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Stochastic LQI with Markov Chain for Decreasing the Effect of Random Delay in Networked Control System

Stochastic LQI dengan Markov Chain untuk Mengurangi Efek Random *Delay* pada Sistem Kendali Berjaringan

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Abstract

A Networked Control System (NCS) is a control system in which actuation and feedback signals are transmitted over a communication network. One of the key challenges in NCS is the presence of random delays introduced by the communication protocol. This study proposes an adaptive approach for tuning the integral gain (K_{int}) of the Linear Quadratic Integral (LQI) controller, based on both the current delay state and a predicted delay obtained via a Markov chain model, which has not been explored extensively. The proposed method first maps each delay interval to a corresponding K_{int}, establishing a delay-gain pair. Then, the integral gain is dynamically updated at each control cycle by combining the current (K_{int_t}) and the predicted K_{int} for the next time step (K_{int_t+1}), using weighted coefficients a and b, respectively, as follows: K_{int} = a K_{int_t} + b* K_{int_t+1}. Experimental validation demonstrates that, with optimal weights a=0.5 and b=0.5, the proposed method significantly improves system performance. Compared to a fixed (static) K_{int}, it reduces the percentage overshoot from 17.06% to 2.45% and decreases the settling time from 457.6 seconds to 254.06 seconds.*

Keywords: network control system, Stochastic, Linear Quadratic Integral, integral gain, delay time.

SDGs:

INDUSTRY, INNOVATION AND INFRASTRUCTURE

Abstrak

Sistem kendali berjaringan (NCS) merupakan sistem kendali yang mana sinyal umpan balik dan sinyal aktuasi dikirimkan melalui jaringan komunikasi. Salah satu tantangan NCS adalah waktu tunda yang acak yang disebabkan oleh protokol jaringan komunikasi. Penelitian ini mengusulkan adaptif integral gain (K_{int}) kendali LQI berdasarkan waktu tunda terukur dan waktu tunda yang diprediksi oleh Markov chain, yang mana metode ini belum banyak diteliti lebih jauh. Pertama-tama, K_{int} ditentukan berdasarkan setiap rentang waktu tunda sehingga diperoleh pasangan nilai waktu tunda dan K_{int}. Selanjutnya, untuk setiap nilai K_{int} dari waktu tunda yang terukur (K_{int_t}) dan K_{int} dari waktu tunda yang diprediksi (K_{int_t+1}), dikombinasikan dengan memberikan bobot a dan b sehingga total K_{int} untuk setiap siklus perhitungan adalah K_{int} = a* K_{int_t} + b* K_{int_t+1}. Hasil pengujian menunjukkan dengan bobot optimal a dan b adalah 0,5, dan dibandingkan Kint tetap (statis), metode stokastik LQI dapat mengurangi % *overshoot* dari 17.06% ke 2,45% dan *settling time* dari 457,6 ke 254,06 detik.

Kata Kunci: sistem kontrol jaringan, *Stochastic, Linear Quadratic Integral, integral gain,* waktu tunda.

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1. INTRODUCTION

A Networked Control System (NCS) is a distributed control system that contains controlled objects such as sensors, controllers, actuators, and other components where system information and control signals (inputs, outputs) are transmitted over a communication network. Problems in NCS include random delay, and packet loss (Lian, Zhang and Li, 2019; Xue, Yu and Wang, 2019; Zhang *et al.*, 2019; Pang *et al.*, 2021).

Several research have been conducted to find methods to overcome random delay. A study by Steinberger et al., introduced a discrete-time adaptive control method tailored for uncertain linear multivariable networked systems (Steinberger, Horn and Ferrara, 2022). Building on the concept of model reference adaptive control, the authors developed two adaptive laws to address the conservativeness often encountered when time delays are not explicitly known. Other researchers Nafir et al. (Nafir *et al.*, 2021) and Ji et al., (Ji *et al.*, 2018) used the theory of finite-time stability combined with Linear Matrix Inequalities (LMIs), where the conditions for finite-time stabilization and boundedness on NCS with random delay were obtained from the LMIs method. This will result in an adequate finite-time stabilization condition assuming no external disturbances and a finite-time boundedness condition obtained with external disturbances.

