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Optimal performance of networked control systems with bandwidth and coding constraints ☆

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ABSTRACT

The optimal tracking performance of multiple-input multiple-output (MIMO) discrete-time networked control systems with bandwidth and coding constraints is studied in this paper. The optimal tracking performance of networked control system is obtained by using spectral factorization technique and partial fraction. The obtained results demonstrate that the optimal performance is influenced by the directions and locations of the nonminimum phase zeros and unstable poles of the given plant. In addition to that, the characters of the reference signal, encoding, the bandwidth and additive white Gaussian noise (AWGN) of the communication channel are also closely influenced by the optimal tracking performance. Some typical examples are given to illustrate the theoretical results.

1. Introduction

With the development of the communication technology, networked control systems emerge. Networked control systems are spatially distributed systems in which band-limited digital communication channels exist between sensors, actuators and controllers.

In recent years, the applications of networked control systems have been growing rapidly [9,31]. It has been applied in many important areas of military, the robot control and automated highway systems [1,7,29]. Compared with the conventional control systems, networked control systems have witnessed some advantages of being easy for diagnosis, maintenance and installation. On the other hand, due to the introduction of the communication channel, the information is transmitted through the communication channel, some constraints appeared such as networked-induced delay [2,30,32], packet dropout [10,17,23,25], bandwidth constraint [24,28], signal-to-noise ratio (SNR) [3,12] and quantization [4,16,22], which bring some difficulties for analysis and design of the networked control systems and can even destroy the stability of the system. The researches about modeling of the networked control systems and stabilization analysis are fairly mature at present [8,20,26]. The problem of H_∞ output feedback control for networked control systems with packet dropout in feedback channel and forward path was studied in paper [27]. Although it is worthwhile to tackle these problems, many issues of optimal control performance under such network environment remain challenging for us, such as optimal design and optimal tracking performance of networked control systems.

In order to get better performance in the real control applications, extra sensors and actuators have been added into the control system, causing the input signal and the output signal of the given plant to be multivariate. Because of this feature, this system is called the MIMO control system. Compared with single-input single-output (SISO) control systems, MIMO systems are more complicated and have been applied in many fields of controlling the steam pressure and the steam speed, control of the temperature distillation column in petrochemical production due to its practicality. Therefore, it is necessary to explore the tracking performance of MIMO networked control systems. Growing attention has been paid to the study of the intrinsic performance limitation achievable by feedback control [5,6,33]. In general, the minimal tracking error is dependent on the nonminimum phase zeros, unstable poles and time delays [5]. For MIMO linear time-invariant (LTI) systems under disturbance rejection, the analysis method of optimal tracking performance was proposed in paper [33]. In recent years, the topic of optimal tracking performance has been extended to networked control systems [13,14,18]. The optimal

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tracking and regulation performance of discrete-time, MIMO linear time-invariant networked control systems was investigated in paper [19]. The optimal tracking problem for SISO networked control systems over a communication channel with packet dropouts was studied in paper [34]. The optimal tracking performance of MIMO LTI systems over a noisy channel with packet dropouts in the feedback path was investigated in paper [15]. The best tracking problem for SISO networked control system with network-induced delay and bandwidth constraints was studied in paper [35]. Guan et al. [14] studied the optimal tracking performance issue for MIMO LTI systems under networked control with limited bandwidth and additive colored white Gaussian noise channel. The optimal tracking performance problem was studied for MIMO networked control systems with communication constraints in paper [13]. However, [13,15,34,35] show that in order to obtained the minimal tracking error, the channel input energy of networked control systems is often required to have an infinite power in the optimal tracking problem. But this requirement cannot be met in the real world. Therefore, the channel input power constraint of networked control systems should be considered in the performance index to address this issue. Meanwhile, these proposed results do not take into account the influence of the coding and decoding. In this paper, we consider the optimal tracking problem in terms of both the tracking error energy and the channel input energy as well as, the bandwidth and coding–decoding constraints of the communication channel.

The main contribution of this paper is to study the optimal tracking performance of MIMO networked control systems under the communication bandwidth and coding–decoding constraints with the finite channel input power. The optimal tracking performance of MIMO networked control systems is attained by stabilizing compensators under the one-parameter structure. The display expression of the optimal tracking performance of MIMO networked control systems is obtained by spectral factorization technique. The obtained results show that the optimal tracking performance of MIMO networked control systems is constrained by the directions and locations of nonminimum phase zeros and unstable poles of given plant. In addition to that, the characters of the reference signal, coding–decoding, the bandwidth and AWGN are also closely related on the optimal performance. The results also show that the optimal tracking performance is determined by the plant's internal structure and communication parameters, no matter what compensator is adopted. In networked control systems, the bandwidth limitation is inevitable, causing the data dropouts and stochastic delays, in other words, data dropouts and stochastic delays are generated by the bandwidth constraint. In present paper, we investigated the relationship between the bandwidth constraint and the tracking performance of NCSs. Citing the result, we can design the suitable channel bandwidth on demand to make the tracking performance of the whole systems reach the best and meet the requirements of the practical applications. The results will provide us with good guidance on the design of networked control systems. The future research will focus on study of the influence of the data dropouts and stochastic delays with the appropriate bandwidth.

