

Alleviation of Delay in Tele-Surgical Operations Using Markov Approach-Based Smith Predictor

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ABSTRACT

The acceptance of tele-robotics and teleoperations through networked control systems (NCS) is increasing day by day. NCS involves the feedback control loop system wherein the control components such as actuators and sensors are controlled and allowed to share their feedback over real-time network with distributed users spread geographically. The performance and surgical complications majorly depend upon time delay, packet dropout, and jitter induced in the system. The delay of data packet to the receiving side not only causes instability but also affects the performance of the system. In this article, the authors designed and simulated the functionality of a model-based Smith predictive controller. The model and randomized error estimations are employed through Markov approach and Kalman techniques. The simulation results show a delay of 49.926ms from master controller to slave controller and 79.497ms of delay from sensor to controller results to a total delay of 129.423ms. This reduced delay improves the surgical accuracy and eliminates the risk factors to criticality of patient health.

KEYWORDS

Deadtime Compensation, Kalman Estimation, Markov Approach, Networked Control System, Predictive Networked Control System, Tele-Robotics, Telesurgery, Unmanned Aerial Vehicle

INTRODUCTION

The geographically distributed systems which share information (control signals, feedback, and output signals) between distant oriented users through a closed control loop spread all over the network is termed as Networked Control System (NCS) (Sakti & Prajitno, 2017). NCS provides flexible architectural network design to share information and command the systems over the network. Low installation and preservation cost, integration tractability, widespread reachability are few features of NCS that expands its area of applicability such as space command and control applications, industrial automation and process control, tele-operation and tele-surgery, agricultural monitoring and quality control, unmanned aerial vehicles (UAVs) and automated traffic monitoring and control are some of the societal beneficial applications (G. P. Liu et al., 2005; K. Liu et al., 2014; F. Y. Wang & Liu, 2008; Xia et al., 2015).

People in today's era are becoming more and more vigilant in regard to their health. And the recent Covid19 pandemic intensified the coparcenary of NCS to bring forth an interdisciplinary

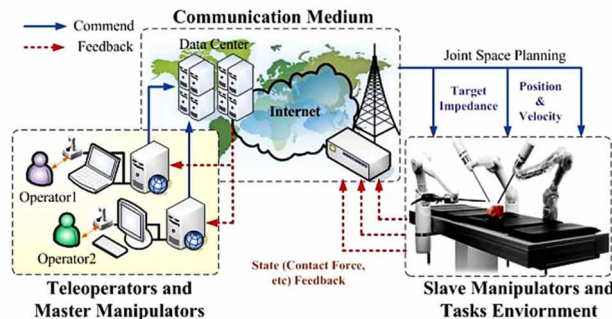
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dimension that explicable the possibility of telesurgery and tele-diagnosis of patients in the field of healthcare and medicine. Telesurgery is a time-sensitive application of a networked control system so, guaranteed time control signals are of utmost priority (Gupta & Chow, 2008; Kumar et al., 2019; Sharma et al., 2018). It integrates multiple complex devices with high-end technology that involves the complex machinery being controlled by surgeons to operate accordingly (Miao et al., 2018; Sahu et al., 2020). The types of equipment involved are very precisely assembled to use for marginal invasive surgeries across the world. The concept of telesurgery is exceptional to the conventional surgery made by a surgeon. The telesurgery is performed by a doctor without touching a patient through a highly reliable network that communicates information signals between the master console installed with the doctor and a slave robot mounted with various robotic arms at the patient end (Fan & Sharma, 2021; Meng et al., 2004). The master console is equipped with a position and motion control panel and feedback monitoring console to observe the real-time condition of the patient. The slave robot is installed with a moving/rotating robotic arm, camera sensors, haptic sensors that facilitate the doctor for remote diagnosis. The doctor located at a distant position to the patient communicates with the slave robot through the master console (Haidegger et al., 2011; Sharma & Kumar, 2019). A diagrammatical procedure of telesurgery is presented in Fig. 1.

