Performance of Neural Network Based Controllers and $\Delta\Sigma$-Based PID Controllers for Networked Control Systems: A Comparative Investigation

1st Chathura Wanigasekara
Electrical and Computer Engineering
The University of Auckland
Auckland, New Zealand
craj855@aucklanduni.ac.nz

2nd Dhafer Almakhles
Communications and Networks Engineering
Prince Sultan University
Riyadh, Saudi Arabia
dalmakhles@psu.edu.sa

3rd Akshya Swain
Electrical and Computer Engineering
The University of Auckland
Auckland, New Zealand
a.swain@auckland.ac.nz

4th Sing Kiong Nguang
Electrical and Computer Engineering
The University of Auckland
Auckland, New Zealand
sk.nguang@auckland.ac.nz

5th Umashankar Subramaniyan
Communications and Networks Engineering
Prince Sultan University
Riyadh, Saudi Arabia
usubramaniam@psu.edu.sa

6th Sanjeevikumar Padmanaban
Energy Technology
Aalborg University
Esbjerg, Denmark
sanjeevi_12@yahoo.co.in

***Abstract*—During the past decade, networked control systems (NCS) has emerged as a viable alternative to traditional control systems due to various advantages it offers which include a reduction in system wiring, increase of system agility etc. However, the performance of various existing controllers such as PID degrades in the networked environment due to the existence of random time-varying delay, packet-dropouts which may cause instability. The present study designs a neural network (NN) based controller for NCS and investigates its performance under random time-varying delay, packet-dropouts. The performance of this controller is compared with both the classical PID and $\Delta\Sigma$-based PID controllers. The robustness of the NN based controllers in the networked environment is studied under different degree of parametric uncertainties considering an example of a DC servo mechanism. The results of the comparative investigation demonstrate that the performance of the NN based controller is superior compared to other controllers.**

***Index Terms*—Networked Control Systems (NCS), Neural Network Controllers, $\Delta\Sigma$-based PID Controllers**

I. Introduction

In the past decade, due to the rapid advancement of computation and communication, there has been a major shift in the paradigm of controller implementation from analogue control to digital control [3]. Further in recent years, due to significant development in wireless communication, the control theorists have combined the communication network with the traditional control system which has given birth to a new area of control paradigm, called as the NCS [4], [7], [8]. In NCS, control system components such as sensors, controllers, and actuators exchange data through a communication network using communication packet which carries signals such as the control input, the plant output and the reference input.

NCS is well-known for some key advantages compared with traditional control systems, e.g. this causes system wiring reduction, increases system agility and the maintenance and diagnosis become less challenging. NCS is now widely being used in process control [9], remote control [12], telemanipulation [14], robotics [15], etc. However, due to information transmission through communication networks, which are often unreliable, NCS face many challenging issues such as network-induced delay [17], packet losses, quantisation errors [18], which can result in instability [19]. The most important issue that NCS faces is the network-induced delay and packet losses that occur during data exchange among devices connected to the shared medium. In an NCS, usually, network-induced time delay varies often randomly. Hence, it is important to study the performance and stability of controllers in NCS under these conditions.

Most of the controllers that are implemented in NCS work only with certain parameters. When the model is subjected to subtle variations, the controllers need to redesigned or re-calibrated, i.e. PID controllers require re-tuning. However, NN based controllers are well known for their generalisation capability. Hence in the present study, the performance of the neural network based controllers are assessed in different conditions, A comparative performance investigation with conventional PID and $\Delta\Sigma$-based PID controller (with and without NCS) has been carried out considering the example of a DC servo mechanism. Note that $\Delta\Sigma$-based PID controller offers several advantages and has been used in many application [5], [6]. The robustness of these controllers under parameter variations has been studied.

The rest of this paper is organised as follows. The NCS model used in this study is elaborated in Section-II. Section-III briefly describes design of NARMA-L2 neural network controllers (Section-III-A) and $\Delta\Sigma$-based PID controller (Section-III-B) respectively. A comparative performance investigation of the NARMA-L2 neural network controller with the conventional PID and the $\Delta\Sigma$-based PID controller is carried out in Section-IV with discussions and conclusions about results in Section-V.

II. Networked Control System

The success of NCS is often critically dependent on the quality of the network, e.g. if its quality is worse, the transfer of information between the controller and the plant cannot happen successfully. Under these circumstances, the information about the control inputs and system state are lost, and the NCS effectively becomes an open loop system. Further, the design of most of the existing controllers requires the knowledge of the systems dynamics. However, in a real-world scenario, the system dynamics cannot be determined precisely due to various uncertainties.

