should be noted that, for designing estimator mechanism (adaptation law), two methods were used, one based on Lyapunov theory and the other based on MIT rule. Simulations were made on a sample system (WSN), for different types of time delay signal. By using the proposed observers, the plant time delay was estimated with an acceptable speed and accuracy in online mode.

At the same time, simulation results are expressive of the fact that the estimator based on Lyapunov stability theory is rather faster and more accurate, comparing to other methods. Also, for delays with rather larger uncertainty bound, the performance of the second proposed estimator (based on Lyapunov stability theory) is reported to be more desirable, comparing to other estimators. Eventually, it should be noted that for improving the performance of the proposed estimator, higher order Pade approximations, rather than time delay factor, could be used in the process of estimator designing, which will definitely increase the accuracy.

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