International Journal of Modern Developments in Engineering and Science
Volume 3, Issue 9, September 2024
https://www.ijmdes.com | ISSN (Online): 2583-3138

Analyzing the Effect of Uncertain Dynamics in Industrial Networked Control System through Control Action

Brijraj Singh Solanki*
Professor, Department of Computer Engineering, Poornima College of Engineering, Jaipur, India

***Abstract*: Industrial Network control systems, which integrate sensors, actuators, and controllers, have demonstrated a rapid development. The low maintenance, simplicity of installation, system cabling, and monitoring of Network Control Systems (NCS) make them useful in a variety of fields. However, targeted attacks can compromise communication over the NCS network. Entrants are more likely to access large amounts of information transmitted through communication channels or networks, thereby diminishing the control over the network system. The proportional integral and derivative control and Kalman filter is employed to analyze the performance of industrial networked control system. The MATLAB Simulink environment is used to simulate the suggested model. The results of the simulation demonstrate how the suggested methodology enhanced system performance of industrial networked control system.**

***Keywords*: Kalman filter, Proportional Integral and Derivative Control, Networked Control System, Packet Loss, Denial of Service (DoS), Delay.**

1. Introduction

Along with Network control systems have developed as a field of technology in which parts are connected remotely via a network of real-time communication [1]. In order to enhance overall system performance, the NCS relies on the secure transmission of packets and messages via communication channels. NCS has numerous industrial applications, including power distribution, oil and gas power plants, water management, transportation, robotics, process industry, space vehicles, and medical treatment, among others, thanks to the quick advancement of information technology [2]. Sensitive information carried over networks can be attacked via packets containing it. There are several methods the hacker can use to obtain the data, including denial of service (DoS), service degradation attack (SD), and eavesdropping.

The study examined the stability of DC/DC converters using the CAN-bus system, accounting for performance degradation metrics like packet dropout and time delay. Markov chains are used to model discrete time delays, and a set of linear matrix inequality equations is used to analyze stability. To demonstrate the system's stability, the voltage controller gain was calculated [3].

Through the use of a position servo system, the performance-degrading parameters random delay and packet loss are also discussed in order to examine the stability of networked control systems. The control gain and optimal performance index were computed using the employed system [4].

The Bernoulli function is used to model packet loss in network control systems, where latency and packet loss are important stability-controlling factors. To demonstrate the measurement quality of the specified method, a few stable methods are obtained [5]-[8].

For feedback networked control systems, the Lyapunov method is presented to simulate stochastic packet loss and sufficient condition with asymptotic stability to capture the effect of time delay [9].

The goal of this paper is to address the issue of uncertain disturbance in NCS and enhance the networked system's transient performance. The proportional integral and derivative control and kalman filter is employed to analyze the performance of industrial networked control system. The MATLAB Simulink environment is used to simulate the suggested model.

The following various sections are presented in the remainder of the article: The articles pertaining to the different types of attacks and the stability of the NCS are explained in Section 2. Section 3 presents the problem identification based on malicious interference and network uncertainty. In the fourth section, the method's efficacy will be discussed. Lastly, Section 5 offers final observations and upcoming research to be done.

2. Literature Work

The introduction of a neural network-based event-triggered controller scheme using a dynamic programming approach allowed for the detection of an attack on non-linear networks and sensors. When the residual exceeds a predetermined threshold, an attack is found. This method took into account a time delay and packet loss attack. The suggested methodology used was more rapid in detecting than the traditional method covered in the literature [10]-[12].

The effects of undesired intrusive data were investigated in [13]-[16], using the proportional integral controller, linear quadratic Gaussian approach, and Kalman-filter in networked

*Corresponding author: brijraj.eic@gmail.com

control systems. It has been demonstrated that this methodology significantly reduced the effect on NCS to a level that is acceptable. Numerous variables chosen to assess the suggested system's performance metrics.

In order to simulate the performance degradation in networked control systems that are vulnerable to packet loss and delay attacks, two queuing approaches were discussed. Denial of Service (DoS) attacks are thought to be the cause of control system parameter degradation. Such a denial-of-service attack degrades the network's quality of service metric, which lowers performance [17]-[20].