The block diagram of a typical NCS considered in this study is shown in Fig. 1.

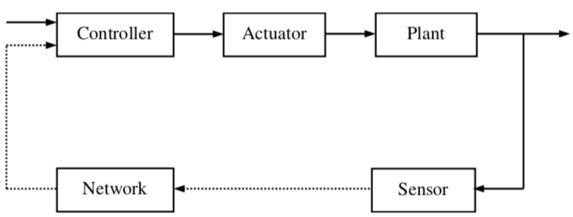

Fig. 1: Considered NCS.

One of the most important parameters which affect the performance of NCS is the presence of inevitable time delay which generally changes at random [17], [20]–[26]. Due to the randomness of the network-induced time-delay, control action at each sampling interval cannot be expected to function precisely. The effects of random time delays have been investigated by several researchers in [20]–[22].

The time delay is usually continuous and is bounded. Further, the current time delay is usually correlated with the past time delays and can be modelled as a Markov chain in [27], [29]; hence they are correlated. However, in this study time delay, τ is changed at random, and it is assumed that this satisfies the relation: $\tau < d \times T_s$, where T_s is the sampling period and d is a positive integer. Further, since data is transmitted through a communication channel, packet dropout is also possible due to network constraints. Hence in this study, it is assumed that the packet dropout probability is p.

III. Controller Design

In this study, a comparative investigation on the performance of the NN based controller (NARMA-L2) with both the conventional PID and $\Delta\Sigma$-based PID controller has been carried out. However, it is pertinent to briefly discuss the procedure of designing such controllers for the sake of completeness.

A. Design of NARMA-L2 Neural Network Controller

The NN controller described in this section is called NARMA-L2 control which can be found in MATLAB neural network toolbox. It essentially gives a control action which resembles that of feedback linearising control. The main idea of this controller is to convert the nonlinear dynamics of the system to linear dynamics. First, the NN is used to identify the model of the system and then it is converted to a controller by following the procedure mentioned below.

In the first step of NARMA-L2 control, identification of the forward dynamics (direct model) of the system is carried out by a NN. Amongst various types of system models, one of the most popular model is the nonlinear autoregressive-moving average (NARMA) model which is described by [30],

$$\begin{aligned} y(n+l) = \mathcal{N}[&y(n), y(n-1), ..., y(n-m+1), \\ &u(n), u(n-1), ..., u(n-m+1)] \end{aligned} \tag{1}$$

where $y(n)$ and $u(n)$ represent system output and system input respectively. In the identification process a NN is trained to approximate the nonlinear function $\mathcal{N}$.

In the present study, the controller is designed such that it follows a reference trajectory described by $y(n+l) = y_r(n+l)$,

$$\begin{aligned} u(n) = \mathcal{G}[&y(n), y(n-1), ..., y(n-m+1), y_r(n+l), \\ &u(n-1), ..., u(n-k+1)] \end{aligned} \tag{2}$$

where $\mathcal{G}$ is a nonlinear function. However, using this type of model requires the function $\mathcal{G}$ to be minimised using the backpropagation algorithm which often is slow [32]. This limitation can be overcome by using an approximate model to represent the system [33]. This is described by,

$$\begin{aligned} \hat{y}(n+l) = \mathcal{A}[&y(n), y(n-1), ..., y(n-m+1), \\ &u(n-1), ..., u(n-k+1)]+ \\ \mathcal{B}[&y(n), y(n-1), ..., y(n-m+1), \\ &u(n-1), ..., u(n-k+1)]\, u(n) \end{aligned} \tag{3}$$

Such models are referred to as in companion form where the next controller input $u(n)$ is not affected by the nonlinearity. This form offers many advantages where it can be easily solved to find the control input that will make the system to follow a reference $y(n+l) = y_r(n+l)$. The controller in the companion form is given by [30],

$$u(n) = \frac{\begin{array}{c} y_r(n+l) - \mathcal{A}[y(n), y(n-1), ..., y(n-m+1), \\ u(n-1), ..., u(n-m+1)] \end{array}}{\begin{array}{c} \mathcal{B}[y(n), y(n-1), ..., y(n-m+1), \\ u(n-1), ..., u(n-m+1)] \end{array}} \tag{4}$$

However, this equation can not be implemented; as the control input $u(n)$ needs to be determined at the same time depending on system output $y(n)$ which is not possible. Hence the modified model which is used is given by,

$$y(n+l) = \mathcal{A}[y(n), y(n-1), ..., y(n-m+1), \\ u(n), u(n-1), ..., u(n-m+1)] \\ +\mathcal{B}[y(n), ..., y(n-m+1), \\ u(n), ..., u(n-m+1)]\, u(n+1) \tag{5}$$

where $l \geq 2$.

