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Optimal Control Strategy to Analyse the Networked Control System Stability

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ABSTRACT: It is crucial to preserve the networked control systems (NCS) transient performance and stability because adding uncertain parameters degrades system performance and introduces instability. Thus, the analysis of NCS system performance under uncertain conditions, such as disturbance, is the focus of this paper. The performance of NCS is demonstrated using control action and some appropriate stability conditions.

The simulation diagram in result section displays effectiveness of proposed methodology and shows a comparative analysis of the response signal with and without control action along with disturbance in NCS. Experiments conducted in the MATLAB Simulink environment demonstrate the efficacy of the suggested methodology.

KEYWORDS: Denial of service (DoS), Delay, Kalman filter, Networked control system, Packet loss, Proportional integral control (PID).

1. INTRODUCTION

It has been noted that information transmission through communication networks has become increasingly important due to the rapid advancement of technology. The literature review demonstrates that hackers are cautious when gathering data by breaking into a network. Attackers can create and execute an attack on a NCS to reduce control performance using the information provided. Numerous examples of attacks have been documented in literature, including the Maroochy water attack, the Stuxnet worm, the cyber grid attack, and the cyber-attack on the German Steel Mill [1].

The author proposed a networked-predictive policy to instantly regulate closed-loop performance in response to network cues. Additionally covered were the necessary conditions for stability, which rely on transmitting data loss and latency for the closed-loop NCS [2], [3]. The NCS stabilization problem with random packet losses is examined in paper [3]. Stability analysis shows that the multi-objective system with uncertainty bound to the suggested method more closely approximates the discrete time system. The author talked about the constrained optimal-switching control problem with an industrial NCS by excluding exogenous dynamics that degrade performance. The attack order in the process was represented by a random distribution procedure, which was used to detect malicious behavior of Industrial NCS. Additionally, the Bernoulli distribution process is employed to model delay [4].

It is observed the control performance improvement plan for the disrupted NCS during a DoS attack. To combat denial-of-service attacks, an event-triggered predictive control methodology is also provided. A controller verifying the system states converged to an alternative invariant set is assessed while taking the disturbance model into account. The author also covered the necessary stability conditions to ensure that the closed loop NCS system is uniformly definitively bound [5].

This paper's primary contribution is an analysis of how external uncertainty and disturbances affect networked control systems. The performance of NCS is demonstrated using control action and some appropriate stability conditions.

This paper is partitioned into the following sections: The section 2 contains the extensive literature review that was done in order to identify the issue. The problem formulation and mathematical expression are defined in Section 3. Section 4 shows the results of the simulation. Section 5 provides support for the final conclusion and future work.

2. LITERATURE REVIEW

In order to mitigate the effects and prevent the obtrusive intended data, stability conditions and optimized control schemes were presented. To alleviate the effects of attacks and intentional disruptions on the NCS, the Kalman-filter, Linear Gaussian Control, and PID controller were introduced. In the face of uncertainties, the design efficiently approximates the system and measurement states. Additionally, the author used optimization algorithms to compute system identification parameters and optimize coefficients, which were then applied to model the intended attack for creating a compromised system [6]. Additionally, certain control laws conditions were presented in [7], [8], [9] to enhance the closed loop networked system's performance.

The co-design framework for stabilization control that was presented for NCS under DoS attack. It also reveals that the controller updates the data using an event-based triggering approach and that the state is measured on a periodic basis. For a given sampling rate and dynamic event triggering, the gain was calculated. Control updates have reportedly decreased and performance against DoS has improved [10]. In order to lessen the impact of malicious attacks and network imperfections, a predictive control for networked-connected control systems (NCCS) was introduced. It is stated that the adopted methodology enhanced system stability and transient performance for varying packet loss values [11], [12].

Using the Bernoulli distribution white sequence, several network imperfections, like packet loss and delay, were modeled. The effects of these parameters on NCS were then examined. To demonstrate the efficacy of the approach, some appropriate stability conditions involving linear matrix inequalities and Lyapunov stability were stated [13], [14], [15].

Additionally, for industrial networked control systems (iNCS), the benefits of optimal control design were explored in [16] along with uncertainty parameters like packet loss and network delay. This design demonstrated the enhanced iNCS transient performance. The effectiveness was assessed with varying packet loss rates and network delays. The author of this paper concentrated on the mean square stabilization issue that occurs in NCS as a result of the long and fading channel. Moreover, the author used the algebraic Riccati equation to present the stability condition [17], [18].

