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Inherent Issues in Networked Control Systems: A Survey

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Abstract— **Due to major advancements in the area of networking over the past decade, a new paradigm of control systems has emerged, namely Networked Control Systems. Such systems differ from classical control systems in that their control loops are closed around communication networks. Thus the need for new stability and performance guarantees arises. In this paper we aim to shed some light on the major advancements and inherent problems in Networked Control Systems.**

I. Introduction

Over the past decade, major advancements in the area of communication and computer networks [48] have made it possible for control engineers to include them in feedback systems in order to achieve real-time requirements. This gave rise to a new paradigm in control systems analysis and design, namely Networked Control Systems (Figure 1). *Networked Control Systems (NCSs), are control systems whose control loop is closed around a communications network.* In such systems, the feedback is no longer instantaneous as in classical control systems. Many systems fall under such classification and several examples of NCSs can be found in various areas such as: Automotive industry [25], [29], [47], teleautonomy [45], [55], teleoperation of robots [1], [16], [41], [42], [43], and automated manufacturing systems [30]. Including the network into the design of such systems has made it possible to increase mobility, reduce the cost of dedicated cabling, ease upgrading of systems, and render maintenance easier and cheaper. The drawback, however, is that the complexity of analysis and design of such systems increases manyfold. In order to achieve better performance in NCSs, several protocols were specifically developed to deal with the stringent demands of such control systems (see [31] for comparison). The main objective of control networks was elegantly stated in [48]: *"Control networks must shuttle countless small but frequent packets among a relatively large set of nodes."*

The paper is intended as a brief survey of established results in the area of NCSs and is divided into two major sections. Section II deals with several models that have been proposed to study the performance and various control schemes in NCSs. In Section III we address three challenges that face control engineers when designing NCSs, namely: Packet loss, time-delay, and limited communication.

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For the remainder of this paper let (A, B) be the system matrices corresponding to a continuous-time LTI system, and (Φ, Γ) are sampled system counterparts with a sample period h.

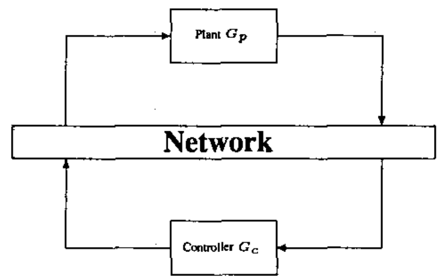

Fig. 1. Networked Control System

II. Existing Models

In this section we concentrate on presenting several models and control methods that have been utilized to deal with NCSs.

A. Sampled-Data

The sampled-data model is the first natural approach for design over networks due to our inability to transmit continuous signals over a digital communications network. The main objective of such technique is to obtain the longest sampling time h that can achieve stability, and consequently lower the usage of the network. In [23] the linear continuous time-invariant system was studied with an ideal uniform sampler $\mathcal{S}_h : v_k = v(t = kh), k \in \mathbb{Z}_+ = \{0, 1, 2, \dots\}$ and the corresponding zero-order hold $\mathcal{H}_T : v(t) = v_k, t \in [kh, (k+1)h), k \in \mathbb{Z}_+$, where v is a generic signal. A linear-quadratic-regulator (LQR) design framework with full-state feedback, for the system (A, B) with the performance index $V = \int_{t_0}^{T} (x^T Q x + u^T R u)\, dt$, the goal is to characterize the stability of the sampled-data system with respect to the same control Lyapunov function that was used to study the non-networked system and a decay rate close to the original closed-loop continuous-time system, i.e. characterize the couple $(P, \epsilon L), \epsilon > 0$, since the original system's stability is characterized by (P, L). The interested reader should consult [23] for stability results, which will be omitted here for brevity.

The sampled-data model was also used in [20], where the network was modelled at an ideal sampler and hold device, and the stability analysis was performed after *lifting* the system into an LTI setting and sufficient results using Lyapunov analysis were obtained on the maximum sampling period.