The performance metrics of closed loop networked control systems subjected to communication network constraints were analyzed using a predictive control technique [21], [22]. Using a rotating inverted pendulum system as an example, the Linear Quadratic Regulator (LQR) technique aims to enhance the performance of networked systems. In this closed loop networked system, communication constraints like packet loss and time delay are regarded as disruptive factors. By using these strategies, the performance increased to the desired level [23]-[25]. Data backup-based compensation is used in [26] to ensure the stability of the suggested system. The set of stability conditions for a networked system with induced delay and packet loss issues was derived using the Lyapunov function. A number of conditions have been established that guide the necessary control input to keep the response at the expected level [27]-[29].

By using the Lyapunov function, linear matrix inequality, and Wirtinger inequality to derive the set of conditions, the problem resulting from the communication constraint is resolved. Improved control system performance under communication constraints was demonstrated by the proposed interval type-2 fuzzy model [30]-[32]. The purpose of the predictive controller is to explain how the planned method reacts to the control system. A denial of service attack could be introduced as a result, which could impact data transfer [33], [34]. An intrusion detection system has been used to calculate the attacks introduced for wireless network management systems, and the authors have also verified the suggested stability procedure [35]-[38].

Attack techniques like denial of service and replay attacks can taint the message data sent from the sensor to the controller or from the controller to the router. To derive stable methods for performance analysis, the horizontal reverse power law and exponential stability are proposed [39]-[41]. A discussion of enhanced distribution grid management control system performance can be found in [42]. The system's effectiveness is demonstrated through the use of time and strategy. The impact of transmission jitter, delay, and packet loss, a major contributor to system instability, is also covered.

A method for minimizing the weighted cost of the linear quadratic Gaussian function is presented in order to maximize the performance of a stochastic linear time-invariant system. In order to determine the optimal cost, the networked system made use of shared communication resources and admit scheduling policies [42].

3. Problem identification and methodology

A. System Description with Packet Loss and Delay

Figure 1 displays the proposed network control system's block diagram. In this instance, a sensor samples the system's response, which is then transmitted to the controller via a wireless communication network. Using an algorithm created specifically for control, the controller determines the control signal based on the reference and sensor sample received through the communication network. The calculated signal that is sent to the actuator via the communication channel to operate the system in accordance with the intended output. It has been discovered in numerous publications that an attacker can impede the control system in any manner (that is, in the forward and/or feedback direction) to reduce NCS performance.

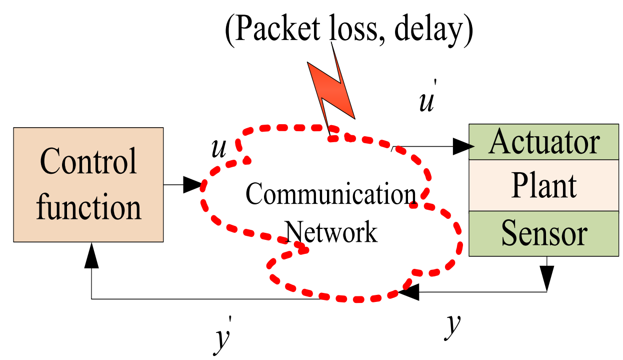

Fig. 1. Introduction of Packet loss and delay in NCS

Through communication, the controller receives the response that the sensor has sampled, and through the communication network, the controller sends the control signal that it has generated. It is assumed that, there is a delay between the actuator and the controller (i.e., "t_{sc}" and "t_{ca}", respectively).

B. Uncertain Delay

The communication network is used to send the controller's generated control signal-which is directed towards the actuator-along with the sensor's sampled response. As a result, there are delays between the controller to actuator signal and the sensor, to controller and additionally, there are processing delays (sensor to controller and controller to actuator delay) that are exactly as small as they should be in relation to other delays. The communication network's length, bandwidth, and other factors all affect this random delay change. The system is getting close to instability because of the delayed disturbance's stochastic nature. Consequently, delay dynamics must be taken into account when designing controllers and system models.