Research on risk-sensitive control (RS) for linear systems with stochastic system parameters found that stochastic parameters cause problems in conventional RS control (Ito *et al.*, 2019). Stochastic research is used in several methods in NCS. Among them is using the frequency domain (Zhou *et al.*, 2017), where the Laplace transformation strategy is used to analyze random delay problems. Several researchers, used H_∞ control for stochastic problems in NCS, where the Improved Free Weighting Matrix (IFWM) method was used to analyze robust stability problems and robust H_∞ for nonlinear stochastic network control systems (Lu *et al.*, 2018; Xie, Li and Xu, 2019; Lee *et al.*, 2020; Lu, Deng and Zhou, 2020).

Most existing studies on time delays in Networked Control Systems (NCS) treat the delay as an assumed parameter rather than a directly measured quantity. While a few works have attempted to quantify delays (Huang *et al.*, 2022; Rsetam *et al.*, 2025), they generally do not consider measurements within delay in Remote Terminal Units (RTUs) that integrate both sensors and plants. Furthermore, prior research has primarily focused on delay characterization without analyzing its impact on specific control strategies. These gaps present opportunities addressed in this study. Additionally, the integration of delay prediction techniques, such as Markov chains, with state-based control methods employing non-zero setpoints (e.g., Linear Quadratic Integral [LQI] control), remains an open and promising research direction.

This research proposes method to solves the random delay problem by the Linear Quadratic Stochastic algorithm with Markov Chain. The first is to identify the plant model to get the value of the transfer function and state-space, the second is to add a state observer to suppress the error value from the modeling results and the original plant signal. The third is to get the appropriate Q and R values. The fourth is the Markov chain design to get the value of the transition matrix P, and the last is tuning the integral gain (K_{int}) parameter for a specific delay time range. The Kint is based on the measured delay time (K_{int_t}) and the predicted delay time (K_{int_t+1}) resulting from the stochastic process.

2. METHODOLOGY

The procedure carried out in this paper is first applied identification method to obtain a model of the plant system used, as shown in Figure 1. The second is to measure the Delay Time to determine the minimum and maximum delay induced by the network at the plant. The third is to find the appropriate Q and R values based on the performance index value. The fourth is to get the value of the transition matrix P from the stochastic process with the Markov Chain to predict the value of the next delay time. Finally, integral gain scheduling is performed after the four stages to obtain an adaptive integral gain (K_{int}) value.

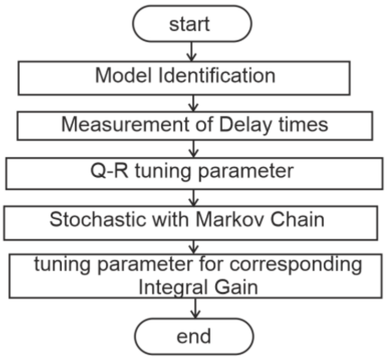

Figure 1. Research procedure.

2.1. Plant Structure

Figure 2 depicts the system's block diagram. This research sets main functions such as controller program, delay measurement, sending a control signal, and receiving feedback signal in the Master Terminal Unit (MTU). All signals are transferred through ethernet protocol communication (using UDP). The sent control signal is then received by the Remote Terminal Unit (RTU), gained, and driven the plant (see Figure 3). The speed sensor is deployed as feedback and is sent back by RTU to MTU.

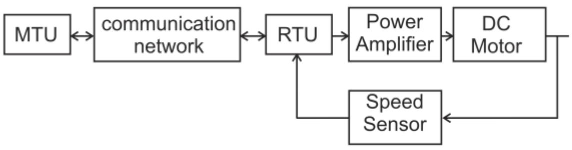

Figure 2. System block diagram.

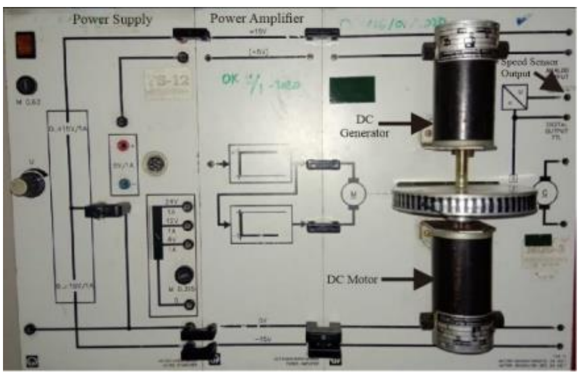

Figure 3. Motor plant.

