Study of Network-Induced Delays on Networked Control Systems

Jitendra Kumar, Vishal Goyal and Devbrat Gupta

Abstract Networked control systems (NCSs) are significant and foremost multidisciplinary research areas for many decades. This paper is mainly oriented toward recent developments and challenges of network-induced delays due to inclusion of data network in NCSs. Network delays deteriorate the control performance and stability of the NCSs. The time-varying delays can be measured in real time by calculating the time difference of sending and receiving control packets. Various compensation techniques are reviewed to mitigate the effect of constant, time-varying, and stochastic delay. Lastly, some conclusions are drawn and the future research scope is directed.

Keywords Networked control systems · Network-induced delays · Communication networks · Study · Delay compensation

1 Introduction

The classical definition of Networked control systems (NCSs) can be given as: When a generalized feedback control system is closed via a communication channel, which may be connected with other nodes externally to the control system, then it is called an NCS. In another way, NCSs are the basic feedback control systems in which the control loops are connected via a real-time communication network [1–4]. The simplified model of NCS is shown in Fig. 1. Literature suggest that NCSs have been one of the leading investigated topics in multidisciplinary area for many decades. In classical feedback systems, the interconnection among the sensors, actuators, and

J. Kumar · V. Goyal · D. Gupta (✉)
Department of Electronics and Communication Engineering, GLA University, Mathura 281406, UP, India
e-mail: devbrat.gupta1@gmail.com

J. Kumar
e-mail: jitendra.kumar@gla.ac.in

V. Goyal
e-mail: vishal.glaitm@gmail.com

M. L. Kolhe et al. (eds.), *Advances in Data and Information Sciences*,
Lecture Notes in Networks and Systems 94,
https://doi.org/10.1007/978-981-15-0694-9_2

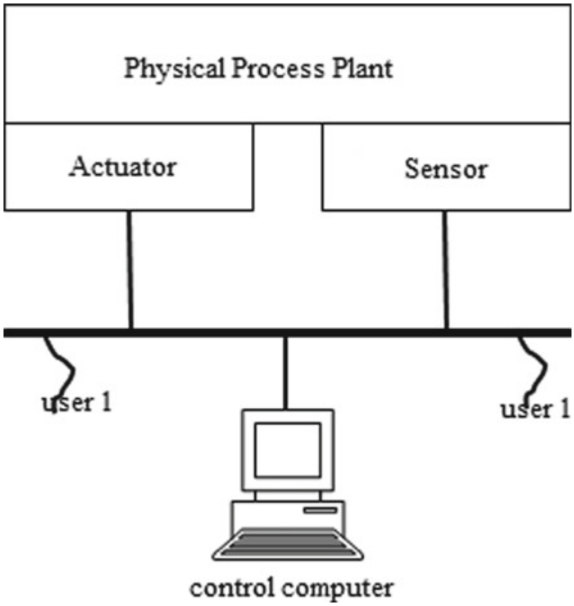

Fig. 1 Simplified NCSs

controllers are mainly realized by port-to-port connections by the communication network medium, due to which it creates many difficulties such as wiring complexities, low flexibility, and maintenance. These types of difficulties appear everywhere which motivated the rise of networked control systems with lesser cabling costs, cheaper hardware network, modularity, and flexibility in system design where automated controlled plants with increasing complexity are situated [5].

NCSs have increasing popularity among various industries with their variety of advantages over traditional control systems. It deals with interference, network congestion, data dropout, efficient data communication. It combines major industrial fields like automation and control field, computer science and network field, etc. [2].

In modern control systems, the goal is to design stable and feasible control techniques that can achieve various tasks with lesser reconfiguration cost and with ease of maintenance. A point-to-point framework is inactive from a reconfigurable opinion and it does not address the issues like interchangeability and reliability [6, 7]. The induction of communication networks gave the idea of remotely controlling a system which arises NCS. In recent years, use of wireless communication medium has been revolutionized. A conceptual model of NCS where information such as reference input, plant output, controlled output, etc., is shared via a communication network among control system elements such as actuators to drive control outputs as seen in Fig. 2 [1].