B. Model-Based NCS Control

The authors of [38] present an extended structural analysis of NCSs, using an eigenvalue approach. In their model, the network resides between the sensors attached to the plant, and the actuators. The network is modelled as a fixed-rate sampling (h) of the continuous plant. They also provide a model plant $(\hat{A}, \hat{B})$ that provides a state estimate $(\hat{x}(t))$, and the error between the actual plant and the model plant $(e(t) = x(t) - \hat{x}(t))$ is used to augment the state-vector, with the input being $u(t) = K\hat{x}(t)$. The idea behind this setting is to only transmit the measured state vector via the network periodically, and construct the state between the samples using the model plant. This reduces the communication bandwidth requirement of the networked system, hence lowering the utilization of the network. Then, stability analysis is applied to the following augmented system $\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A+BK & -BK \\ \tilde{A}+\tilde{B}K & \hat{A}-\tilde{B}K \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \triangleq \Lambda \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$ where $\tilde{A} = A - \hat{A}$ and $\tilde{B} = B - \hat{B}$, in order to obtain necessary and sufficient conditions for guaranteeing stability of the closed-loop system. They analyze the performance of the system when the full state and partial state are available for feedback. Finally, they end with an analysis for discrete-time systems. This method has been extended recently into a stochastic setting in [39] where almost sure and mean-square stability conditions were obtained for random delays.

C. Perturbation

The use of perturbation theory (see [26]) has been a very effective tool for studying the stability of NCSs in [5], [57], [58], [59], [60], [61], [65], [66]. Let $\hat{u}(t)$ and $\hat{y}(t)$ are perturbed versions of the original signals $u(t)$ and $y(t)$, after passing through the network.

The error introduced by the network is $e(t) \triangleq \begin{bmatrix} \hat{y}(t) \\ \hat{u}(t) \end{bmatrix} - \begin{bmatrix} y(t) \\ u(t) \end{bmatrix}$ and the augmented system involves the plant $(x_p(t))$, controller $(x_c(t))$ and the error state vectors as follows: $\dot{z}(t) \triangleq \left[\frac{\dot{x}(t)}{\dot{e}(t)}\right] \triangleq \begin{bmatrix} \dot{x}_c(t) \\ \dot{x}_p(t) \\ \hline \dot{e}(t) \end{bmatrix} = \Lambda z(t)$. The controller is designed to stabilize the network-free system and a perturbation analysis is performed over the networked system.

A try-once-discard (TOD) protocol is introduced, where the next node[1] to transmit data on a multi-node network is decided on dynamically or statically based on the highest weighted error from the last transmission. The goal of analysis for this protocol is to find a maximum transmission interval τ_m that guarantees satisfactory stability performance of the NCS.

[1] A node denotes every component of the system that is connected to the network, such as sensors and actuators

D. Hybrid Systems

NCS have been cast into a hybrid systems context [4], [9], [65], [66]. The motivation behind this model is that with the presence of the network, a control system becomes dependent on packet transmission and reception, hence the system's input changes/switches at each packet arrival. Consequently, the NCS has continuous dynamics (plant) and discrete dynamics (control-loop), yielding a hybrid system. In [65], [66] results previously derived for the stability of hybrid systems were utilized to find bounds on the maximum delay allowed by be introduced by the network. In particular, [65] models the network as a constant delay τ introduced into the full state feedback as follows:

$$\dot{x}(t) = Ax(t) - BK\hat{x}(t), \quad t \in [kh+\tau, (k+1)h+\tau]$$
$$\hat{x}(t^+) = x(t-\tau), \qquad t \in [kh+\tau, k = 0,1,2,\ldots]$$

where h is the sampling period. Then the trajectory of the delayed state vector $x(t-\tau)$ is solved for, in terms of $x(t)$ and $\hat{x}(t)$. The bound on the delay τ results from imposing Schur stability conditions on the following matrix. $H = \begin{pmatrix} e^{Ah} & -E(h)BK \\ e^{A(h-\tau)} & -e^{-A\tau}(E(h)-E(\tau))BK \end{pmatrix}$, where for a given matrix M, $E(h)M \equiv \int_0^h e^{A(h-\eta)} M d\eta$.

Another approach that was presented in [4], [9], involved a specialization of the Witsenhausen hybrid-state continuous time model in [62], which was extended in to include N systems connected through a network, with the key assumption that the network induced delays are ignored. The performance of the extended hybrid model was illustrated through a Heating Ventilating and Air Conditioning (HVAC) temperature control system for 3 rooms.

III. NCS Inherent Issues

There are several issues that arise when dealing with NCS such as packet loss, time-delay, and limited communication.

A. Packet Loss

Packet loss is an inherent problem with most computer networks (see [11]) due to several factors such as transmission time-outs, transmission errors and limited buffer size. Lately, there have been several attempts to study the effect of packet loss on the performance of the networked system [35], [52], [65], [66].