Figure 1. Overview of NCS based telesurgery



Once the decussation position is marked, the robotic arm fitted with surgical tools and camera starts performing the various surgical procedures like cutting, stop bleeding, and suture of wounds. Although NCS has given credibility to impassable processes like telesurgery, some inadequacies hinder its widespread. Though, the involvement of control of components over the network introduces new challenges too. The distribution of intelligence, integration of components, time delay in transmission and computation of control signals, the disappearance of data packets are major issues that can be viewed in NCS (Farajiparvar et al., 2020; Pavitra et al., 2020; Ren et al., 2021).

For time-sensitive applications, if time delay for a control signal exceeds a tolerable limit it deteriorates the system performance and destabilizes the closed control loop of the system. Madder et al. (2020) in their article published in *Robotic Medicine* presented the effect of time delay on the performance of surgeons performing telesurgery. They involve a robotic system to operate telesurgery over a distance of 100 miles and simulate network latency at different rates and observed that up to 400 milliseconds i.e., 400ms latency the surgical procedures can be satisfactorily performed, between 100ms to 250ms did not have any significant effect but more than 400 ms delay deteriorate the surgeon's performance. (Y. Liu et al., 2021; Lum et al., 2008; H. Sun et al., 2021) investigated the effect of time delay on surgical procedures and decision making of a surgeon concerning the control signals to slave robots at remote sites (operation site). Orosco et al. (2021) revealed the concept of negative motion scaling i.e., a time-delayed movement of instruments of the robotic arm

in comparison to master controller movement. They showed that delay effects create a dilemma to surgeon's control decisions which in turn lead to precarious circumstances. Review literature was presented by Sun et al. (2014) where they showed a solution to wave reflection through the wave variable method which is an extension passivity theory. Machines do not have sensations as humans have, all inputs to machines are observed by sensors, so it is very difficult during telesurgery to know about the haptic feedback of patients. Uddin & Ryu (2016) presented in detail the different predictive control approaches to compensate for the time delay over the network. The uncertainty by time delay was modeled by Kebria et al. (2018) in their research article. They surveyed various adaptive based approaches, neural network approaches and fuzzy-based approaches to explain the causes of time delay, packet loss, jitter and blackout seen in internet-based approaches.

In this paper, we have introduced a modified Smith predictor controller that works on a model-based predictive networked control system (MBPNCS). The Markov approach and Kalman estimations are implied to compensate for the delay between the master console and slave robotic system. The proposed structure complies with the high precision and low latency of data delay over the network. It is concerned with the compensating of delays through the use of a predictive method in order to execute telesurgery without experiencing any difficulties. The approach developed in the article provides timely assistance to the surgeon on the master side who is operating on a patient who is located at a different place. This paper is categorized into 5 sections, the basic introduction of NCS and effects of delay in telesurgery in section 1 is followed by section 2 representing the working principle of Conventional Smith predictor and its design etiquettes. Section 3, describes the design procedure and algorithms of the Markov approach for the modified Smith Predictor Controller. Section 4 elucidates the Simulation and Results that is further followed by Section 5 with Conclusion.

CONVENTIONAL APPROACH TOWARDS SMITH PREDICTOR CONTROLLER

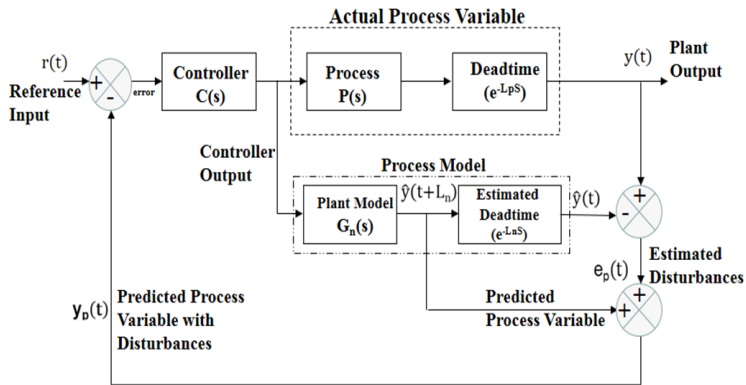
The stability performance of controllers is limited by the time delay involved in the process. The optimized solutions to compensate for the delay in networked control systems open up new ideas to fundamental principles of estimation (Assellaou et al., 2018). As a challenge to stochastic time-delay systems, conventional approaches are supported with optimal techniques to draw stability in the system. The discretization of the Linear Quadratic Gaussian (LQG) controller can be used to estimate the time delay beyond the critical limit to avoid blackout in the communication channel that stabilizes the system (Li et al., 2018). Over time different model-based approaches for remotely controlled operations are reviewed by Kebria et al. (2019). The Smith predictor controller was developed as delay dominated controller to deal with large dead time (Kaya, 2003; Kumar et al., 2021).