Basically, NCSs are divided into two classes: the first one is control-over-network and second is control of network. The study of performance issues of network such as networking protocol, routing control, the efficacy of the control system with network as data transmission medium (either shared or wirelessly) is being achieved in control

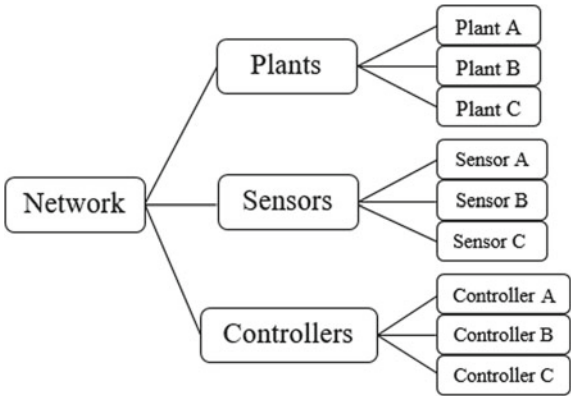

Fig. 2 Conceptual model of NCS

of network. This paper represents the control-over-network part. The research of networked control system is focused on two types of quality of the system, i.e., the quality of service (QoS) and the quality of control (QoC). In the present study, it has been focused on QoC to review the stability performance of the system due to effect of network-induced delays furthermore [3].

2 NCSs: Brief Evolution

Origins of control systems can be noticeable before 1868 when famous physicist J. C. Maxwell conducted dynamics analysis of the centrifugal governor [8]. In the late 1950s, the computer was added in control system and further it has been extensively used. Honeywell proposed TDC-2000 in mid 1980s [9, 10]. The enhancement of shared data networks such as slotted ALOHA widely evolved to use modern network protocols [4]. In early years, Gupta and Chow surveyed the history and evolution of NCSs. In 1969, the Advanced Research Projects Agency situated in U.S. (Department of Defense) has established the first working data switching network, i.e., ARPANET. Around 1980s, controller area network (CAN) was introduced as one of the fieldbus. The time-sensitive decentralized control, i.e., fieldbus was used in industrial network around 1988. Nowadays, wireless NCSs (WNCSs) are advent and standard for high-level data rates and integrity [1]. The motive behind WNCS is ease of installation, modularity, and rapid deployments of copious fascinating applications such as smart highways (or bridges), factory automation, vehicle communication, etc. Sensor nodes are commercially accessible in abundance due to brisk development in communication, sensing hardware, and low-power computational ability. Military, teleoperation, telerobotics, and medical applications can often use optical fiber network to guarantee speedy, robust, and unfailing communication. The Internet of Things (IoT) is suggested in many applications due to low cost where the plant and the controller are remotely located. Almost all the available networks have some small delay which subsequently deteriorates the control performance. While overviewing the analysis and synthesis of NCSs, delays are the main concern toward getting better stability performance. So certain aspects of network-induced delays are considered [10–15].

3 Literature Review on Various Delays

The inclusion of data networks in feedback loops of NCSs, give many advantages such as cost-effectiveness, robustness, and flexibility toward applications used. But some issues like network delays arise due to the insertion of these data networks and they degrade the NCS control performances which also affect the stability of system. Tipsuwan and Chow suggest some fundamental and recent control methodologies for NCSs to overcome some of the challenges and issues [4]. Yang has suggested a basic architecture and reviewed two important categories related to conventional large-scale NCSs [5]. The first one is control analysis and synthesis, the other one is network scheduling, protocol, and architecture. Brindha and Mendiratta have surveyed the development history of NCS furthermore and suggested the improvement of NCS performance in areas like propagation time and reduction of overall network-induced time lag with synthesis of robust and optimal controller [2]. Xia et al. summarized various phases in NCSs like quantizer, estimator, fault detection, and network predictive control and also proposed the future advancement in cloud techniques and cloud control systems [3]. This paper is mainly focused on quantization and how quantization improves the stability performance of the system.

Zhang et al. made an extensive survey about recent advancements in NCSs in his research work [7]. The synthesis, analysis, and modeling of the system have been majorly focused in his work. A new delay compensation algorithm with a feedback control law is proposed, which are connected via the CAN buses addition to a time-domain Smith predictor. It was observed that if the resulting delays are too large for an NCS with time constraints, the performance of the NCS will be degraded. This could eventually lead to possible physical harm to the controlled process or even threaten human lives. For example, in traffic NCS problem control-over-network can be observed [16–20].