The NN controller (NARMA-L2) model is given by [30],

$$u(n+1) = \frac{\begin{array}{c} y_r(n+l) - \mathcal{A}[y(n), ..., y(n-m+1), \\ u(n), ..., u(n-m+1)] \end{array}}{\begin{array}{c} \mathcal{B}[y(n), ..., y(n-m+1), \\ u(n), ..., u(n-m+1)] \end{array}} \tag{6}$$

This controller described in (6) is implemented in conjunction with the NARMA-L2 plant model (5).

B. Design of $\Delta\Sigma$-Based PID Controller

The design principle of $\Delta\Sigma$-based PID controller is briefly described in the following section. One of the key components of the $\Delta\Sigma$-based control system is the $\Delta\Sigma$ modulator. It is consisted of two main components, a $\Delta\Sigma$ encoder ($\mathcal{E}_{\Delta\Sigma}$) and a $\Delta\Sigma$ decoder ($\mathcal{D}_{\Delta\Sigma}$). The schematic of $\mathcal{E}_{\Delta\Sigma}$ and $\mathcal{D}_{\Delta\Sigma}$ is shown in Fig-2. Encoder and decoder are connected through a digital channel interface. As represented in Fig-2, the thick solid lines show the weighted signal and the dotted line shows the bitstream (BS) signal. The input signal $\hat{e}$ is encoded into a BS signal $\hat{\delta}$ by $\mathcal{E}_{\Delta\Sigma}$ which consists of one integrator, one two-level quantizer and a multiplexer. The decoder $\mathcal{D}_{\Delta\Sigma}$ which consists of single multiplexer reconstructs the estimated input of $\mathcal{E}_{\Delta\Sigma}$. The conversion of the input of $\mathcal{E}_{\Delta\Sigma}$ is done through error feedback.

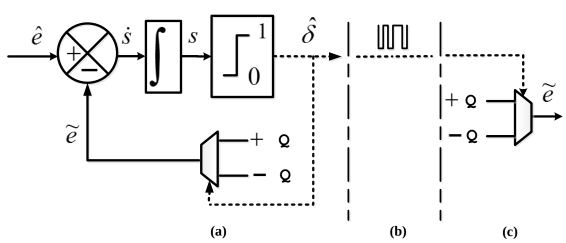

Fig. 2: $\Delta\Sigma$-based encoder/decoder. (a). Encoder (b). Communication Channel (c). Decoder

Note that, the conventional linear controller design technique is based on an approximate linear model of a system. This linear model can be obtained by perturbing the system dynamics around a desired operating point. Therefore, linear controller behaves optimally around linearisation point. In the following, we, therefore, briefly describe the feedback control design of $\Delta\Sigma$ based control design under the assumption that the system is linear. Consider a linear time-invariant (LTI) plant described by,

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{7}$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$ and $y \in \mathbb{R}^p$ denote the states of the linearised plant, the inputs and the output of the linearised plant, respectively. Here, a analogue controller is used to stabilise the system described in (7) asymptotically. The dynamics of the analogue controller is described as,

$$\begin{aligned} \dot{x}_c &= A_c x_c + B_c e \\ u &= C_c x_c + D_c e \end{aligned} \tag{8}$$

where $x_c \in \mathbb{R}^v$ and e denote respectively the states of the controller and the error signals. It is convenient to assume the reference signal to be zero ($r = 0$), without loss of generality, hence $e = -y$. By combining (8) with (7) gives the dynamics of the closed loop system as:

$$\dot{x}_{cl} = A_{cl} x_{cl} \tag{9}$$

where

$$x_{\text{cl}} = \begin{bmatrix} x \\ x_c \end{bmatrix}, \; A_{cl} = \begin{bmatrix} A - BD_cC & BC_c \\ -B_cC & A_c \end{bmatrix} \tag{10}$$

Assume that the controller (8) has been designed such that, A_{cl} is strictly stable. Note that by inserting the $\Delta\Sigma$ based encoder and decoder in the control system gives the $\Delta\Sigma$ based control system which is shown in Fig-3. Here, $\mathcal{E}_{\triangle\Sigma}$ encodes feedback signals to BS signals at the transmitter. Then those BS signals go through $\mathcal{D}_{\triangle\Sigma}$ to produce $\tilde{e}$. Ideally $\hat{e} = \tilde{e}$.