Figure 4 depicts the proposed control structure. This research aims to find an appropriate control strategy as the delay over the network behaves randomly (not with a fixed sampling time). According to Figure 4, state-space parameters (A, B, C) are derived from the plant model. As the states are used in the control algorithm, a state observer (in the form of an L matrix) is added to estimate states corresponding to plant dynamics. The subsequent parameter, K, is obtained using a Linear Quadratic Regulator (LQR). The process design is evaluated using the cost function parameter (J-Fucntion). The remaining parameter, K_{int}, is the main factor to overcome the random delay. In this research, the proposed algorithm will adaptively change this parameter.

2.2. Delay Time Measurement

The delay time in the networked control system will be influenced by the delay in the data transmission process in each communication protocol used. The delay that will be used in this paper is the delay in sending manipulated value (MV) data from the master terminal unit (MTU) to the remote terminal unit (RTU) and sending PV data from the RTU to MTU, which affects the Delay Time in the control system using a network communication protocol, namely the User Datagram Protocol (UDP).

The size of the delay value generated will affect the existing delay time in the control system, resulting in changes in the plant's transient response. Figure 5 shows the overall Delay Time measurement process in one looping program on a networked control system.

The equation to get the Total Delay Time (TDM) is stated in equation (1).

$$\mathrm{TDM} = \mathrm{TsMTU} + \mathrm{T1} + \mathrm{TsRTU} + \mathrm{T2} \quad (1)$$

where TsMTU is the sampling time of the Master Terminal Unit (MTU), T_1 is the transmission delay when sending the MV signal, TsRTU is the Remote Terminal Unit (RTU) sampling time, and T_2 is the transmission delay when sending the PV signal. The measurement process for T_1 is calculated at the MTU, and for T_2, it is at the RTU.

2.3. Stochastic with Markov Chain

According to the principle of a stochastic process with a Markov chain, the transition matrix, as stated in equation (2), is first introduced. In this matrix, the sum of each row must be equal to 1.

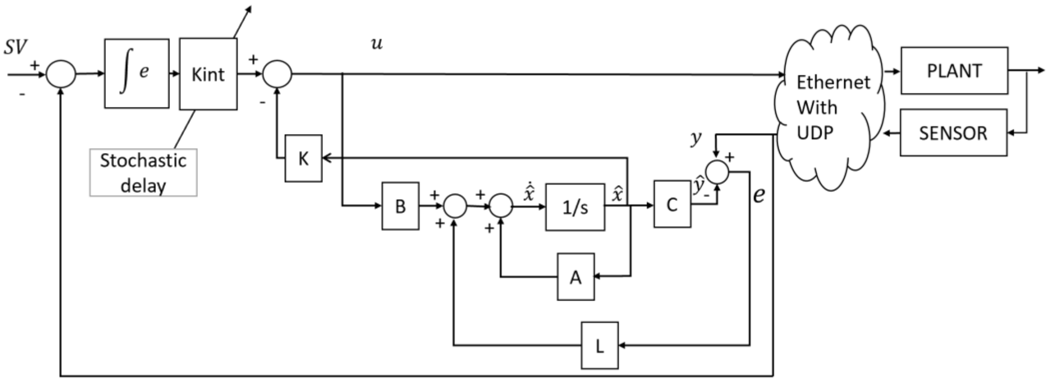

Figure 4. Control block diagram.

