Original Research Article: full paper

(2022), «EUREKA: Physics and Engineering»
Number 6

NETWORKED CONTROL SYSTEM STABILITY ANALYSIS OF PIPELINE SYSTEM WITH NETWORKED-INDUCED DELAY

Muhammad Ridho Rosa✉
School of Electrical Engineering [1]
mridhorosa@telkomuniversity.ac.id

Erwin Susanto
School of Electrical Engineering [1]

Mohd Fadzil Hassan
Centre for Research in Data Science (CeRDaS)
Department of Computer & Information Sciences
Universiti Teknologi PETRONAS
Persiaran UTP Seri Iskandar, Perak, Malaysia, 32610

[1]*Telkom University*
1 Jl. Telekomunikasi, Bandung, Indonesia, 40257

✉**Corresponding author**

Abstract

This paper presents the design of Networked Control Systems (NCS) for pipeline systems. NCS plays an important role in controlling and monitoring large-scale systems such as pipeline systems. To implement the NCS, one must derive the pipe model and consider the network communication constraints. Here, the pipeline model is divided into two sections for simplicity. For example, in a long pipeline system, one can use a higher number of sections in order to give a better result for the analysis. Then let's consider a networked-induced delay as the network communication constraint. The discretize pipe dynamics model is derived to support the NCS scheme in the pipeline system. The stability analysis of the proposed NCS is derived by taking into account the small and the large networked-induced delay. Then the optimal LQR control is designed for both stabilizing and tracking. The stability region of the pipeline system in the NCS scheme with networked-induced delay is derived and depicted to provide stability information. The design of the proposed controller under network constraint (networked-induced delay) must consider the stability plot that is divided into the stable region and unstable region. In this research, let's assume that it is possible to measure the exact time delay and then consider the allowable sampling time for the controller. The proposed controller is designed by considering the NCS scheme with time delay both for regulator and tracking problems. By using the proposed controller, the pipeline system can be controlled in the presence of network-induced delay, which commonly occurs in a distributed system. The simulation verifies the stability analysis of the proposed optimal control for the pipeline systems with the NCS scheme under networked induced delay.

Keywords: networked control systems, optimal control, fluid flow control, pipe system, delay analysis.

DOI: 10.21303/2461-4262.2022.002469

1. Introduction

The exponential development and research in communication technologies allow users to send a large amount of information in a short time. This advancement makes the implementation of NCS more feasible and profitable. In case the sensors, actuators, and controllers in a control loop are coordinated by the exchange of information over a communication network, it can be classified as NCS [1, 2]. NCS can be found in many technological areas such as underwater unmanned vehicle [3], platoon vehicles [4], smart grids [5], transportation [6, 7], distributed robot system [8], and many other applications.

In the oil and gas sector, monitoring and controlling pipeline and remote facilities are critical objectives that need to be achieved [9, 10]. Oil and gas facilities are large-scale engineering systems in which monitoring and control functions are required for their safe and economical operation, i.e. leak detection [11]. The leak detection method is based on the dynamic modeling of the fluid in a pipe. The measured flow and simulated flow were than compared to identify the leakage.

Since the nature of the systems is geographically distributed, NCS plays an important role in achieving the objective of oil and gas facilities efficiently. The challenges for implementing the NCS in the oil and gas facilities are the stability analysis in the presence of network communication constraints. These constraints can be random sampling intervals [12], varying communication delays [13], packet dropout and quantization [14], and security issues [15, 16]. The aim of this research is to assess the NCS scheme in a pipeline system under the network communication constraint using numerical simulation. Using predefined networked induced delay, short and long delay, let's measure the limit of the allowable networked induced delay, which leads to a stable closed-loop system.

The main contribution of this paper is the design of optimal control LQR for a pipeline system where the NCS structure with networked-induced delay is considered. Additionally, the stability region of the LQR control for the short and long delay is derived for regulator problem and tracking problem. The numerical analysis of the allowable networked-induced delay and the sampling time of the controller is using MATLAB.

2. Materials and methods

This section discusses the fluid dynamics, the design of the optimal controller LQR, and the stability of the proposed controller in the presence of networked-induced delay.