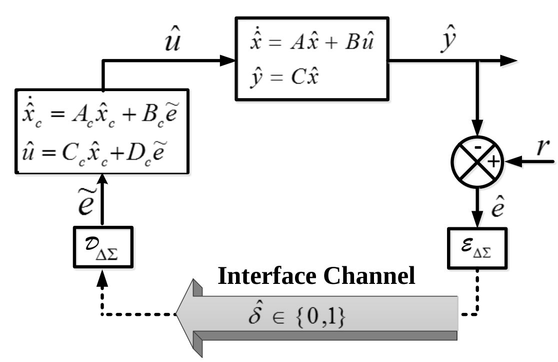

Fig. 3: Configuration of $\Delta\Sigma$ based control system.

It is important to consider the problem of incorporating $\mathcal{E}_{\triangle\Sigma}$ and $\mathcal{D}_{\triangle\Sigma}$ with the system described in (9). Note that $\boldsymbol{Q}$ matrix of dimension $p \times p$ and is positive definite. Here, p is the number of $\triangle\Sigma$-Modulators that is being used. Also, $\boldsymbol{Q}$ and $-\boldsymbol{Q}$ denote upper and lower gains of two-level quantizers respectively. Then the estimated signals which is also the outputs of $\mathcal{D}_{\triangle\Sigma}$), are defined by,

$$\begin{aligned} \tilde{e} &= \operatorname{diag}\left\{\mathcal{E}_{\triangle\Sigma_j} \circ \mathcal{D}_{\triangle\Sigma_j}\right\} * \hat{e} \\ &= \boldsymbol{Q} \operatorname{sgn}(s) \end{aligned} \tag{11}$$

where $\dot{s} = \hat{e} - \tilde{e}$. The states of the feedback system can be defined as,

$$\begin{bmatrix} \dot{\hat{x}}_{cl} \\ \dot{s} \end{bmatrix} = \begin{bmatrix} A_1 & \mathbf{0} \\ A_2 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \hat{x}_{cl} \\ s \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \tilde{e} \tag{12}$$

where $\hat{x}_{cl} = [\hat{x} \quad \hat{x}_c]^T$ and

$$\begin{aligned} A_1 &:= \begin{bmatrix} A & BC_c \\ \mathbf{0} & A_c \end{bmatrix}, \quad B_1 := \begin{bmatrix} BD_c \\ B_c \end{bmatrix} \\ A_2 &:= [-C \quad 0], \quad B_2 := -I_p \end{aligned} \tag{13}$$

with $A_1 \in \mathbb{R}^{(n+v)\times(n+v)}$, $A_2 \in \mathbb{R}^{p\times(n+v)}$ $B_1 \in \mathbb{R}^{(n+v)\times p}$ and $B_2 \in \mathbb{R}^{p\times p}$.

From (11) we can see that feedback signals are switched signals. However, the system described in (12) becomes a differential equation with a discontinuous right hand side. According to [34], [35], (12) can be can be analyzed using equivalent control method. Detailed analysis of the stability conditions and convergence analysis of $\Delta\Sigma$(BS) based controllers shown in Fig.4 can be found in [1] and in [2], [10], [11], [13], [16], [28], [31], [36].

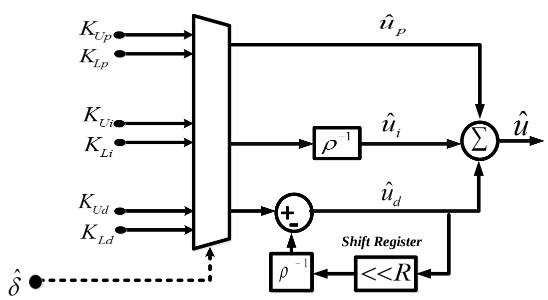

Fig. 4: $\Delta\Sigma$-based PID controller.

Fig.4 shows the schematic diagram of $\Delta\Sigma$-based PID controller. Here, $[K_{Lp},K_{Up}]$,$[K_{Li},K_{Ui}]$,$[K_{Ud},K_{Ud}]$, and N_d denote respectively the lower and upper bounds of the proportional gains, the integral gains, the differentiator gains, and the filter coefficient of the differentiator. Following measures are taken to lower hardware consumption. To replace the multiplier with a *shift register* N_d is selected such that $N_d h = 2^{-R}$, where $R \in \mathbb{N}_0$. The output of the $\Delta\Sigma$-based PID controller is given by,

$$\hat{u}(t) = K_p + \frac{K_i h}{\rho} + \frac{K_d N_{d\rho}}{\rho + N_d h} \tag{14}$$

