Volume 12, Issue 3
June 2023

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Joint Design and Implementation of a Discrete Time Sliding Mode Controller over Wireless Medium

[1]Krutika Paradkar and [2]Dipesh Shah

[1]Department of Instrumentation and Control Engineering, IEEE Student Member, Research Scholar, Sardar Vallabhbhai Patel Institute of Technology, Gujarat Technological University, Ahmedabad, India

[2]Department of Instrumentation and Control Engineer, IEEE Senior Member, Sardar Vallabhbhai Patel Institute of Technology, Gujarat Technological University, Ahmedabad, India

E-mail: [1]krutikabhagwat@gmail.com, [2]dipeshshah.ic@gmail.com

ABSTRACT

This paper explores a wireless and robust control approach for controlling the position of a DC motor plant. The main focus is directed toward designing a sliding mode controller with discrete-time implementation for Wireless DSMC, incorporating the use of estimated sliding variables and Gao's reaching law principle. This novel approach bridges operational technology (OT) and information technology (IT).To realize this concept, we've integrated a closed circuit to control the Wireless Networked Control System (WNCS) that features a discrete-time Kalman filter algorithm at the controller side. This algorithm predicts the model, corrects wireless received signals and mitigates the effect of losses and delays in data packets. The filtered and corrected signals from the discrete-time Kalman filter DTKF are then fed into the DSMC to enable precise position control of the DC motor plant. Our design leverages the IEEE 802.15.4 wireless medium. One challenge to address is the variability in delays in communication between sensors and controllers, which is dependent on the sampling period of the sensors and the wireless network setup. We develop a sliding surface and a DSMC with Gao's reaching law principle, based on the Kalman filter state estimation algorithm. The ultimate objective of this paper is to present an innovative, robust Wireless DSMC design that aligns with the Industry 4.0 paradigm. We've implemented this WNCS closed-loop system using Truetime 2.0 software and provided simulation results to illustrate the effectiveness of our proposed design. It is evident from our findings that this control strategy exhibits robustness even in the presence of uncertainties within the wireless network

Keywords: *Joint design, Wireless networked control systems, Discrete-time Kalman Filter, Discrete-time Sliding Mode controller, Truetime 2.0.*

1. INTRODUCTION

In [1], a detailed discussion of controller design aspects for the wireless network is given. The closed-loop system ought to exhibit preferred dynamic and steady-state response attributes. Designing networked control systems using a wireless LAN is presented in [2]. Mobile functioning, easy installation and fast implementation are advantages of Wireless networked control systems (WNCSs).In a wireless communication environment, time delays exhibit random characteristics. When attempting to directly assess the system's state, it is typically necessary to make an estimation effort to reduce the impact of sensor noise. Addressing observer-related challenges when measurement and process noise are present. That involves the application of a time-varying optimal observer known as the Kalman filter [3, 4]. The Kalman filter is employed to mitigate the impact of packet delay or loss on the controller's end. Research into state estimation is discussed in [5], with references to the utilization of the Kalman filter during the Apollo moon landings detailed in [6, 7]. NCS is designed over WSNs in [8] in which Extended Kalman Filter is proposed as a state estimation algorithm. In [9] sliding mode predictive control is designed for NCS using Kalman Predictor to estimate the network delays. Modified Kalman filters are proposed for the network delay and loss [10], [11], [12], [13]. In [14], introduces the design of a wireless PI controller with integral mode. In [15], illustrates how an integral mode controller can compensate for time delays. Furthermore, in [16], the idea of wireless computation is explored. To reduce packet loss rates, [17] suggests the use of a Kalman filter, while [18] focuses on state and disturbance estimation through a discrete-time Kalman filter (DTKF)

We propose a new design for the practical implementation of a robust wireless controller for the WNCS. The overall proposed WNCS design is illustrated in Fig. 1, where the plant with actuator nodes and sensor nodes arewireless transceiver with a proposed controller. The rest of the structure of the paper is outlined as: Section II: Motivation behind this joint design work. Wireless communication in detail for the proposed WNCS is described in Section III: discrete-time Kalman filter design and its estimated and corrected states for the WNCS in Section IV. True-time software is used to propose our closed-loop WNCS. The design at the controller side uses the discrete-time Kalman filter and DSMC Gao's principle. Section V delves into an in-depth analysis of the simulation results generated by the proposed DSMC controller, while Section VI outlines the conclusion and explores potential avenues for future directions.

