

Performance Accretion in Delay Compensation of Networked Control System Using Markov Approach-Based Randomness Estimation in Smith Predictor

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ABSTRACT

By the second decade of the 21st century, there has been a multi-faceted technological development in the field of networked control system (NCS). This progression in NCS has not only revealed its significant applications in various areas but has also unveiled various difficulties associated with it that hampered the operations of networked control system. Network-induced delays are issues that promote many other issues like packet dropout and brevity in bandwidth utilization. In this research article, network-induced delay has been curtailed by using the harmony between Smith predictor and Markov approach. The error estimation of the Smith predictor controller used for the simulation is carried out through a Markov approach which allows the control of the system to operate smoothly by optimizing the control signal. To implement the proposed method, the authors have simulated a third order system in Matlab/Simulink software.

KEYWORDS

Delay Compensation, Markov Approach, Networked Control System, Packet Dropout, PID Controller, Signal-to-Error Ratio, Smith Predictor Controller

INTRODUCTION

In today's perspective the development of science and technology has fetched a wide change in the field of control system. Now-a-days, the control system is not only confined within the structure of the institutional framework, but is performing tasks globally and the network is rooted to do so. This mutual form of control system with network is called networked control system (NCS), elucidated by Yang, (2006), Liu & Wang (2008), and Chow & Gupta, (2009). Wherein, Antsaklis & Baillieul, (2007), and Bemporad et., al., (2010) described that Control is established through the network on the control system components such as reference input, control signals and the output-feedback of the plant is shared through sensors over the network (Kizito et. al., 2020 and Guo et. al., 2010). Networked control systems have been emerged as a major technique for regulating, directing, and commanding modern scientific and industrial systems in a broader form relatively than a conventional control system. Networked control systems have provided a wide variety of effective amenities at the

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ground level such as working up the complexity of wiring, extending work efficiency, ease of system operation, upgradation and maintenance, low cost and reduced space and improves efficiency and accessibility with reduced power requirements (Zelinka & Amadei, 2019; Antsaklis, 2005, and Gao et. al., 2008). Adapted challenges in designing networked control systems encourage all researchers to work in this area such as delay in receiving control signals and output signals, packet dropout, and inappropriate use of channel bandwidth (Yu & Zhang, 2008). Apart from the encouraging approaches of NCS there are certain limitations which constantly gain the attention of the researchers across the globe, like network-induced delay, signal quantization, narrowing bandwidth, packet dropout, communication security are few issues of prime concern (Ghabi et. al., 2018 and Zhang et. al., 2015).

In the past few years, the researchers are constantly trying to improve the NCS sector through various approaches and algorithms. Network-induced time delays performs a significant role for the deprived performance of networked control systems, one of the main reasons differentiating system instability (Wang et. al., 2007, and Zhang et. al., 2016). The various kinds of delay in a networked control system can be illustrated through Fig. 1, representing state dynamics of control system can be defined by state equation of the system as:

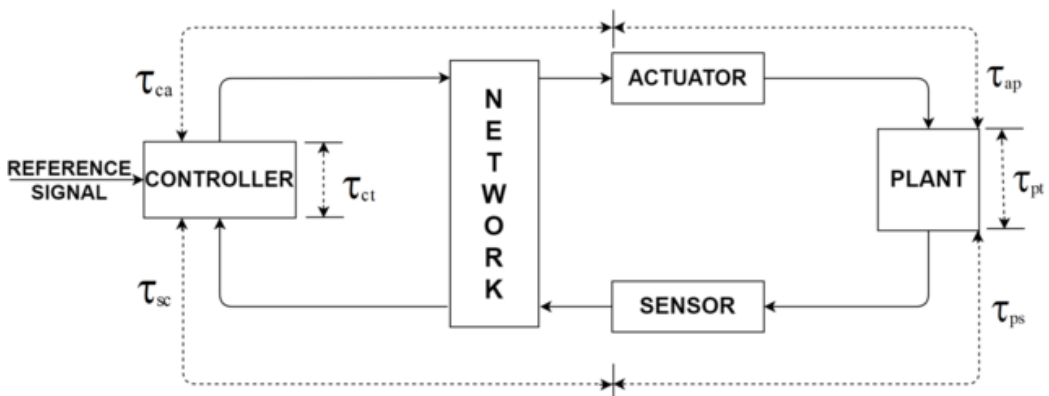
$$x(k+1) = Ax(k) + Bu(k - \tau(k)) \tag{1}$$

where the state vector $x(k)$, is $R^{n \times 1}$, input vector, $u(k)$ is $R^{m \times 1}$, square matrix A & B have dimensions as $R^{n \times n}$ & $R^{n \times m}$ respectively. $\tau(k)$ is the total delay in the system that can be limited as τ_{max} such that $0 \leq \tau(k) \leq \tau_{max}$. Similarly, system output can be expressed as integration of state variables and inputs as:

$$y(k) = Cx(k) + Du(k) \tag{2}$$

where, output vector y is $R^{p \times 1}$, output matrix C is $R^{p \times n}$ and D is transmission matrix having dimensions $R^{p \times m}$.