Smith Predictor

To restrict the limitation of large delays or deadtime over the system performance Smith predictor controller was designed as shown in Fig. 2. The structure of the Smith predictor is divided into two parts: the primary controller which may be a PI or PID controller or it can be a higher-order controller and the predictor structure. The plant of the system is described as actual process variable that consists of process $P(s)$ involved and disturbance, $e^{-L_p s}$ in the plant (Vrečko et al., 2001). The predictor structure is composed of an actual model or estimated model, $G_n(s)$ of the plant and estimated deadtime $e^{-L_n s}$ equivalent to actual deadtime or disturbance involved in the plant. So, the complete process model of the predictor structure can be written as $P_n(s) = G_n(s)e^{-L_n s}$. The $G_n(s)$ is also called an ideal model or fast model of the plant. A control signal from the controller $C(s)$ will parallelly actuate the actual process variable and process model of the plant (Sigurd Skogestad, 2018).

The plant output $y(t)$ generated is subtracted from the estimated output $\hat{y}(t)$ of the process, model to produce an estimated disturbance $e_p(t)$. As the plant model $G_n(s)$ is the fast model actuated

Figure 2. Conventional Smith Predictor Controller and its functions (Santacesaria & Scattolini, 1993)



by control signal $C(s)$ produces a predicted output or the open-loop prediction of the actual plant gets added to the estimated disturbance as a feedback signal to the controller. This feedback signal is termed as a predicted process variable with disturbances ($y_p(t)$) (Bogdanovs et al., 2019). The resultant transfer function of the model can be written as eq. 1

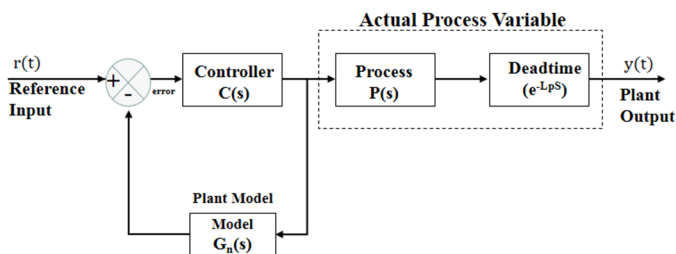
$$\frac{Y(s)}{R(s)} = \frac{C(s)P(s)e^{-L_p s}}{1 + C(s)G_n(s) + C(s)[P(s)e^{-L_p s} - G_n(s)]e^{-L_n s}} \quad (1)$$

If modeling errors or disturbances are infinitesimally small such that can be ignored and the difference between disturbances (actual and estimated) is negligible then the estimated disturbance can be overlooked then the predictor output $y_p(t)$ will be deadtime free output of the plant. Under such conditions, $C(s)$ is tuned as there is no deadtime in the system. Mathematically it can be represented as:

$$P(s) = G_n(s),$$

$$e^{-L_n s} = e^{-L_p s}$$

Figure 3. Ideal Smith predictor controller in case of perfect modeling



Considering these conditions in eq. 1, will cancel out the third term in the denominator and can be written as,

$$\frac{Y(s)}{R(s)} = \frac{C(s)P(s)e^{-L_p s}}{1 + C(s)G_n(s)} \quad (2)$$

As it can be seen in eq.2 that $Y(s)$ has a negative exponential growth rate, then $Y(s) \rightarrow 0$ as $t \rightarrow \infty$ will stabilize the system.

RANDOM DELAY ESTIMATION USING MARKOV MODEL

Markov analysis is considered as a useful modeling and analysis methodology having vibrant applications in stochastic applications showed that a discrete networked control, is represented by considering a state-transition diagram (Mahmoud & Hamdan, 2018; Pabreja, 2020). The rate of transition between different states predicts the future states of the system. For a networked control system, the Markov model defines the consecutive representation of possible events between the two states controller node and sensor node. The successful transition between these states can be marked as a packet received otherwise packet dropout (Zhu & Chai, 2019). The Markov model mensurates the probability of a system in a particular state, it estimates the count of system transitions between the two mentioned states and the time for which a system spends in a particular state. The definitive operations modes for different systems can be estimated by considering Markovian jump linear systems (MJLSs) (Wen & Li, 2009). The abrupt changes such as components failures, subsystem upgrades/repairs or environmental changes, etc. result in abrupt state transitions.