2. MOTIVATION

WNCS and its design for Industry 4.0 is going to introduce new challenges in areas of control, communication and computation as it is a joint design approach. The primary motivationof this paper is to propose a new WNCS design

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

approachand its implementation. There are several designs availablefor the closed-loop NCS networked control system. In industry 4.0 wireless controller implementations are an emerging era. DSMC design in NCS needs to extend to the wireless domain called WNCS. Thus motivated, in this implementation of DSMC we proposed a discrete-time Kalman filter which predicted and corrected the received signal at the controller receiver end. DSMC computes the estimated sliding variable and reaching law as a controller output. Truetime 2.0 software [21], on the MATLAB platform, is used for our proposed design and implementation.

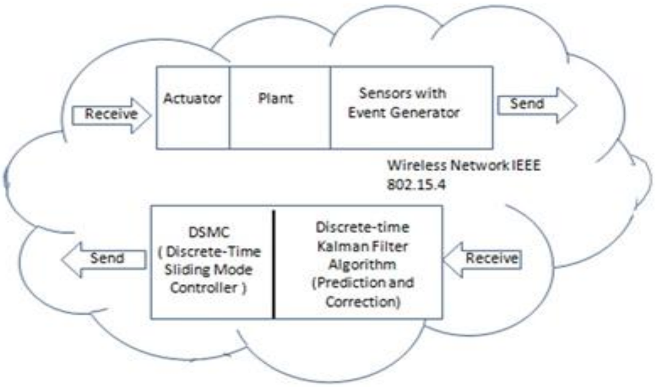

Fig. 1. Schematic diagram of Proposed WNCS

3. PROBLEM FORMULATION

The main concept of the proposed design is to construct a DSMC where sensor/actuator nodes and controller nodes communicate in a wireless medium.

$$\dot{x}(t) = Ax(t) + Bu(t) + Dd(t) \quad (1)$$

$$y(t) = Cx(t) \quad (2)$$

In equations 1 and 2, the system state vector $x \in R^n$, control input $u \in R^m$ and output $y \in R^p$. Matrices $A \in R^{n\times n}$, Matrices $B \in R^{n\times m}$, Matrices $C \in R^{p\times n}$, Matrices $D \in R^{n\times m}$ have the suitable dimensions. Additionally, d(t) is the bounded matched disturbance $|d(t)| \leq d_{max}$, and τ denotes the delay of a wireless network. The equations 1 and 2 are discretized at a sampling interval h of 30ms.

$$x(k+1) = Fx(k) + G(u(k) + w(k)) + d(k) \quad (3)$$

$$y(k) = Cx(k) + v(k) \quad (4)$$

In equations 3 and 4, disturbance d(k), random process noise w(k) is considered with zero mean and 0.0036 variance, and measurement noise v(k).

4. DISCRETE-TIME KALMAN FILTER AND DSMC CONTROLLER

The discrete-time Kalman filter design in Fig. 2 is placed on the controller side which consists of two modules called the predictor module and the Correction module [20]. Discrete-time Kalman filter process model is given by equation 5 where, state transition matrix A is to update X_{k-1} the previous state vector, while control-input matrix B is applied on control vector u_k. Process noise vector $w_{k-1,}$ follows a Gaussian distribution with zero mean and covariance Q, expressed as $w_{k-1} \sim N(0, Q)$.

$$X_k = A_k X_{k-1} + B_k u_k + w_{k-1} \quad (5)$$

The measurement model for the DTKF, as shown in equation 6, involves Y_k measurement vector, C measurement matrix, and measurement noise vector v_k. It's important to note that v_k is assumed to follow a Gaussian distribution with zero mean and covariance R, expressed as $v_k \sim N(0, R)$. Both Q and R are adjustable tuning parameters.

$$Y_k = C_k X_k + v_k \quad (6)$$

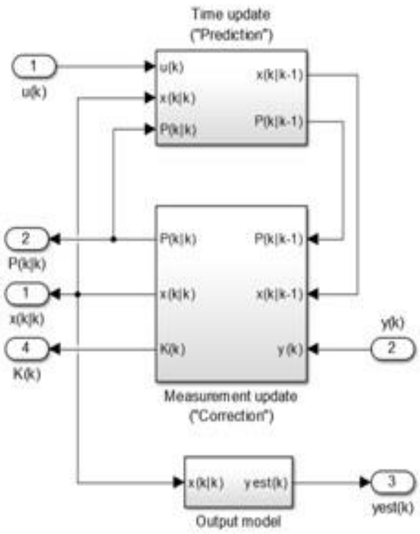

Fig.2. DTKF Algorithm

In Fig 2 the DTFK Discrete time Kalman Filter Algorithm is applied, where 1. The time update prediction block is given in Fig 3 in which State Prediction and Prediction of error covariance are calculated and 2. The measurement update ("Correction") block is given in Fig 4 in which constant gain is calculated to update the states and to update the error covariance.