Fluid Dynamics in Pipeline System. The fluid dynamics in a pipe can be derived by using the water hammer equation [17]. The following equation shows the flow and the pressure dynamics in partial differential equation:

$$\frac{\delta Q}{\delta t} = -Ag\frac{\delta P}{\delta z} - \frac{fQ|Q|}{2DA}; \ \frac{\delta P}{\delta t} = -\frac{v_s^2}{gA}\frac{\delta Q}{\delta z}, \tag{1}$$

where Q is the liquid flow rate $\left(\mathrm{m}^3/\mathrm{s}\right)$, P is the pressure head (m), t is time coordinate (s), z is the space coordinate (m), A is cross-sectional area of the pipe $\left(\mathrm{m}^2/\mathrm{s}\right)$, v_s is the speed of sound $(\mathrm{m/s})$, g is the gravitational constant $\left(\mathrm{m}^2/\mathrm{s}\right)$, D is the diameter of pipe (m), and f is the frictional coefficient (non-dimensional). In the purpose of monitoring, the pipe may be discretized in space that is divided into N sections. Let's note that, the pipe with length L must be divided into N sections of uniform size. Thus, it is possible to modify (1) in discretize form:

$$\frac{\delta Q}{\delta t} = -Ag\frac{P_i - P_{i-1}}{z_i - z_{i-1}} - \frac{f_i Q_i|Q_i|}{2DA}; \ \frac{\delta P}{\delta t} = -\frac{v_s^2}{gA}\frac{Q_{i+1} - Q_i}{z_{i+1} - z_i}, \tag{2}$$

where i is the index of the pipeline section, let's assume piping with two sections to facilitate the proposed NCS scheme for the pipeline systems. **Fig. 1** shows the pipeline system which divided into two sections.

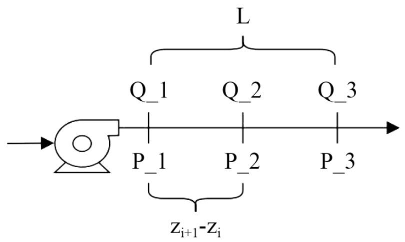

Fig. 1. Pipeline system with 2 sections

In **Fig. 1**, the sensors and actuators in i is divided by length $\delta_z = z_{i+1} - z_i$. The length δ_z can be quite long for a pipeline system where wired communication could be inefficient. By the consideration mentioned above, there are the dynamic equations of pipe systems for $N = 2$:

$$\dot{P}_1 = -\frac{v_2^2}{gA_1}\frac{Q_2 - Q_1}{z_2 - z_1};\ \dot{P}_2 = -\frac{v_s^2}{gA_2}\frac{Q_3 - Q_2}{L - (z_2 - z_1)};$$

$$\dot{Q}_2 = -A_2 g\frac{P_2 - P_1}{z_2 - z_1} - \frac{f_1}{2DA_2}Q_2|Q_2|;\ \dot{Q}_3 = -A_3 g\frac{P_3 - P_2}{L - (z_2 - z_1)} - \frac{f_2}{2DA_3}Q_3|Q_3|. \quad (3)$$

Here, let's linearize the flow rate dynamics by assuming the $|Q_2|$ and $|Q_3|$ are constant with predefined value of C_0. Then the dynamics in (3) can be written in the state-space form:

$$\dot{x}(t) = Ax(t) + Bu(t),$$

$$y(t) = Cx(t), \quad (4)$$

as follows:

$$\begin{bmatrix} P_1 \\ Q_2 \\ P_2 \\ Q_3 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{C_1}{C_2} & 0 & 0 \\ \frac{C_3}{C_2} & -C_4C_0 & -\frac{C_3}{C_2} & 0 \\ 0 & \frac{C_5}{C_2} & 0 & -\frac{C_5}{C_2} \\ 0 & 0 & \frac{C_6}{C_2} & -C_7C_0 \end{bmatrix} \begin{bmatrix} P_1 \\ Q_2 \\ P_2 \\ Q_3 \end{bmatrix} + \begin{bmatrix} \frac{C_6}{C_2} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{C_6}{C_2} \end{bmatrix} + \begin{bmatrix} Q_1 \\ P_3 \end{bmatrix},$$

$$y = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} P_1 \\ Q_2 \\ P_2 \\ Q_3 \end{bmatrix}, \quad (5)$$

where A is the dynamic matrix of the pipeline system, B is the input matrix of the pipeline system, and C is the considered output matrix. The constants are defined as follows:

$$C_1 = \frac{v_s{}^2}{gA_1},\ C_4 = \frac{f_1}{2DA_2},\ C_7 = \frac{f_2}{2DA_3},$$

$$C_2 = z_2 - z_1,\ C_5 = \frac{v_s{}^2}{gA_2},$$

$$C_3 = A_2 g,\ C_6 = A_3 g.$$

LQR Control. Here, let's design the discrete-time optimal control LQR for continuous-time system. The stability analysis of the NCS requires the state-feedback control gains to be defined. One can use any state-feedback control that provides the constant state-feedback gains such as pole-placement, LQR, etc. Here, the LQR control is used to give the optimal solution by minimizing the cost function:

$$J = \int_0^\infty \left(x^T(t)Qx(t) + u^T(t)Ru(t)\right)\mathrm{d}t, \quad (6)$$

