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Review of Uncertain Dynamics in Networked Control System for Analysis of Stability

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***Abstract*: It is extremely important to maintain the performance and stability of network control systems (NCS), since the addition of uncertain parameters worsens the system performance and makes instability. Thus, the analysis of the performance of the NCS system in uncertain conditions, such as a violation, is the center of this article. The effectiveness of NCS is demonstrated using control actions and some associated stability conditions. The figure shows that response signal tracks the reference signal even when experienced disturbance. To overcome from disturbance H-infinity control along with proportional integral control action is used in this methodology. The different simulated diagram demonstrates the suggested methodology's efficacy. Experiments conducted in MATLAB Simulink demonstrate the effectiveness of the proposed methodology.**

***Keywords*: Packet loss, Denial of service (DoS), delay, Kalman filter, proportional integral control (PID), networked control system.**

1. Introduction

It has been observed that the rapid advancement of technology has made information transmission through communication networks increasingly important. The review of the literature indicates that hackers are cautious when using network intrusions to obtain data. With the information given, attackers can design and carry out an attack on an NCS to lower control performance. The Maroochy water attack, the Stuxnet worm, the cyber grid attack, and the cyber-attack on the German Steel Mill are just a few of the many examples of attacks that have been documented in the literature [1].

In response to network cues, the author suggested a networked-predictive policy that would instantly control closed-loop performance. The prerequisites for stability, which depend on latency and data loss during transmission for the closed-loop NCS, were also discussed [2].

The control performance improvement plan for the NCS that was disrupted during a denial-of-service attack is observed. An event-triggered predictive control methodology is also presented to counter denial-of-service attacks. Considering the disturbance model, a controller confirming that the system states converged to a different invariant set is evaluated. In order to guarantee that the closed loop NCS system is uniformly definitively bound, the author also discussed the stability conditions that must be met [3].

In paper [4], the NCS stabilization problem with random packet losses is studied. The multi-objective system with uncertainty bound to the proposed method more nearly approximates the discrete time system, according to stability analysis. The constrained optimal-switching control problem with an industrial NCS was discussed by the author, removing exogenous dynamics that lead to performance degradation. A random distribution procedure was used to represent the attack order in the process, which was used to identify malicious activity on the part of Industrial NCS. Furthermore, delay is modeled using the Bernoulli distribution process [5], [6].

The main contribution of this paper is an analysis of the impact of external disturbances and uncertainty on networked control systems. To overcome from disturbance H-infinity control along with proportional integral control action is used in this methodology. With control action and a few suitable stability conditions, NCS's performance is demonstrated.

The sections of this paper are organized as follows: The thorough literature review that was conducted to determine the problem is included in section 2. Section 3 defines the problem formulation and mathematical expression. The simulation's results are displayed in Section 4. Section 5 offers evidence in favor of the final judgment and further research.

2. Literature Review

The co-design stabilization control framework, which was demonstrated for NCS under DoS attack. It also reveals that the state is periodically measured and that the controller updates the data using an event-based triggering strategy. The gain was computed for a specific sampling rate and dynamic event triggering. It has been reported that performance against DoS has improved and control updates have decreased [7].

Stability conditions and improved control schemes were presented in order to lessen the effects and stop the intended data from being obtrusive. The Kalman-filter, Linear Gaussian Control, and PID controller were developed to lessen the impact of attacks and deliberate disruptions on the NCS. The design accurately approximates the system and measurement states in the face of uncertainty. In addition, the author employed optimization algorithms to optimize coefficients and compute system identification parameters, which were subsequently used to model the planned attack aimed at compromising the system [8], [9]. Furthermore, certain control law conditions

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were provided in [10], [11] to improve the performance of the closed loop networked system.

Networked-connected control systems (NCCS) were given a predictive control to mitigate the effects of malicious attacks and network imperfections. According to [12], [13] the adopted methodology improved system transient performance and stability for a range of packet loss values.