The DSMC controller uses the Kalman filter output to compute the control signal using Gao's principle presented in this paper. In equation 7, discrete time sliding surface is the estimated sliding variable as per the proposed design. The sliding gain, C_k, is determined by employing the discrete LQR method. Accurate tuning of Q and R matrices is required while implementation. This proposed design incorporates the utilization of the reaching law based on switching is introduced by Gao et al. in 1995.

$$s(k) = C_k \, x(k) \quad (7)$$

Euler discretization of the continuous reaching law is given by equation 8 where, $(1 - qh) > 0$ and $h, q, \epsilon > 0$.

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

$$s(k+1) = (1 - qh)s(k) - \epsilon h\,\mathrm{sgn}[s(k)] \quad (8)$$

From previous equations 7 and 8, we can write equation 9.

$$C_k\, x(k+1) = (1 - qh)s(k) - \epsilon h\,\mathrm{sgn}[s(k)] \quad (9)$$

From equations 9 and 3 proposed controller can be given by equation 10.

$$u(k) = -(C_k G)^{-1}[(C_k F x(k) - (1 - qh)s(k)) + \epsilon h\,\mathrm{sgn}[s(k)]] - d(k) \quad (10)$$

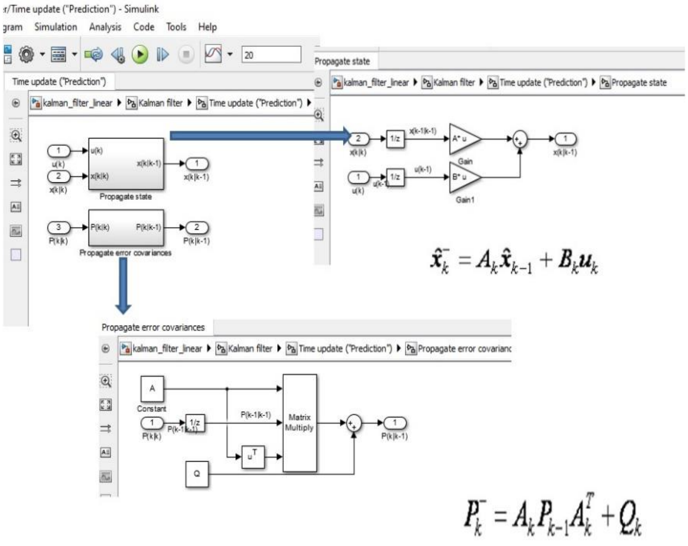

Fig. 3. Time update Prediction

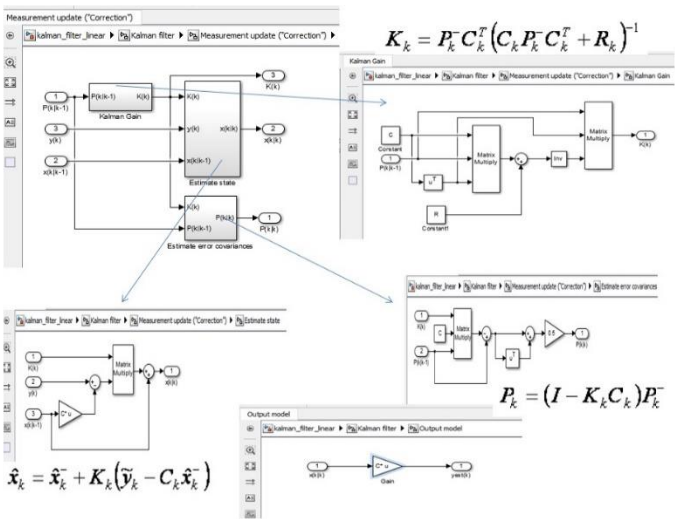

Fig. 4. Measurement update ("Correction")

In the proposed design QSMB quasi-sliding mode band is obtained where s(k + 1) sign will be opposite to s(k). So, the QSMB can be obtained by substituting s(k + 1) = − s(k) with s(k) > 0 in equation 8.

$$s(k+1) = (1 - qh)s(k) - \epsilon h\,\mathrm{sgn}[s(k)]$$

$$-s(k) = (1 - qh)s(k) - \epsilon h$$

$$0 = (2 - qh)s(k) - \epsilon h$$

So, QSMB is given by equation 11.

