Robust Congestion Control based on Loop-Shaping Method with Kalman Filter for TCP/AQM System

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Abstract

This paper presents the LQ-Servo control with observer for TCP/AQM system considering an input time-delay. This controller structure is made by taking a traditional servo mechanism based on Linear Quadratic approach and by augmenting a new state variable to the feed forward loop. In order to estimate the state of TCP window packet size, the control structure is extended with observer based on Kalman filter.

Keywords: *AQM, Congestion Control, Kalman Filter, Loop-Shaping, Observer, TCP packets*

1. Introduction

Computer networks have been explosively increased, and have confronted severe congestion collapse problems according to growth of packets. In resent year, Misra et al. [1] developed a methodology to model and obtain expected transient behavior of networks with Active Queue Management Routers supporting TCP flows. Hollot et al. approximated its linearized model [2] using small-signal linearization about an operating point to gain insight for the purpose of feedback control, and designed the PI controller [3] based on the linear control theory. Aweya et al. [4] and Ren et al. [5] have used fundamental control theories to analyze and develop for AQM. Its main contribution is to convert the congestion control algorithm into the controller design problem within the framework of control theory in AQM system.

More recently, Yang and Suh [6] proposed the robust PID controller based on LQ approach for AQM system based on LQ-PID tuning method [7]. The robust AQM controllers have developed by the optimal control theory based on the Linear Matrix Inequalities (LMI) [8] and the robust μ-analysis technique [9] for the stability and performance issues in AQM. And, Azume et al. [10] presented the congestion controller using Linear Quadratic with observer. And also, Yang et al. [11, 12] developed the LQ-Servo controller based on Loop-Shaping Method [13]. It was not completely measured the TCP window packet size of AQM systems.

For considering this one, this paper proposed an improved version of previous work [11] and [12] in order to estimate the TCP window packets of AQM system. In order to estimate the TCP window packet size, we propose the LQ-Servo control with observer based on Kalman filter in this paper.

2. Linear Model of TCP/AQM System

A non-linear dynamic model for TCP flow control is developed using fluid-flow and stochastic differential equations in [1]. For the control theoretical analysis, it was approximated as a linearized constant model by small-signal linearization about an operating point (W_0, q_0, p_0), see [2] for linearization details, which is as following:

$$\delta\dot{W}(t) = -\frac{2N}{R_0^2 C}\delta W(t) - \frac{R_0 C^2}{2N^2}\delta p(t - R_0)\,,\ \delta\dot{q}(t) = \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t) \tag{1}$$

where $\delta W(t) \doteq W - W_0$, $\delta q(t) \doteq q - q_0$, $\delta p(t) \doteq p - p_0$, $\dot{W}(t)$ denotes the time-derivative of $W(t)$, $\dot{q}(t)$ denotes the time-derivative of $q(t)$, $W \doteq$ Expected TCP window size (packets), $q \doteq$ Expected queue length (packets, $R_0 \doteq$ Round-trip time (seconds), $C \doteq$ Link capacity (packets/second), $N \doteq$ Load factor (number of TCP sessions), $p \doteq$ Probability of packet mark/drop, and $t =$ Time. The expected queue length q and the expected TCP window size W are positive value and bounded quantities. And also, the probability of packet mark (drop) p takes value only in $0 \le p \le 1$.

The transfer function of TCP/AQM model indicates as following:

$$P(s) = P_{tcp}(s)P_{queue}(s)e^{-sR_0} = \frac{\frac{C^2}{2N}}{(s + \frac{2N}{R_0^2 C})(s + \frac{1}{R_0})}e^{-sR_0} \tag{2}$$

where $P_{tcp}(s)$ denotes the transfer function from loss probability $\delta p(t)$ to window size $\delta W(t)$, $P_{queue}(s)$ denotes the transfer function from $\delta W(t)$ to queue length $\delta q(t)$.