The following requirements for sample time "τ_s" must be satisfied for effective packet deliver [12]:

$$\tau_s > t_{sc} + t_{ca} + t_p (\text{processing delay}) \quad (1)$$

C. Probability of Packet Loss Distribution

In order to control the process, the actuator receives signals from the controller after it has sampled the sensor signal. When the signal moves across the communication network, packet loss could happen. Both the forward and feedback directions may experience packet loss issues. Modeling packet loss requires taking into account the distribution function given as [12]:

$$p(\gamma_k) = \begin{cases} p, & if\, \gamma_k = 1 \\ 1-p, & if\, \gamma_k = 0 \end{cases} \tag{2}$$

The packet loss rate is shown here as $p \in [0,1]$. If the packet is lost at instant k, then "$\gamma_k = 0$," and if the packet arrives successfully at instant k, then "$\gamma_k = 1$".

When transmitting packets, the idea of timestamp theory is used. Each packet is stored in a buffer that has a timestamp. The linear time-invariant (LTI) system is used to represent the system with networked delay and packet loss as [12].

$$x(k+1) = Ax(k) + \gamma_k Bu(k-\tau_s) \tag{3}$$

$$y(k) = Cx(k) \tag{4}$$

Equation (3) represents the state vectors "$x(k)$" and control vectors "$u(k)$". Similarly, Eq. (4), represents the output signal "$y(k)$" and *A, B, C* are various matrices of the proper sizes.

4. Simulation Result Analysis

The MATLAB Simulink environment is utilized to present various simulation diagrams that demonstrate the efficacy of the proposed methodology.

The plant dynamics are presented by following expression,

$$Plant = \frac{-0.0272s^2 - 0.0005s - 2.187}{s^3 + 15.1s^2 + 28.58s - 103.4} \tag{5}$$

The parameters of proportional integral derivation control are given as P=-0.07460, I=-0.03709 and D= -0.018109.

Figures 2 through 5 show the different simulations that were performed on MATLAB. The simulation results that show the response signal produced without disturbance and using PID control and kalman filter are shown in Figure 2. The response signal follows the step input and produced desired signal. Figure 3 depicts the introduction of disturbances in networked control system.

Figure 4 simulates the generation of response signals while taking the disturbance and the PID control policy into account. Following the introduction of the disturbance and PID control policy with kalman filter for disturbance removal, the response signal accurately tracks the step input.

