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Guaranteed Cost Control for Uncertain Nonlinear Systems with Mixed Time-Delays: The Discrete-Time Case

Bo Shen[a], Zidong Wang[b,c,*], and Hailong Tan[a]

***Abstract*—In this paper, the guaranteed cost control problem is investigated for a general class of discrete-time uncertain nonlinear systems with mixed time-delays. The mixed time-delays under consideration comprise both the discrete and the distributed delays. By using the completing-the-square technique, the discrete and distributed time-delays are handled in a unified framework. Then, by constructing an appropriate Lyapunov functional, a sufficient condition is established under which the closed-loop control system is stable and an adequate performance index is guaranteed over all admissible uncertainties as well as mixed time-delays. Based on the sufficient condition, the nonlinear cost-guaranteed controller is designed and an explicit expression of the controller parameter is obtained. Finally, a numerical simulation example is presented to demonstrate the effectiveness and applicability of the results derived.**

***Index Terms*—Discrete-time systems; guaranteed cost control; mixed time-delays; nonlinear systems; uncertain systems.**

I. Introduction

Control technology has achieved considerable development and various control approaches have been available in the existing literature, see e.g. [3], [8], [14], [15], [17], [19]. Guaranteed cost control (GCC) has been recognized as an effective robust control approach for systems with parameter uncertainties. The cost-guaranteed controller can not only stabilize the uncertain systems but also guarantee an adequate index of the performance over all admissible uncertainties. Owing to such an intrinsic advantage, in the past few decades, the GCC problems have received an ever-increasing research interest and an immense body of literature has been available on a variety of uncertain systems [23], [28]. For instance, in [6], the cost-guaranteed controllers have been designed for linear systems. In [22], the fuzzy GCC approach has been proposed for nonlinear systems by using the Takagi-Sugeno (T-S) fuzzy model. For more general nonlinear systems, some efforts have also been made, see e.g. [2], [25] for representative results on, respectively, the minimax GCC problem, the adaptive GCC problem and the reliable GCC problem. Nonetheless, the research progress on the GCC problem for general nonlinear systems is far from satisfactory and almost all existing results have been mainly concerned with the *continuous-time* case. So far, to the best of the authors' knowledge, the GCC problem for *general discrete-time nonlinear systems* has not been investigated yet and therefore remains to be important and challenging.

On another research front, the time-delay systems have become an attractive topic of research since the frequently encountered time-delays serve as a well-known source for deteriorating control performance. As such, in the past two decades or so, much attention has been devoted to the control/filtering problems with various kinds of time-delays, see e.g. [9], [11], [16], [20], [21]. According to the way they occur, the time-delays can be generally classified as discrete time-delays and distributed time-delays, both of which have been extensively investigated [10], [26], [27]. As for the GCC problem, much effort has been made towards the analysis and synthesis problems for various time-delay systems, see e.g. [1], [5], [7]. However, it should be pointed out that, in almost all existing results related to the GCC problems, only the *discrete* time-delays have been taken into account, and the *mixed* time-delays (i.e., the situation with simultaneous presence of both discrete and distributed delays) have been largely overlooked despite their practical significance in engineering systems. Indeed, it is mathematically nontrivial to establish a unified framework to handle both discrete and distributed time-delays, and also analyze/synthesize the GCC systems with such mixed time-delays, especially when the systems are inherently nonlinear. It is, therefore, the primary motivation of this paper to overcome the identified challenges by launching a study on *the GCC problem for general nonlinear discrete-time systems with mixed time-delays*.

Indeed, the general nonlinear characteristic of the system, parameter uncertainties as well as the mixed time-delays significantly complicates the guaranteed cost control problem and should be properly handled by using the existing methods or developing the new techniques. Three challenging issues we have to deal with are identified as follows: 1) how can we choose an appropriate analysis approach to dealing with the effects of parameter uncertainties and mixed time-delays on the stability of the closed-loop systems in a general nonlinear framework; 2) how can we establish an existence condition for the nonlinear guaranteed cost controller such that, for all possible uncertainties and mixed time-delays, the closed-loop

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