In [65], [66], a sufficient stability analysis was presented using Lyapunov-type analysis, where packet loss/no-loss was modelled as a switch that results with two plant models corresponding to the either case, and the control is a simple state feedback $u_k = -Kx_k^{net}$, where the vector x_k^{net} is the state after the network/switch, which takes the value x_k when the packet is delivered or x_{k-1}^{net} if the packet is lost. With the above setting, a minimum bound on the successful transmission rate r given by

$\frac{1}{1-\frac{\log[\lambda_{max}^2(A-BK)]}{\log[\lambda_{max}^2(A)]}} < r \leq 1.$

The stochastic counterpart of the above approach was undertaken in [35], [52], where the probability of dropping a packet is p, an approach that results with a closed-loop Markovian jumping system $\underline{x}_{k+1} = \Gamma_{\theta_k}\underline{x}_k$, where Γ_k^i is the closed-loop system matrix that evolves according to the outcome of the Markov chain ($\theta_k \in \{0,1\}$) at time step k, and $\underline{x}_k$ is the augmented state vector that involves the state of the plant $\bar{x}_k$, and that of the controller. The following mean square stability theorem for the closed loop summarizes.

Theorem 1: [52] Given $p_j, \quad j \in \{1,2\}$, the closed-loop system is mean-square stable if and only if there exists a matrix $P > 0$ such that $P - \sum_{j=1}^{2} p_j \Gamma_j^T P \Gamma_j > 0$.

B. Delay Analysis

A major problem in NCS is that the network introduces random delays. Since the network is utilized to transmit packets of the sampled values of the output/state of the system, and several systems might be connected to the same network, delay is inevitable and might cause deterioration of the system performance. There are several references that deal with the delay specifically for NCSs [2], [6], [17], [19], [27], [44], [49], [64]. The general framework for the analysis of time delay in NCS involves a continuous plant $G(s)$, a sampler (S_h) with rate h, and a zero-order hold (H_h) device (ZOH), and a discrete controller $C(z)$. The network introduces two delays, the first τ_k^{sc} between the sensors and the controller , and another τ_k^{ca} between the controller and plant actuators. Like all sampled-data control systems, there is also an underlying computational delay τ^c representing the time the controller consumes to provide the desired input signal, however, this delay is usually absorbed into τ_k^{ca} (see [2]). A proposition that suggests lumping both delays into one delay $\tau = \tau_k^{sc} + \tau_k^{ca}$ is provided in [17], to which the reader is referred.

There are two inherent problems in NCS that result from network-induced delays [17], [49]:

Message rejection: When two or more samples from the sensors reach the controller between two sampling instants, then one of the messages is discarded.

Vacant Sampling: When no data arrives to the controller during one sampling period, then the controller uses the previous sample or an interpolated one.

Assuming that the two delays can be lumped into τ, then 3 cases may arise: $\tau < h$, $\tau = \alpha h$, or $\tau = \alpha h + \tau'$, where $\alpha \in I\!N$ and $\tau' < h$.

Case #1: $\tau < h$

In this case the delay is less than the sampling period and the system is modelled as in [2].

$x_{k+1} = \Phi x_k + \Gamma_0 u_k + \Gamma_1 u_{k-1}$, where $\Phi = e^{Ah}$, $\Gamma_0 = \int_0^{h-\tau} e^{A\eta} d\eta B$, and $\Gamma_1 = e^{A(h-\tau)} \int_0^{\tau} e^{A\eta} d\eta B$. This model was used along in a stochastic optimality setting in setting in [44] with the addition of disturbances v_k and w_k

$x_{k+1} = \Phi x_k + \Gamma_0 u_k + \Gamma_1 u_{k-1} + v_k$

$y_k = C x_k + w_k$,

where w_k and v_k are uncorrelated zero mean Gaussian white noise stochastic processes. With such setup, the delay τ_k is random and depends on the network load which is modelled as a Markov process. For each state of the network load, Low, $Medium$, or $High$, there exist a corresponding distribution for the delay. The delay switches between different states, and an LQG optimal control problem is solved to generate a controller that guarantees stability.

Case #2: $\tau = \alpha h$, where $\alpha \in I\!N$

In such case where the delay is an integer multiple of the sampling period, it can be considered as a sensor-induced delay and a similar analysis can be followed as in [15]. We construct an augmented system by delaying the state α times by a period h, which renders a virtually delay-free system that can be used for analysis or design.

Case #3: $\tau = \alpha h + \tau'$

The discrete model here is combination of the previous two models and is represented as follows.

Cases 1 and 3 were studied in [6] and an augmented system with the system input being a part of the state vector was derived. Intervals for the allowable delay that maintains stability of the system were obtained for the integrator example.

Further results on delay in NCSs can be found in [34], where asynchronous sampling time is assumed for the sensors and controller. The value of α was considered to be of random nature in [27] and stability is intended in the Mean Square sense. We conclude this section by mentioning one scheme that was presented in [10] involved equipping the system with a queue on the sensor side and transmitting the size of the queue to the controller that uses this information in the estimation of the non-delayed state.