IV. Simulation Results

In this study, we have compared the performance of the NARMA-L2 neural network controller with the $\Delta\Sigma$-based PID controller and the classical PID controller. All these controllers are designed to control a DC servo mechanism. Performance of these controllers was assessed under three scenarios. In the first scenario (Case-1) the performance of these controllers is investigated without the network. Next, in the second scenario (Case-2), the performance is analysed when the controllers are implemented using a communication network i,e. With NCS. The various imperfections of the network such as packet-dropouts and network-induced time-delay are considered in this study. During the investigation, the bound in the delay is taken to be 5, i.e. $d = 5$ and the probability of packet dropout $p = 10\%$. In this scenario, the ratio of the viscous friction B and the shaft inertia J, denoted as a i.e. $a = \frac{B}{J}$ is taken equals to 10. In the third scenario (Case-3), the robustness of all these controllers is studied by varying the system parameters which is reflected in the parameter a.

Fig.5 Fig.6 and Fig.7 shows respectively the performance of PID controller, $\Delta\Sigma$-based PID controller and NARMA-L2 neural network controller without NCS. From these figures, it is evident that the performance of all these controllers is virtually indistinguishable from a practical perspective.

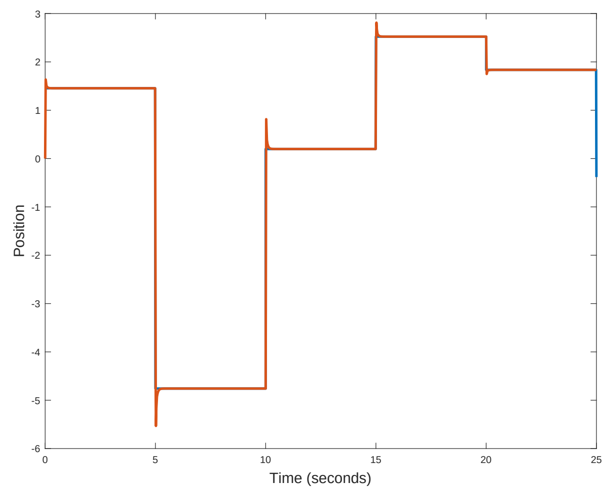

Fig. 5: Tracking performance of conventional PID controller under nominal conditions i.e. $a = 10$ without NCS (Case-1).

Next, the performance of these controllers is studied considering an imperfection communication network. The tracking performance of these controllers are shown in Fig.8 Fig.9 and Fig.10. It can be seen that the performance of all three controllers is almost similar to scenario one. Note that the PID gains, as well as the weights of NN based controller used for this scenario, is the same as in the first scenario. From the results, it is observed that despite the presence of induced network delay and packet dropout, the performance of these controllers is almost similar to the Case-1. This shows under this range of packet dropout and time-delay, these controllers are robust.

At the final stage of this study, an investigation is carried out to determine whether these controllers are robust against various degrees of parametric uncertainty. The parameter $a = B/J$ of the system is varied over a wide range from the nominal value of 10 to 0.5. It was observed that all these controllers are robust when a was changed from the

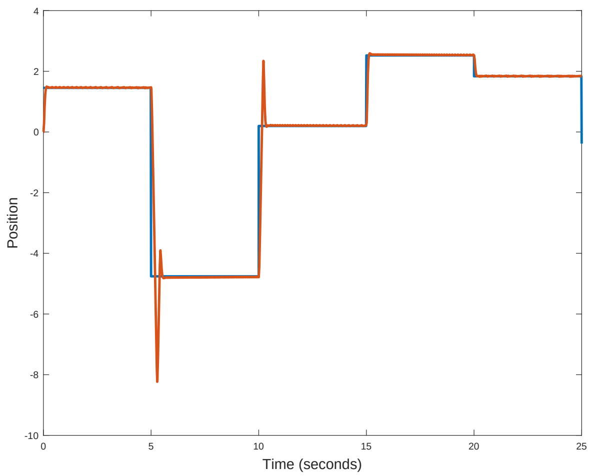

Fig. 6: Tracking performance of $\Delta\Sigma$-based PID controller under nominal conditions i.e. $a = 10$ without NCS (Case-1).

