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Control for networked control systems with remote and local controllers over unreliable communication channel ☆

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ABSTRACT

This paper is concerned with the problems of optimal control and stabilization for networked control systems (NCSs), where the remote controller and the local controller operate the linear plant simultaneously. The main contributions are two-fold. Firstly, a necessary and sufficient condition for the finite horizon optimal control problem is given in terms of the two Riccati equations. Secondly, it is shown that the system without the additive noise is stabilizable in the mean square sense if and only if the two algebraic Riccati equations admit the unique solutions, and a sufficient condition is given for the boundedness in the mean square sense of the system with the additive noise. Numerical examples about unmanned aerial vehicles model are shown to illustrate the effectiveness of the proposed algorithm.

1. Introduction

Networked control systems (NCSs) are control systems consisting of controllers, sensors and actuators which are spatially distributed and coordinated via certain digital communication networks (Gao, Xu, & Zhang, 2017; Ju & Zhang, 2018; Zhang, Branicky, & Phillips, 2001). Recently, NCSs have received considerable interest due to their applications in different areas, such as automated highway systems, unmanned aerial vehicles and manufacturing systems (Horowitz & Varaiya, 2000; Seiler, 2001). Comparing with the classical feedback control systems, NCSs have vast superiority including low cost, reduced power requirements, simple maintenance and high reliability. However, the packet dropout occurred in the communication channels of NCSs brings in challenging problems (Ahmadi, Salmasi, Noori Manzar, & Najafabadi, 2014). Therefore, it is of great significance to study NCSs with unreliable communication channels where the packet dropout happens.

The research on the packet dropout can be traced back to Hadidi and Schwartz (1979) and Nahi (1969). Sinopoli et al. (2004) introduced the Kalman filter with intermittent observations and the optimal estimator is defined as $\hat{x}_{k|k} = E[x_k|\{z_k\}, \{\gamma_k\}]$ with conditioning on the arrival process $\{\gamma_k\}$. Qi and Zhang (2016) derived the optimal estimator without conditioning on the arrival process $\{\gamma_k\}$ and obtained the optimal controller for the systems subject to the state packet dropout. In Gupta, Hassibi, and Murray (2007), the optimal linear quadratic Gaussian control for system involving the packet dropout is studied by decomposing the problem into a standard LQR state-feedback controller design, along with an optimal encoder–decoder design. The stabilization problem is investigated in Xiong and Lam (2007) for NCSs with the packet dropout. For systems subject to input delay and packet dropout, Liang, Xu, and Zhang (2017) derived a sufficient and necessary condition for the mean-square stabilization. Nevertheless, the aforementioned literatures are merely involved in a single controller.

Inspired by the previous work (Ouyang, Asghari, and Nayyar 2016), the NCSs under consideration of this paper are depicted as in Fig. 1, which is composed of a plant, a local controller, a remote controller and an unreliable communication channel. The state x_k can be perfectly observed by the local controller. Then, the state x_k is sent to the remote controller via an unreliable communication channel where the packet dropout occurs with probability p. We define y_k as the observed signal of the remote controller. When the remote controller observes the signal y_k, an acknowledgment is sent from the remote controller to the local controller whether the state is received. Hence, the local controller can observe the signal y_k as well. The two controllers will not perform their control actions until they observe the signal y_k. At time k, information $\{y_0, \ldots, y_k, u_0^R, \ldots, u_{k-1}^R\}$ are available to the remote controller u_k^R, while the local controller u_k^L uses information $\{x_0, \ldots, x_k, y_0, \ldots, y_k, u_0^R, \ldots, u_{k-1}^R\}$ to make decision. Besides, the

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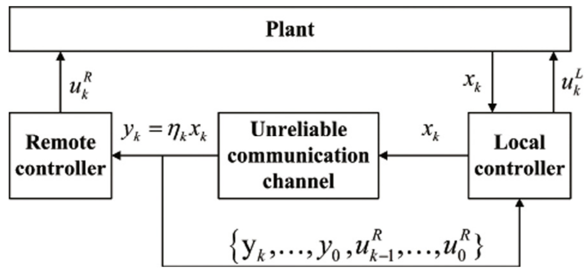

Fig. 1. Overview of NCSs with an unreliable communication channel.

channels from the controllers to the plant are assumed to be perfect. The aim of the optimal control is to minimize the quadratic performance cost of NCSs and stabilize the linear plant.

The NCSs model stems from increasing applications that appeal for remote control of objects over Internet-type or wireless networks where the communication channels are prone to failure. For example, the local controller can be an integrated chip on the unmanned aerial vehicle (UAV) that implements moderate control and the remote controller can be a ground-control center (GCC). When the UAV flies over a suspected area looking for hiding ground-based enemies, it reports the current status to the remote GCC via wireless communication channel. The remote GCC receives the mission states and issues the following-up commands to the UAV (Shim, Kim, & Sastry, 2000). However, generally, the UAV is poor in the transmission capability and the GCC is equipped with complete communication installation which is capable of powerful transmission. Thus, the downlink from the local controller to the remote controller is prone to failure and the uplink from the remote controller to the local controller is perfect.