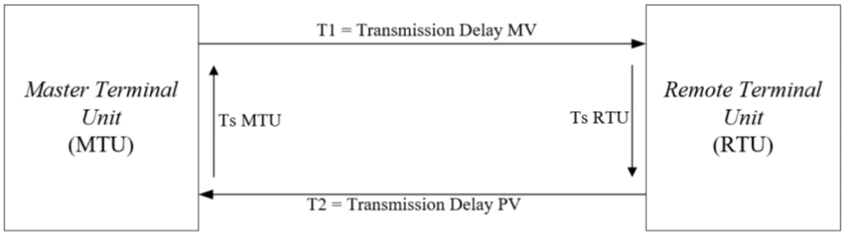

Figure 5. Block diagram of delay time measurement.

$$P = \begin{bmatrix} P_{00} & P_{10} & \cdots & P_{0n} \\ P_{01} & P_{11} & \cdots & P_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ P_{n0} & P_{n1} & \cdots & P_{nn} \end{bmatrix} \quad (2)$$

In this research, the transition matrix P corresponds to the value of the time delay. The next probability of delay time, P^n, will be calculated using Equation (3). This equation shows that the prediction state vector (P^n) is obtained from the initial state vector value P^{n-1} multiplied by the transition matrix P. The final predicted state vector is determined based on its largest vector value.

$$P^n = P^{n-1}P \quad (3)$$

2.4. Linear Quadratic Integral (LQI)

As plant is non-zero setpoint, Linear Quadratic Integrator (LQI) is employed due to simplicity in input gain design (just weighting factor from error integration), instead of LQR using multiplication of several matrices. The structure of LQI used in this research is depicted in Figure 4. After determining the value of K_{int} (in the beginning, it is set constant), matrix Q, and R, the goal is to find matrix K, which is derived from equation (4), after finding P in equation (5). The evaluation is conducted by tuning matrix Q and R and measuring the cost function (J-function) as stated in equation (6). In this research, as a measurement standard, the J function is measured from the beginning of the system to the rise time (for the effective measurement, it is defined when the signal starts from 0 to 100%).

$$K = R^{-1}B^{T}P \quad (4)$$

$$A^{T}P + PA - PBR^{-1}B^{T}P + Q = 0 \quad (5)$$

$$J = \int_{0}^{Tr}(x^{T}Qx + u^{T}Ru)dt \quad (6)$$

2.5. Gain scheduling of Integral Gain (K_{int})

In control methods implemented on digital or embedded systems, the execution of control algorithms requires sampling time values. However, in Networked Control Systems (NCS), these values can vary randomly, potentially degrading control performance. To mitigate this effect, one approach is to predict the delay and compensate for it by adaptively adjusting the integral gain (K_{int}) in the Linear Quadratic Integral (LQI) controller.

In this study, the stochastic delay time corresponds to the integral gain (K_{int}). In the LQI method, the simplest component to modify is the integral gain (K_{int}), rather than the state feedback gain (K), which is typically obtained by tuning the

Q-R matrices and solving the Algebraic Riccati Equation (ARE). The integral gain functions as a linear scalar, and its selection in this study is based on a trial-and-error approach, which revealed a correlation between (K_{int}) and the system response. Historically, in the original LQI method, such gains are often tuned manually.

This research proposes equation (7) to obtain the K_{int} of LQI, where K_{int_t} is the integral gain according to the latest measured delay, and K_{int_t+1} is the integral gain predicted by the method. This method also introduces the weighting of both integral gains. Both variables, a and b, are manually tuned to obtain the best control response (overshoot, rise time, settling time, error steady-state).

$$K_{int} = a*K_{int\_t} + b*K_{int\_t+1} \quad (7)$$

3. RESULTS AND DISCUSSION

3.1. Model Plant

The model plant was derived by the identification method as a state in Equation (8) for the Laplace form and Equations (9) and (10) for the state-space form.

$$G(s) = \frac{45.29}{s^2+72.45s+95.45} \quad (8)$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -72.45 & -95.45 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u \quad (9)$$

$$y = \begin{bmatrix} 0 & 45.29 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (10)$$

3.2. Parameter Tuning Results

To find the appropriate matrix Q and R, the experiment is first conducted using the same integral gain (K_{int}); here, it is 0. 004. Table 1 shows the results of the tuning values for combination parameters (Q_{11}, Q_{22}, R). The chosen matrices are based on their lowest J-Function. The response result shown in Figure 6 with %Overshoot (%OS) = 17.06%, rise time (Tr)=167.44s, settling Time (Ts)=457.6s, and Error steady state (ess)=0%.