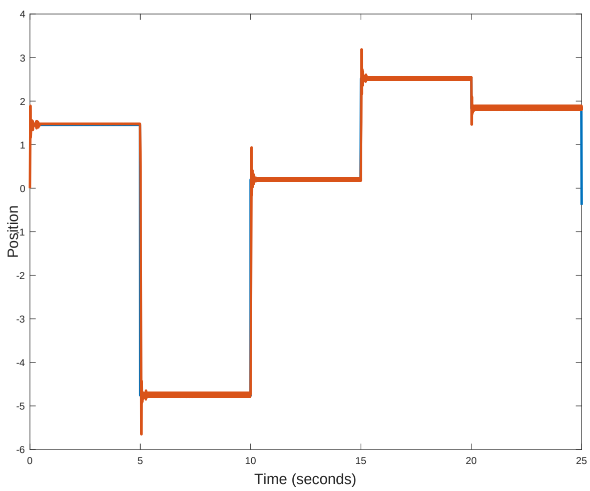

Fig. 7: Tracking performance of NARMA-L2 neural network controller under nominal conditions i.e. $a = 10$ without NCS (Case-1).

nominal value of 10 to 4. However, the performance of both the classical PID controller and $\Delta\Sigma$-based PID controllers deteriorate significantly and become unstable with further reduction of the parameter a. The design of the NN based controller is robust against a wide range of parametric variation and is stable. The tracking performance of this controller is shown in Fig.11.

V. Conclusions

A NN based controller is designed to control the position of a DC servo mechanism. The performance of the NARMA-L2 neural network controller is compared with two other controllers, namely $\Delta\Sigma$-based PID controller and conventional PID controller respectively. The results of the simulations show that the NARMA-L2 NN controller performs better than all the other two controllers in different scenarios. It is noted that the NARMA-L2 NN controller could follow the reference

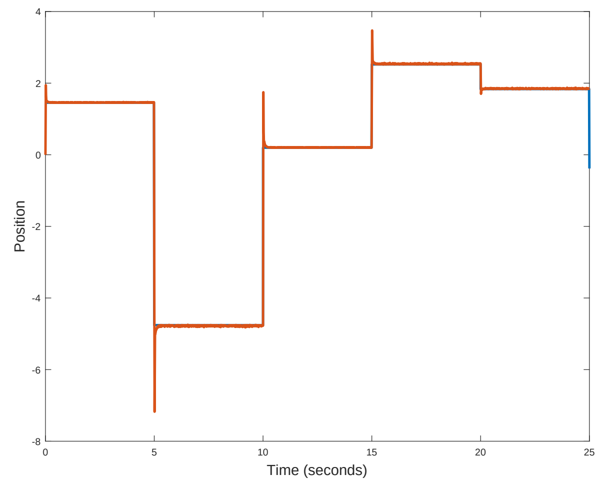

Fig. 8: Tracking performance of conventional PID controller with NCS considering $a = 10$, $d = 5$, $p = 10\%$ (Case-2).

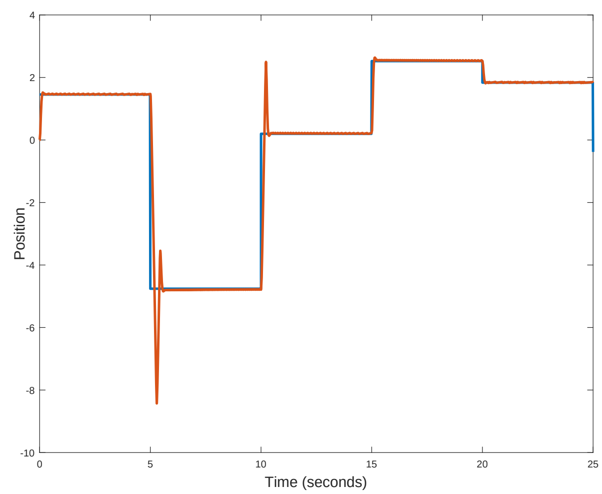

Fig. 9: Tracking performance of $\Delta\Sigma$-based PID controller with NCS considering $a = 10$, $d = 5$, $p = 10\%$ (Case-2).

signal even with the changes of system parameters in a wide range, where both the other controllers are unstable.

References

[1] D. J. Almakhles, A. K. Swain, and N. D. Patel, "Stability and performance analysis of bit-stream-based feedback control systems," *IEEE Transactions on Industrial Electronics*, vol. 62, pp. 4319-4327, 2015.

[2] D. J. Almakhles, A. K. Swain, and N. D. Patel, "Adaptive quantizer for networked control system," *Proceedings of European Control Conference*, pp. 1404-1409, 2014.

[3] P. R. Kumar, "Fundamental issues in networked control system," *Proceedings of the 3rd WIDE Ph.D. School on Networked Control System*, Siena, Italy, 2009.

[4] M. S. Branicky, S. M. Phillips, and W. Zhang, "Stability of networked control systems: explicit analysis of delay," *Proceedings of American Control Conference*, pp. 2352-2357, 2000.