where J is the cost function, Q is the weighting matrix related to the performance or states, R is the weighting matrix related to the effort given to the system. In regulator problem, the control law $u(t)$ of the LQR control satisfies:

$$u(t) = -Kx(t), \quad (7)$$

where K is the optimal state-feedback gain. It is known that the optimal gain K can be defined as:

$$K = R^{-1}B^{T}P, \tag{8}$$

where the matrix P is a positive symmetric definite matrix, $P = P^{T} > 0$, that satisfies the Algebraic Riccati Equation:

$$A^{T}P + PA + Q - PBR^{-1}B^{T}P = 0. \tag{9}$$

Additionally, in tracking problem, the purpose of the LQR control is to give the optimal solution that makes the output of the system to be equal to the reference, $y(t)$ equal to $r(t)$ as time goes to infinity. Thus, the control law $u(t)$ in equation (6) must be modified by adding pre-compensation gain K_f:

$$u(t) = -Kx(t) + K_f r(t), \tag{10}$$

where the pre-compensation gain satisfies:

$$K_f = \left(C\left(sI - (A - BK)\right)^{-1} B\right)^{-1}. \tag{11}$$

By assuming the system's parameter is known, the pre-compensation gain K_f can be derived. **Fig. 2** shows the proposed LQR control structure in the non-NCS scheme.

Here, let's assume the measurement of the entire states $x(k) = y(k)$ In line with [18], the sensor works in a time-driven mode, while the actuator and controller work in an event-driven fashion. In the regulator problem and the tracking problem, the reference $r(t)$ satisfies $r(t) = 0$ and $r(t) \neq 0$, respectively. Let's note that the controller receives the measurement of the state from the system only at sampling instant $t_k = kh$ where h is the sampling time. By the consideration above, there are a discrete-time controller and continuous-time pipeline systems. Thus the optimal state-feedback gain must be designed in a discrete-time fashion:

$$K_d = R^{-1}\Gamma P_d, \tag{12}$$

where the Gamma is the input matrix of the system with sampling time h that satisfies $\Gamma = \int_0^h e^{As} \mathrm{d}s B$, and the matrix P_d is a positive symmetric definite matrix, $P_d = P_d^T > 0$, that satisfies the Algebraic Riccati Equation:

$$\Phi^{T}P_d + P_d\Phi + Q - P_d\Gamma R^{-1}\Gamma^{T}P_d = 0, \tag{13}$$

where Phi is the dynamic matrix of the system with sampling time h that satisfies $\Phi = e^{Ah}$.

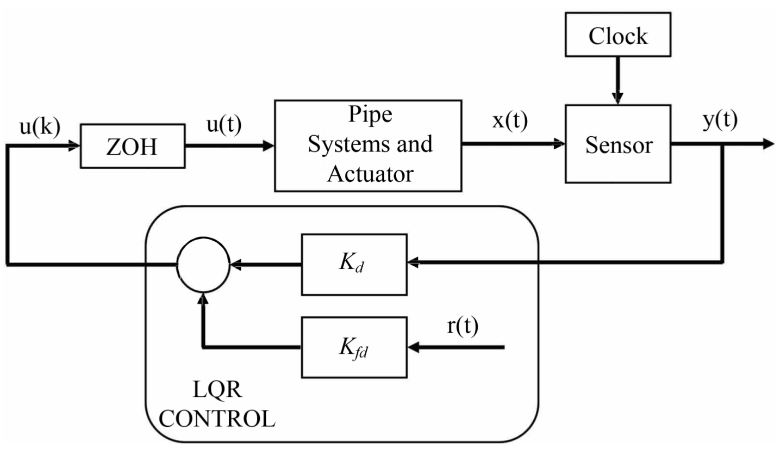

Fig. 2. Linear Quadratic Regulator structure with discrete-time controller and continuous-time system

Then the pre-compensation gain defined in equation (11) now defined as:

$$K_{fd}=\left(C\left(sI-\left(A-BK_d\right)\right)^{-1}B\right)^{-1}. \tag{14}$$

Networked Control System. In the NCS, the controller components are separated by a network that caused a system to affect by networked induced delay. These delays are usually defined as the sensor-to-controller delay (tau_{sc}) and the controller-to-actuator delay (tau_{ca}). Both of (tau_{sc}) and (tau_{ca}) are represented as (tau). **Fig. 3** shows the NCS overview of the proposed LQR control for the pipeline system.