Figure 1. Delay representation in networked control system



For a feedback loop of networked control system various delays emerge that affect the working of the system. These delays are related as:

$$\tau_{total} = \tau_{sc} + \tau_{ca} + \tau_{ap} + \tau_{pt} + \tau_{ps} + \tau_{ct} \quad (3)$$

the total delay τ_{total} is sum of τ_{sc} , τ_{ca} , τ_{ap} , τ_{pt} , τ_{ps} and τ_{ct} are defined as, delay in receiving signal from feedback sensor over the network to controller, delay in control signal from controller to actuator through network, delay in actuating the control signal at the actuator to plant, delay in evolving processing time at plant unit, delay in acquisition of sensor data by sensor and the delay due to computational time taken by the controller to generate sequence of control signals respectively. Primarily, the network-induced delay provokes the issue of packet dropout and bandwidth congestion leads to system instability (Galli, 2019; Yue et. al., 2005; Wang et. al., 2009; Sharon & Liberzon, 2010; Zhang et. al., 2012; Yan & Xia, 2016). In the development process of networked control systems so far, various researchers have designed NCS, validating network-induced delays and packet dropouts and analyzed system stability and other aspects. Various experiments have performed using Markov chain to design LQG optimal controller and the random delays unveiled in NCS have been validated (Bhuyan et. al., 2012; Zhai et. al., 2013). Xiong & Lam (2009), showed that transitions of Markov chains are modeled as delays in linear systems with discrete-time jump for NCS and proposed a method to design state and output feedback controllers. For a variety of NCSs, an exquisite work in regard to induced-delay and packet dropout has been performed by developing numerous approaches (Omamo et. al., 2020 and Gao et. al., 2008). Over the past few years, researchers in the field of NCS have assayed various techniques to compensate different types of time delays, such as network induced time delays, uncertain time delays, and random time delays to stabilize the system (Zhang et. al., 2011). In NCS, network-induced delays and data packet dropouts occur one-after-another, when the delay-time between the controller-to-actuator through the communication network exceeds the data receiving time or the threshold time, it causes data-packet dropout (Salima et. al., 2018 and Jiang et. al., 2009). Several researchers working in the research area of NCS have catered PID based Smith predictor controller to compensate the delay induced in NCS but found it difficult to cope-up with the randomness in the delay. The focal of this paper lies with the uncertainty of the network-induced delay that causes instability which are challenging to evaluate. For this purpose, in this research article it is proposed that the randomness of induced feedback delay can be estimated through Markov approach in a Smith predictor controller. For this purpose, in this research article a modified Smith predictor controller is proposed wherein, the randomness of induced feedback delay can be estimated through Markov approach in a Smith predictor controller. The other sections of the paper are elaborated as: Section 2 explains the working principle of modified Smith predictor along with its limitations and applications. The procedure to estimate the randomness of induced-delay in feedback channel of networked control system using Markov approach is elucidated in Section 3. In Section 4, simulation results of modified Smith predictor controller is compared with various controllers to evaluate best suited controller to compensate the uncertain delay that augments the system performance, is supported with conclusion in Section 5.

ARCHITECTURAL DEVELOPMENT OF MODIFIED SMITH PREDICTOR CONTROLLER

Markov Approach to Estimate Randomness in Delay

Markov approach is a convenient modeling and exploration technique that have resilient applications in time-domain estimations and reliability analysis. The state transition diagram represents rate of

transition among various possible states of the system that supports to estimate the future state of the system (Wenjua et. al., 2008; Donkers et. al., 2011; Shi & Li, 2015). For the networked control system mentioned in this paper, the Markov approach is used to predict the randomness in delay, Fig. 2 represents the successive depiction of delay estimation in NCS model along with possible state-transition diagram between two states i.e., controller node and sensor node as shown in Fig. 3.