$$s(k) = \frac{\epsilon h}{(2 - qh)} \quad (11)$$

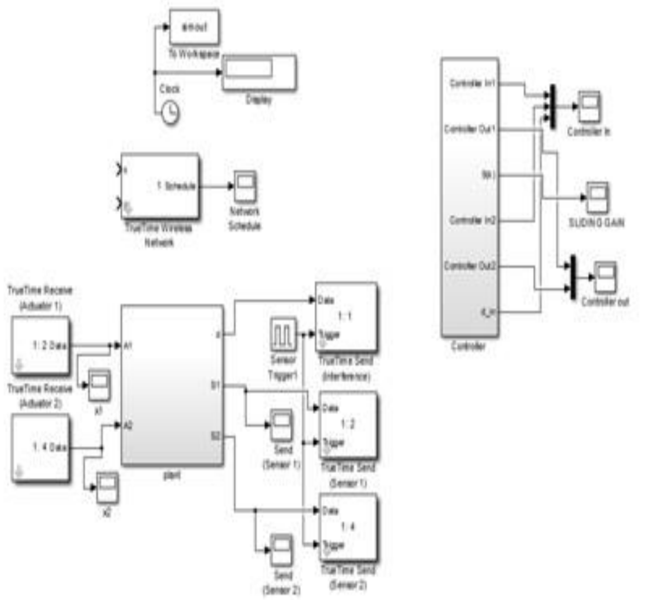

Fig. 5. Proposed WNCSs closed loop implementation

5. SIMULATION RESULTS

In Fig 5 WNCSs closed loop implementation in Truetime 2.0 simulation is given in which two state variables X1, X2, and disturbance node d are the wireless transceiver nodes communicating with the proposed controller. In the proposed closed loop of WNCS, the route taken by packets travelling from the sensor to the controller is referred to as the forward path, while the route from the controller to the actuator is termed the feedback path [22]. Fig 6 illustrates the transmission receiver nodes on the controller side. DC Servo Motor Plant with disturbance and random noise (zero mean and 0.0036 variances) model is considered in Fig 7. A mathematical model of a position-controlled DC Servo Motor is given in equation 13 for the implementation of the proposed WNCS [24] [19].

$$\frac{\Theta(s)}{Va(s)} = \frac{Km}{S\,[JmRmS + (Km)2]} \quad (13)$$

In this context, Θ(s) represents the output (position), Vm denotes the input, Jm signifies the rotor inertia (4 x 10^-6 kg-m^2), Rm stands for the terminal resistance (8.4 ohms), and Km signifies the motor back emf constant (0.042 Vs per radian), the parameters A, B, C, and D for the state space model of the position-controlled DC servo motor are

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

computed [23] [14].

$$A = \begin{bmatrix} -201 & 0 \\ 1 & 0 \end{bmatrix},\quad B = \begin{bmatrix} 1 \\ 0 \end{bmatrix},\quad C = [\,0 \quad 1\,],\quad D = \begin{bmatrix} 1 \\ 1 \end{bmatrix}.$$

The system is discretized with a sampling interval h is 30 milliseconds, we get

$$x(k+1) = Fx(k) + Gu(k) + d(k) \qquad (14)$$

$$y(k) = C\,x(k), \qquad (15)$$

Where,

$$F = \begin{bmatrix} 0.001836 & 0 \\ 0.004753 & 1 \end{bmatrix},\quad G = \begin{bmatrix} 0.004753 \\ -0.0001242 \end{bmatrix},$$

$$C = [\,0 \quad 1\,].$$

d(k) is 1-D sampled based sine with 2 amplitude zero bias and 100 samples. Discrete-time Kalman filter 1-D Parameters A, B, and C are calculated for the proposed implementation.

$$A = \begin{bmatrix} 1 & 0.03 \\ 0 & 1 \end{bmatrix},\quad B = \begin{bmatrix} 0.00045 \\ 0.03 \end{bmatrix},\quad C = [\,3600 \quad 0\,].$$

Initial conditions (Kalman filter for the x1 state) xo = 1,uo = 0 and initial conditions (Kalman filter for the x2 state) xo = -1, uo = 0. Po = 0.03*eye (1), Q = 0.03*eye(1), R=1, sample time = 0.03 s. E[x(0)-xo][x(0)-xo]' = Po , Q = Ew(k)w'(k) , R = Ev(k)v'(k). In Fig 8 estimated state X1 and estimated process output signal Y are shown for further consideration of the DSMC input signal. In Fig 9 estimate state X2 and estimated process output signal Y are shown for further consideration of the DSMC input signal. Estimated states from the 1-D Discrete-time Kalman filter are given to Gao's law as per the proposed wireless DSMC designand implementation shown in Fig 10. The discrete LQR method is employed to calculate the sliding gain $C_s = [3.9723 \quad 6.3246]$, R = 1 and $Q = \begin{bmatrix} 1600 & 0 \\ 0 & 40 \end{bmatrix}$.

The quasi-sliding band |s (k)| ranges from +3.8 to -3.8 with tuning parameters q = 10, $\epsilon = 217$. Wireless trans receiver nodes are in the same wireless network in which data rate 1e7 bits/s, transmit power 30 dBm (1000.00 mW), receiver signal threshold -48 dBm (1.58e-05 mW), path-loss exponent 3.5 and no packet loss probability is considered.

