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Stabilization of Industrial Networked Control System with Transient Parameters

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***Abstract*: Network control systems, which integrate sensors, actuators, and controllers, have demonstrated a rapid development. The low maintenance, simplicity of installation, system cabling, and monitoring of Network Control Systems (NCS) make them useful in a variety of fields. A networked control systems (NCS) stability and transient performance must be maintained because adding uncertain parameters degrades system performance and makes it unstable. This paper thus examines the transient (Rise Time, Settling Time, Overshoot and Peak Time) analysis of NCS system performance under uncertain conditions, such as disturbance with the help of different compensator design. Experiments conducted in the MATLAB Simulink environment demonstrate the efficacy of the suggested methodology.**

***Keywords*: Rise Time, Settling Time, Overshoot, Peak Time, Service Degradation attack (SD attack), Networked Control System, Network Delay, Compensator, Packet Loss.**

1. Introduction

Network control systems have developed as a field of technology in which parts are connected remotely via a network of real-time communication [1]. In order to enhance overall system performance, the NCS relies on the secure transmission of packets and messages via communication channels. NCS has numerous industrial applications, including power distribution, oil and gas power plants, water management, transportation, robotics, process industry, space vehicles, and medical treatment, among others, thanks to the quick advancement of information technology [2].

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 [3]. Through the use of a position servo system, the performance-degrading parameters random delay and packet loss are also discussed in order to examine the stability of networked control systems. The control gain and optimal performance index were computed using the employed system [4].

The Bernoulli function is used to model packet loss in network control systems, where latency and packet loss are important stability-controlling factors. To demonstrate the measurement quality of the specified method, a few stable methods are obtained [5]-[8]. For feedback networked control systems, the Lyapunov method is presented to simulate stochastic packet loss and sufficient condition with asymptotic stability to capture the effect of time delay [9].

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 used to model delay. The performance of Industrial NCS was analyzed by the author using various attacking scenarios [4].

This paper thus examines the transient (Rise Time, Settling Time, Overshoot and Peak Time) analysis of NCS system performance under uncertain conditions, such as disturbance with the help of different compensator design.

The following various sections are presented in the remainder of the article: The articles pertaining to the different types of attacks and the stability of the NCS are explained in Section 2. Section 3 presents the problem formulation based on malicious interference and network uncertainty. In the fourth section, the method's efficacy will be discussed. Section 5 concludes with some final observations and work that needs to be done.

2. Literature Review Work

The introduction of a neural network-based event-triggered controller scheme using a dynamic programming approach allowed for the detection of an attack on non-linear networks and sensors. When the residual exceeds a predetermined threshold, an attack is found. This method took into account a time delay and packet loss attack. Compared to the traditional approach covered in the literature, the suggested methodology used was more quickly detected [10], [11].

The effects of undesired intrusive data were investigated in [12], [13] using the proportional integral controller, linear quadratic Gaussian approach, and Kalman-filter in networked control systems. It has been demonstrated that this methodology significantly reduced the effect on NCS to a level that is acceptable. A number of parameters were chosen in order to assess the suggested system's performance metrics.

For NCS that was subjected to a DoS attack, a co-design framework for stabilization and control was presented. Furthermore, it is disclosed that the state is measured on a periodic basis and that the controller updates the data using an event-based triggering strategy. With a specified sampling rate,

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the gain was calculated for dynamic event triggering. It has been stated that performance against DoS has improved and there are fewer control updates [14], [15]. A predictive control was introduced for networked-connected control systems (NCCS) in order to lessen the effects of malicious attacks and network imperfections. The methodology used is said to have enhanced system stability and transient performance for a range of packet loss values [16].

An analysis of the performance metrics of closed-loop networked control systems subject to communication network constraints was conducted using the predictive control approach [17]. Using a rotary inverted pendulum system as an example, the Linear Quadratic Regulator (LQR) technique aims to enhance the performance of networked systems. Communication restrictions like packet loss and latency are regarded as unsettling elements in closed-loop networks. These strategies were used, and the performance increased to the desired level [18], [19].

The impact of instabilities terms on NCS is examined in [20], where it is suggested that attacks can be announced via a communication channel in either a forward or feedback manner. Kalman Filter (KF) and sufficient conditions of stability are used to discuss the impact of these deliberate attacks, process noise, and measurement noise on the networked control system's overall performance. Using induced delay and packet loss, the event-triggered scheme designed for channel sharing is used to assess the continuous-time networked control system's performance. The effectiveness of the approach presented is demonstrated by using event-triggered and Lyapunov functions to study the performance parameter and controller [21]. Additionally, the effects of packet loss in networked systems were assessed in [22].