The proposed model will be applied in many realistic systems, such as remote monitoring robot surgery, in which patient is considered as the plant, and robot is considered as the controller. The remote expert obtains information by the network transmission, and information of expert will be returned to the robot by the network transmission. Thus we study the relationship among the tracking performance, structural characteristics of plant and communication parameters (bandwidth limitations and coding constraints in this paper).

The rest of the paper is organized as follows. The problem is formulated in Section 2. The optimal tracking performance expression with bandwidth and coding–decoding constraints of communication channel is obtained in Section 3. Some typical examples are given to illustrate the obtained results in Section 4. The conclusion and future research directions are presented in Section 5.

2. Problem formulations

For any complex number z, we denote its complex conjugate by $\bar{z}$. For any signal $x(k)$, we denote its z-transform by $\tilde{x}(k)$. The transpose, conjugate transpose and Euclidean norm of a matrix A are denoted by A^T, A^H and $\|A\|$, respectively. For any unitary vectors u and v, we define the angle $\angle(u,v)$ between them by $\angle(u,v)=|u^Hv|$. The expectation operator is defined as $E\{\cdot\}$. Let the open unit circle be denoted by $\mathbb{D}\triangleq\{z:|z|<1\}$, the closed unit circle be denoted by $\overline{\mathbb{D}}\triangleq\{z:|z|\le 1\}$, the unit circle by $\partial\mathbb{D}\triangleq\{z:|z|=1\}$, and the complement of $\overline{\mathbb{D}}$ is $\overline{\mathbb{D}}^c\triangleq\{z:|z|>1\}$. Denote the Euclidean vector norm $\|\cdot\|_2$ and $\|\cdot\|_F$ as the Frobenius norm, in addition $\|G\|_F=\mathrm{tr}(G^HG)$. The space $\mathcal{L}_2$ is the Hilbert space with inner product:

$$\langle F,G\rangle:=(1/2\pi)\int_{-\pi}^{\pi}\mathrm{tr}[F^H(e^{i\theta})G(e^{i\theta})]\,d\theta.$$

It is well known that $\mathcal{L}_2$ can be decomposed into two orthogonal subspaces $\mathcal{H}_2$ and $\mathcal{H}_2^{\perp}$ given by [19]

$$H_2:=\left\{G:G(z)\in\overline{\mathbb{D}}^c,\ \|G\|_2^2:\ =\sup_{r>1}(1/2\pi)\int_{-\pi}^{\pi}\|G(re^{i\theta})\|_F^2\,d\theta<\infty\right\}$$

$$H_2^{\perp}:=\left\{G:G(z)\in\mathbb{D},\ \|G\|_2^2:=\sup_{r<1}(1/2\pi)\int_{-\pi}^{\pi}\|G(re^{i\theta})\|_F^2\,d\theta<\infty\right\}.$$

Finally, let $\mathbb{R}\mathcal{H}_\infty$ denote the set of all stable, proper, and rational transfer function matrices.

The optimal tracking performance for MIMO discrete-time systems with the channel noise and bandwidth limitations was studied in paper [13], however, in the actual information transmission, coding and decoding is often required and the communication channel can also exist between the controller and the given plant, what is more, input power constraint also existed, therefore, compared with [13], we present a new model (MIMO networked control systems with bandwidth in the feedback channel and assume coding, decoding in the forward channel) such as Fig. 1, the main goal of this part is to obtain the optimal tracking performance with the channel input power constraint.

In this setup, G denotes the plant model and K represents the one degree compensator, whose transfer function matrices are denoted as $G(z)$ and $K(z)$, respectively. The communication channel is characterized by three parameters: the channel transfer function matrices F, A and A^{-1}, and the additive Gaussian white noise n. F represented the bandwidth limitation. In this paper, F is chosen to be low-pass Butterworth filters. A and A^{-1} represented the encoder and decoder, respectively, whose transfer function matrices are denoted as $A(z)$ and $A^{-1}(z)$. The signals of r and y denote the reference input and the system output, respectively, whose z-transform are $\tilde{r}$ and $\tilde{y}$. In this paper, we consider that a reference signal r is a random process and $r(k)=(r_1(k),\ldots,r_l(k))^T$, the additive noise process n is supposed to be a zero-mean i.i.d. AWGN, and the noise signals in different channels

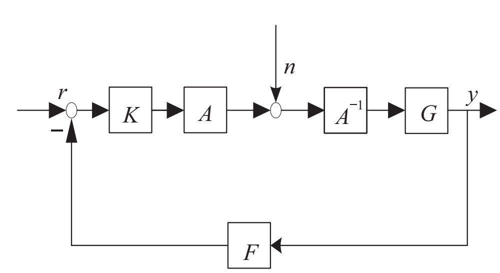

Fig. 1. Networked control systems with bandwidth and coding.