Figure 2. Various delays in networked control system

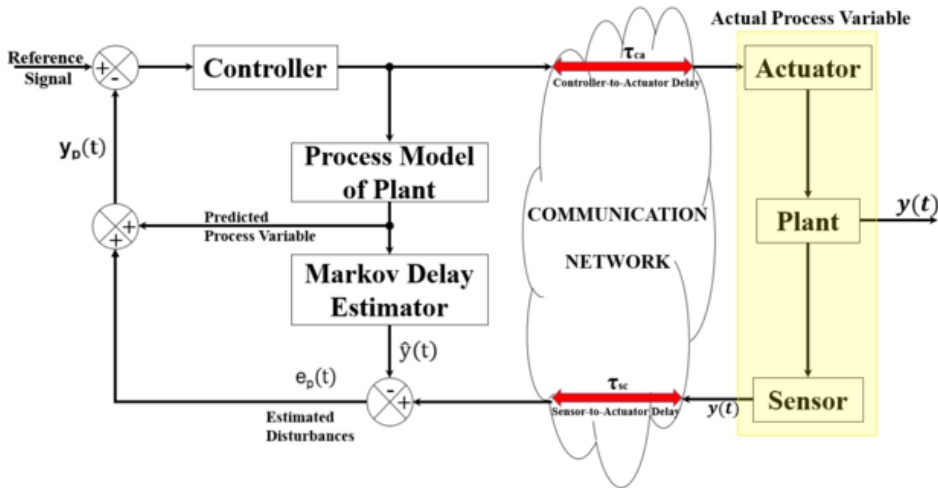
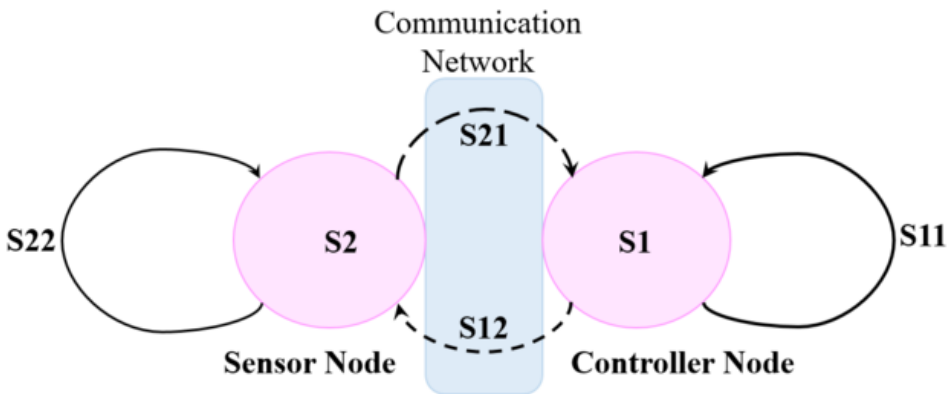


Figure 3. Markov model of induced delay in NCS



For each successful transition between the states i.e., transition from sensor node to controller node can be noted as packet received otherwise it can be regarded as packet dropout. The Markov approach admeasures the likelihood of the system in a specific state, the duration of the occurrence of the state i.e., it estimates the time for which a system spend time in a particular state and count of system transitions among the mentioned states (Costa & Frogoso, 1993; Li et. al., 2009; Mahmoud et. al., 2012). The insertion of communication network affects the system stability and performance through randomness behavior. An algorithm is developed for delay estimation using Markov approach,

is mentioned in Table 1. The sufficient and necessary condition to design the modified Smith predictor controller can be established via modeling the two random delays as two independent Markov chains and comparing with the actual delay in the network to get the optimum control input to the actual plant process (Ma et. al., 2010; Ishido et. al., 2011; Qu et. al., 2016). The notations mentioned in the Table 1 are discussed further in this section.