To explain how the planned method reacts to the control system, a predictive controller was created. A denial of service attack could result from this, which could impact data transfer [23]. In addition to validating the suggested method for stability, the authors have also computed the attacks introduced for wireless network management systems using an intrusion detection system [24].

The Bernoulli distribution process was used to analyze the networked control system's 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 [25]. In this article, the network effects of packet loss and random delay 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 [26], [27]. A method for minimizing the weighted cost of the linear quadratic Gaussian function is presented in order to maximize the performance of a stochastic linear time-invariant system. In order to determine the optimal cost, the networked system made use of shared communication resources and admit scheduling policies [28].

Additionally, in [29] the authors described a comparative analysis approach that used a conventional proportional integral controller and a neural network-based controller to demonstrate how well the reference trajectory performed while the system parameters were changing.

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 [30]. 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, in the presence of quantization and denial-of-service attacks, the time-varying Lyapunov functional method was employed to determine the necessary and sufficient conditions to ensure the exponential stability of the NCS system [31].

A novel technique for identifying abnormalities brought on by attacks that are specifically impacted by packet losses and network delays was presented in paper [32]. 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 [33]. 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 [34]. 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 [35].

The delta operator was used in [36] to address robust fault detection issues in NCS with packet dropout and time-varying delay. When the packet loss is described by the Markovian jump system, the system model's parameter uncertainties arise from the transformation of the time delay. Matrix inequality in linear form is used to determine the weight and gain matrix of the robust fault detection filter.

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 [37]. 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 [38]. The problem of fault detection in wireless NCS experiencing packet loss was examined in the paper [39]. 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 [40], [41].

Markov chains were used by the authors in [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 modeling

Figure 1 displays the proposed network control system's block diagram. In this instance, a sensor samples the system's response, which is then transmitted to the controller via a wireless communication network. Using an algorithm created specifically for control, the controller determines the control signal based on the reference and sensor sample received through the communication network.

The calculated signal that is sent to the actuator via the communication channel to operate the system in accordance with the intended output. It has been discovered in numerous publications that an attacker can impede the control system in any manner (that is, in the forward and/or feedback direction) to reduce NCS performance.

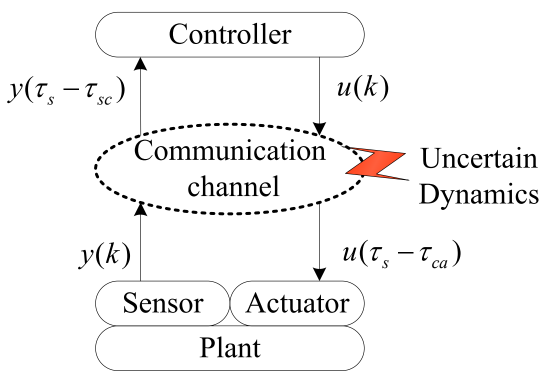

Fig. 1. Uncertain Dynamics in NCS

A. Plant Description

The following is a description of the system dynamics for a discrete linear time-invariant system with disturbance:

$$x(k+1) = Ax(k) + Bu(k) + \varphi(k) \tag{1}$$

$$y(k) = Cx(k) + \omega(k) \tag{2}$$

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. There are Process Gaussian noise "$\varphi(k)$" and measurement Gaussian white noise "$\omega(k)$" with zero mean and covariance, "Q" and "R".

B. Probability Distribution for Packet Loss

After obtaining the sampled sensor signal, the controller instructs the actuator to control the system dynamics. As the signal passes through the communication network, packet loss is possible. Packet loss is a problem that can arise in both forward and feedback directions. Consider the following distribution function in order to model packet loss [21]:

$$p(\gamma_k) = \begin{cases} p, & if\, \gamma_k = 1 \\ 1-p, & if\, \gamma_k = 0 \end{cases} \tag{3}$$

Packet loss rate is represented by, $p \in [0,1]$. At an instant *k*, if packet is lost, then $\gamma_k = 0$, and for successful arrival of packet at an instant *k*, the $\gamma_k = 1$.