After getting the values of the Q and R parameters, the next step is to find the integral gain (K_{int}) parameter value for a specific delay time range. Table 2 below is a set of K_{int} for specific delay ranges.

Table 1. Linear Quadratic Interal (LQI) parameter tuning results.

Tuned parameters		State feedback gain		J-Function
[q11 q12; q21 q22]	R	K_{11}	K_{12}	
[1 0;0 1]	**1**	**0.007**	**0.0052**	**1180**
[1 0;0 1.5]	1	0.007	0.0079	1267
[1 0;0 2]	1	0.007	0.0105	1233
[0.5 0;0 2]	2	0.0018	0.0052	2451
[0.5 0;0 3]	2	0.0018	0.0079	2447
[1 0;0 3]	2	0.0036	0.0079	2445
[2 0;0 5]	3	0.0047	0.0087	3707
[2 0;0 0.5]	2	0.0069	0.0013	2347
[2 0;0 1]	2	0.0069	0.0026	2498

Table 2. K_{int} with a specific range of delay time.

Range	K_{int}	Transient Response			
		OS (%)	Tr (s)	Ts (s)	ess
31 - 32	0.00017	7.11	213.37	515.68	0
33 - 34	0.0002	11.18	160.83	430.75	0
35 - 36	0.00023	12.88	177.95	503.03	0
37 - 39	0.00015	17.06	234.87	230.15	0

3.3. Stochastic LQI

Table 3 is a random delay obtained from measurement. The state changes in delay time are 31, 32, 33, 34, 35, 36, 37, 38, and 39. These will be then mapped to XTs1 (when the delay is 31 ms) and to XTs9 (when the delay value is 39 ms). Table 4 shows the frequency value of the state changes that occur. According to the probability matrix rule (the sum of each row equals 1), Table 5 is the transition matrix used.

The transition matrix is arranged based on the value of the frequency of state changes and the probability P_{ij}. According to Table 5, the transition matrix P is obtained as follows:

$$P = \begin{bmatrix} 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.2 & 0.2 & 0.2 & 0.2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.14 & 0 & 0 & 0.57 & 0 & 0.14 & 0.14 \\ 0 & 0 & 0 & 0 & 0.24 & 0.21 & 0.21 & 0.29 & 0.06 \\ 0 & 0 & 0 & 0 & 0.14 & 0.43 & 0.24 & 0.16 & 0.03 \\ 0 & 0 & 0 & 0.05 & 0.13 & 0.36 & 0.25 & 0.2 & 0.02 \\ 0 & 0 & 0 & 0 & 0.07 & 0.39 & 0.5 & 0.04 & 0 \\ 0 & 0 & 0 & 0 & 0.27 & 0.27 & 0.36 & 0.09 & 0 \end{bmatrix}$$

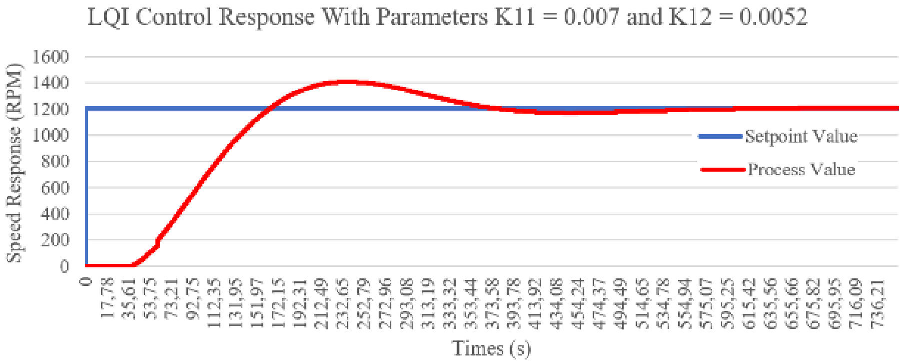

Figure 6. LQI control response with K11 = 0.007 and K12 = 0.0052

Table 3. Consecutive delay measurement.