In Fig 11, a stable sliding variable response for the proposed design is given to minimize error or tracking deviation, the control signal of the proposed design is given in Fig. 12 and the desired control performance of the X1 and X2 states is given in Fig. 13 where Quasi Sliding band is -0.5 to +0.5 sec and settling time Ts is 4 sec. The schedule of wireless nodes for the no packet loss probability for the proposed design is shown in Fig 14. The proposed DSMC design with Discrete Time Kalman Filter, in the wireless medium is successfully implemented. While implementation the parameters are tuned to get an optimized response.

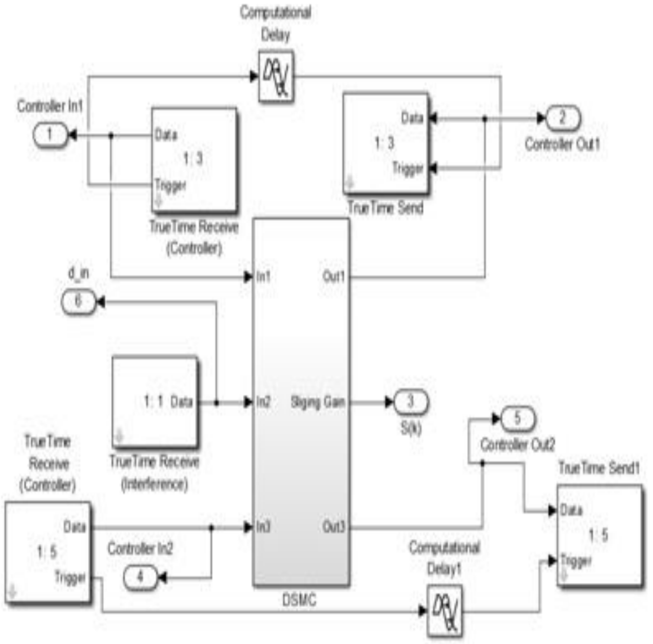

Fig. 6. Wireless Tx and Rx nodes at the controller side

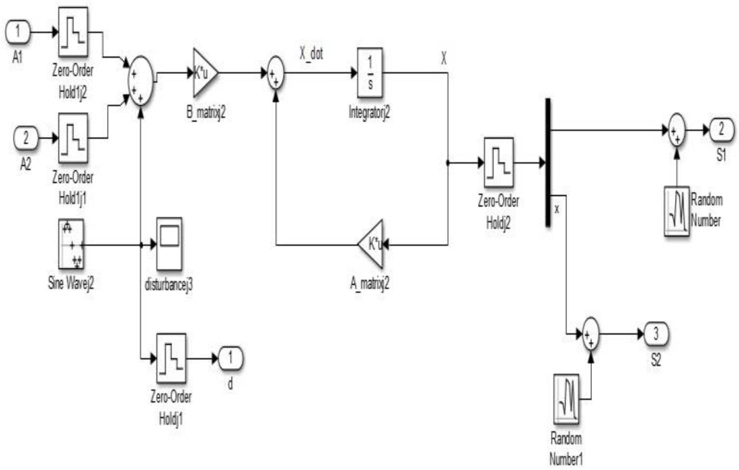

Fig. 7. DC Servo Motor Plant model implementation

6. CONCLUSIONS

In this paper, the design of the robust and wireless DSMC strategy for the DC motor in which the estimated s(k) and Gao's reaching law is presented. The estimated sliding variable uses estimated and corrected wireless received state information at a discrete time Kalman filter. The topology of the wireless nodes, radio coverage of the IEEE 802.15.4 wireless medium and disturbance in wireless channels are major concerns while designing the robust control and wireless communication jointly. Simulation outcomes have been given to showcase the efficacy and suitability of the innovative design, which has been identified as groundbreaking within the context of Industry 4.0, particularly concerning remote control capabilities and robustness.