In [19], [20] the impact of instabilities terms on NCS is examined, and it is shown that attacks can be announced via a communication channel in either a forward or backward direction. The impact of process and measurement noise, in addition to these deliberate attacks, on the networked control system's system performance is examined using the Kalman Filter (KF) and adequate stability conditions. The continuous-time NCS using induced delay and packet loss is assessed using the event-triggered scheme designed for channel sharing. Event-triggered and Lyapunov functions are used to analyze the performance parameter and controller, illustrating the efficacy of the approach that has been presented [21], [22]. Additionally, the impact of packet loss in networked systems has been assessed in [23], [24], [25].

The Bernoulli distribution process was used to analyze the NCS time delay and packet loss issue. When state feedback control design is included, network control systems perform better, as shown by the exponential stability condition [26], [27].

In this article, the network effects of random delay and packet loss for the nonlinear stabilization NCS problem were covered. To simulate a fuzzy switched system with an unknown dynamic parameter, the T-S fuzzy model was introduced. Using slow and fast switching dwell time methodology, the exponential stability was presented [28]. Additionally, an observer-based stability problem involving packet loss and time delay in both directions—sensor-controller and vice versa—was examined for NCS. Additionally, the author calculates the stabilized closed loop system's gain matrix.

A backward difference equation is used to analyze the discrete-time proportional derivative controller in the presence of packet loss and random network-delay. The effectiveness of the planned controlled NCS experienced packet loss in the True-Time simulator. The results demonstrated that when a packet is lost, the battery uses more energy [29], [30]. A neural network-based technique for identifying anomalies in a communication channel was presented by the author. Due to time delays and packet loss, NCS experienced uncertainty. Additionally, in [31] the authors provided a comparative analysis approach that compared the performance of the reference trajectory when the system parameters were changing using a neural network-based controller and a conventional proportional integral controller.

A controller was created using a back-stepping technique for a nonlinear networked system. In order to tackle this issue, a number of fuzzy logic techniques are proposed, and a nonlinear function prediction is made. According to the above-mentioned strategy, one can distinguish the input delay by employing an auxiliary signal. Using a switching controller solves the stability issue caused by packet loss and delay. The cone-complementarity-linearization (CCL) algorithm was also used to present sufficient conditions of stability [32]. The topic of designing H-infinity controllers for event-triggered NCS in the face of quantization and denial-of-service attacks is further covered in this article. Next, the necessary and sufficient conditions to ensure the exponential stability of the NCS system in the presence of quantization and denial were derived using the time-varying Lyapunov functional method [33].

A novel technique for identifying abnormalities brought on by attacks that are specifically impacted by packet losses and network delays was presented in paper [34]. This method is intended to detect cyber-attacks that target communication networks. The detection residual was used by the proposed observer-centered strategy to identify network attacks. The observer gain matrix design is aided by the application of LMI-based techniques. The upper bound for network delay is also determined, and the asymptotic stability of the networked system is discussed using an event-triggering methodology [35]. In paper [36], the delta operator was used to solve robust fault detection problems in NCS with packet dropout and time-varying delay. The Markovian jump system is used, and the transformation of the time delay results in parameter uncertainties in the system model.

This paper presents a co-design approach state feedback control gains and event triggered condition for NCSs with packet loss and short network-induced delays. Because the design is based on a switched model, exponential stability of the system is guaranteed. Furthermore, a self-triggered condition emerges. Ultimately, a numerical example demonstrates that the suggested approach lowers the control signal update frequency to a predetermined point in order to preserve system performance [37].

The problem of fault detection in wireless NCS experiencing packet loss was examined in the paper [38]. The author also takes into account a model class that has multiple disruptions and time delays. It is also assumed that packet loss happens between the actuator and controller. The author provided a sufficient condition using a Lyapunov approach, and the fault observer is represented as a switching discrete time linear system with time-delay [39].

The author calculated the upper bound on packet loss and induced delay while taking the NCS decay rate into account, which limited the control system's maximum overshoot. Using Lyapunov-Krasovskii techniques, a set of stability conditions was also derived [40].