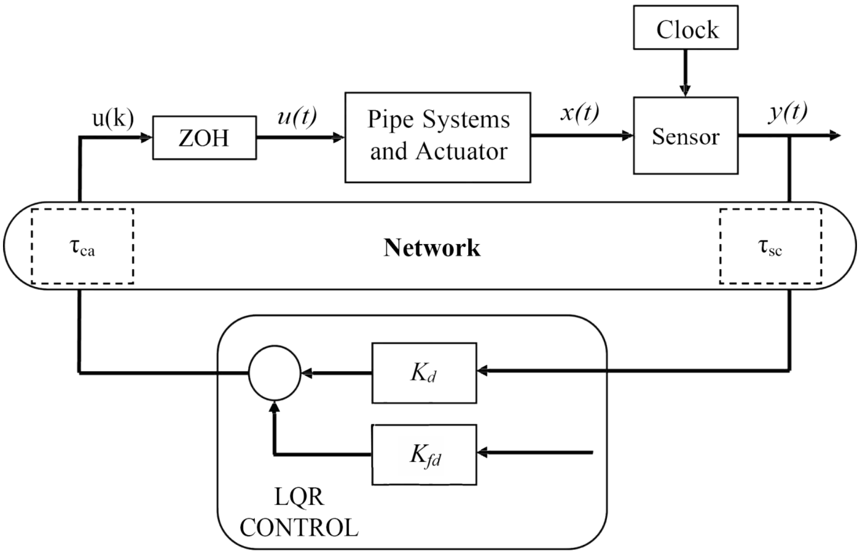

Fig. 3. Network Control System overview of Linear Quadratic Regulator controller of pipeline system

The discrete-time controller and continuous-time pipeline systems can be defined as:

$$\dot{x}(t)=Ax(t)+B\hat{u}(t),$$

$$\hat{u}(t)=u_k, \tag{15}$$

where u_k is the delayed discrete-time input corresponding to the measurement data at sampling instant s_k. Then the stability analysis of the proposed controller is derived in the NCS model with short and long delays. The proposed NCS model is in line with the NCS model derived in [13, 19].

In the short delay case, let's assume the networked-induced delay is smaller than the sampling time, tau in the following range [0, h]. The open-loop discrete-time NCS model with sampling time h can be derived from equation (15) that leads to the following NCS model with a short delay:

$$x_{k+1}=e^{Ah}x_k+\int_0^{h-\tau}e^{As}Bu_k\mathrm{d}s+\int_{h-\tau}^{h}e^{As}Bu_{k-1}\mathrm{d}s. \tag{16}$$

By defining the NCS model state $\xi_s=\left[x^T{}_k \quad u^T{}_{k-1}\right]^T$ and the control law in equation (6) (regulator problem), let's obtain the closed-loop discrete-time NCS model:

$$\begin{bmatrix}x_{k+1}\\ u_k\end{bmatrix}=\begin{bmatrix}e^{Ah}-\int_0^{h-\tau}e^{As}BK\mathrm{d}s & \int_{h-\tau}^{h}e^{As}B\mathrm{d}s\\ -K & 0\end{bmatrix}\begin{bmatrix}x_k\\ u_{k-1}\end{bmatrix}, \tag{17}$$

where

$$A_s = \begin{bmatrix} e^{Ah} - \int_0^{h-\tau} e^{As} BK\mathrm{d}s & \int_{h-\tau}^{h} e^{As} B\mathrm{d}s \\ -K & 0 \end{bmatrix}.$$

The tracking problem of LQR controller with control law (10) following the same procedure, and note that the stability analysis is only dependent on the dynamic matrix with short delay A_s. Keep in mind that the dimension of the matrix A_s depends on the size of the matrix A and B.

Let's assume the networked-induced delay greater than the sampling time in the long delay case, tau in the following range $[h, 2h]$. Thus the sampling interval $[s_k, s_{k+1}]$ will be affected by the delayed control input u_{k-2} and u_{k-1}. The open-loop discrete-time NCS model with sampling time h can be derived from equation (15) which leads to the following NCS model with a long delay:

$$x_{k+1} = e^{A(s_{k+1}-s_k)} x_k + \int_{s_k}^{s_k+\tau-h} e^{A(s_{k+1}-s_k)} Bu_{k-2}\mathrm{d}s + \int_{s_{k+\tau-h}}^{s_{k+1}} e^{A(s_{k+1}-s_k)} Bu_{k-1}\mathrm{d}s, \quad (18)$$

then it is possible to rewrite the equation (18) in the following form:

$$x_{k+1} = e^{Ah} x_k + \int_h^{h-\tau_d} e^{A\sigma} Bu_{k-2}(-\mathrm{d}\sigma) + \int_{h-\tau_d}^{0} e^{A\sigma} Bu_{k-1}(-\mathrm{d}\sigma),$$

$$= e^{Ah} x_k + \int_{h-\tau_d}^{h} e^{A\sigma} Bu_{k-2}\mathrm{d}\sigma + \int_0^{h-\tau_d} e^{A\sigma} Bu_{k-1}\mathrm{d}\sigma, \quad (19)$$