Volume 12, Issue 3
June 2023

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

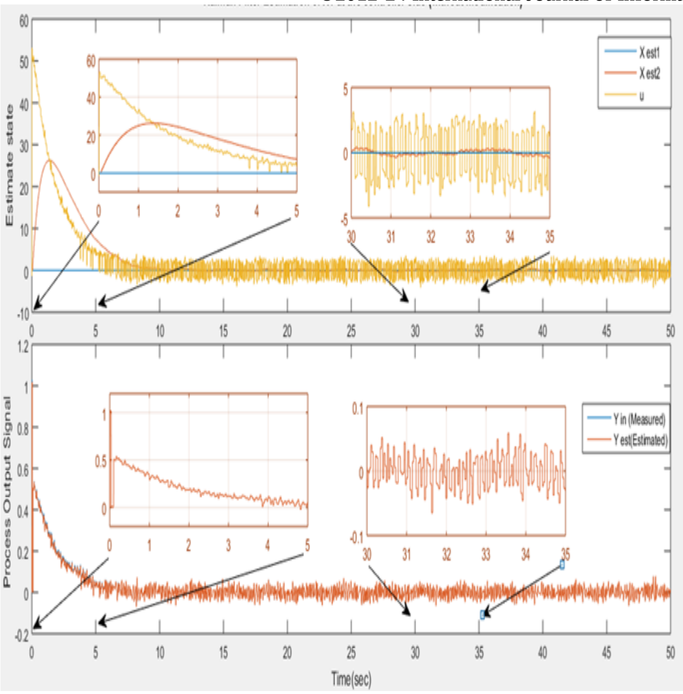

Fig. 8. Kalman Filter Estimation for state X1

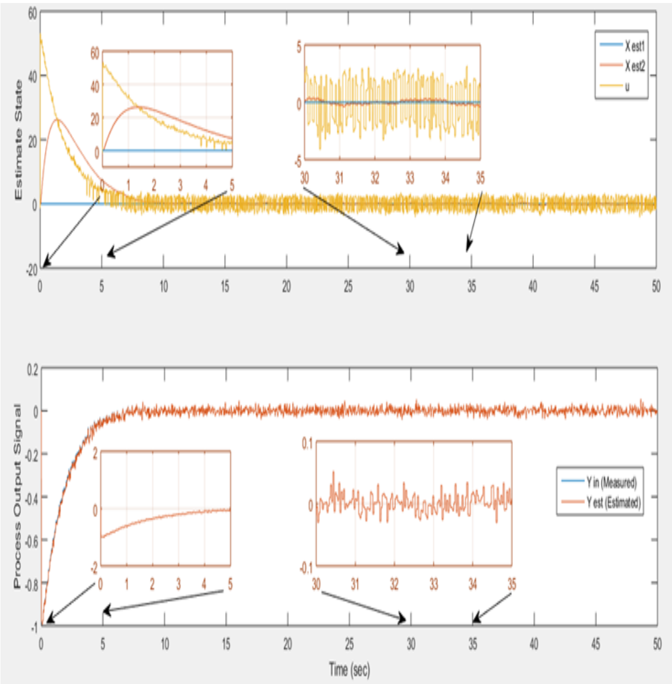

Fig. 9. Kalman Filter Estimation for state X2

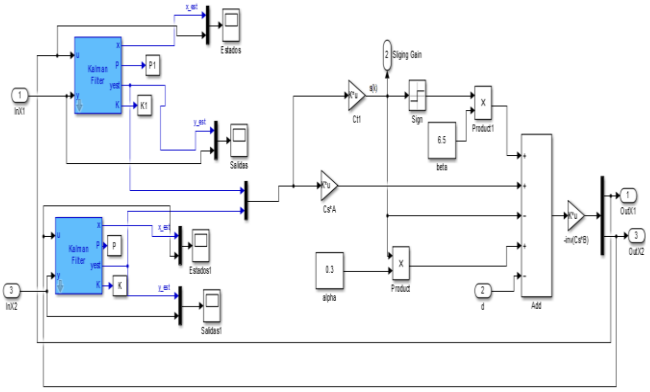

Fig. 10. WNCSs using Discrete-time Kalman filter and Gao's law

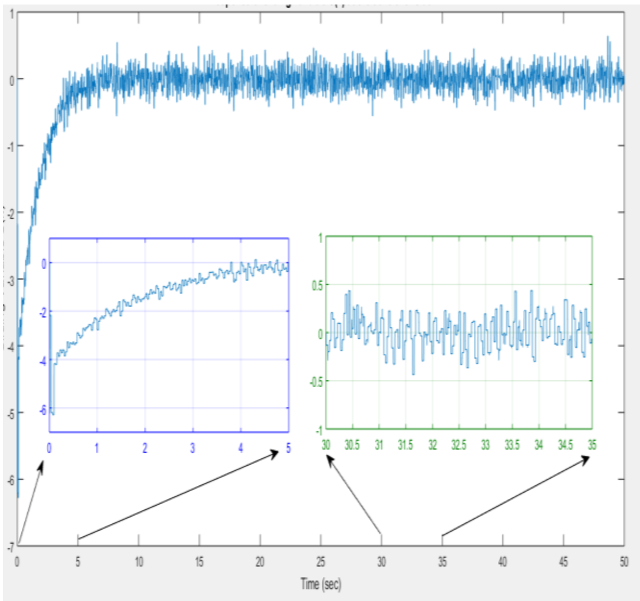

Fig. 11. Estimated Sliding Variable S(k) implementation

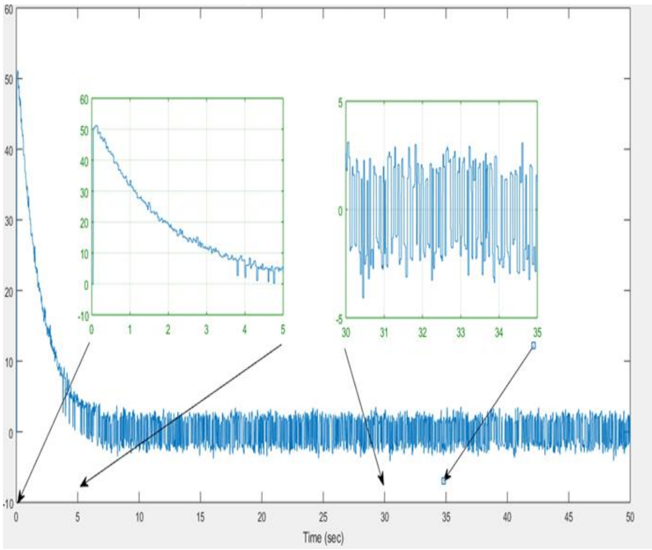

Fig. 12. Control signal response

ITEE Journal
Information Technology & Electrical Engineering
ISSN: - 2306-708X

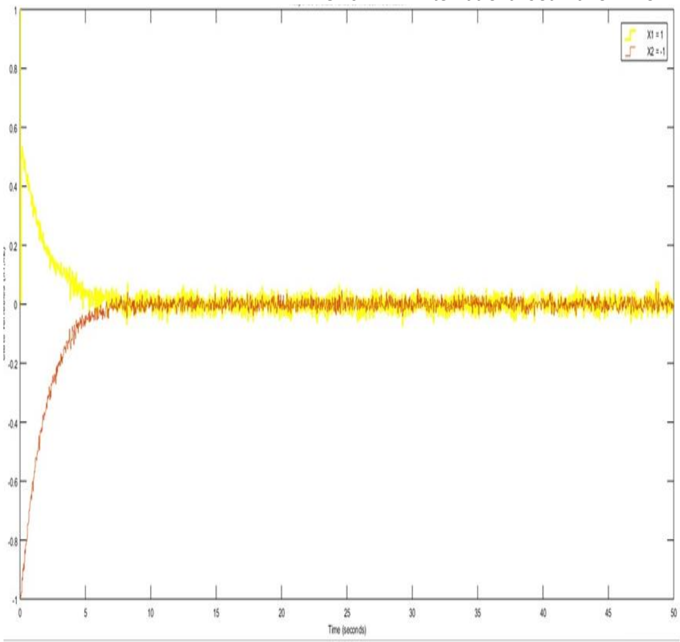

Fig. 13. States X1,X2 Response