To develop the Markov transition-based state-space model with the inclusion of random delay induced in the system can be modeled as per the algorithm shown in Table 1.

Hence, the estimation of delay and packet drop modifies the state equation that is implemented in the Smith predictor controller.

In spite of the advantages and possiblens, the involvement of communication networks in feedback control loops intricates the solution of networked control systems (NCSs), which in turn originate new riveting and challenging problems (Song et al., 2011). Because of delays induced in the network, the control signals and feedback signals transmitted through networks are usually approachable with some probability. Based on this fact, it is said that the mode-independent control method considered here is usually considered in NCSs (Y. Wang et al., 2020).

$$s_a(t+1) = A s_p(t) + B u(t) \quad (3)$$

$$y_p(t) = C s_p(t)$$

A, B, and C are known real constants defined earlier with eq. (3), $s_p(t) \in R^n$, represents the present state of the system $s_a(t+1)$ represents the 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 $\in R^m$.

Since random time delay occurs across the network. The two types of delay include s-c and c-a called feedback and feedforward delays. The feedback delays are more important as control inputs are a function of feedback inputs (K. Liu et al., 2019). Delays lead to packet dropout so it is important to cater to them carefully so as to ensure the early prediction of the system state and control input for

Table 1. Algorithm to develop model-based delay estimation of plant

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 modeled as Markov Chain
Step 4:	Consider $\alpha(t)$ defines the state of the link between sensor – controller. Such that, If, $\alpha(t) = 0$, means the 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 modeled as: $\bar{y}(t) = (1 - \alpha(t))y(t - \alpha(t)) + \alpha(t)\bar{y}(t - 1)$ Such that, $\alpha(t) = \begin{cases} 0, & \text{if X is closed and the packet is received} \\ 1, & \text{if X is open and the packet is lost} \end{cases}$
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 the 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 we get, $s_a(t+1) = A[s_p(t)^T \quad \bar{y}(t - 1)^T]^T + BK(\alpha(t), \tau(t))\bar{y}(t)$ $s_a(t+1) = \bar{A}(\alpha(t))s(t) + \bar{B}(\alpha(t))Hs(t - \tau(t))$

that state. 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 model. Suppose $\tau(t)$ represent the delay of the feedback channel being modelled by markov chain (Raj & Azad, 2019). 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 we can say that previous state of delay will affect the current delay. 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 can be expressed as,

$$\bar{y}(t) = (1 - \alpha(t))y(t - \alpha(t)) + \alpha(t)\bar{y}(t - 1) \quad (4)$$

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 the data packet is lost.

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

$$u(t) = K(\alpha(t), \tau(t))y(t) \quad (5)$$

Here, $K(\alpha(t), \tau(t))$ is the 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. (5) for the closed-loop system of eq. (3) becomes,

$$s_a(t + 1) = A[s_p(t)^T \quad \bar{y}(t - 1)^T]^T + BK(\alpha(t), \tau(t))\bar{y}(t) \quad (6)$$

$$s_a(t + 1) = \bar{A}(\alpha(t))s(t) + \bar{B}(\alpha(t))Hs(t - \tau(t)) \quad (7)$$

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

$$t = -\tau \max_{max}$$

Here,

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

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

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

In the system (7), $\{\alpha(t), t \in Z\}$ 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 $i, j \in Z_1, Z_2$