4. Result Analysis

The MATLAB Simulink environment is utilized to present various simulation diagrams that demonstrate the efficacy of the proposed methodology. This section presents a numerical problem with simulation results to observe the suggested methodology. The plant dynamics in this numerical problem are given by the following equations.

Transfer function of plant is: $G = {}^{1}\!/_{(0.5 * s + 1)}$ (4)

Figures 2 through 5 display the various simulation results. Figure 2 illustrates the simulation result, which indicates that even when communication channel disturbances are introduced, the response signal continues to track the input signal. The rise time under different compensator design is shown in Figure 2.

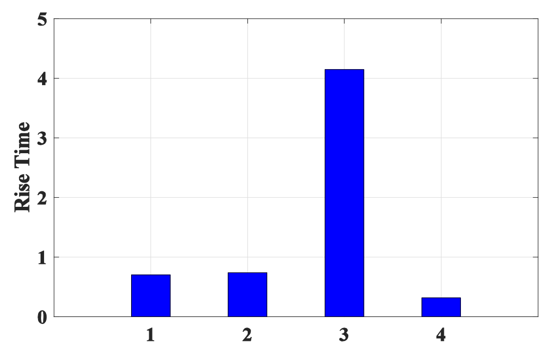

Fig. 2. Rise time under different compensator design in NCS

The settling time under different compensator design is shown in Figure 3.

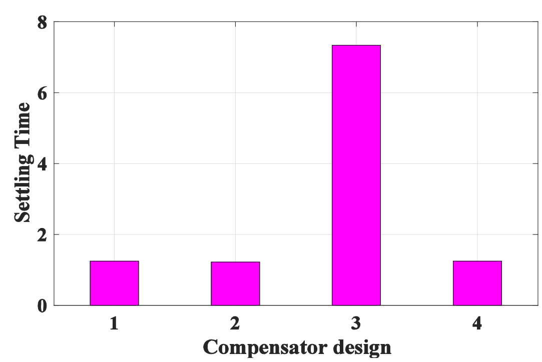

Fig. 3. Settling time under different compensator design in NCS

The overshoot under different compensator design is shown in Figure 4. There are no overshoot in compensator design 1, 3 and 4. The peak time under different compensator design is shown in Figure 5. From Figure 5 it can be observed that peak time much higher in compensator design 3 compare to other design.

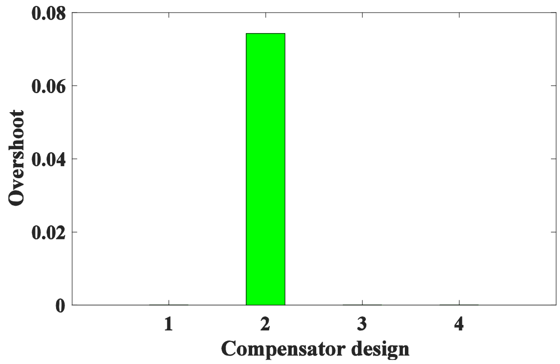

Fig. 4. Overshoot under different compensator design in NCS

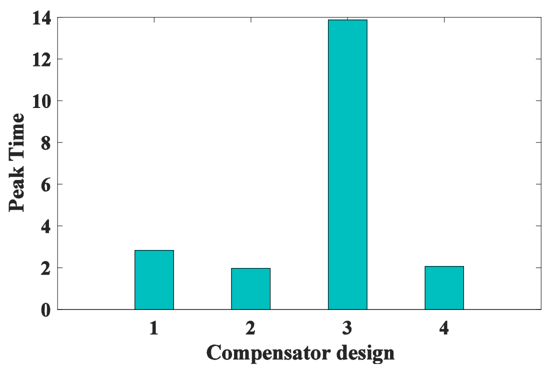

Fig. 5. Peak time under different compensator design in NCS

5. Conclusion with Future scope

Since the introduction of uncertain parameters results in a degradation of system performance and instability, the stability and transient performance of networked control systems are of utmost importance. This paper thus examines the transient (Rise Time, Settling Time, Overshoot and Peak Time) analysis of NCS system performance under uncertain conditions, such as disturbance with the help of different compensator design.

The rise time under different compensator design is shown in Figure 2. The settling time under different compensator design is shown in Figure 3. The overshoot under different compensator design is shown in Figure 4. There are no overshoot in compensator design 1, 3 and 4. The peak time under different compensator design is shown in Figure 5. From Figure 5 it can be observed that peak time much higher in compensator design 3. This demonstrates the strength of the suggested methodology.

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

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