Further, the concern of stability for discrete-time time-delay systems is reexamined. The Lyapunov–Krasovskii method is the most common technique to analyze the stability of time-delayed systems. To check the stability of the system, it has to find the maximum bounded delayed region such that time-delay system remains stable within this region [19]. Short time-varying delay is proposed within the region of maximal bound for defined stabilization techniques. On the basis of these techniques, stability criteria are defined. When NCS is utilized with STVD, it gets converted into time-varying discrete-time system with the help of robust control methods changed into corresponding time-invariant system. Zhang et al. proposed a delay reduction technique in which NCSs are linked via CAN where a feedback control law is suggested with the help of time-domain smith predictor to estimate the future state [14].

The asymptotic stability property of a feedback system by using augmentation is analyzed and obtained bilinear matrix inequality is transformed into a linear matrix inequality. Schenato explained the framework for optimal estimation design with two different time-invariant estimation architecture which does not depend upon the packet delay [20]. But tradeoffs appeared between packet loss and packet delay because the sensor measurements and their control packets are matter of random delay and loss simultaneously.

Shi and Yu focused on the output feedback stabilization of NCSs where the random delays are framed as Markov chain to design of a controller which is based on both the delays, i.e., measurement-to-controller and controller-to-final control element. After that closed-loop control system was transformed and output feedback controller was explored through linear matrix inequality to support stochastic stabilization [21]. Zhang et al. [14] proposed an output feedback delay control technique in which the stochastic network induced delay is modeled as Markov chain. A framework as Markovian jump linear system was designed for closed-loop control system for controller design. Heemels et al. show the tradeoffs between network delays, transmission interval, and their stability performance. Modeling of sampled-data NCS with random delays, packet loss, and quantization are performed as a nonlinear time-delay system with two consecutive delay mechanisms. Further, LK functional is used to solve the network-based H_∞ control problems in [22–28].

4 Challenges in Control-Over-Network

4.1 Issues on Control Performances

When network delays and data collisions are not taken into consideration, the control algorithm is simple and stable but problem persists when random time-varying delay occurs [29].

4.2 Limitations on Networks

Due to the insertion of the network and usage of a communication channel in NCSs, it degrades the stability as well as performance of the system. Such problems are appeared due to signal sampling, data quantization, communication delays (network-induced random delays), packet loss, packet disorder, channel fading, medium access constraints, power constraints, network constraints, etc. [2].

4.3 Delays

In general, delays are two types one is constant delays and other is random delays [18]. At the beginning of NCS-related research, the characteristics modeling or random delays are difficult so the easier approach is to model the delay as a constant directly. Random (Stochastic) delays are divided into two parts; one is dependent as their probability distribution governed by Markov chain while other is mutually independent stochastic delay. Random delays are trickier time-varying systems. NCSs are stable for all constant delays but become unstable when the delay varies [30–32].