nth-measurement	delay (ms)																			
1-20	31	33	32	32	33	34	33	33	33	31	34	38	36	37	37	38	37	38	35	37
21-40	36	38	36	36	36	38	36	36	38	37	37	39	37	37	34	36	37	39	36	36
41-60	37	38	37	36	36	37	37	36	35	36	37	36	36	38	36	38	35	36	38	35
61-80	35	39	36	36	37	38	37	37	35	36	39	37	36	35	38	37	35	38	36	37
81-100	36	36	37	38	36	38	36	36	35	36	35	38	36	37	37	36	36	38	38	34
101-120	39	37	36	36	39	38	36	36	35	38	36	35	35	37	36	36	37	38	37	36
121-140	38	36	36	36	36	36	36	36	38	37	36	35	38	36	38	37	38	37	34	36
141-160	37	36	36	36	36	36	38	37	37	38	36	36	38	37	37	35	36	37	35	35
161-180	37	36	37	38	36	37	36	36	36	38	37	36	37	38	37	36	38	36	37	36
181-200	36	35	38	36	36	36	37	35	36	38	35	37	37	37	36	35	37	36	36	37
201-220	38	37	37	39	35	37	37	37	37	36	36	36	35	38	37	35	38	37	36	36
221-240	38	37	35	39	37	36	35	36	37	35	37	38	37	34	36	36	38	36	36	36
241-260	36	38	36	35	38	38	36	37	36	39	35	37	38	37	35	35	38	37	36	35
261-280	35	37	37	37	35	35	36	36	35	39	36	37	34	36	37	37	36	35	37	38
281-300	37	37	36	36	36	37	37	35	35	39	35	35	36	37	35	38	37	36	36	38

Table 4. State change frequency.

	X_{Ts1}	X_{Ts2}	X_{Ts3}	X_{Ts4}	X_{Ts5}	X_{Ts6}	X_{Ts7}	X_{Ts8}	X_{Ts9}
X_{Ts1}	0	0	1	1	0	0	0	0	0
X_{Ts2}	0	1	0	0	0	0	0	0	0
X_{Ts3}	1	1	1	1	0	1	0	0	0
X_{Ts4}	0	0	1	0	0	4	0	1	1
X_{Ts5}	0	0	0	0	8	7	7	10	2
X_{Ts6}	0	0	0	0	10	30	17	11	2
X_{Ts7}	0	0	0	3	8	22	15	12	1
X_{Ts8}	0	0	0	0	3	18	23	2	0
X_{Ts9}	0	0	0	0	3	3	4	1	0

Table 5. Probability of P_{ij}.

	X_{Ts1}	X_{Ts2}	X_{Ts3}	X_{Ts4}	X_{Ts5}	X_{Ts6}	X_{Ts7}	X_{Ts8}	X_{Ts9}
X_{Ts1}	0	0	0.50	0.50	0	0	0	0	0
X_{Ts2}	0	1	0	0	0	0	0	0	0
X_{Ts3}	0.20	0.20	0.20	0.20	0	0.20	0	0	0
X_{Ts4}	0	0	0.14	0	0	0.57	0	0.14	0.14
X_{Ts5}	0	0	0	0	0.24	0.21	0.21	0.29	0.06
X_{Ts6}	0	0	0	0	0.14	0.43	0.24	0.16	0.03
X_{Ts7}	0	0	0	0.05	0.13	0.36	0.25	0.20	0.02
X_{Ts8}	0	0	0	0	0.07	0,39	0.50	0.04	0
X_{Ts9}	0	0	0	0	0.27	0.27	0.36	0.09	0

An example of a verification experiment has been conducted based on equation (3). With P^0 = [0.07 0.13 0.53 0.13 0.07 0.07 0 0 0] (for first looping, it is derived from direct measurement calculation), the P^1 can be calculated as follows

$$P^1 = P^0 P$$

$$P^1 = [0.07\ 0.13\ 0.53\ 0.13\ 0.07\ 0.07\ 0\ 0\ 0]\ P$$

$$P^1 = [0.11\ 0.24\ 0.16\ 0.14\ 0.03\ 0.22\ 0.03\ 0.05\ 0.02]$$

According to P^1, the highest probability is 0.24 (X_{TS2}). Referred to Table 2, it means that K_{int_t+1} is 0.00017. Assumed the latest measured delay is 34 ms (K_{int_t} is 0.0002), the K_{int} is calculated as follows:

$$K_{int} = K_{int\_t} + K_{int\_t+1}$$

$$= 0.0002 + 0.00017 = 0.00037$$

According to the verification experiment, this calculation rule results in non-optimal response parameters (mainly for % overshoot). Therefore, it is needed to be enhanced by adding a weighting factor as equation (7). Table 6 shows the effect of the weighting factor on transient responses. Considering the optimal transient response, the weighting factors are 0.5 and 0.5 for a and b, respectively.