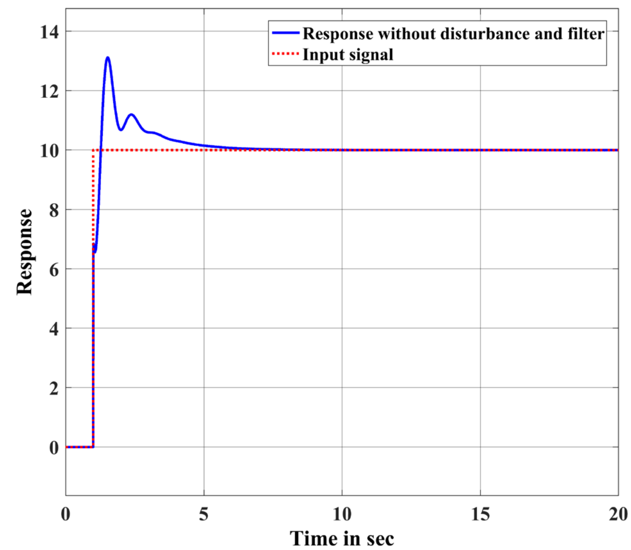

Fig. 2. Output/ Response without disturbance and with PID control

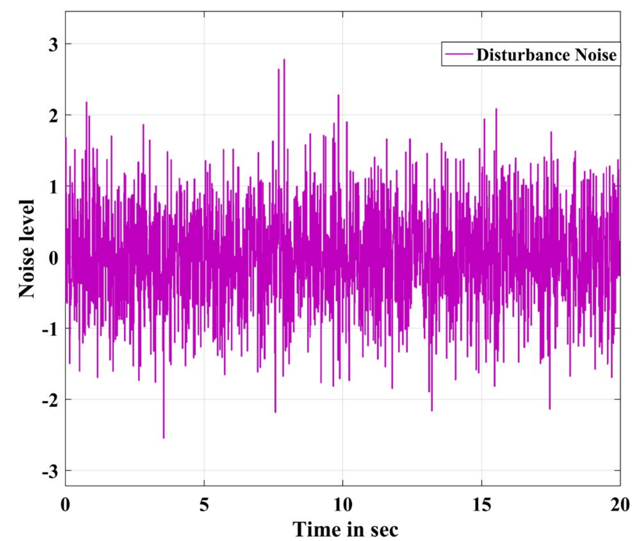

Fig. 3. Generation of disturbance

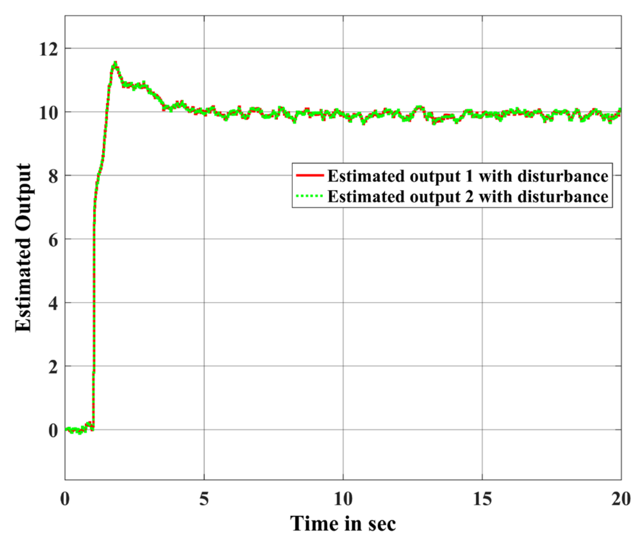

Fig. 4. Estimated output with PID control and Kalman filter with disturbance

5. Conclusion and Future scope

This section presents the final thoughts regarding the networked control system performance metrics under various uncertain conditions. The MATLAB Simulink environment is used to simulate the suggested model. The results of the simulation, which range from Fig. 2 to Fig. 4, demonstrate how the suggested methodology enhanced system performance.

The simulation results are shown in Figure 2, which shows the response signal produced without a disturbance while using PID control. After creating a disturbance, the response signal follows the step input. The response signal follows the step input and produced desired signal. Figure 3 depicts the introduction of disturbances in networked control system.

Figure 4 simulates the generation of response signals while taking the disturbance and the PID control policy into account. Following the introduction of the disturbance and PID control policy with kalman filter for disturbance removal, the response signal accurately tracks the step input. The NCS system is controlled by an enhanced PID control and kalman filter which rejects the disturbance.

In order to mitigate the effects of uncertain disturbances dynamics, future research will examine the event triggered control architecture for non-linear NCS.

References

[1] N. Zhao, W. Xing, P. Shi, and C. P. Lim, "Event-Triggered Control for Networked Systems Under Denial of Service Attacks and Applications," IEEE Trans. Circuits Syst. I Regul. Pap., vol. 69, no. 2, pp. 811–820, 2022.

[2] M. Pajic, J. Weimer, N. Bezzo, O. Sokolsky, G. J. Pappas, and I. Lee, "Design and Implementation of Attack-Resilient Cyberphysical Systems: With a Focus on Attack-Resilient State Estimators," IEEE Control Syst., vol. 37, no. 2, pp. 66–81, 2017.

[3] Z. H. Pang and G. P. Liu, "Design and implementation of secure networked predictive control systems under deception attacks," IEEE Trans. Control Syst. Technol., vol. 20, no. 5, pp. 1334–1342, 2012.

[4] S. McLaughlin et al., "The Cybersecurity Landscape in Industrial Control Systems," Proc. IEEE, vol. 104, no. 5, pp. 1039–1057, 2016.

[5] B. S. Solanki, K. Renu, and S. Srinivasan, "Stability and Security Analysis with Identification of Attack on Industrial Networked Control System: An Overview," Internetworking Indones. J., vol. 11, no. 2, pp. 3–8, 2019.

[6] B. Singh Solanki, R. Kumawat, and S. Srinivasan, "Optimal switching control design for industrial networked control system with uncertain exogenous dynamics," Mater. Today Proc., vol. 79, no. Part 2, pp. 286–291, 2023.

[7] G. Bhatnagar, N. Gobi, H. Aqeel, and B. S. Solanki, "Sparrow-based Differential Evolutionary Search Algorithm for Mobility Aware Energy Efficient Clustering in MANET Network," Int. J. Intell. Syst. Appl. Eng., vol. 11, no. 8s, pp. 135–142, 2023.