For the augmented state space model, see [11] for the augmented state space model details, let the state variable $x(t)$ of Eq. (1) be defined as:

$$x(t) = \begin{bmatrix} x_r(t) & y_p(t) & z_p(t) \end{bmatrix}^T = \begin{bmatrix} x_p(t) & z_p(t) \end{bmatrix}^T = \begin{bmatrix} \delta W(t) & \delta q(t) & \int_0^t q(\tau)\, d\tau \end{bmatrix}^T \tag{3}$$

and Eq. (2) can be represented with state-space model:

$$\dot{x}(t) = Ax(t) + Bu(t - R_0)\,,\ y(t) = Cx(t) \tag{4}$$

where $y(t) = \delta q(t)$ is an output variable, $u(t - R_0) = \delta p(t - R_0)$ is a input-time-delayed control variable, $x_p(t) = \begin{bmatrix} x_r(t) & y_p(t) \end{bmatrix}^T$. And the system matrix, input matrix and output matrix of (4) can be expressed as following:

$$A = \begin{bmatrix} A_p & 0 \\ C_p & 0 \end{bmatrix}, B = \begin{bmatrix} B_p \\ 0 \end{bmatrix}, C = \begin{bmatrix} C_p & 0 \end{bmatrix}. \tag{5}$$

where, $A_p = \begin{bmatrix} -\frac{2N}{R_0^2 C} & 0 \\ \frac{N}{R_0} & -\frac{1}{R_0} \end{bmatrix}, B_p = \begin{bmatrix} -\frac{R_0 C^2}{2N^2} \\ 0 \end{bmatrix}, C_p = \begin{bmatrix} 0 & 1 \end{bmatrix}.$

3. LQ-Servo Controller

This section presents the LQ-Servo control for TCP/AQM based on Linear Quadratic approach and the extended structure with observer based on Kalman filter

3.1. LQ-Servo Structure

Without loss of generality, the optimal servo problem based on Linear Quadratic approach, that is called LQ-Servo, is to find the optimal control law $u(t)$ by minimizing the cost functions

$$J = \int_0^\infty \{x^T(t) \cdot Q \cdot x(t) + u(t) \cdot \rho \cdot u(t)\} dt \qquad (6)$$

where a weighting matrix Q is symmetric and positive semi-definite, and a weighting factor ρ is positive value.

Then, we use the general control law for regulating

$$u(t) = -G\, x(t) \qquad (7)$$

where $G = -\rho^{-1} B^T K$ and $K = K^T$ is a solution matrix of the algebraic Riccatti's equation:

$$KA + A^T K + Q - \frac{1}{\rho} KB\, B^T K = 0 \qquad (8)$$

Suppose the gain matrix G is decomposed into $G = \lfloor g_r \quad g_y \quad g_z \rfloor$, the optimal control input of (**7**) can be expressed by the augmented state-variable $x(t)$ as following:

$$u(t) = -g_r x_r(t) - g_y y_p(t) - g_z z_p(t) \qquad (9)$$

Therefore, the LQ-Servo structure of TCP/AQM is shown in Figure 1 to ensure that zero steady state error is robustly achieved in response to a constant reference commands

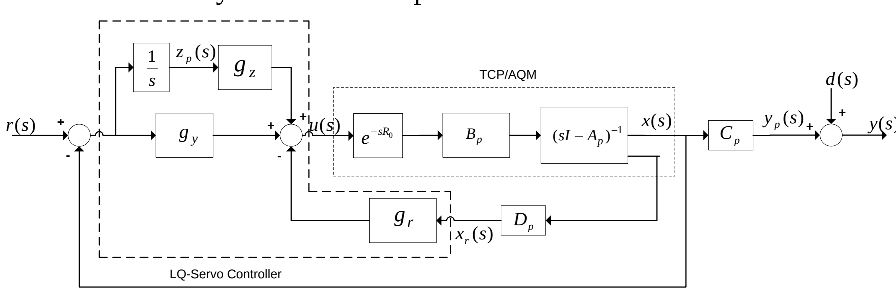

Figure 1. LQ-Servo Control Structure for TCP/AQM

The LQR (Linear Quadratic Regulator) is able to guarantee the stability robustness, but it is hard to deal with the performance issues because it does not consist of an output feedback.

For this problem, the LQ-Servo structure with an output feedback in TCP/AQM system is developed by the augmented state variable description in this paper.

In this paper, the TCP/AQM systems have the input-time delay such as Eq. (4), then, we extend the optimal input for considering time-delay as following:

$$u(t) = -Ge^{A_c t}e^{A(R_0 - t)}x(t),\ 0 \le t < R_0 \qquad \textbf{(10)}$$

$$u(t) = -Ge^{A_c R_0}x(t),\ t \ge R_0 \qquad (11)$$

where Eq.(10) and Eq.(11) are proved in the previous research paper[11][13].