The response of the chosen weighting is depicted in Figure 7. If compared to the fixed K_{int}, the proposed method can enhance %OS (from 17.06 % to 2.45%) and settling time (from 457.6 s to 254 s) but slower in rise time (from 167.44 s to 259.25 s).

As shown in Table 6, the ability of adaptive K_{int}, as obtained from equation (7), is able to find appropriate K_{int} corresponding to the last delay measurement and the delay prediction (detail shown in Table 2), thus it can enhance transient responses (%OS, Tr, Ts, ess).

Table 6. Weighting tuning.

weighted		Transient response			
a	b	% OS	Tr (s)	Ts (s)	ess
1	1	16.1	116.86	345.21	0
0.5	0.5	**2.45**	**259.25**	**254.06**	0
0.6	0.4	**2.55**	**287.86**	282.1	0
0.85	0.15	**2.26**	341.33	334.5	0
0.95	0.05	**2.18**	354.09	347	0
0.3	0.7	16.09	122.21	357.21	0
0.1	0.9	15.83	112.24	328.47	0
K_{int} = 0.004		17.06	167.44	457.6	0

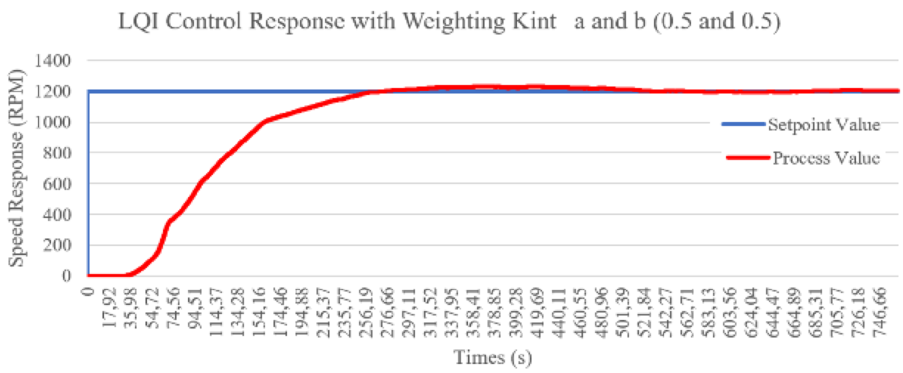

Figure 7. Step response with gain 0.5 for both a and b.

4. CONCLUSION

This study uses a stochastic Linear Quadratic Integral (LQI) with Markov chain to overcome random delay in the Networked Control System (NCS). In this research each the loop control sampling time, also stated as delay time, consists of time in MTU, sending, receiving, and RTU, is measured directly. According to measurement experiment, it showed that there is delay time variation due to communication networks (varied from 31 to 39 ms), which affect the control response.

In this research, for certain range of delay, the integral gain (Kint) is tuned to get proper response qualities (%OS, Tr, Ts, ess) so there will be a pairing between range delay and K_{int}. For each K_{int} value of the current measured delay (K_{int_t}) and K_{int} of the predicted delay (K_{int_t+1}), it can be combined by giving weights a and b so that the total Kint for each calculation cycle is $K_{int} = a^* K_{int\_t} + b^* K_{int\_t+1}$. According to trial-error of a-b value, compared to static K_{int}, it is found 0.5 for both a-b giving the optimum transient response by decreasing 14.61% of overshoot and 203.54 second faster of settling time.

This study has still several limitations (but open broader research opportunity) such as a single node plant, using UDP for communication protocol, and applied to stable plant model (DC motor). Other future research opportunities are comparing LQI to other methods such as MPC, MRAC, and MIMO based control system.

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