where tau_d is the difference between the delay time and sampling time, $tau_d = tau - h$, and $sigma = s_{k+1} - s_k$ is the difference of sampling interval. By defining the NCS model state $\xi_l = \left[x^T{}_k \quad u^T{}_{k-2} \quad u^T{}_{k-1}\right]^T$, and the control law in equation (7) (regulator problem), let's obtain the closed-loop discrete-time NCS model:

$$\begin{bmatrix} x_{k+1} \\ u_{k-1} \\ u_k \end{bmatrix} = \begin{bmatrix} e^{Ah} & \int_{h-\tau_d}^{h} e^{A\sigma} B\mathrm{d}\sigma & \int_0^{h-\tau_d} e^{A\sigma} B\mathrm{d}\sigma \\ 0 & 0 & I \\ -K & 0 & 0 \end{bmatrix} \begin{bmatrix} x_k \\ u_{k-2} \\ u_{k-1} \end{bmatrix}, \quad (20)$$

where

$$A_l = \begin{bmatrix} e^{Ah} & \int_{h-\tau_d}^{h} e^{A\sigma} B\mathrm{d}\sigma & \int_0^{h-\tau_d} e^{A\sigma} B\mathrm{d}\sigma \\ 0 & 0 & I \\ -K & 0 & 0 \end{bmatrix},$$

is the dynamic matrix with long delay. Now, the stability analysis can be derived from dynamic matrices A_s and A_l by checking the eigenvalues inside the unit circle. In the case of time $delay > 2h$, the same procedure can be derived where extra state must be added in the state.

3. Results and discussion

This section will show the proposed LQR control simulation results for the pipeline system in the NCS scheme with networked induced delay. Under the proposed NCS scheme, let's assess the allowable limit of networked-induced delay and the permissible sampling time for the controller. To achieve the research objective, first, let's create the dynamics model of the pipeline system, then implement the optimal control LQR, and finally, change the control system structure to align with the NCS scheme. To define the dynamics model of the pipeline system, let's use the following Pipeline system parameters described in **Table 1**.

Table 1
Pipeline Parameters

Parameter	Value
f	1
D	0.6096 (m)
g	9.8 (m/s^2)
v_s	343 (m/s)
$z_{i+1}-z_i$	200 (m)

Let's choose the weighting matrices Q and R:

$$Q=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix};\ R=\begin{bmatrix}100&0\\0&100\end{bmatrix}. \quad (21)$$

It is possible to use any positive definite Q and R for the numerical simulation, but in practice, one must consider the input saturation, such as the control valve signal. In this case let's choose the Q and R matrices that gives slow transient response for better representation. The optimum gain K_d is calculated by using ARE (12):

$$K_d=\begin{bmatrix}0.0092&-0.3194&0.0026&-0.0916\\0.0003&0.0865&0.0018&-0.0868\end{bmatrix}, \quad (22)$$

and the pre-compensation gain K_{fd} is calculated by using equation (14):

$$K_{fd}=\begin{bmatrix}0.0118&4.2056\\1.0021&-392.8842\end{bmatrix}. \quad (23)$$

Fig. 4 shows the stability region for the NCS for both short and long networked induced delay. Two cases are considered by defining time delay tau_a and tau_b depicted with the red circle in **Fig. 4**.