Furthermore, the advantages of optimal control design were examined in [14], [15] for industrial networked control systems (iNCS) in addition to uncertainty parameters like packet loss and network delay. The improved iNCS transient performance was demonstrated by this design. The efficacy was evaluated under various network latency and packet loss rates. This paper's author focused on the mean square stabilization problem that arises in NCS because of the channel's long fading length. Additionally, the stability condition was presented by the author using the algebraic Riccati equation [16], [17].

The white sequence of the Bernoulli distribution was used to model a number of network imperfections, including packet loss and delay. Next, the impact of these parameters on NCS was investigated. Some suitable stability conditions involving linear matrix inequalities and Lyapunov stability were stated [18], [19] in order to illustrate the effectiveness of the method.

The event-triggered scheme intended for channel sharing is used to evaluate the continuous-time NCS using induced delay and packet loss. The performance parameter and controller are analyzed using event-triggered and Lyapunov functions, demonstrating the effectiveness of the method that has been proposed [20]-[22].

In [23]-[25] the influence of instabilities terms on NCS is investigated, and it is demonstrated that attacks can be announced in a forward or backward direction via a communication channel. In addition to these intentional attacks, the effect of process and measurement noise on the system performance of the networked control system is investigated with the use of the Kalman Filter (KF) and suitable stability conditions.

Additionally, [26] have evaluated the effects of packet loss in networked systems. Author employed the Bernoulli distribution process to analyze the packet loss and time delay problem in NCS. Network control systems perform better when state feedback control design is included, as demonstrated by the exponential stability condition [27]-[29].

Furthermore, an observer-based stability problem for NCS was investigated. This problem involved packet loss and time delay in both directions, from sensor to controller and vice versa. The author also computes the gain matrix of the stabilized closed loop system [30].

The network effects of packet loss and random delay for the nonlinear stabilization NCS problem were discussed in this article. The T-S fuzzy model was introduced to simulate a fuzzy switched system with an unknown dynamic parameter. The exponential stability was demonstrated using the slow and fast switching dwell time methodology [31]-[33].

Back-stepping was used to create a controller for a nonlinear networked system. Several fuzzy logic techniques are proposed to address this problem, and a nonlinear function prediction is made. Using an auxiliary signal, one can determine the input delay in accordance with the previously stated strategy. The stability problem brought on by packet loss and delay is resolved by using a switching controller. In order to present sufficient conditions of stability, the cone-complementarity-linearization (CCL) algorithm was also employed [34].

The discrete-time proportional derivative controller is analyzed in the presence of packet loss and random network delay using a backward difference equation. In the True-Time simulator, packet loss occurred during the planned controlled NCS's effectiveness. The findings showed that the battery consumes more energy when a packet is lost [35], [36]. The author described a neural network-based method for spotting irregularities in a communication channel. NCS encountered uncertainty as a result of packet loss and time delays. Furthermore, the authors of [37]-[39] offered a comparative analysis method that contrasted the reference trajectory's performance between a neural network-based controller and a traditional proportional integral controller when the system parameters changed.

In a paper [40], [34], a novel method for determining abnormalities caused by attacks that are particularly affected by packet losses and network delays was presented. The goal of this technique is to identify cyber-attacks directed towards communication networks. The suggested observer-centered approach employed the detection residual to recognize network attacks. The use of LMI-based techniques aids in the design of the observer gain matrix. Using an event-triggering methodology, the asymptotic stability of the networked system is discussed and the upper bound for network delay is also determined [41], [42].

This article goes into further detail on designing H-infinity controllers for event-triggered NCS against quantization and denial-of-service attacks. Next, the time-varying Lyapunov functional method [43], [44] was used to derive the necessary and sufficient conditions to guarantee the exponential stability of the NCS system in the presence of quantization and denial.

The delta operator was utilized in paper [45] to address robust fault detection issues in NCS that included time-varying delay and packet dropout. The time delay is transformed using the Markovian jump system, which introduces parameter uncertainties into the system model. The state feedback control gains and event triggered condition for NCSs with packet loss and brief network-induced delays are presented in this paper using a co-design approach.

The system's exponential stability is ensured by the switched model upon which the design is based. Moreover, a condition that is self-triggered appears. In the end, a numerical example shows that the proposed method maintains system performance by lowering the control signal update frequency to a predefined point [46].

