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Optimal control for stochastic linear quadratic singular periodic neuro Takagi–Sugeno fuzzy system with singular cost using ant colony programming

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ABSTRACT

In this paper, optimal control for stochastic linear singular periodic neuro Takagi–Sugeno (T–S) fuzzy system with singular cost is obtained using ant colony programming (ACP). To obtain the optimal control, the solution of matrix Riccati differential equation (MRDE) is computed by solving differential algebraic equation (DAE) using a novel and nontraditional ACP approach. ACP solution is equivalent or very close to the exact solution of the problem. The ACP solution is compared with the solution of traditional Runge Kutta (RK) method. An illustrative numerical example is presented for the proposed method.

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1. Introduction

A fuzzy system consists of linguistic IF–THEN rules that have fuzzy antecedent and consequent parts. It is a static nonlinear mapping from the input space to the output space. The inputs and outputs are crisp real numbers and not fuzzy sets. The fuzzification block converts the crisp inputs to fuzzy sets and then the inference mechanism uses the fuzzy rules in the rule-base to produce fuzzy conclusions or fuzzy aggregations and finally the defuzzification block converts these fuzzy conclusions into the crisp outputs. The fuzzy system with singleton fuzzifier, product inference engine, center average defuzzifier and Gaussian membership functions is called as standard fuzzy system [1].

Two main advantages of fuzzy systems for the control and modeling applications are (i) fuzzy systems are useful for uncertain or approximate reasoning, especially for the system with a mathematical model that is difficult to derive and (ii) fuzzy logic allows decision making with the estimated values under incomplete or uncertain information [2]. Fuzzy controllers are rule-based nonlinear controllers, therefore their main application should be the control of nonlinear systems. Stable fuzzy control of linear systems has been studied by a number of researchers. It is well-known that nowadays fuzzy controllers are universal nonlinear controllers. All these studies are preliminary in nature and deeper studies can be done. For optimality, it seems that the field of optimal fuzzy control is totally open.

Neural networks or simply neural nets are computing systems, which can be trained to learn a complex relationship between two or many variables or data sets. Having the structures similar to their biological counterparts, neural networks are representational and computational models processing information in a parallel distributed fashion composed of interconnecting simple processing nodes [3]. Neural net techniques have been successfully applied in various fields such as function

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approximation, signal processing and adaptive (or) learning control for nonlinear systems. Using neural networks, a variety of off line learning control algorithms have been developed for nonlinear systems [4,5].

Neuro fuzzy systems are a combination of two popular soft computing techniques: neural networks and fuzzy systems. Neural networks have the capability to learn from examples, yet the learned knowledge cannot be represented explicitly. On the other hand, knowledge in fuzzy systems is represented via explicit fuzzy if then rules, yet fuzzy systems have no learning capability. Neuro fuzzy system is a hybrid approach in which a fuzzy system is trained using techniques similar to those applied to neural networks. One of the first neuro fuzzy systems was Adaptive Network-based Fuzzy Inference System (ANFIS) [6]. ANFIS represents a Takagi–Sugeno fuzzy system as a multilayer feedforward network which can be trained via backpropagation algorithm. Neural networks and fuzzy systems can be combined to join its advantages and to cure its individual illness. Neural networks introduce its computational characteristics of learning in the fuzzy systems and receive from them the interpretation and clarity of systems representation. Thus, the disadvantages of the fuzzy systems are compensated by the capacities of the neural networks. Hayashi and Buckley [7] showed that a feedforward neural network could approximate any fuzzy rule based system and any feedforward neural network may be approximated by a rule base fuzzy inference system [8]. Fusion of Artificial Neural Networks (ANN) and Fuzzy Inference Systems have attracted the growing interest of researchers in various scientific and engineering areas due to the growing need of adaptive intelligent systems to solve the real world problems [9–11].

Stochastic linear quadratic regulator (LQR) problems have been studied by many researchers [12–16]. Chen et al. [17] have shown that the stochastic LQR problem is well posed if there are solutions to the Riccati equation and then an optimal feedback control can be obtained. For LQR problems, it is natural to study an associated Riccati equation. However, the existence and uniqueness of the solution of the Riccati equation in general, seem to be very difficult problems due to the presence of the complicated nonlinear term. Zhu and Li [18] used the iterative method for solving stochastic Riccati equations for stochastic LQR problems. There are several numerical methods to solve conventional Riccati equation as a result of the nonlinear process essential error accumulations may occur. In order to minimize the error, recently the conventional Riccati equation has been analyzed using neural network approach see [19–21]. A variety of numerical algorithms [22] have been developed for solving the algebraic Riccati equation.

Singular systems contain a mixture of algebraic and differential equations. In that sense, the algebraic equations represent the constraints to the solution of the differential part. These systems are also known as degenerate, differential algebraic, descriptor or semi state and generalized state space systems. The complex nature of singular system causes many difficulties in the analytical and numerical treatment of such systems, particularly when there is a need for their control. The system arises naturally as a linear approximation of system models or linear system models in many applications such as electrical networks, aircraft dynamics, neutral delay systems, chemical, thermal and diffusion processes, large scale systems, robotics, biology, etc., see [23–25]. As the theory of optimal control of linear systems with quadratic performance criteria is well developed, the results are most complete and close to use in many practical designing problems. The theory of the quadratic cost control problem has been treated as a more interesting problem and the optimal feedback with minimum cost control has been characterized by the solution of a Riccati equation. Da Prato and Ichikawa [26] showed that the optimal feedback control and the minimum cost are characterized by the solution of a Riccati equation. Solving the MRDE is the central issue in optimal control theory.

Linear singular periodic systems represent a broad class of time evolutionary phenomena and are often the product of problem formulation in system theory when the variables used are the natural describing variables of the underlying process. This topic has received a lot of attention over the last 30 years [27]. In control systems and signals, periodic models are used for the control of multirate industrial plants, the prediction of cyclostationary stochastic processes and the design of digital filters [28]. Much work has been done on the study of periodic system and periodic optimization problems.

Ant colony programming is a metaheuristic approach that is inspired by the behavior of real ant colonies, to find a good enough solution to the given problem in a reasonable amount of computation time. It allows the programmer to avoid the tedious task of creating a program to solve a well-defined problem [29]. ACP is a stochastic search technique that is carried out on a space graph where the nodes represent functions, variables and constants. Functions are usually defined mathematically in terms of arithmetic operators, operands and boolean functions. The set of functions defining a given problem is called a function set F and the collection of variables and constants to be used are known as the terminal set T.

Ants are able to find their way efficiently from their nest to food sources. While searching for food, ants initially explore the area surrounding their nest in a random manner. As soon as an ant finds a food source, it evaluates the quantity and the quality of the food and carries some of it back to the nest. During the return trip, the ant deposits a chemical pheromone trail on the ground. The quantity of pheromone deposited which may depend on the quantity and quality of the food, will guide other ants to the food source. If an ant has a choice of trails to follow, the preferred route is the trail with the highest deposit of pheromone [30]. This behavior helps the ants to find the optimal route without any need for direct communication or central control. Therefore the artificial ants used in the ACP have some features taken from the behavior of real ants, for example,

(a) Artificial ants move in a random fashion.
(b) Choice of a route of an artificial ant depends on the amount of pheromone.
(c) Artificial ants co-operate in order to achieve the best result.

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