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

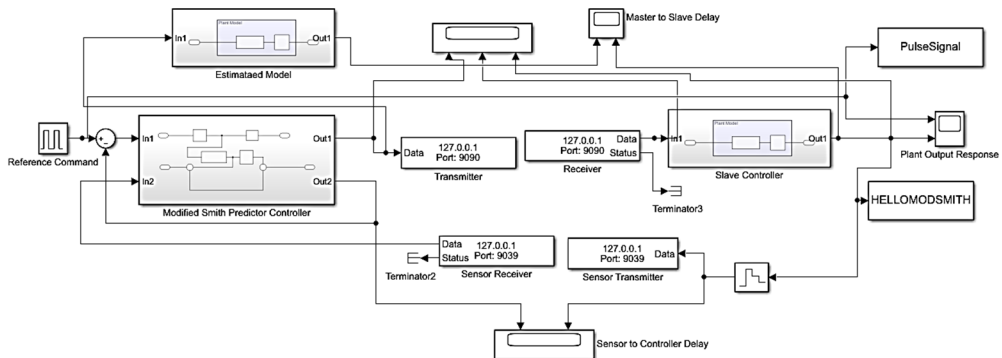
For $\alpha(t) = i, i \in \bar{X}_1$ and $\alpha(t)$ in mode $i=0$ and $i=1$ the $\alpha(t)$ in (7) take value $\alpha(t) = 0$ and $\alpha(t) = 1$ respectively. $\bar{A}(\alpha(t))$ and $\bar{B}(\alpha(t))$ are known constant matrices of appropriate dimensions.

The modified state-space equation of the system mentioned in eq. (7) can be considered as a Markov jump linear system having two Markov chains which detail the behavior of the system for induced delays between sensor-to-controller and data packet dropouts. This enables us to analyze and synthesize such NCS by applying Markov jump linear system and helps us to estimate 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).

SIMULATION AND RESULT ANALYSIS OF MODIFIED SMITH PREDICTOR

A Smith predictor (SP) also widely known as dead time compensator, can be considered rather than PID control for long delay time processes. 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 pieces of literature discussed earlier with different controllers but they are not for the networked control system. In our study, we design the smith predictor, for a networked control system where a dc motor is controlled via a slave controller over the network maintained through UDP protocol as represented in Fig. 4.

Figure 4. Modified Smith Predictor controller structure designed in Simulink



The simulations are performed using Matlab/Simulink software. The estimation of the random feedback delay is achieved through a single Markov jump linear system.

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

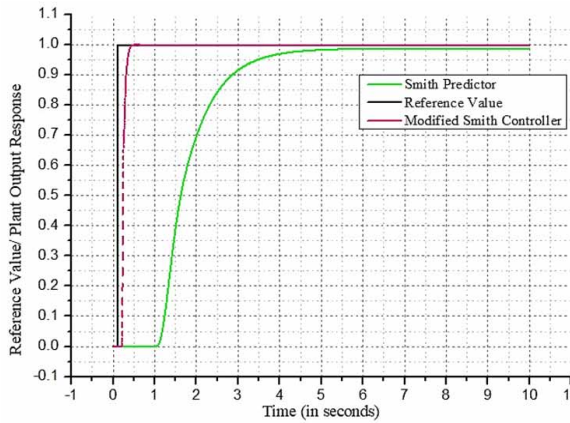
Parameters	Type of Controllers				
	PI	PD	PID	Smith Predictor	Proposed Modified Smith Predictor
Rise Time (units of time)	0.528 sec	0.334 sec	0.572 sec	0.0015 sec	0.00012 sec
Slew Rate (per units of time)	1.508 /sec	1.296 /ms	1.398 /sec	519.024 /ksec	71.337 /psec
Preshoot (in %)	0.532	0.602	0.521	0.505	0.505
Overshoot (in %)	5.851	19.88	3.646	0.501	0.505
Undershoot (in %)	1.739	4.55	1.996	1.997	-0.505
Settling Time (in Sec)	0.43 sec	Infinite	0.39 sec	0.48 sec	0.316 sec

To elucidate the effectiveness of the modified smith predictor it is compared with different controllers such as PI, PD, PID, and Smith predictor. A comparison is drawn in Table 2. The modified smith predictor gives 34.16% improvement in settling time as compared to the conventional Smith predictor, which shows that the modified Smith predictor performs as an effective deadtime compensator to attain process stability in systems with long time delays.

The issues of 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 also delivers a robust improvement in the closed-loop.