C. Limited Communication

Recent developments in NCS have targeted the issue of limited communication available for control. By introducing the network into the control system, issues like channel/network capacity, encoding/decoding schemes and quantization arise. With regard to control systems, the capacity of the channel/network and its ability to convey a reasonable amount of information plays an important role in characterizing the stability of the system. Furthermore, the measured system outputs must be transmitted in a packet form over the network, hence the need for sampling, quantization and encoding/decoding.

A recent line of research in [40], [53], [54] aims to characterize the interplay between communications and control, and to explore the effect of channel coding/decoding schemes on the stability of control systems in the deterministic and stochastic sense. In the same vein, a new notion of capacity called *any-time capacity* was introduced in [50].

Another trend for studying NCS has focused on invoking new quantization schemes that reduce the number of bits to be transmitted over the channel/ network, hence providing the ability to use channels with limited capacities, as will be seen later.

1) Information Theoretic Approach: In [7], the concept of *attention* was introduced to the control of systems. The method involves solving an optimization problem to minimize an *attention functional* given by $\zeta = \int_\omega \psi\left(x, t, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial t}\right) dxdt$ The outcome of this study is to obtain a measure for the control effort that has to be applied to the system to achieve stability. The more the input of the system varies with respect to time ($||\frac{\partial u}{t}||$) and the system state ($||\frac{\partial u}{\partial x}||$), the more attention we need for the system, and the more complex is the control law. This fact reflects on the NCS in the form of bit-rate; the more attention we need for the system the higher the bit-rate has to be. Furthermore, the bit-rate affects the capacity required from the network/channel in an information theoretic context which is the main focus in [24], [37], [50], [53], [54].

The extensive study in [53] has elegantly cast the control problem over networks into an information theoretic context. The network in an NCS problem was thought of as a channel with optimal encoding/decoding and maximum available bit-rate. The goal was to derive a bound on the minimum bit-rate required for stability using different encoding and decoding schemes, a bound which was stated as $R > \sum_{i=1}^{l} \lambda_i^u(A)$, where $\lambda_i^u(A)$ are the unstable eigenvalues of the matrix A, and $l \leq n$ is the corresponding number of unstable eigenvalues. Consequently, there is a clear connection between the unstable eigenvalues of the system under consideration (control setting) and the bit-rate required (information theoretic setting). Hence the information rate required depends on the amount of attention to be given to the system, since the stable eigenvalues do not require attention and they decay to the origin asymptotically.

2) Quantization Schemes: It is well known [2], [46] that once quantization is introduced into the control loop, it leads to a complicated nonlinear analysis and possible limit cycles. Over the past ten years, the quantization issue has become the subject of several studies for NCSs [8], [12], [13], [14], [18], [22], [23], [32], [33], [36], [56], [3] in order to describe its impact on the performance of the control system and introduce new quantization schemes that achieve lower bit-rates, which in turn decrease the use of the network in the feedback loop.

To the best of the authors' knowledge, most of the aforementioned studies were influenced by the leading work in [12], which was not motivated from an NCS point of view. The main concern was to demonstrate the behavior of discrete-time linear systems subject to quantization and operating under state feedback control law. A very striking observation is that under quantized state feedback control law given by $u_k = f^k(\mathcal{Q}(x_0), \ldots, \mathcal{Q}(x_k))$ the set of initial conditions that have trajectories tending to the origin as $k \rightarrow \infty$ has Lebesque measure zero, where $\mathcal{Q}$ is a uniform quantization mapping and Φ has at least one unstable eigenvalue. Hence under such limited information about the states, traditional asymptotic stability cannot be achieved. Accordingly, the notion of *containability* was introduced in [63] which basically describes a trapping region around the origin in which the state can be contained.

The next step in the analysis of quantized NCS was presented in [8], [14]. The main idea in [8] was to make the sensitivity of a uniform quantizer time-variant and include its dynamics in the analysis, via utilizing a zooming factor $z \in \{-1, 1\}$ that increases/decreases the quantization sensitivity $\Delta(t)$ to allow sufficient qualitative indication of the state location that guarantees stability. With such approach the stability of the un-quantized state/output can be extended to the quantized version since under state feedback, there exists a control policy of the form $u(t) = -KI_{[k_0\tau,\infty)}(t)\Delta(t), \mathcal{Q}(x(t))$ where $\mathcal{Q}$ is a uniform quantizer with sensitivity $\Delta(t)$ and $k_0 > 0$, such that the solution of the closed-loop system

$$\begin{pmatrix} \dot{x}(t) \\ \Delta(t) \end{pmatrix} = \begin{pmatrix} Ax(t) - Bu(t) \\ G(z, \lfloor t/\tau \rfloor, q(x(\lfloor t/\tau \rfloor)), \Delta(\lfloor t/\tau \rfloor \tau)) \end{pmatrix}$$

approaches 0 as $t \rightarrow \infty$, hence asymptotic stability is regained.