Table 1. Feedback Delay estimation algorithm using Markov approach

Algorithm for feedback delay estimation in NCS	
Step 1:	Define the state model of the system as, $s_a(t + 1) = A s_p(t) + B u(t)$
Step 2:	Define the output of the plant as, $y_p(t) = C s_p(t)$
Step 3:	Suppose $\tau(t)$ to be the delay introduced between sensor – controller network modelled as Markov Chain
Step 4:	Consider $\alpha(t)$ defines the state of the link between sensor – controller. Such that, If, $\alpha(t) = 0$, means packet is received successfully and $\bar{y}(t) = y_p(t - \tau(t))$ Whereas if, $\alpha(t) = 1$, the packet is lost $\bar{y}(t) = y_p(t - 1)$
Step 5:	The behavior of sensor-controller delay is modelled as: $\bar{y}(t) = (1 - \alpha(t))y(t - \alpha(t)) + \alpha(t)\bar{y}(t - 1)$ Such that, $\pm(t) = \begin{cases} 0, & \text{if X is closed and packet is received} \\ 1, & \text{if X is open and packet is lost} \end{cases}$
Step 6:	The delay will affect the next state of the system. Hence, the controller will be given as: $u(t) = K(\alpha(t), \tau(t))y(t)$ Here, $K(\alpha(t), \tau(t))$ is output feedback controller gain.
Step 7:	To Check the controllability of the system $s(t) = [s_p(t)^T \quad \bar{y}(t - 1)^T]^T$
Step 8:	Modify the system state defined in Step 1 using Step 7 will result to, $s_a(t + 1) = A[s_p(t)^T \quad \bar{y}(t - 1)^T]^T + BK(\alpha(t), \tau(t))\bar{y}(t)$ $s_a(t + 1) = \bar{A}(\alpha(t))s(t) + \bar{B}(\alpha(t))Hs(t - \tau(t))$

To modify the input control signal, Markov approach helps to estimate the delay in the Smith predictor controller that advances the system performance and improves stability of the system.

The dynamics of the system can be represented as state space equation

$$s_a(t+1) = As_p(t) + Bu(t) \tag{4}$$

$$y_p(t) = Cs_p(t)$$

A, B and C are known real constant defined earlier with eq. (1), $s_p(t) \in R^n$, represents present state of the system $s_a(t+1)$ represents future state of the system $y_p(t)$ represents the output vector of the plant and $u(t)$ signifies the control input vector to the plant $\in R^m$.

As it is known that the two types of induced delays occur across the communication network i.e., s-c and c-a delays also called as feedback delays, such that feedback and feedforward delays.

Since random time delay occurs across the network. The two type of delay include s-c and c-a called feedback and feedforward delays. The feedback delays are of prime concern as control inputs are functions of these delays. The delays lead to packet dropout the feedback delays are more important as control inputs are function of feedback inputs. Delays lead to the packet dropout so it is important to cater them carefully so as to ensure the early prediction of the system state and control input for that state (Auxilia et. al., 2020 and Jing et. al., 2007). The Markov chain can be used to model the feedback in the state form and stabilization of the system can be obtained by optimizing the modelled state. Suppose $\tau(t)$ represent the delay of the feedback channel being modelled by Markov chain. As each component of a chain every other component similarly, while designing state of delay using Markov chain delay measured (observed) in the one cycle will affect the future delay measurement, or it can be said that previous state of delay will affect the current delay (Sun et. al., 2010; Postoyan & Netic, 2011). So, $\tau(t)$ can be modelled as homogeneous Markov chain that take values.

$$\bar{X}_2 = \{0, 1, 2, \dots, x_2\}$$

X denotes network switches between s-c, $\alpha(t)$ denotes the state s and $\alpha(t) = [0, 1]$

When X is in $\alpha(t) = 0$, successful reception of the data packet and

$$\bar{y}(t) = y_p(t - \tau(t))$$

Whereas if X is in the state $\alpha(t) = 1$ the packet is lost

$$\bar{y}(t) = y_p(t - 1)$$

The nature of induced delay from sensor-to-controller and data packet dropout is expressed as,

$$\bar{y}(t) = (1 - \alpha(t))y(t - \alpha(t)) + \alpha(t)\bar{y}(t - 1) \tag{5}$$

where,

$\alpha(t) = 0$, implies that network switch (X) is closed and reception of data packet,

whereas,

$\alpha(t) = 1$, implies that network switch (X) is closed and data packet is lost. (6)

Now, the mode dependent output feedback controller can be defined as

$$u(t) = K(\alpha(t), \tau(t))y(t) \quad (7)$$

Here, $K(\alpha(t), \tau(t))$ is output feedback controller gain.