The transmission technique known as event triggering was used to solve the distributed NCS's packet loss and delay issues. For the subsystem to be stable for the input signal, the author designed a controller. In order to make the system asymptotically stable, ascertain the solution to the problem using the linear matrix inequality method and estimate the gain for bounded delay Markov chains were used by the authors in [41], [42], [43] to simulate packet loss and networked delay caused by NCS. It is assumed that the system's uncertainty is moving either forward or backward. A set of stability conditions was estimated using the Lyapunov function to demonstrate the efficacy of the employed technique.

3. PROBLEM FORMULATION

Figure 1 depicts the suggested networked control system. Following the collection of plant samples, the data or measured signal is transferred from the sensor to the control.

The communication medium that the information/measured signal travels through could be susceptible to various kinds of uncertainty. For the plant to operate properly, the controller section computes the desired signal and forwards it to the actuator via a communication medium.

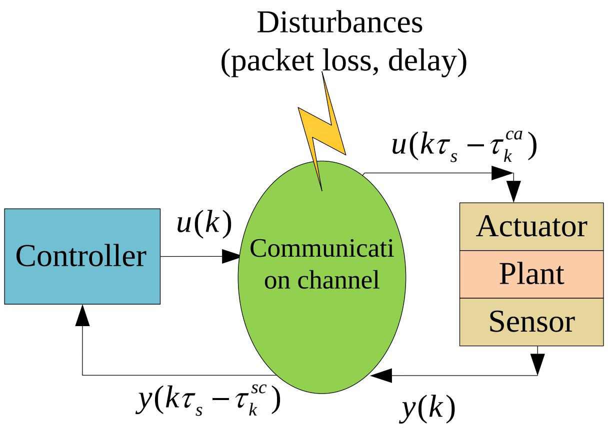

Fig. 1. NCS with disturbances (packet loss/delay)

A. Plant Description:

The linear time-invariant discrete system dynamics with disturbance are described as follows [40]:

$$x_{(k+1)}=Ax_{(k)}+Bu_{(k)}+\varphi_{(k)} \tag{1}$$

$$y_{(k)}=Cx_{(k)}+\omega_{(k)} \tag{2}$$

The A, B, C are matrices with the proper dimensions and the state-vector $x_{(k)}$, measurement signal $y_{(k)}$, control-vector $u_{(k)}$, and process Gaussian noise "$\omega_{(k)}$" and measurement Gaussian white noise "$\varphi_{(k)}$" with zero mean and covariance, Q and R, respectively, are the two types of noise. It is assumed to satisfy the controllability "(A, B)"and observability "(A, C)".

B. Linear Quadratic Gaussian (LQG) control:

A quadratic objective function and a linear-state space approach form the foundation of the Linear Quadratic Gaussian (LQG) control. The LQG compensator's state-space representation is written as [40]:

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

$$u_{(k)} = -Kx_{(k)} \tag{4}$$

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

The cost-function value is minimized by the control function that was designed as

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

where "Q" is the square-weighting matrix and "R" is the square-control-cost matrix which are symmetric and square.

C. Control Element

The actuator, which controls the plant to produce the intended response, receives the control action from the PID Controller. 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 K_p is proportional gain, $u(t)$ is the control signal, $e(t)$ is error signal, derivative time is T_d and T_i is integral time.

4. SIMULATION RESULT ANALYSIS

This section presents a numerical problem with simulation results to observe the suggested methodology. The methodology's efficacy is demonstrated by the addition of a different control action. The plant dynamics in this numerical problem are given by the following equations, which are explained below.

Transfer function of plant is:

$$G = \frac{3}{(3s+1)} * \exp(-0.4 * s) \tag{7}$$

The compensator is defined by following expression

$$Comp = \frac{3s+1}{(12s+1)} \tag{8}$$

The MATLAB Simulink environment is used to run the simulation. The various simulated performance results are displayed in Figures 2 through 4. The Figure 2 simulation results demonstrate how the response signal continues to track the input signal even when a communication channel disturbance is introduced.

