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Controlled Output Feedback to Stabilize Networked Control System

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***Abstract*: Maintaining the stability and transient performance of networked control system (NCS) is prime requirement because introduction of uncertain parameter causes degraded system performance and make the system unstable. So, this paper deals with the analyzing NCS system performance experienced uncertainty like disturbance. Some suitable stability condition also presented and linear quadratic regulator is used to show performance of NCS. The experimental work carried out on MATLAB Simulink environment to shows the effectiveness of the proposed methodology.**

***Keywords*: Denial of Service (DoS), Networked Control System, Kalman Filter, Delay, Proportional Integral Control, Packet Loss.**

1. Introduction

With rapid development in technology, it has been observed that information transmission through communication network became crucial. It is seen from the literature work that intruders are prudent in collecting information through breaching the network. From that information attackers are able to design the attack and able to launch that attack on networked control system to degrade the control performance. There are several examples of attacks as reported in literature like Stuxnet worm, Maroochy water attack, cyber grid attack and cyber-attack on German Steel Mill [1].

Author presented networked-predictive policy to control the performance of closed-loop without any delay prompted by networks. Also discussed the sufficient conditions of the stability which are dependent on transmitting data loss and delay for the closed-loop NCS [2]. In paper [3], the stabilization problem of NCS studied with random packet-losses. It is observed with stability analysis that discrete time system is more closely approximated by the multi-objective system with uncertainty bound to the proposed method. Author discussed constrained-optimal switching control problem with industrial networked control system through exclusion of performance deteriorating exogenous dynamics. For detection of malicious behavior of Industrial NCS, a random distribution procedure was used to represents the attack order in the process. Also delay is modeled through Bernoulli distribution process. Author used different attacking scenario to analyze the performance of Industrial NCS [4].

The control performance improvement scheme for the disturbed NCS under denial-of-service attack is discussed. Also, an event-triggered predictive control methodology is offered to improve over denial-of-service attacks. With considering the disturbance model, a controller confirming the system states converged to a different invariant set is evaluated. Author also discussed sufficient condition of stability to guarantee the uniformly definitive boundness of closed-loop NCS system [5].

The main contribution of this paper is to analyze the effect of external uncertainty and disturbance in networked control system. Some suitable stability condition also presented and linear quadratic regulator is used to show performance of NCS.

This paper is organized in following section, Section 2 includes the extensive literature work carried out to find problem. Section 3 defines the problem formulation and mathematical expression. The simulation result is presented in section 4. Final conclusion and future work is supported by section 5.

2. Literature Review Work

The optimized control schemes and stability condition presented to lessen the effects and avert the annoying intended intrusive data. The Kalman-filter, Linear Gaussian Control and PID controller presented to lessen the impact of attacks and intended disturbance on the NCS. The design approximates the system and measurement states efficiently in the presence of uncertainties. Author also computed system identification parameters and optimized coefficient with the help of optimization algorithms which were further administered to model the intended attack for designing a compromised system [6]. Furthermore in [7], [8] some control laws condition was presented to improve the performance of closed loop networked system.

The stabilization control co-design framework presented for NCS which experienced DoS attack. Also it is revealed that the measurement of state is periodic and controller update the information based on event based triggering approach. The gain was computed for dynamic event triggering with given sampling rate. It is expressed that control updates are less and shown improved performance against DoS [9]. To mitigate the impact due to network imperfection and malicious attack a predictive control was presented for networked-connected control system (NCCS). It is expressed that employed

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methodology improved the transient performance and system stability for different value of packet loss [10].

Various network imperfection including packet loss and delay modeled using Bernoulli distribution white sequence and analyzed the impact of these parameter on NCS. Some suitable stability condition with Lyapunov stability and linear matrix inequalities was stated to show the effectiveness of methodology [11]. Furthermore in [12], the advantages of optimal control design discussed with uncertainty parameters i.e. packet loss and network delay for industrial networked control system (iNCS). Such design shown the improved transient performance of iNCS. The performance evaluated for different packet loss rate and induced network delay. In this article author focused on the mean square stabilization problem arises in NCS due to long and fading channel. Author also presented stability condition using Algebraic Riccati Equation [13].