Suppose, $s(t) = [s_p(t)^T \quad \bar{y}(t-1)^T]^T$ is an augmented state vector. The above mentioned control vector in eq. (7) for the closed loop system of eq. (1) becomes,

$$s_a(t+1) = A[s_p(t)^T \quad \bar{y}(t-1)^T]^T + BK(\alpha(t), \tau(t))\bar{y}(t) \quad (8)$$

$$s_a(t+1) = \bar{A}(\alpha(t))s(t) + \bar{B}(\alpha(t))Hs(t - \tau(t))$$

$$s(t) = \phi(t)$$

$$t = -\tau_{\max}, -\tau_{\max} + 1, \dots, 0$$

Here,

$$\bar{A}(\alpha(t)) = \begin{bmatrix} A\alpha(t) & BK(\alpha(t), \tau(t)) \\ 0 & \alpha(t)I \end{bmatrix}$$

$$\bar{B}(\alpha(t)) = \begin{bmatrix} (1 - \alpha(t))BK(\alpha(t), \tau(t))C \\ (1 - \alpha(t))C \end{bmatrix}$$

$H = [I \quad 0]$, $\tau_{\max} = \max(\tau(t))$ and $\phi(t)$ is initial condition of $x(t)$.

In the system (8), $\{\alpha(t), t \in Z\}$ and $\{\tau(t), t \in Z\}$ are two discrete time homogeneous markov chains independent in nature taking values in a finite set $\bar{X} = \{0, 1\}$ and $\bar{X}_2 = \{0, 1, 2, \dots, x_2\}$ with transition probabilities:

$$P_r \{ \alpha(t+1) = j \mid \alpha(t) = i \} = \Pi_{ij} \text{ from } i \text{ to } j.$$

$$\Pi_i = P_r(\Pi_0 = i)$$

$$P_r \{ \tau(t+1) = n \mid \tau(t) = m \} = \lambda_{mn} \text{ from } m \text{ to } n.$$

where, $\Pi_{ij} \geq 0$ and $\lambda_{mn} \geq 0$ for all $i, j \in Z_1, Z_2$

$$\sum_{j=0}^1 \Pi_{ij} = 1 \text{ and } \sum_{n=0}^{s_2} \lambda_{mn} = 1$$

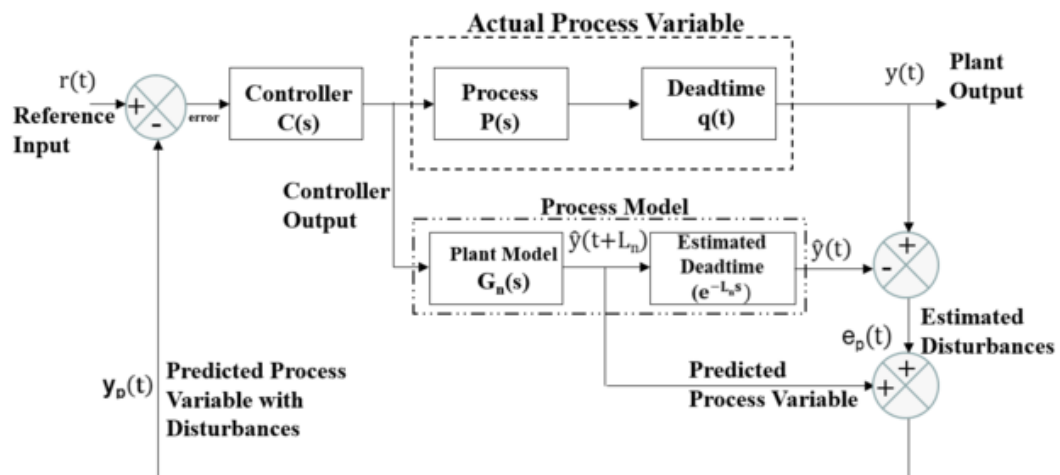
For $\alpha(t) = i$, $i \in \overline{X_1}$ and $\alpha(t)$ in mode $i = 0$ and $i = 1$ the $\alpha(t)$ in (8) take value $\alpha(t) = 0$ and $\alpha(t) = 1$ respectively. $\overline{A}(\alpha(t))$ and $\overline{B}(\alpha(t))$ are known constant matrices of appropriate dimensions.

The modified state space equation of the system mentioned in eq. (8) can be considered as a Markov jump linear system having two Markov chains which details about the behavior of the system for induced delays between sensor-to-controller and data packet dropouts. This enable us to analyse and synthesize such NCS by applying Markov jump linear system and help us to evaluate the modified state space model of the plant. The Markov approach estimates the uncertain feedback delay and compares for estimated disturbance $e_p(t)$, which modify the disturbance variables for the predicted process.