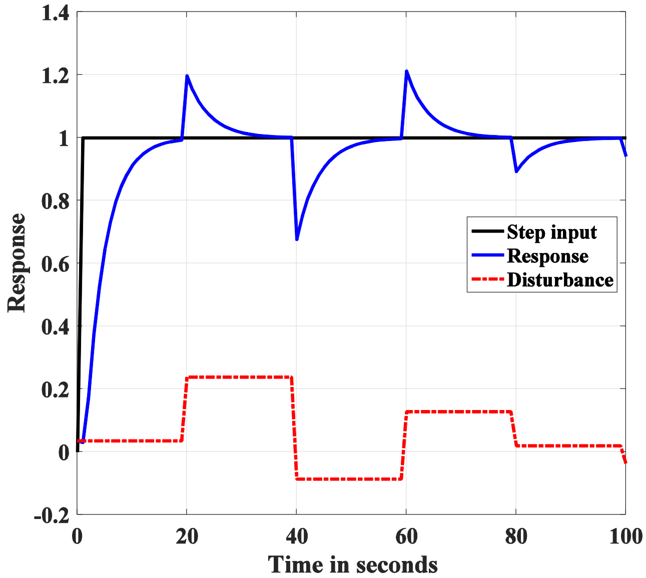

Fig. 2: Response signal without control action along with disturbance

Figure 3 present the response signal with control action along with disturbance in NCS. This demonstrates the efficacy of the suggested methodology.

The simulation diagram in Figure 4 displays comparative analysis of the response signal with and without control action along with disturbance in NCS. Different simulated diagram shows the effectiveness of proposed methodology.

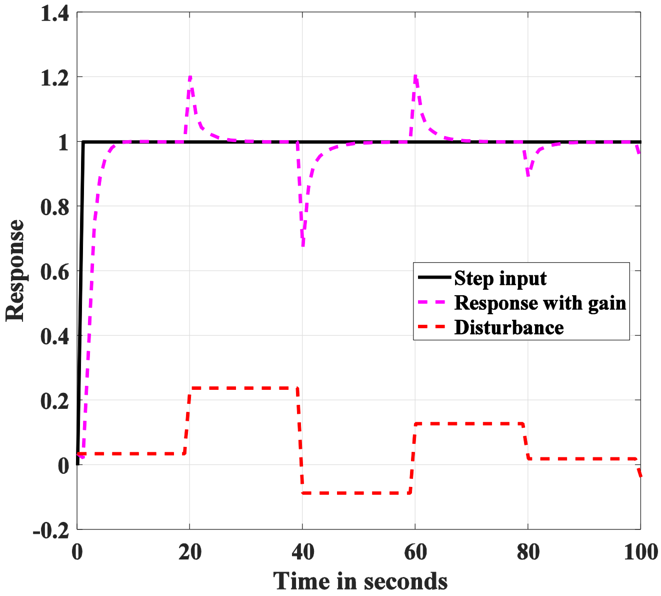

Fig. 3: Response signal with control action along with disturbance

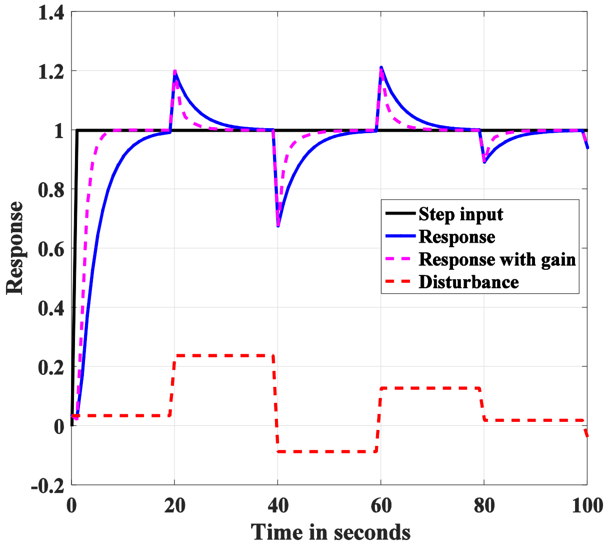

Fig. 4: Control signal generation without disturbance in NCS

5. CONCLUSION AND FUTURE SCOPE

The networked control system's stability and transient performance are crucial because the introduction of an uncertain parameter degrades system performance and makes it unstable. Thus, the analysis of NCS system performance under uncertain conditions, such as disturbance, is the focus of this paper. The performance of NCS is demonstrated using control action and some appropriate stability conditions. The simulation's output, as seen in Figure 2, indicates that even when a communication channel disturbance is introduced, the response signal continues to track the input signal. Figure 3 present the response signal with control action along with disturbance in NCS. This demonstrates the efficacy of the suggested methodology.

The simulation diagram in Figure 4 displays comparative analysis of the response signal with and without control action along with disturbance in NCS. This demonstrates how successful the suggested methodology is.

Future research will focus on enhancing the nonlinear NCS's transient performance when faced with uncertainty and using optimal control scheme.

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