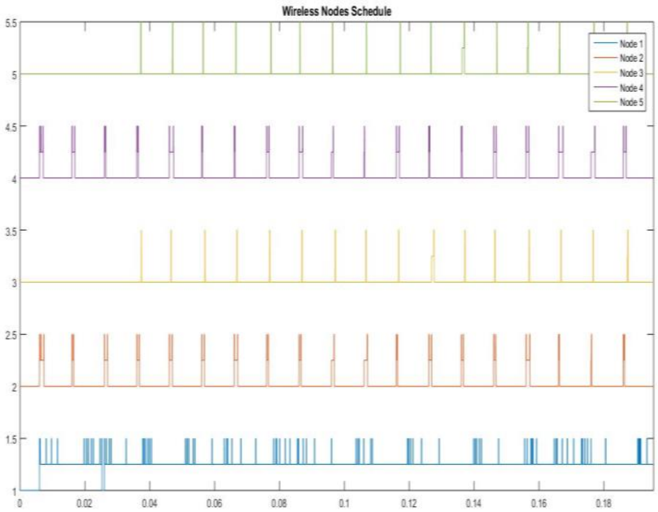

Fig. 14. Schedule for no packet loss probability

REFERENCES

[1] P. Park, S. Coleri Ergen, C. Fischione, C. Lu and K. H. Johansson,"Wireless Network Design for Control Systems: A Survey," IEEE Communications Surveys and Tutorials, vol. 20, no. 2, pp. 978–1013, 2018.

[2] M. Drew, X. Liu, A. Goldsmith, and K. Hedrick, "Networked control system design over a wireless LAN," in Proc. 44th Conf. Decision and Control and European Control Conf., pp. 6704-6709, Dec. 2005.

[3] R. G. Brown and P. Y. C. Hwang,"Introduction to Random Signal Analysis and Kalman Filtering with Matlah Exercises and Solutions," John Wiley and Sons, Inc., 1996.