The paper [47] looked at the issue of fault detection in wireless NCS that is experiencing packet loss. The author also considers a model class with numerous delays and disruptions. Additionally, it is assumed that packet loss occurs in the controller-actuator relationship. A switching discrete time linear system with time-delay is used to represent the fault observer, and the author used a Lyapunov approach to provide a sufficient condition [48].

The authors in [49]-[51] simulated packet loss and networked delay brought on by NCS using Markov chains. It is assumed that the uncertainty of the system is either increasing or decreasing. To show how effective the used method is, a set of stability conditions was estimated using the Lyapunov function.

By accounting for the NCS decay rate, the author computed the upper bound on packet loss and induced delay, thereby limiting the maximum overshoot of the control system. Additionally, a set of stability conditions was derived using Lyapunov-Krasovskii techniques [52]. The packet loss and delay problems of the distributed NCS were resolved by using the transmission technique known as event triggering. The controller was designed by the author to ensure that the subsystem was stable for the input signal. Author [53] determine the solution to the problem using the linear matrix inequality method and estimate the gain for bounded delay in order to make the system asymptotically stable.

3. Problem formulation

The suggested networked control system is shown in Figure 1. The data or measured signal is transferred from the sensor to the control after the plant samples are collected.

The information/measured signal may be subject to different types of uncertainty depending on the communication medium. The controller section computes the desired signal and transmits it to the actuator through a communication medium so that the plant can function as intended.

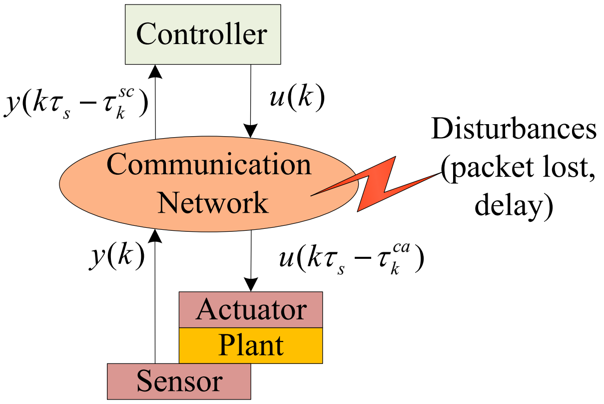

Fig. 1. Networked Control System with disturbances (packet loss/delay)

A. *Description of Plant Dynamics*

The plant dynamics with disturbance for linear time-invariant discrete system are presented as follows [52]:

$$x_{k+1} = Ax_k + Bu_k + \varphi_k \tag{1}$$

$$y_k = Cx_k + \omega_k \tag{2}$$

The state-vector "x_k", measurement signal "y_k", control-vector "u_k", and process Gaussian noise "φ_k" and measurement Gaussian white noise "ω_k" with zero mean and covariance, Q and R, respectively, are the two types of noise, and A, B, C are matrices with the appropriate dimensions. It is presumed to meet the requirements for both controllability and observability

B. *Linear Quadratic Gaussian Control (LQG)*

The LQG control is based on a quadratic objective function and a linear-state space approach. The state-space representation of the LQG compensator is expressed as [52]:

$$x_{k+1} = (A - BK - LC + LDK)x_k + Ly_k \tag{3}$$

$$u_k = -Kx_k \tag{4}$$

Where is Kalman filter gain matrix is "L"and "K" is optimal-regulator gain matrices.

The control function, which was intended to minimize the cost-function value, is represented as,

$$J = \int_0^{\infty} \left[x^T Mx + u^T Nu \right] dt \tag{5}$$

Where "M" is the square-weighting matrix and "N" is the square-control-cost matrix which are symmetric and square.

C. *Control Element*

The PID Controller sends the control action to the actuator, which directs the plant to produce the desired response. The PID control action is defined as,

$$u(t) = K_p . \left(e(t) + \frac{1}{T_i} \int_0^t e(t)dt + T_d \frac{de(t)}{dt} \right) \tag{6}$$

Where "T_i" is integral time, derivative time is "T_d", "$u(t)$" is the control signal, "$e(t)$" is error signal and "K_p" is proportional gain.