Modified Smith predictor design and development

The designing schema of a networked control system have been considered time delay an important performance constraint. It is briefed by Smith (1957), Onat et. al. (2010), and Poorani & Anand, (2013) that sulky and diminished performance observed for processes with large time delays can be improved by incorporating derivative action with PI control. Due to their ease in designing and overwhelming performance for a broad range of industrial applications the Proportional–Integral–Derivative (PID) controllers are extensively used. Additional phase lag in the processes due to long time-delays are not easy to control efficiently with the use of PID controller and that may tends to destabilize the system. To compensate the delay an effective way is to introduce the Smith predictor controller (SPC) in the system. It have good set point response as it minimizes the delay characteristics of feedback loop (Adam et. al., 2000; Liu et. al., 2005; Grimholt & Skogestad, 2013; Oliveria et. al., 2017).

Figure 4. Process model of Classical Smith Predictor Controller



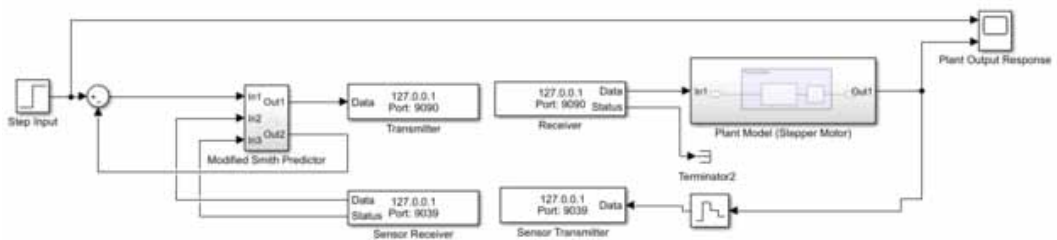
The predicted output of the controller $y_p(t)$ will be error-free if the estimated disturbance will have minimized effect on the predicted process variable. As shown in Figure 4, the Smith predictor controller includes a conventional controller to predict the delayed free process of the plant model (Liu, 2010, 2017; Batista & Jota, 2018). The classical Smith predictor is mentioned using two parts one is primary controller $C(s)$ which can be PID or any other higher order controller and second is predictor that consist of estimated model of the plant having estimated dead time represented as $G_n(s)$ and $e^{-L_n s}$ in the process as shown in Figure 2. Hence, the predictor module of the Smith predictor is given as $G_n(s) e^{-L_n s}$. Mahmoud & Khairy (2017) mentioned that it computes the open-loop prediction of system. The estimated deadtime can be obtained by taking the difference of output actual process variable and process model (Zhong, 2003; Yang et. al., 2013). In this literature the modified Smith predictor is designed incoherence with Markov approach. The Markov approach is implemented to estimate the deadtime ($e^{-L_n s}$) introduced in the process model to compare with the actual delayed feedback obtained from the plant output which empower us to estimate the modified state space of the system as also mentioned by equation 8. The Markov approach estimates the uncertain feedback delay and compares for estimated disturbance $e_p(t)$, which modify the disturbance variables for the predicted process.

Simulation and Result Analysis of Modified Smith Predictor

A Smith predictor controller (SPC) also broadly identified as dead time compensator that can uphold long delay time processes as compared to the PID controller. The Smith predictor layoff the internal delays from the closed-loop transfer function and provides a better set-point as compared to other conventional controllers. For better system performance, set-point is considered as secondary objective the prime concern is to deal with the rejection of the disturbances tracked in many processes in control applications.

But the techniques evolved earlier for rejection of process disturbance do not gain much popularity as it is difficult in the process industries to deal with set-point and disturbances simultaneously. A number of smith predictor structures have been proposed in the different literatures with different controllers but they are not for networked control system. In this research article author design the smith predictor in Figure 5, for a networked control system where a stepper motor is controlled over the network.

Figure 5. Implementation of proposed modified Smith predictor for networked control system



The estimation of the random feedback delay is achieved through single Markov jump linear system. The system is simulated by using Matlab/Simulink software. The observations mentioned in

Table 2, clarify the performance parameter comparison of different controllers such as PI, PD, PID and Smith predictor modified smith predictor.