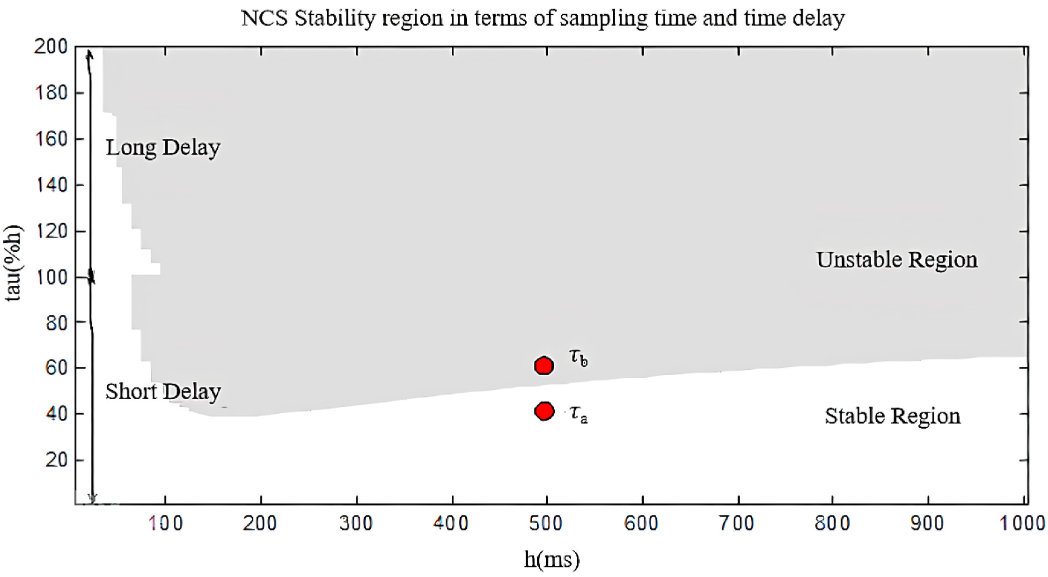

Fig. 4. Stability plot region of the Network Control System with short and long delay

In first case (**Fig. 4,** tau_a), let's consider the time delay tau_a that is equal to 40 % of sampling time $h = 500$ ms. **Fig. 5, 6** show the states response of LQR regulator problem and tracking problem respectively.

It can be seen in **Fig. 5** that all states response goes to zero which verify the stability region analysis in **Fig. 4.** In **Fig. 6** it can be seen that the outputs $y_1(t)$ and $y_2(t)$ is equal to the reference signal $r_1(t) = 0.5$ and $r_2(t) = 0.5$.

In second case (**Fig. 4**, tau_b), let's consider the time delay tau_b that is equal to 60 % of sampling time $h = 500$ ms. **Fig. 7, 8** show the states response of LQR regulator problem and tracking problem respectively.

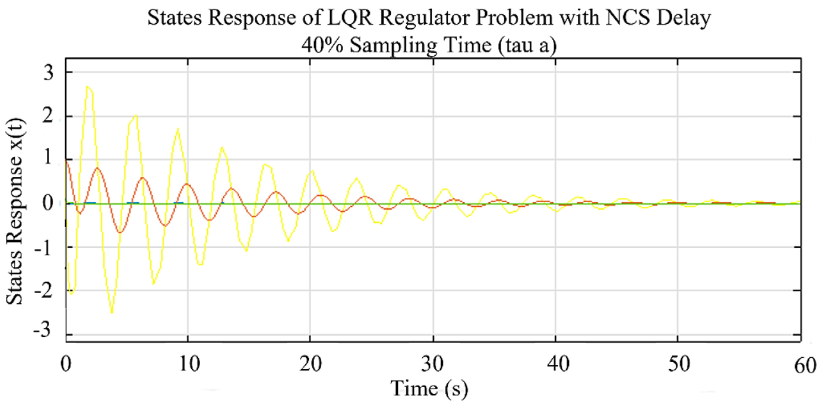

Fig. 5. Regulator problem of Linear Quadratic Regulator control in Network Control System with networked-induced delay tau_a

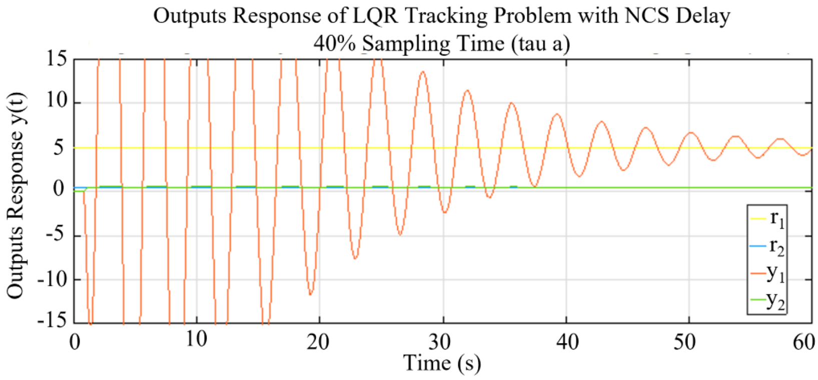

Fig. 6. Tracking problem of Linear Quadratic Regulator control in Network Control System with networked-induced delay tau_a

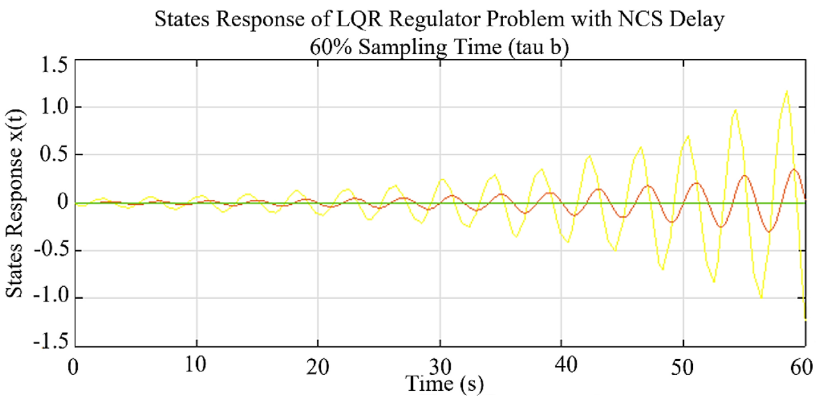

Fig. 7. Regulator problem of Linear Quadratic Regulator control in Network Control System with networked-induced delay tau_b