3.2. LQ-Servo Structure with Kalman Filter

The state variable W of TCP windows packet size can't be measured exactly on router itself. Thus we propose the LQ-Servo control with observer based on Kalman filter in order to estimate the state variable of TCP windows packet size. The proposed control structure is shown in Figure 2.

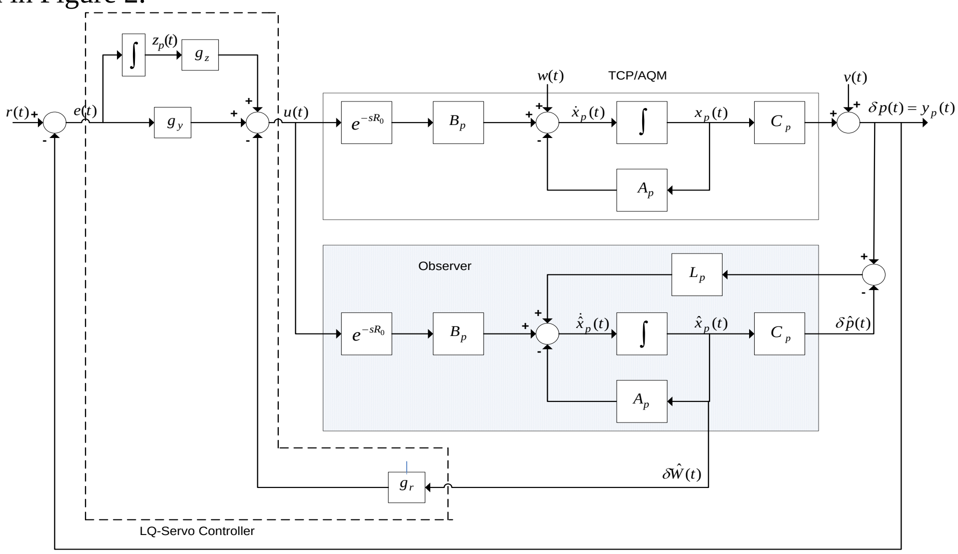

Figure 2. LQ-Servo Control Structure with Kalman Filter for TCP/AQM

The state $x(t)$ is estimated by using the following observer:

$$\dot{\hat{x}}_p(t) = A_p\hat{x}_p(t) + B_p u(t - R_0) - L_p(y_p(t) - C_p\hat{x}_p(t)) \qquad \textbf{(12)}$$

where L_p is an observer gain. And, considering an estimated error state $e_p(t) = x_p(t) - \hat{x}_p(t)$, the error system is indicated as following:

$$\dot{e}_p(t) = \dot{x}_p(t) - \dot{\hat{x}}_p(t) = A_p(x_p(t) - \hat{x}_p(t)) + L_pC_p(x_p(t) - \hat{x}_p(t)) = (A_p + L_pC_p)e_p(t) \qquad \textbf{(13)}$$

If (C_p, A_p) is observable, then the observer gain L_p is determined as a synthesis problems of a Kalman filter in case of considering a white noise. Therefore, the general augment state space description of TCP/AQM system and error dynamics can be expressed as following:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t - R_0) - L_p C_p e_p(t)\,,\ \dot{e}_p(t) = (A_p + L_p C_p)e_p(t) \qquad \textbf{(14)}$$

Remark 1. In this paper, the observer gain L_p is determined as synthesis problems of a Kalman filter by MATLAB, the selection procedure of weighting factor Q is determined by Loop-Shaping method [12] in order to satisfy the frequency domain design specifications such as good disturbance rejection, command following and noise attenuation. The optimal control input Eq. (10) and Eq. (11) for considering input time-delay are obtained from optimal gain $G = \lfloor g_r \quad g_y \quad g_z \rfloor$ which is achieved by Riccatti's equation (8).

4. Conclusion

This paper proposes the LQ-Servo control with observer for TCP/AQM system considering an input time-delay. This controller structure is made by taking a traditional servo mechanism based on Linear Quadratic approach and by augmenting a new state variable to the feed forward loop. In order to estimate the state of TCP window packet size, we extend the control structure with observer based on Kalman filter. In order to meet such the frequency domain design specifications such as good disturbance rejection, command following and noise attenuation, the new loop shaping method is developed by shifting all zeros to a larger pole of TCP/AQM model to determine the design parameters.

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