The effect of instabilities terms on NCS is inspected in [14], [15], and it is presented that attacks may be announced in the forward or feedback direction via communication channel. The result of these intended attacks along with process and measurement noise on system performance of networked control system is discussed through Kalman Filter (KF) and sufficient conditions of stability. The event-triggered scheme constructed for sharing channels is used to evaluate the performance of continuous-time networked control system employing induced delay and packet loss. The performance parameter and controller are studied with the use of event triggered and Lyapunov function which depicted the effectiveness of presented methodology [16], [17]. Furthermore the effect due to packet loss in networked system evaluated in [18], [19].

The problem due to time delay and packet lost for networked control system analyzed with Bernoulli distribution process. The exponential stability condition used to state the improved performance of network control systems with inclusion of state feedback control design [20], [21]. This article discussed the network that are caused by random delay and packet loss for nonlinear stabilization NCS problem. The T-S fuzzy model was presented to model fuzzy switched system with uncertain dynamic parameter. The exponential stability was presented with slow and fast switching dwell time methodology [22], [23]. Furthermore, observer-based stability problem was analyzed for NCS with packet lost and time delay in both directions i.e. sensor-controller and vice versa. Also, author determine the gain matrix for the stabilized closed loop system [24], [25].

The discrete-time proportional derivate controller is analyzed through a backward difference equation in presence of random network delay and packet lost. The True-Time simulator used to show the efficacy of the designed controlled NCS undergone packet loss. The output proven that battery consumes extra amount of energy with packet loss [26]. Author presented a neural network-based method for the detection of abnormalities in communication channel. The uncertainty was encountered in NCS due to packet loss and time delay [1]. Also, in [27], [28] author presented comparative analysis approach through neural network-based controller and conventional proportional integral controller to show the performance of reference trajectory while system parameters keep changing.

A controller was designed for nonlinear networked system using back-stepping approach. To address this problem, a collection of fuzzy logic strategies are suggested and a prediction for the nonlinear-functions is created. The strategy mentioned above suggests using an auxiliary signal to differentiate the input delay [29]. The stability problem due to packet loss and delay is resolved with employing switching controller. Also, sufficient condition of stability was presented through cone-complementarity-linearization (CCL) algorithm [30], [31]. Further this article discusses the issue of designing H-infinity controllers for event-triggered NCS in the presence of quantization and DoS attacks. Next, the time-varying Lyapunov functional method used to derive the necessary and sufficient conditions to guarantee the exponential stability of the NCS system in the existence of quantization and denial of service attacks [32], [33].

In paper [34], a new method presented for detecting cyber-attacks that target communication network by identifying abnormalities caused by attacks that specifically impacted by network delays and packet losses. The suggested observer centered strategy identified network attacks using the detection residual. The use of LMI-based techniques aids in the design of the observer gains matrices. The asymptotic stability of the networked system discussed through involving event-triggering methodology and it is also determined the upper bound for delay of network [35], [36]. Paper [37], discussed a method for solving robust fault detection problems in NCS with packet dropout and time-varying delay using the delta operator. Parameter uncertainties in the system model are a result of transforming the time delay, while the Markovian jump system is used to describe the packet loss. The robust fault detection filter's gain matrix and weight matrix are determined using linear matrix inequality.

A co-design method of event-triggered condition and state feedback control gains for NCSs with short network-induced delays and packet loss is presented in this paper. This design is based on a switched system model which ensures the system exponentially stable. In addition, a self-triggered condition is developed. Finally, a numerical example shows that with the proposed method, the update frequency of control signal is reduced to a certain level to maintain the system performance [38].

The paper [39], explored the issue of fault detection in wireless NCS experienced packet loss. Author also considers a model class with several disturbances and time delays; it is also assumed that packet loss occurs in between controller and actuator. The fault observer is represented as a switching discrete time linear system with time-delay, and author presented a sufficient condition with a Lyapunov approach [39].

Author estimated the upper bound for packet loss and induced delay with consideration of decay rate for the NCS which bounded the maximum overshoot in control system. Also derived some set of stability condition using Lyapunov-Krasovskii techniques [40], [41]. Event triggering transmission methodology was adopted to overcome the problem of delay and packet loss in distributed NCS. Author designed a controller for subsystem to be stable for input signal. Also determine solution to problem using linear matrix inequality method and estimated the gain for bounded delay to make system to be asymptotically stable [42]. Author in [43], [44] used Markov chains to modeled the packet loss and networked delay induced in NCS. The uncertainty in system is assumed to be in forward and/or backward direction. Some set of stability conditions was estimated through Lyapunov function to show the effectiveness of method used.

3. Problem Formulation and Methodology

The proposed networked control system is shown in figure 1. The information/measured signal is transferred from sensor to control after taking samples from plant.