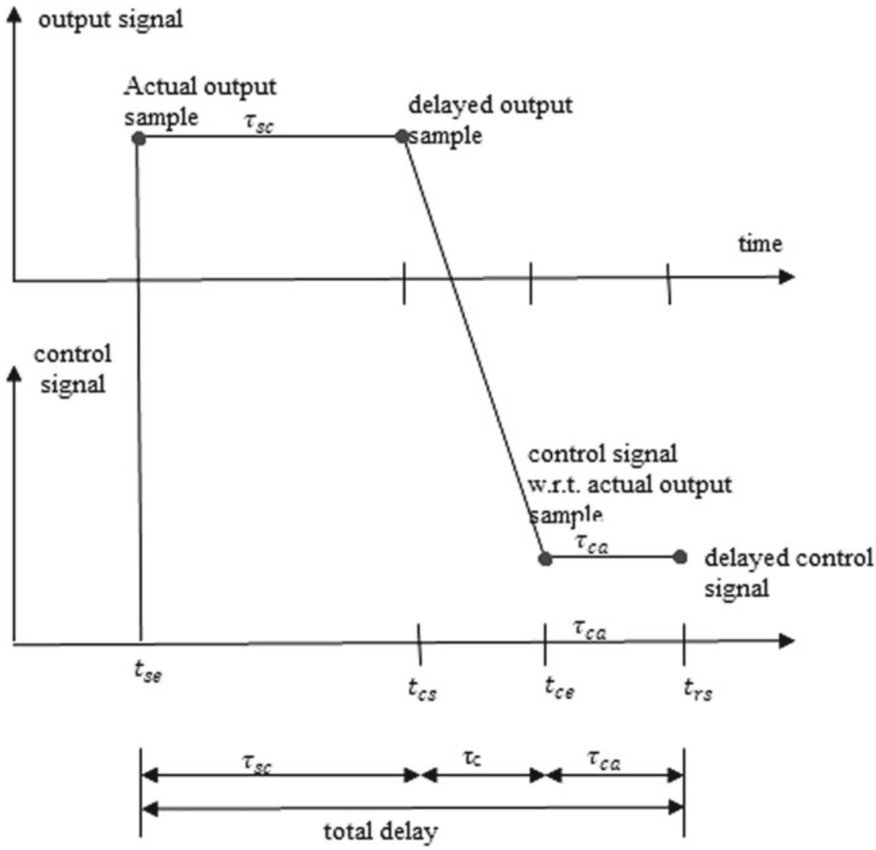

Fig. 3 Diagram of network-induced delays [4]

4.4 Network-Induced Delays

When communication networks are induced in NCSs data transfer between the controller and a system installed remotely, it shows network delays [33, 34]. Tipsuwan and Chow suggested the direction of data transfers as there are many delays like measuring device-to-controller delay τ_{sc} and the controller-to-final control element delay τ_{ca} including computational delay are calculated in [4] as,

$$\tau_{sc} = t_{cs} - t_{se} \tag{1}$$

$$\tau_{ca} = t_{rs} - t_{ce} \tag{2}$$

where t_{cs} defined as the time taken for the controller to collect the data of measurement from sensor, t_{se} is defined as the time taken from sensor to error signal, t_{rs} is the time taken from reference signal to sensor and t_{ce} is the time taken for the primary controller to send the signal from transducer. A network delay for NCS formulations is shown in Fig. 3. The three basic delays, i.e., propagation delay, frame time delay and waiting time delay occur on a LAN i.e., local area network. Propagations of delays in NCSs are shown in Fig. 3.

5 Conclusion and Future Scope

NCS is multidisciplinary research area with broad applications. It uses data network to connect the components of the control system. This arises many technical issues like time delay, packet dropout, bandwidth limitation, quantization, etc. Some of the recent advancements in delay compensation techniques and modeling are exclusively summarized. However, this review does not consider other significant issues like medium access constraint, power constraints, sampling, and channel fading. Although NCSs have been very propitious research fields for many years, there are alarming and unresolved issues like explicit dependency between network delays and packet dropouts to be considered for future research.

References

1. Gupta, R. A., & Chow, M. Y. (2010). Networked control system: Overview and research trends. *IEEE Transactions on Industrial Electronics, 57*(7), 2527–2535.
2. Brindha, M., & Mendiratta, J. K. (2013). Networked control system—A survey. *International Journal of Modern Education and Computer Science, 5*(6), 42.
3. Xia, Y. Q., Gao, Y. L., Yan, L. P., & Fu, M. Y. (2015). Recent progress in networked control systems—A survey. *International Journal of Automation and Computing, 12*(4), 343–367.