[8] J. Hu, F. Zhou, and Y. Zhang, "Observer-based Event-triggered Control for a Class of Networked Control Systems under Denial of Service Attacks," Chinese Control Conf. CCC, vol. 2022-July, pp. 959–964, 2022.

[9] T. Li, W. A. Zhang, and L. Yu, "Improved Switched System Approach to Networked Control Systems with Time-Varying Delays," IEEE Trans. Control Syst. Technol., vol. 27, no. 6, pp. 2711–2717, 2019.

[10] M. Zhu and S. Martinez, "On the performance analysis of resilient networked control systems under replay attacks," IEEE Trans. Automat. Contr., vol. 59, no. 3, pp. 804–808, 2014.

[11] B. S. Solanki, "Control System for Wind Power Plant," Int. J. Sci. Dev. Res., vol. 4, no. 3, pp. 473–476, 2019.

[12] B. S. Solanki, "Controlled Output Feedback to Stabilize Networked Control System," Int. J. Mod. Dev. Eng. Sci., vol. 3, no. 9, pp. 1–5, 2024.

[13] P. Wang and W. Che, "Quantized H∞ control for networked control systems with random packet losses," Proc. 2015 27th Chinese Control Decis. Conf. CCDC 2015, pp. 6557–6562, 2015.

[14] S. Solanki, B.S., Kumawat, R., Srinivasan, "Optimized Control Function with Estimation of System Parameters Against Attack for Networked Control System," in Intelligent Computing Techniques for Smart Energy Systems. Lecture Notes in Electrical Engineering, 2022, vol. 862, pp. 515–528.

[15] B. Singh, "Solar Power Generation by PV Technology," IRE Journals, vol. 1, no. 9, pp. 260–265, 2018.

[16] X. Tang, M. Wu, M. Li, and B. Ding, "On Designing the Event-Triggered Multistep Model Predictive Control for Nonlinear System Over Networks With Packet Dropouts and Cyber Attacks," IEEE Trans. Cybern., pp. 1–13, 2021.

[17] B. S. Solanki, R. Kumawat, and S. Srinivasan, "Averting and Mitigating the Effects of Uncertainties with Optimal Control in Industrial Networked Control System," Proc. - 2021 IEEE Int. Symp. Smart Electron. Syst. iSES 2021, pp. 316–318, 2021.

[18] B. S. Solanki, "Optimal Control Strategy to Analyse the Networked Control System Stability," Int. J. Curr. Sci. Res. Rev., vol. 07, no. 09, pp. 7160–7167, 2024.

[19] B. S. Solanki, R. Kumawat, and S. Srinivasan, "An Impact of Different Uncertainties and Attacks on the Performance Metrics and Stability of Industrial Control System," in Lecture Notes in Networks and Systems, 2021, vol. 204, pp. 557–574.

[20] P. Wang and G. Feng, "A study of optimal control strategy of networked control systems with stochastic delay and packet losses," CARE 2013 - 2013 IEEE Int. Conf. Control. Autom. Robot. Embed. Syst. Proc., pp. 1–5, 2013.

[21] B. Singh and O. P. Sharma, "Analysis of Coded and Uncoded Digital Modulation Techniques," Int. J. Electron. Commun. Technol., vol. 4, no. 4, pp. 46–48, 2013.

[22] H. Li, M. Y. Chow, and Z. Sun, "State feedback stabilisation of networked control systems," IET Control Theory Appl., vol. 3, no. 7, pp. 929–940, 2009.

[23] B. S. Solanki, R. Kumawat, and S. Srinivasan, "Synthesize the Effect of Intrusion and Imperfection on Networked-Connected Control System with Optimal Control Strategy," 2021 10th Int. Conf. Inf. Autom. Sustain. ICIAfS 2021, pp. 105–110, 2021.

[24] B. S. Solanki, "Review of Uncertain Dynamics in Networked Control System for Analysis of Stability," Int. J. Mod. Dev. Eng. Sci., vol. 3, no. 9, pp. 11–15, 2024.

[25] D. Zhang and W. Ding, "Robust H∞ Filtering for Networked Control Systems with Random Delays and Packet Dropout via Delta Operator," IECON Proc. (Industrial Electron. Conf., vol. 2019-Octob, pp. 533–538, 2019.