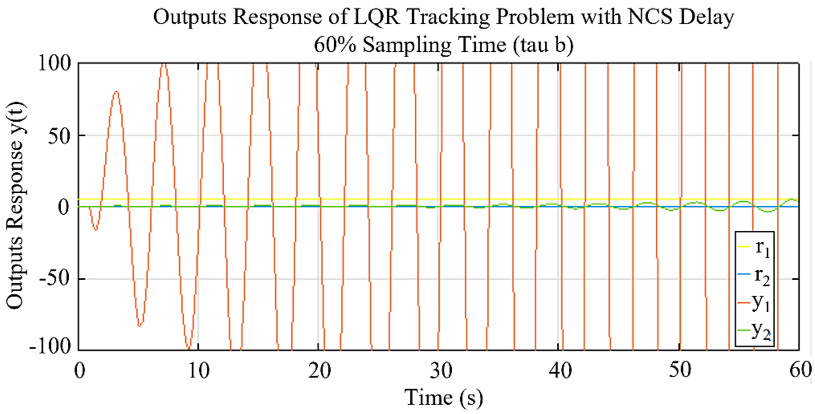

Fig. 8. Tracking problem of Linear Quadratic Regulator control in Network Control System with networked-induced delay tau_b

It can be seen in **Fig. 7, 8** that the states go to infinity for both regulator and tracking problems. Thus **Fig. 5–8** verify the stable and unstable region in the stability region analysis in **Fig. 4**. The objective of this research is summarized in **Fig. 4**, which shows the limit of the allowable networked induced delay of NCS in a pipeline system. In practice, one must choose the point far from the unstable area in **Fig. 4** and consider the input saturation, such as valve opening. In the presence of uncertain time delay, the more advanced control must be considered, i.e. adaptive control. Future work will include the design of NCS with networked constraints where the controller gain changing by time, adaptive control, to handle the uncertain networked induced delay [20], and the design of decentralized MPC in NCS scheme [21].

4. Conclusions

This work showed the stability analysis of the LQR optimal control in pipeline system where the NCS scheme is considered with network induced time delay, short and long time delay. The stability region is derived and verified where the sampling time range between 0–1000 ms and the time delay in the range of 0–200 %. It is also shown that the regulator and tracking problem of LQR control of the pipeline system satisfies the derived stability region of NCS with networked-induced delay. The numerical simulation was carried out to verify the stability analysis of NCS with networked induced delay. To achieve a better transient response, one can tune the weighting matrix Q and R.

Conflict of Interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

Data availability

Manuscript has no associated data.

Financing

We gratefully acknowledge the support from Telkom University and Universiti Teknologi PETRONAS with the International Collaboration grant number KWR.0013/PNLT3/PPM-LIT/2020.

References

[1] Tipsuwan, Y., Chow, M.-Y. (2003). Control methodologies in networked control systems. Control Engineering Practice, 11 (10), 1099–1111. doi: https://doi.org/10.1016/s0967-0661(03)00036-4

[2] Zhang, W., Branicky, M. S., Phillips, S. M. (2001). Stability of networked control systems. IEEE Control Systems, 21 (1), 84–99. doi: https://doi.org/10.1109/37.898794

[3] Wang, Y.-L., Han, Q.-L. (2018). Network-based modelling and dynamic output feedback control for unmanned marine vehicles in network environments. Automatica, 91, 43–53. doi: https://doi.org/10.1016/j.automatica.2018.01.026