The idea of zooming in and out-type quantization was also explored in [18] as well as in [33]. Specifically, in [33], the quantizer maintains a fixed number of partitions, but starts with large quantization partitions that shrink as the trajectory approaches the origin.

A slightly different idea was proposed in [14] for the design of the quantizer, in which the objective was to quantize as coarsely as possible while maintaining stability. The measure of coarseness depends on the *quantization density* measure defined by $\eta_{\mathcal{Q}} = \lim_{\epsilon \rightarrow 0} \sup \frac{\#\mathcal{Q}[\epsilon]}{-\ln \epsilon}$, where $\mathcal{Q}$ is a quantizer that stabilizes the system and $\#\mathcal{Q}[\epsilon]$ is the number of levels that $\mathcal{Q}$ has in an interval $[\epsilon, 1/\epsilon]$. The coarsest quantizer corresponds to the quantizer with the smallest quantization density. It was shown that a quantizer which is coarsest with respect to a CLF $V(x)$ is of logarithmic type, i.e. the levels are far apart when the state trajectory is far from the origin and get closer in a logarithmic fashion once close to the origin. The idea is that imprecise knowledge of the state is enough to steer the trajectory in the direction of the origin. Once close to the origin, more precise knowledge is required to reach the origin. The quantization density is redefined to include the effect of uniform sampling of period h as follows: $\eta_{\mathcal{Q},h} = \frac{1}{h} \lim_{\epsilon \rightarrow 0} \sup \frac{\#\mathcal{Q}[\epsilon]}{-\ln \epsilon}$ This density measures the coarseness of the quantizer in space (quantization) as well as in time (sampling), and the optimal sampling time satisfies the following equality: $h^* = \frac{\ln(1+\sqrt{2})}{\sum_{i=1}^{k} \lambda_i^u(A)}$, where $\lambda_i^u(A)$ corresponds to the unstable eigenvalues of the system matrix A. Furthermore, the base for the optimal logarithmic quantizer and the optimal sampling period are independent, hence they can be chosen separately. The latter result result can be compared to that given in [18].

Another interesting analysis appeared in [22] and assumes there are two quantizers one residing between the plant sensors and the controller, and another between the controller and the plant actuators. This procedure is the more general in the sense that the network resides on both sides of the plant/controller, not solely between the plant sensors and controller.

a) Chaotic Behavior: Since asymptotic stability can not be achieved in the traditional sense, the analysis in [12] proceeds to characterize an invariant *trapping set* $\mathcal{D}$ to which all the trajectories tend after some time N, depending on the initial condition x_0. The analysis then aimed at characterizing the behavior of the system once the trajectory enters the invariant set $\mathcal{D}$. For scalar systems, there exists an invariant probability measure μ defined on $\mathcal{D}$ such that: $\mu : \mathcal{D} \rightarrow \mathcal{D}$. Then, system inside $\mathcal{D}$ operates on a density f as an initial condition. Hence, the evolution of the state trajectory can be characterized through the use of the *Frobenius-Perron* operator $\mathcal{P}$ (see [28]), and there exists an invariant distribution under which the system evolves. This idea along with the *cell-to-cell mapping* [21] has recently reappeared in [51], in which an autonomous quantized system can be represented by the evolution of the density defined on the state-space described by the F-P operator, and a *density discretizer* D_N, i.e.

$$f_{k+1}(x) = \mathcal{P} f_k(x), \qquad \text{given} \quad f_0(x)$$
$$\mathbb{P}(Q(x)|f_0(x)) = D_N f_k(x),$$

where the discretizer D_N is defined by $D_N : \mathcal{D} \rightarrow \mathcal{W}^N$, which is a projection of the density f onto an N-dimensional space, that represents the volume of the density resident in each quantization hyperbox.

IV. Conclusions

This paper has exposed the reader to several results pertaining to the analysis and design of Networked Control Systems. Several models that were utilized in the study of NCS such as sampled-data, model-based, and hybrid were presented briefly. Also some of the most critical problems in the design of NCS such as packet loss, network induced time-delays, and limited communication in the control loop were presented.

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