[26] X. L. Zhu, X. Zhang, J. Wei, and H. Lin, "Output-Based Dynamic Event-Triggered Control for Networked Control Systems with Delays and Packet Losses Without Acknowledgements," IEEE Trans. Automat. Contr., vol. 68, no. 12, pp. 7120–7135, 2023.

[27] T. Kumar, M. Sharma, and B. S. Solanki, "New Designs and Analysis of Multi-Core Photonic Crystal Fiber Using Ellipse with Different Radiuses and Angles," in International Conference on Artificial Intelligence: Advances and Applications 2019, 2020, pp. 151–159.

[28] B. Singh and O. P. Sharma, "Analysis of BER in BPSK and GMSK Employing Different Coding," IFRSA's Int. J. Comput., vol. 2, no. 4, pp. 736–741, 2012.

[29] M. Klugel et al., "Joint Cross-Layer Optimization in Real-Time Networked Control Systems," IEEE Trans. Control Netw. Syst., vol. 7, no. 4, pp. 1903–1915, 2020.

[30] S. P. Singh and B. S. Solanki, "A Trading Model on Block chain Smart Contracts for the Shared Energy in Brazil," 4th Int. Conf. Emerg. Res. Electron. Comput. Sci. Technol. ICERECT 2022, pp. 1–5, 2022.

[31] R. Gupta, B. S. Solanki, M. Kumar, and R. Murugan, "Detecting Malware on the Android Phones Based on Golden Jackal Optimized Support Vector Machine," Int. J. Intell. Syst. Appl. Eng., vol. 11, no. 8s, pp. 01–07, 2023.

[32] L. Jianning, S. Hongye, W. Zhengguang, and C. Jian, "Stabilization of wireless networked control system with multi-packet transmission policy," Chinese Control Conf. CCC, pp. 5770–5774, 2012.

[33] M. Khademi, I. Izadi, M. Kamali, and F. Sheiholeslam, "An Adaptive Fuzzy Backstepping Controller for Delay Compensation in Networked Control Systems," ICEE 2019 - 27th Iran. Conf. Electr. Eng., pp. 1157–1162, 2019.

[34] M. Palmisano, M. Steinberger, and M. Horn, "Optimal Finite-Horizon Control for Networked Control Systems in the Presence of Random Delays and Packet Losses," IEEE Control Syst. Lett., vol. 5, no. 1, pp. 271–276, 2021.

[35] W. Ren and J. Xiong, "H∞Control of Linear Networked and Quantized Control Systems with Communication Delays and Random Packet Losses," IEEE Trans. Syst. Man, Cybern. Syst., vol. 52, no. 6, pp. 3926–3936, 2022.
[36] B. S. Solanki, "Stability and Performance Analysis of Networked Control System Experienced Variable Uncertain Dynamics," Int. J. Mod. Dev. Eng. Sci., vol. 3, no. 9, pp. 6–10, 2024.
[37] J. N. Singh and B. S. Solanki, "Utilization of Computational Intelligence in the Development of a Health Monitoring System for Induction Machines," 2022 Int. Conf. Futur. Technol. INCOFT 2022, pp. 1–6, 2022.
[38] Y. Qi, X. Zhao, and X. Zhao, "Event-Triggered Control for Networked Switched Systems Subject to Data Asynchronization," IEEE Syst. J., vol. 15, no. 4, pp. 5197–5208, 2021.
[39] B. S. Solanki, "Design of an Optimal Reliable Controller for Industrial Networked Control System to Mitigate Network Imperfections," 2022.
[40] B. S. Solanki, "Mitigating Effect of Uncertain Exogenous Dynamics by Parametric Performance Improvement with Optimal Control Design," Int. J. Eng. Trends Technol., vol. 70, no. 5, pp. 209–220, Jun. 2022.
[41] W. Ren and J. Xiong, "Tracking Control of Nonlinear Networked and Quantized Control Systems with Communication Delays," IEEE Trans. Automat. Contr., vol. 65, no. 8, pp. 3685–3692, 2020.
[42] Z. Hu, F. Deng, M. Xing, and J. Li, "Modeling and Control of Itô Stochastic Networked Control Systems with Random Packet Dropouts Subject to Time-Varying Sampling," IEEE Trans. Automat. Contr., vol. 62, no. 8, pp. 4194–4201, 2017.