[5] D. J. Almakhles, A. K. Swain, and A. Nasiri, "The dynamic behaviour of data-driven $\Delta - M$ and $\Delta\Sigma - M$ in sliding mode control,"*International Journal of Control*, vol. 90, pp. 2406–2414, 2017.

[6] D. J. Almakhles, A. K. Swain, A. Nasiri, and N. Patel, "An adaptive two-level quantizer for networked control systems,"*IEEE Transactions on Control Systems Technology*, vol. 25, pp. 1084–1091, 2017.

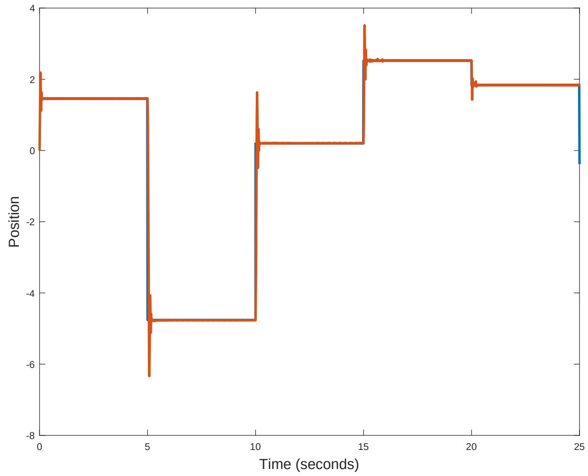

Fig. 10: Tracking performance of NARMA-L2 neural network controller with NCS considering $a = 10$, $d = 5$, $p = 10\%$ (Case-2).

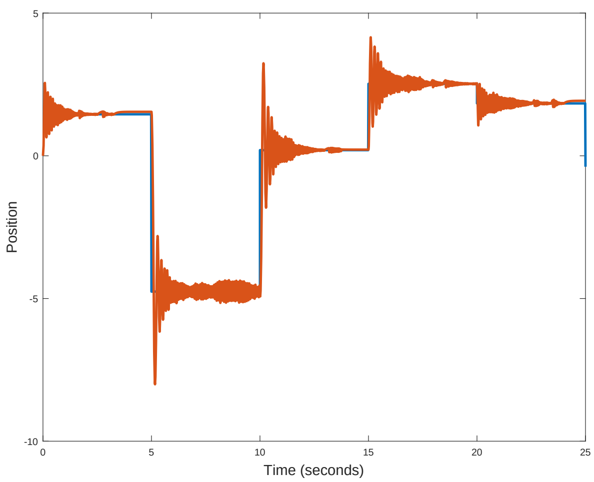

Fig. 11: Tracking performance of NARMA-L2 neural network controller with NCS considering $a = 1$, $d = 5$, $p = 10\%$ (Case-3).

[7] P. Antsaklis, and J. Baillieul, "Special Issue on Networked Control Systems," *IEEE Transactions on Automatic Control*, vol. 49, pp. 1421-1423, 2004.

[8] P. F. Hokayem, and C. T. Abdallah, "Networked control systems: a sampled-data approach," *Proceedings of IEEE International Symposium on Intelligent Control*, pp. 415-419, 2003.

[9] S. Yang, X. Chen, and J. L. Alty, "Design issues and implementation of Internet-based process control systems," *Control Engineering Practice*, vol. 11, pp. 709-720, 2003.

[10] D. J. Almakhles, A. K. Swain, and A. Nasiri, "The dynamic behaviour of data-driven Δ-M and $\Delta\Sigma$-M in sliding mode control,"*International Journal of Control*, vol. 90, no. 11, pp. 2406–2414, 2017.

[11] D. J. Almakhles, N. D. Patel, and A. K. Swain, "A two-loop linear control utilizing $\Delta\Sigma$ modulator," *Proceedings of the 11th Workshop on Intelligent Solutions in Embedded Systems (WISES)*, pp. 1-6, 2013.

[12] K. C. Lee, and S. Lee, "Remote controller design of networked control systems using genetic algorithm," *Proceedings of IEEE International Symposium on Industrial Electronics*, pp. 1845-1850, 2001.

[13] D. J. Almakhles, A. K. Swain, and N. D. Patel, "Delta-Sigma based bit-stream controller for a D.C. motor," *Proceedings of IEEE Region 10 Conference*, pp. 1-5, 2012.

[14] T. T. Ho, and H. Zhang, "Internet-based telemanipulation," *Proceedings of IEEE Canadian Conference on Electrical and Computer Engineering*, pp. 1425-1430, 1999.