The information/measured signal travels through communication medium which may be vulnerable to different type uncertainty. After computing the desired signal by the controller section, it is forwarded to actuator through communication medium for proper functioning of plant.

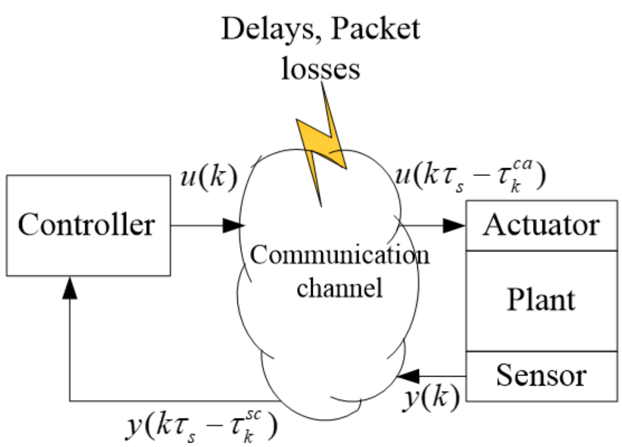

Fig. 1. Introduction of uncertainty (packet loss and delay) in NCS

A. Plant Description

The system dynamics described as discrete linear time-invariant system with disturbance as follows:

$$x(k+1) = Ax(k) + Bu(k) + \varphi(k) \quad (1)$$

$$y(k) = Cx(k) + \omega(k) \quad (2)$$

The state-vector is $x(k)$, measurement signal is $y(k)$, the control-vector is $u(k)$ and A, B, C are matrices with appropriate dimensions. The $\varphi(k)$ is process Gaussian noise, and $\omega(k)$ is measurement Gaussian white noise having zero mean and covariance's Q and R, respectively. The controllability and observability is assumed to be satisfied by (A, B) and (A, C), respectively.

B. Linear Quadratic Gaussian (LQG) Control

The Linear Quadratic Gaussian (LQG) control is based on a linear-state space approach, a quadratic objective function. A state-space representation of the LQG compensator is expressed as:

$$x(k+1) = (A - BK - LC + LDK)x(k) + Ly(k) \quad (3)$$

$$u(k) = -Kx(k) \quad (4)$$

where is Kalman filter gain and is optimal-regulator gain matrices.

The designed control function minimizes the cost-function value as,

$$J = \int_0^\infty \left[x'Qx + u'Ru \right] dt \quad (5)$$

where Q is symmetric and square-weighting matrix and R is symmetric and square control-cost matrix.

4. Simulation Result Analysis

To observe the proposed methodology a numerical problem with simulation results is presented in this section. The effectiveness of the methodology shown with the inclusion of linear quadratic control action. In this numerical problem, the plant dynamics are presented with following equations as described below.

Transfer function of plant is:

$$G = \frac{0.2143s + 0.2039}{s^2 - 1.861s + 0.8606} \quad (6)$$

The control gain with co-variances of process and measurement noise with zero mean $Q = 0.01I_3$ and $R = 0.1I_2$ is given as:

$$L = \left[2.4171, 0.1769; -2.7134, -0.5075\right] \quad (7)$$

The simulation is performed on MATLAB Simulink environment. The different simulation obtained are shown from figure 2 to figure 6. The simulation results as shown in figure 2 represent that response signal is tracking input signal even after disturbances is introduced in the communication channel. This shows the effectiveness of the proposed methodology.

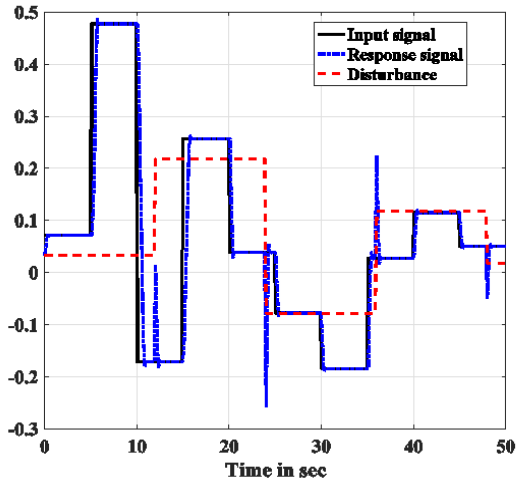

Fig. 2. Response signal along with disturbance in NCS

Figure 3 shows the output rate of the system with disturbance in the NCS. Next figure 4 and 5 shows the generation of control signal without disturbance and with disturbance, respectively.