[4] M. S. Grewal, and A. P. Andrews,"Kalman Filtering: Theory and Practice Using MATLAB," 2nd ed., Wiley-Interscience.

[5] D. Simon,"Optimal state estimation: Kalman, H infinity, and nonlinear approaches," John Wiley and Sons, 2006.

[6] B. Cipra, "Engineers Look to Kalman Filtering for Guidance," SIAM News, Vol. 26, No. 5, August 1993.

[7] R. H. Battin, "Theodore von Karman Lecture: Some Funny Tilings Happened on the Way to the Moon," 27th Aerospace Sciences Meeting, Reno, Nevada, AIA A-89-0861,1989.

[8] H. Li, X. Li, J. Wang, and H. Ma, "Design of networked control system based on wireless sensor networks," in Proc. ICIA '09. International Conference on Information and Automation, June. 2009, pp. 22-24.

[9] W. Yang, L. Fan, and J. Luo, "Design of discrete-time sliding mode observer in the networked control system," Proceedings of Chinese Control and Decision Conference, pp. 1884-1887, Dec. 2010.

[10] L. Schenato, B. Sinopoli, M. Franceschetti, K. Poola, and S. Sas- try,"Foundations of control and estimation over lossy networks," Proceedings of the IEEE, vol. 95, no. 1, pp. 163–187, 2007.

[11] B. Li, Y. Ma, T. Westenbroek, C. Wu, H. Gonzalez, and C. Lu, "Wire- less routing and control: A cyber-physical case study," in ACM/IEEE ICCPS, 2016

[12] M. Sahebsara, T. Chen, and S. L. Shah, "Optimal h2 filtering in networked control systems with multiple packet dropout," IEEE Trans- actions on Automatic Control, vol. 52, no. 8, pp. 1508–1513, 2007.

[13] B. Demirel, Z. Zou, P. Soldati, and M. Johansson, "Modular design of jointly optimal controllers and forwarding policies for wireless control," IEEE Transactions on Automatic Control, vol. 59, no. 12, pp. 3252– 3265, 2014.

[14] W. Jantapoon, V. Tipsuwanporn and A. Numsomran, "The Design of PI with Delayed-Time Integral Mode Controller for Wireless Networked Control System," 2021 21st International Conference on Control, Automation and Systems (ICCAS), Jeju, Korea, Republic of, 2021

[15] Ana, P. M. de S., Marchenko, N., Popovski, P., & Soret, B. (2021). "Age of Loop for Wireless Networked Control Systems Optimization," 2021 IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE PIMRC 2021)

[16] Park, P., Di Marco, P., & Fischione, C. (2021). Wireless for Control: Over-the-Air Controller. 1–5. http://arxiv.org/abs/2105.13503

[17] Silva, C. A. G. da, & Santos, E. L. dos. (2023). A Compensation Model for Packet Loss Using Kalman Filter in Wireless Network Control Systems. Energies, 16(8), 1–15.

[18] S. Yim, "Active Roll Stabilization With Disturbance Feedforward Control," in IEEE Access, vol. 9, pp. 19788-19799,2021.

[19] https://www.goddardconsulting.ca/control-system-design/kalman

[20] Anton Cervin, Dan Henriksson, Martin Ohlin,

"TrueTime 2.0 Reference Manual," Department of Automatic Control, Lund University, Sweden, 2016.

[21] Dipesh Shah and Axaykumar Mehta, "Discrete Time Sliding Mode Control for Network Control System," Systems, Control and Decision, Springer, 2018.

[22] R.C.Dorf and R.H. Bishop, "Modern Control Systems.Pearson Prentice Hall," Upper Saddle River, 11 th ed., NJ, 2008.

[23] Dipesh Shah. Discrete-time sliding mode control for networked control system. PhD Thesis, Gujarat Technological University, 2017

[24] Astrom ,K., J.Apkarian, P.Karam, M.Levis, and J.Falcon, Student Work- book: QNET DC Motor Control Trainer for NIELVIS. Quanser, 2015.

AUTHOR PROFILES

K. Paradkar B.E. Instrumentation and Control (2010) and M.E. Applied Instrumentation (2012). Currently, she is pursuing a full-time Ph.D. from Sardar Vallabhbhai Patel Institute of Technology, Gujarat Technological University, Ahmedabad, Gujarat, India. Her research topic is wireless networked control systems.

D. Shah B.E. Instrumentation and Control (2007), M.E. in Applied Instrumentation (2010), Ph.D. in the Networked Control System (2017), Postdoctoral in Biomedical Engineering (2019-2020) degree from Gujarat University Ahmedabad, Gujarat Technological University, GTU and IIT Gandhinagar, respectively. He is a traction software development engineer at Alstom Transportation and a GTU-recognized PhD Supervisor.