[15] K. Han, S. Kim, Y. Kim, and J. Kim, "Internet control architecture for Internet-based personal robot," *Autonomous Robots*, vol. 10, pp. 135-147, 2001.

[16] D. J. Almakhles, N. D. Patel, and A. K. Swain, "Bit-stream control system: Stability and experimental application," *Proceedings of the International Conference on Applied Electronics (AE)*, pp. 1-6, 2013.

[17] W. Zhang, M. S. Branicky, and S. Phillips, "Stability of networked control systems," *IEEE Control System Magazine*, vol. 21, pp. 84-99, 2001.

[18] W. P. Heemels, A. R. Teel, N. V. Wouw, and D. Nesic, "Networked Control Systems With Communication Constraints: Tradeoffs Between Transmission Intervals, Delays and Performance," *IEEE Transactions on Automatic Control*, vol. 55, pp. 1781-1796, 2010.

[19] J. Wu, and T. Chen, "Design of networked control systems with packet dropouts," *IEEE Transactions on Automatic Control*, vol. 52, pp. 1314-1319, 2007.

[20] S. Li, Z. Wang, and Y. Sun, "Observer-based compensator design for networked control systems with long time delays," *Proceedings of 30th Annual Conference of IEEE Industrial Electronics Society*, pp. 678-683, 2004.

[21] C. Wang, Y. Wang, and H. Gao, "Compensation time-varying delays in networked control system via delay-dependent stabilization approach," *Proceedings of IEEE International Conference on Control Applications*, pp. 248-253, 2004.

[22] D. Yue, Q. Han, and C. Peng, "State feedback controller design of networked control systems," *Proceedings of IEEE International Conference on Control Applications*, pp. 242-247, 2004.

[23] O. Beldiman, G. C. Walsh, and L. Bushnell, "Predictors for networked control systems," *Proceedings of American Control Conference*, pp. 2347-2351, 2000.

[24] Z. Wang, J. Yang, D. Tang, and X. Wang, "Compensation for the networked control systems with the long time delay," *Proceedings of IEEE International Conference on Systems*, pp. 3170-3175, 2003.

[25] A. Wu, D. Wang, and J. Liang, "Application of generalized predictive control with neural network error correction in networked control system," *Proceedings of Fifth World Congress on Intelligent Control and Automation*, pp. 1386-1390, 2004.

[26] H. Hur, J. Lee, S. Lee, and M. Lee, "Compensation of time delay using a predictive controller," *Proceedings of IEEE International Symposium on Industrial Electronics*, pp. 1087-1092, 1999.

[27] F. Liu, and Y. Yao, "Modeling and analysis of networked control systems using hidden Markov models," *Proceedings of International Conference on Machine Learning and Cybernetics*, pp. 928-931, 2005.

[28] D. J. Almakhles, "Two-level quantised control systems: sliding-mode approach, " *International Journal of Control*, vol. 90, no. 11, pp. 1–9, 2018.

[29] L. Zhang, Y. Shi, T. Chen, and B. Huang, "A new method for stabilization of networked control systems with random delays," *Proceedings of American Control Conference*, pp. 633-637, 2005.

[30] MATLAB and Neural Network Toolbox Release 2017b, *The MathWorks, Inc.*, Natick, Massachusetts, United States.

[31] D. J. Almakhles, N. D. Patel, and A. K. Swain, "Conventional and hybrid bit-Stream in real-time system," *Proceedings of the 11th Workshop on Intelligent Solutions in Embedded Systems (WISES)*, pp. 1-6, 2013.

[32] K. S. Narendra, and P. Kannan, "Learning Automata Approach to Hierarchical Multiobjective Analysis," *IEEE Transactions on Systems, Man and Cybernetics*, vol. 20, pp. 263-272, 1991.

[33] K. S. Narendra, and S. Mukhopadhyay, "Adaptive Control Using Neural Networks and Approximate Models," *IEEE Transactions on Neural Networks*, vol. 8, pp. 475-485, 1997.

[34] Vadim I. Utkin, "Sliding Modes in Control and Optimization," *Springer Berlin Heidelberg*, 1992.

[35] Jean-Jacques E. Slotine, and Weiping Li, "Applied Nonlinear Control," *Prentice-Hall*, 1991.

[36] D. J. Almakhles, N. Pyle, H. Mehrabi, A. K. Swain, and A. P. Hu, "Single-bit modulator based controller for capacitive power transfer system," *Proceedings of the IEEE 2nd Annual Southern Power Electronics Conference (SPEC)*, pp. 1-6, 2016.