Table 2. Comparison of performance parameters of proposed modified Smith predictor controller with conventional controllers

Parameters	Type of Controllers				
	PI	PD	PID	Smith Predictor	Proposed Modified Smith Predictor
Rise Time (units of time)	0.528 sec	0.334 sec	0.572 sec	0.0015 sec	0.00012 sec
Slew Rate (per units of time)	1.508 /sec	1.296 /ms	1.398 /sec	519.024 /ksec	71.337 /psec
Overshoot (in %)	5.851	19.88	3.646	0.501	0.505
Settling Time (in Sec)	0.43 sec	Infinite	0.39 sec	0.48 sec	0.316 sec
Signal to Error Ratio (SER)	6.757	3.744	6.872	6.893	7.269

The modified smith predictor gives 34.16% improvement in settling time as compared to conventional Smith predictor, which shows that modified Smith predictor as an effective deadtime compensator to attain process stability in systems with long time-delays. The transfer function of the plant model is

$$P(s) = \frac{107}{s^3 + 11s^2 + 91s + 108.3} \quad (8)$$

The issues of the stability can be achieved by subsiding the controller gain. However, the response obtained in this case for the smith predictor is very sluggish about 519.024/ksec which is further improved by modified Smith predictor 71.337/psec, a faster slew rate improves the bandwidth of the system and hence reduce the time delay and probability of packet dropout. The slew rate of the simulated controllers for networked control system can be compared from Table 2. Where lowest slew rate is provided by PI controllers and higher slew rates in modified Smith predictor structure can be observed that delivers a robust improvement in the closed loop performance of the WNCS over conventional controllers to achieve stable processes. In this paper author have compared the performance of PI, PID, and SP and modified Smith predictor controllers for step input shown in Figure 6 and 7. A careful glance over the Figure 6 and 7 indicates a comparative study of the effect of delay in the system with the output response curves of the system using various controllers are different than the reference input.

Figure 6. Transient response comparison of PI, PD and PID controller

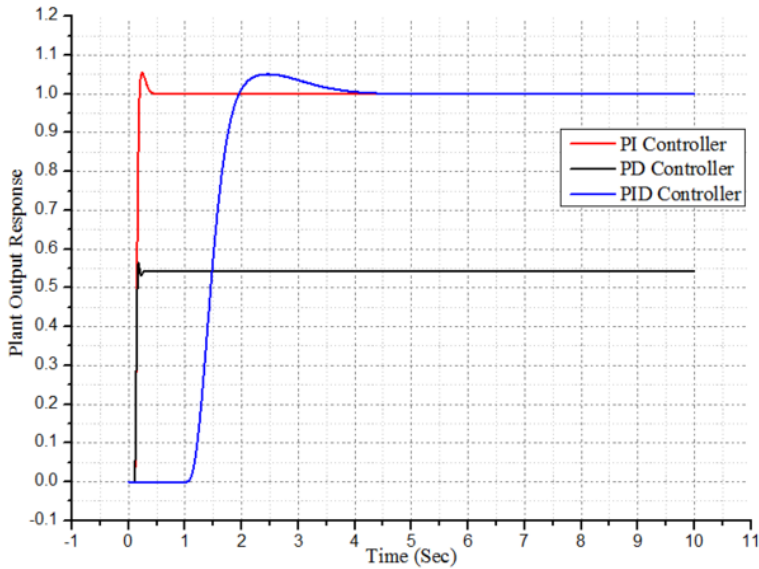
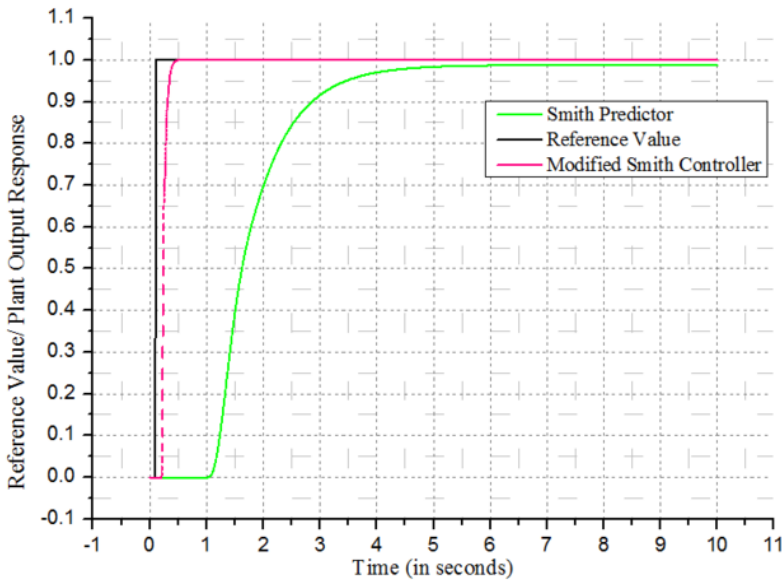