PID controllers are the workforce of the industry but with the high demand of precision they are becoming sluggish and are overtaken by Smith predictor controllers for large deadtime and rapid response to integrating process, the modified Smith predictor controller proves a better output response in comparison to Smith predictor controller that can be observed from the Fig. 5. In our design we have used values, $P = 1.91234$, $I = 3.2145$, $D = 0.00923981$, and filter coefficient, $N =$

Figure 5. Step input response comparison between conventional Smith predictor and proposed modified smith predictor controller

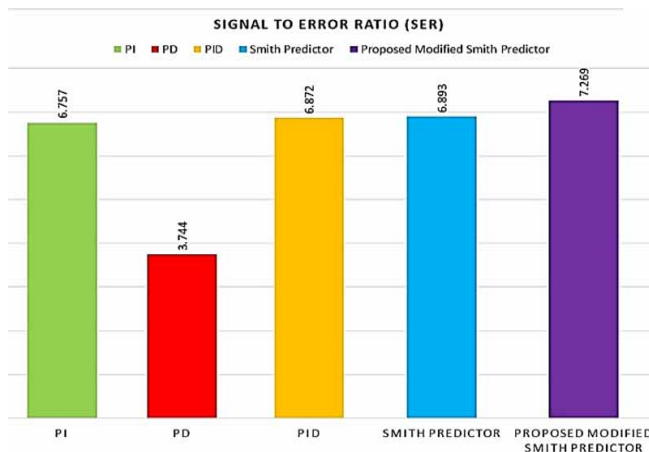


20 for a continuous-time PID controller to design the randomized error and model estimation-based Smith predictor for networked control system and state-space model as given below:

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

The networked control system has broadly two types of applications, one is time-sensitive i.e., time-critical and the second is time-insensitive applications also termed as time non-critical applications. It is evident from Fig. 6 that the modified Smith predictor has a rise-time of 1.2×10^{-4} sec, which is suitable for time-sensitive applications such as medical and defense applications for a robust improvement in the closed-loop performance to achieve stable processes. The delay compensation improves as the Signal-to-Noise ratio (SER) increases.

Figure 6. Comparison of signal to error ratio of different controllers with proposed modified Smith predictor controller



It can be clarified from Fig. 6 that the SER value of the proposed modified Smith predictor controller is found to be 5.2% improved in comparison to other controllers. The simulated time delay between master controller to slave controllers is 49.926ms and the delay between the sensor to the controller is 79.497ms, these results in a total delay of 129.423ms of total delay for a complete round trip. The total delay also includes the 29.942ms of computational delay by slave controller to actuate according to the control command signal. All these improved performance characteristics of the proposed modified Smith predictor controller grades to accurate compensation of induced time delay in the system that improves the performance of tele-surgical operations and success probability of teleoperations. This improved approach will not only reduce the risk factors over geographical barriers but also enhance the advantageous feasibility of real-time clinical decisions and patient care.

CONCLUSION

In tele-surgical operations, the accessibility of the resources depends upon how fluently these can be performed and controlled through the network which indirectly is contingent upon the infinitesimally small effect of induced delays on the system. In the case of NCS, network-induced delays are found very critical because these delays severely affect the performance of the system. To compensate for these delays, this paper proposes a modified Smith predictor controller. The proposed predictive controller adopts Markov modelling for estimating the random delays. Therefore, the proposed predictive controller can compensate effectively for the delay having uncertainty. In this paper, simulations with the help of MATLAB/Simulink have been performed for various delay compensation schemes. Results ensure that the proposed modified Smith predictive controller scheme has a noteworthy improvement over Smith Predictor (without Markov) and other conventional controllers in terms of different network-induced delays, rise-time, slew rate, overshoot, and settling time. Hence, it can be concluded that the proposed modified predictor is suitable for time-critical applications such as teleoperations and telesurgery where delay with randomness influences the performance of networked control systems. Telesurgery is a medical and technological marvel that will benefit mankind and society. Although it has been intriguing, clinical viability has persisted out of reach, mainly owing to the negative effects of communication delays on patient outcomes. Latencies in teleoperation tasks is severely influenced by inevitable signal delays, which leads in delayed procedures, less dexterity in action, and an impact of human errors. In the future, other approaches such as the Kalman approach, relational neural networks, machine learning, deep learning in conjunction with Smith Predictor may be used to find an aid in the reduction of time delay. The telesurgery may also prove to be effective in space exploration and underwater explorations.

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