[4] Li, S. E., Zheng, Y., Li, K., Wang, L.-Y., Zhang, H. (2018). Platoon Control of Connected Vehicles from a Networked Control Perspective: Literature Review, Component Modeling, and Controller Synthesis. IEEE Transactions on Vehicular Technology, 1–1. doi: https://doi.org/10.1109/tvt.2017.2723881
[5] Singh, A. K., Singh, R., Pal, B. C. (2015). Stability Analysis of Networked Control in Smart Grids. IEEE Transactions on Smart Grid, 6 (1), 381–390. doi: https://doi.org/10.1109/tsg.2014.2314494
[6] Liang, K.-Y., van de Hoef, S., Terelius, H., Turri, V., Besselink, B., Mårtensson, J., Johansson, K. H. (2016). Networked control challenges in collaborative road freight transport. European Journal of Control, 30, 2–14. doi: https://doi.org/10.1016/j.ejcon.2016.04.008
[7] Park, P., Khadilkar, H., Balakrishnan, H., Tomlin, C. J. (2014). High Confidence Networked Control for Next Generation Air Transportation Systems. IEEE Transactions on Automatic Control, 59 (12), 3357–3372. doi: https://doi.org/10.1109/tac.2014.2352011
[8] Rosa, M. R., Baldi, S., Wang, X., Lv, M., Yu, W. (2019). Adaptive hierarchical formation control for uncertain Euler-Lagrange systems using distributed inverse dynamics. European Journal of Control, 48, 52–65. doi: https://doi.org/10.1016/j.ejcon.2018.11.001
[9] Yu, H., Guo, M. (2012). An efficient oil and gas pipeline monitoring systems based on wireless sensor networks. 2012 International Conference on Information Security and Intelligent Control. doi: https://doi.org/10.1109/isic.2012.6449735
[10] Ali, S., Ashraf, A., Qaisar, S. B., Kamran Afridi, M., Saeed, H., Rashid, S. et al. (2018). SimpliMote: A Wireless Sensor Network Monitoring Platform for Oil and Gas Pipelines. IEEE Systems Journal, 12 (1), 778–789. doi: https://doi.org/10.1109/jsyst.2016.2597171
[11] Rui, Z., Han, G., Zhang, H., Wang, S., Pu, H., Ling, K. (2017). A new model to evaluate two leak points in a gas pipeline. Journal of Natural Gas Science and Engineering, 46, 491–497. doi: https://doi.org/10.1016/j.jngse.2017.08.025
[12] Yang, H., Xia, Y., Shi, P. (2010). Stabilization of networked control systems with nonuniform random sampling periods. International Journal of Robust and Nonlinear Control, 21 (5), 501–526. doi: https://doi.org/10.1002/rnc.1607
[13] Cloosterman, M. B. G., van de Wouw, N., Heemels, W. P. M. H., Nijmeijer, H. (2009). Stability of Networked Control Systems With Uncertain Time-Varying Delays. IEEE Transactions on Automatic Control, 54 (7), 1575–1580. doi: https://doi.org/10.1109/tac.2009.2015543
[14] van Loon, S. J. L. M., Donkers, M. C. F., van de Wouw, N., Heemels, W. P. M. H. (2013). Stability analysis of networked and quantized linear control systems. Nonlinear Analysis: Hybrid Systems, 10, 111–125. doi: https://doi.org/10.1016/j.nahs.2013.03.004
[15] Sathishkumar, M., Liu, Y.-C. (2020). Resilient event-triggered fault-tolerant control for networked control systems with randomly occurring nonlinearities and DoS attacks. International Journal of Systems Science, 51 (14), 2712–2732. doi: https://doi.org/10.1080/00207721.2020.1801880
[16] Sargolzaei, A., Abbaspour, A., Al Faruque, M. A., Salah Eddin, A., Yen, K. (2018). Security Challenges of Networked Control Systems. Sustainable Interdependent Networks, 77–95. doi: https://doi.org/10.1007/978-3-319-74412-4_6
[17] Guill´en, M., Dulhoste, J.-F., Besancon, G., Santos, R. (2012). Study of a flow model for detection and location of leaks and obstructions in pipes. HAL. Available at: https://hal.archives-ouvertes.fr/hal-00741054
[18] Astrom, K., Wittenmark, B. (2011). Computer-Controlled Systems: Theory and Design. Prentice Hall.
[19] Cloosterman, M., van de Wouw, N., Heemels, M., Nijmeijer, H. (2006). Robust Stability of Networked Control Systems with Time-varying Network-induced Delays. Proceedings of the 45th IEEE Conference on Decision and Control. doi: https://doi.org/10.1109/cdc.2006.376765
[20] Rosa, M. R. (2020). Leader-Follower Synchronization of Uncertain Euler-Lagrange Dynamics with Input Constraints. Aerospace, 7 (9), 127. doi: https://doi.org/10.3390/aerospace7090127
[21] Zheng, Y., Li, S., Qiu, H. (2013). Networked Coordination-Based Distributed Model Predictive Control for Large-Scale System. IEEE Transactions on Control Systems Technology, 21 (3), 991–998. doi: https://doi.org/10.1109/tcst.2012.2196280

Received date 21.06.2022
Accepted date 31.10.2022
Published date 29.11.2022

How to cite: *Rosa, M. R., Susanto, E., Hassan, M. F. (2022). Networked control system stability analysis of pipeline system with networked-induced delay. EUREKA: Physics and Engineering, 6, 74–83. doi: https://doi.org/10.21303/2461-4262.2022.002469*