4. Tipsuwan, Y., & Chow, M. Y. (2003). Control methodologies in networked control systems. *Control Engineering Practice, 11*(10), 1099–1111.
5. Ulz, T., Pieber, T., Steger, C., Matischek, R., & Bock, H. (2017, September). Towards trustworthy data in networked control systems: A hardware-based approach. In *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation* (pp. 1–8). IEEE.
6. Yang, T. C. (2006). Networked control system: A brief survey. *IEE Proceedings-Control Theory and Applications, 153*(4), 403–412.
7. Zhang, D., Shi, P., Wang, Q. G., & Yu, L. (2017). Analysis and synthesis of networked control systems: A survey of recent advances and challenges. *ISA Transactions, 66,* 376–392.
8. Maxwell, J. C. (1868). I. On governors. *Proceedings of the Royal Society of London, 16,* 270–283.
9. Guo, L., Tang, Y., Liu, Z., & Xiong, W. (2010, June). The theory and architecture of network control system. In *2010 International Conference on Intelligent Computing and Cognitive Informatics* (pp. 183–186). IEEE.
10. Goodwin, G. C., Haimovich, H., Quevedo, D. E., & Welsh, J. S. (2004). A moving horizon approach to networked control system design. *IEEE Transactions on Automatic Control, 49*(9), 1427–1445.
11. Ke-You, Y., & Li-Hua, X. (2013). Survey of recent progress in networked control systems. *Acta Automatica Sinica, 39*(2), 101–117.
12. Zhang, X. M., Han, Q. L., & Yu, X. (2016). Survey on recent advances in networked control systems. *IEEE Transactions on Industrial Informatics, 12*(5), 1740–1752.
13. Richard, J. P. (2003). Time-delay systems: An overview of some recent advances and open problems. *Automatica, 39*(10), 1667–1694.
14. Zhang, H., Zhang, Z., Wang, Z., & Shan, Q. (2016). New results on stability and stabilization of networked control systems with short time-varying delay. *IEEE Transactions on Cybernetics, 46*(12), 2772–2781.
15. Hespanha, J. P., Naghshtabrizi, P., & Xu, Y. (2007). A survey of recent results in networked control systems. *Proceedings of the IEEE, 95*(1), 138–162.
16. Liu, S., Liu, P. X., & Wang, X. (2017). Stability analysis and compensation of network-induced delays in communication-based power system control: A survey. *ISA Transactions, 66,* 143–153.
17. Gao, H., Meng, X., & Chen, T. (2008). Stabilization of networked control systems with a new delay characterization. *IEEE Transactions on Automatic Control, 53*(9), 2142–2148.
18. Ge, Y., Chen, Q., Jiang, M., & Huang, Y. (2013). Modeling of random delays in networked control systems. *Journal of Control Science and Engineering, 2013,* 8.
19. Zhang, H., Shi, Y., Wang, J., & Chen, H. (2018). A new delay-compensation scheme for networked control systems in controller area networks. *IEEE Transactions on Industrial Electronics*.
20. Schenato, L. (2006, December). Optimal estimation in networked control systems subject to random delay and packet loss. In *Proceedings of the 45th IEEE Conference on Decision and Control* (pp. 5615–5620). IEEE.
21. Shi, Y., & Yu, B. (2009). Output feedback stabilization of networked control systems with random delays modeled by Markov chains. *IEEE Transactions on Automatic Control, 54*(7), 1668–1674.
22. Zhang, J., Lam, J., & Xia, Y. (2014). Output feedback delay compensation control for networked control systems with random delays. *Information Sciences, 265,* 154–166.
23. Heemels, W. M. H., Teel, A. R., Van de Wouw, N., & Nesic, D. (2010). Networked control systems with communication constraints: Tradeoffs between transmission intervals, delays and performance. *IEEE Transactions on Automatic Control, 55*(8), 1781–1796.
24. Francis, B. A. (1987). Lecture notes in control and information sciences. *A Course in H_∞ Control Theory* (p. 88).
25. Xiao, L., Hassibi, A., & How, J. P. (2000). Control with random communication delays via a discrete-time jump system approach. In *Proceedings of the 2000 American Control Conference (ACC)* (Vol. 3, pp. 2199–2204). IEEE.

26. Soucek, S., Sauter, T., & Koller, G. (2003, November). Effect of delay jitter on quality of control in EIA-852-based networks. In *ECON'03. 29th Annual Conference of the IEEE Industrial Electronics Society* (Vol. 2, pp. 1431–1436). IEEE.
27. Xie, G., & Wang, L. (2004, December). Stabilization of networked control systems with time-varying network-induced delay. In 2004 43rd IEEE Conference on Decision and Control (CDC) (Vol. 4, pp. 3551–3556). IEEE.
28. Zhang, L., Shi, Y., Chen, T., & Huang, B. (2005). A new method for stabilization of networked control systems with random delays. *IEEE Transactions on Automatic Control, 50*(8), 1177–1181.
29. Liu, X. G., Martin, R. R., Wu, M., & Tang, M. L. (2006). Delay-dependent robust stabilisation of discrete-time systems with time-varying delay. *IEE Proceedings-Control Theory and Applications, 153*(6), 689–702.
30. Gao, H., Chen, T., & Lam, J. (2008). A new delay system approach to network-based control. *Automatica, 44*(1), 39–52.
31. Gao, H., & Chen, T. (2007). New results on stability of discrete-time systems with time-varying state delay. *IEEE Transactions on Automatic Control, 52*(2), 328–334.
32. Meng, X., Lam, J., Du, B., & Gao, H. (2010). A delay-partitioning approach to the stability analysis of discrete-time systems. *Automatica, 46*(3), 610–614.
33. Wang, J. (2015, August). A brief survey on networked control systems. In *2015 IEEE International Conference on Mechatronics and Automation (ICMA 2015)* (pp. 212–216). IEEE.
34. Baillieul, J., & Antsaklis, P. J. (2007). Control and communication challenges in networked real-time systems. *Proceedings of the IEEE, 95*(1), 9–28.