4. Simulation Result Analysis

In order to observe the suggested methodology, a numerical problem with simulation results is presented in this section. The addition of an additional control action demonstrates the effectiveness of the methodology. The following equations, which are explained below, provide the plant dynamics in this numerical problem:

A=[-1,-1;1,0], B=[4;0], C=[0.55,1.65], D=[0] (7)

The simulation is run in the MATLAB Simulink environment. Figures 2 through 3 show the different simulated performance outcomes. The simulation results shown in Figure 2 show how the response signal tracks the input signal following the control signal. This proves that the recommended methodology is effective.

The figure 3 shows that response signal tracks the reference signal even when experienced disturbance. To overcome from disturbance H-infinity control along with PID control action is used in this methodology. The different simulated diagram demonstrates the suggested methodology's efficacy.

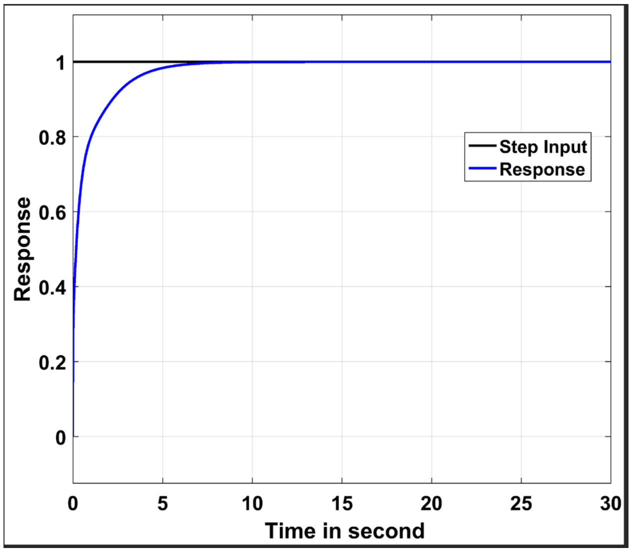

Fig. 2. Response signal without disturbance along with proposed methodology

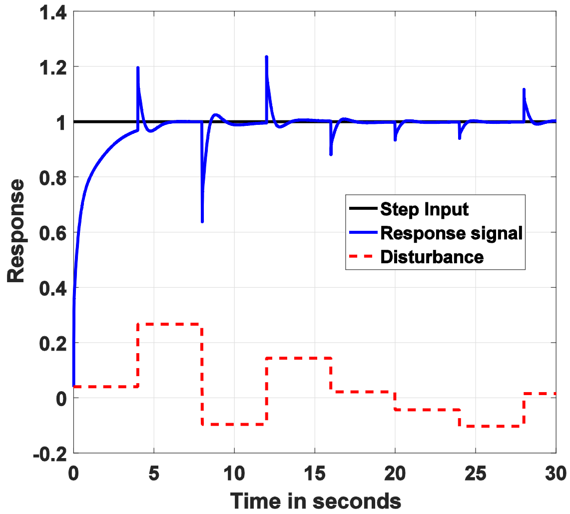

Fig. 3. Response signal with disturbance along with proposed methodology

5. Conclusion with Future Scope of Work

The stability and transient performance of the networked control system are critical because the introduction of an uncertain parameter causes the system to become unstable and perform worse. This paper thus focuses on the analysis of NCS system performance under uncertain conditions, like disturbance. With control action and a few suitable stability conditions, NCS's performance is demonstrated. Figures 2 through 3 show the different simulated performance outcomes. The simulation results shown in Figure 2 show how the response signal tracks the input signal following the control signal. This proves that the recommended methodology is effective.

The figure 3 shows that response signal tracks the reference signal even when experienced disturbance. To overcome from disturbance H-infinity control along with PID control action is used in this methodology. The different simulated diagram demonstrates the suggested methodology's efficacy.

Subsequent investigations will concentrate on optimizing the control scheme and improving the transient performance of the nonlinear NCS in the presence of uncertainty.

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