Figure 7. Comparison of Delay Compensation between Smith predictor controller and modified Smith predictor controller



To design proposed modified Smith predictor author have used the values as, $P = 2.0$, $I = 3.4$ and $D = 0.1$ for a continuous-time PID controller for networked control system with state space model of dc motor mentioned as

$$A = \begin{bmatrix} -11 & -91 & -108.3 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, C = [0 \ 0 \ 107] \text{ and } D = [0]$$

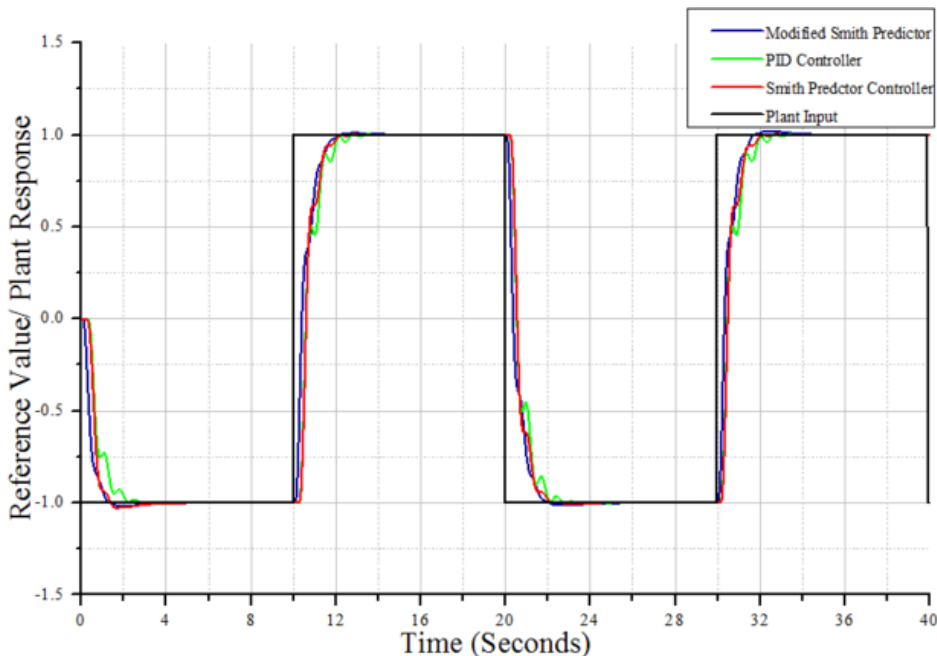
The networked control system has broadly two types of applications, one is time sensitive i.e., time critical and second is time insensitive applications also termed as time non-critical applications.

The similarity between the input reference signal and output response can be brought closer by using modified Smith predictor controller as presented in Fig. 7 using red color curve. Another performance parameter used in this literature is signal to error ratio (SER) defined as

$$SER = \frac{\sum (X(t))^2}{\sum (X(t) - \hat{X}(t))^2}$$

Where, $X(t)$ is the reference control signal and $\hat{X}(t)$ is the output signal of the system. The values of SER for different controllers are mentioned in Table 2, showing that the delay compensation approach improves the value of SER in modified Smith predictor which in-turn mends the system performance compared to the classical Smith predictor.

Figure 8. Delay compensation comparison of PID controller, Smith predictor controller and modified Smith predictor controller



The juncture of network-induced delays into the control input signal across the network results in disturbances in the output signal, causing differences in the output signal in comparison to the reference signal. In this paper the application of proposed Markov based approach improve the system

performance. It provides better SER value as mentioned in Table 2 as compared to SER mentioned in Gamal et. al. (2016) and offer robust output response.

CONCLUSION

The network-induced delays in a NCS found precarious and relentlessly affects the system performance. In order to stabilize the system, this paper proposes a modified Smith predictor controller. To estimate the uncertainty in delay the proposed predictive controller accepts the Markov modelling which estimate induced-delay of the system. Therefore, the proposed predictive controller efficiently compensate the randomness of the induced-delay. Hence, it improves the SER of the system and provide stable response output. To realize the various delay compensation schemes and system response, simulations have been performed with the help of Matlab/ Simulink. Results presented in the literature make certain that the proposed modified Smith predictor controller using Markov approach have a remarkable improvement over Smith Predictor (without Markov approach) and other controllers in terms of various controller parameters. There is significant improvement in SER leads to better response and stabilization. Hence, it can be concluded that proposed scheme is well appropriate for time critical applications where randomness in delay degrades the performance of the system.

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