Since the studied problem consists of one remote controller and one local controller, it can be reviewed as two decision-maker problem. In Xu, Shi, and Zhang (2018), the leader–follower game is considered. Sheng, Zhang, and Gao (2014) and Xu, Zhang, and Chai (2015) studied the Nash strategy and Stackelberg strategy respectively. Note that for Nash equilibrium it is necessary for each controller to access the optimal control strategies of each other, and for Stackelberg strategy it is assumed that one player is capable of announcing his strategy before the other. Therefore, these approaches are unavailable to deal with this work. Due to the asymmetric information for the remote controller and the local controller, the analysis and synthesis for the optimal control remain challenging. In Ouyang et al. (2016), the finite-horizon optimal strategies were elegantly solved by using the dynamic program based on the common information approach. Furthermore, Asghari, Ouyang, and Nayyar (2018) extended their work to a networked control system consisting of a remote controller and multiple local controllers. Note that the stabilization problem has not yet been solved while it is the foundation problem of the infinite horizon control.

Recently some significant progress for the optimal LQ control has been made by proposing the approach of solving the forward and backward differential/difference equations. See Zhang, Li, Xu, and Fu (2015) and Zhang and Xu (2017) for details. Inspired by these works, this paper studies the optimal control and stabilization problems for the NCSs with remote and local controllers over unreliable communication channel. The key technique is to apply the Pontryagin's maximum principle to develop a direct approach based on the solution to the forward and backward stochastic difference equations (FBSDEs), which will lead to a non-homogeneous relationship between the state estimation and the costate. The main contributions of this paper are summarized as follows: (1) An explicit solution to the FBSDEs is presented with the Pontryagin's maximum principle. Using this solution, a necessary and sufficient condition for the finite horizon optimal control problem is given in terms of the solutions to the two Riccati equations. (2) For the stochastic systems without the additive noise, a necessary and sufficient condition for stabilizing the systems in the mean-square sense is developed. For the stochastic systems with the additive noise, a sufficient condition is derived for the boundedness in the mean-square sense of the systems.

The rest of the paper is organized as follows. The finite horizon optimal control problem is studied in Section 2. In Section 3, the infinite horizon optimal control and the stabilization problem are solved. Numerical examples about the unmanned aerial vehicle are given in Section 4. The conclusions are provided in Section 5. Relevant proofs are detailed in Appendices.

Notation: R^n denotes the n-dimensional Euclidean space. I presents the unit matrix of appropriate dimension. A' denotes the transpose of the matrix A. $\mathcal{F}(X)$ denotes the σ-algebra generated by the random variable X. $A \geq 0 (> 0)$ means that A is a positive semi-definite (positive definite) matrix. Denote E as mathematical expectation operator. $Tr(A)$ represents the trace of matrix A. I stands for the unit matrix with appropriate dimension. $\mathbf{diag}(A_1, \ldots, A_n)$ is a block diagonal matrix with main diagonal block matrices A_j, $j = 1, \ldots, n$ and the off-diagonal blocks are zero matrices.

2. Finite horizon case

2.1. Problem formulation

Consider the discrete-time system with two controllers as shown in Fig. 1. The corresponding plant is given by

$$x_{k+1} = Ax_k + B^L u_k^L + B^R u_k^R + \omega_k, \tag{1}$$

where $x_k \in R^{n_x}$ is the state, $u_k^L \in R^{n_L}$ is the local control, $u_k^R \in R^{n_R}$ is the remote control, ω_k is the input noise and A, B^L, B^R are constant matrices with appropriate dimensions. The initial state x_0 and ω_k are Gaussian and independent, with mean $(\bar{x}_0, 0)$ and covariance $(\bar{P}_0, Q_{\omega_k})$ respectively.

As can be seen in Fig. 1, let η_k be an independent identically distributed (i.i.d.) Bernoulli random variable describing the state signal transmitted through the unreliable communication channel, i.e., $\eta_k = 1$ denotes that the state packet has been successfully delivered, and $\eta_k = 0$ signifies the dropout of the state packet. Then,

$$\eta_k = \begin{cases} 1, & y_k = x_k, \text{ with probability } 1 - p \\ 0, & y_k = \emptyset, \text{ with probability } p \end{cases} \tag{2}$$

Observing Fig. 1, the remote control u_k^R can obtain the signals $\{y_0, \ldots, y_k\}$. Accordingly, we have that u_k^R is $\mathcal{F}\{y_0, \ldots, y_k\}$-measurable. The local control u_k^L has access to the states $\{x_0, \ldots, x_k\}$ and the signals $\{y_0, \ldots, y_k\}$. In view of (1), we have that u_k^L is $\mathcal{F}\{x_0, \omega_0, \ldots, \omega_{k-1}, y_0, \ldots, y_k\}$-measurable. We denote $\mathcal{F}\{x_0, \omega_0, \ldots, \omega_{k-1}, y_0, \ldots, y_k\}$ and $\mathcal{F}\{y_0, \ldots, y_k\}$ as $\mathcal{F}_k$ and $\mathcal{F}\{Y_k\}$ respectively.

The associated cost function for system (1) is given by

$$\begin{aligned} J_N = & E\Big\{ \sum_{k=0}^{N} [x_k{}' Q x_k + (u_k^L)' R^L u_k^L + (u_k^R)' R^R u_k^R] \\ & + x_{N+1}{}' P_{N+1} x_{N+1} \Big\} \end{aligned} \tag{3}$$

where Q, R^L, R^R and P_{N+1} are positive semi-definite matrices. E takes the mathematical expectation over the random process $\{\eta_k\}$, $\{\omega_k\}$ and the random variable x_0. Thus, the optimal control strategies to be addressed are stated as follows:

Problem 1. Find the $\mathcal{F}_k$-measurable u_k^L and the $\mathcal{F}\{Y_k\}$-measurable u_k^R such that (3) is minimized, subject to (1).