The round trip time delay is presented by the simulation diagram of figure 6. As the round trip time delay increases there are chances of increasing the probability of packet loss and increasing the induced delay.

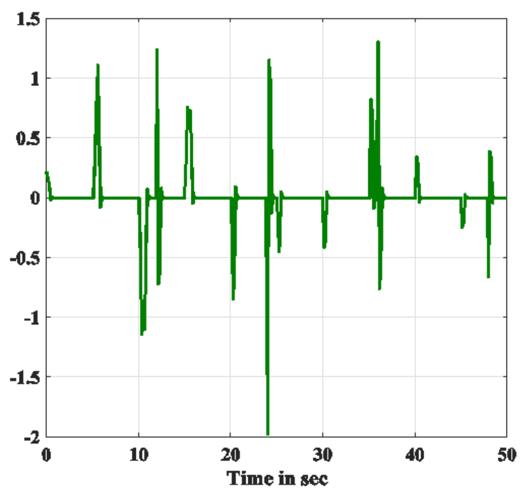

Fig. 3. Output rate with disturbance in NCS

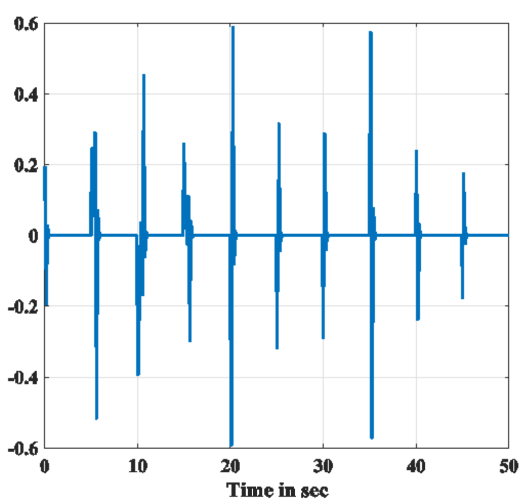

Fig. 4. Control signal generation without disturbance in NCS

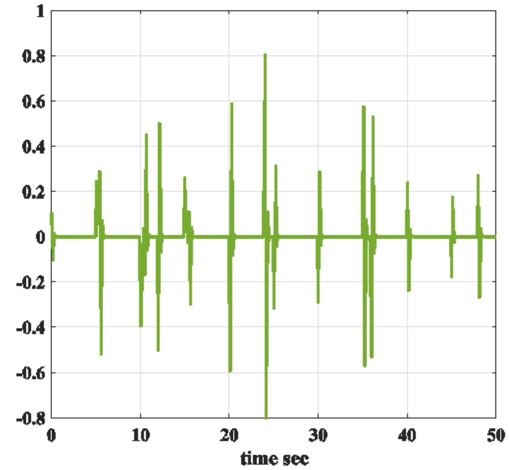

Fig. 5. Generation of control signal with disturbance and LQR in NCS

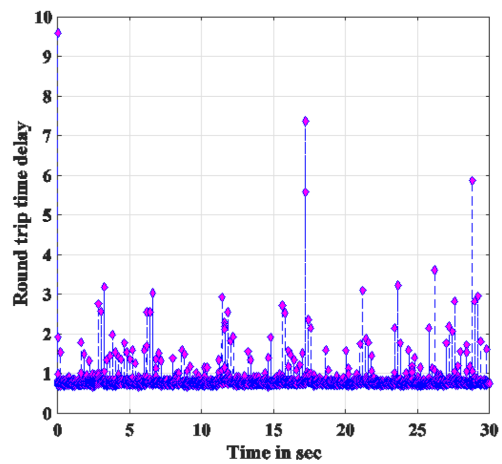

Fig. 6. Round trip time delay

5. Conclusion and Future scope

The stability and transient performance of networked control system is of prime requirement since introduction of uncertain parameter causes degraded system performance and made the system unstable. So, this paper deals with the analyzing NCS system performance experienced uncertainty like disturbance. Some suitable stability condition also presented and linear quadratic regulator is used to show performance of NCS. The simulation results as shown in figure 2 represent that response signal is tracking input signal even after disturbances introduced in the communication channel. This shows the effectiveness of the proposed methodology.

The future work will be carried out on improving the transient performance of nonlinear NCS experienced uncertainty with optimal control strategy.

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