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Immune-inspired self-adaptive collaborative control allocation for multi-level stretching processes

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ABSTRACT

For multi-level stretching processes in large industrial production lines exhibiting complicated non-linear dynamics and interconnected control variables, a novel immune-based self-adaptive collaborative control allocation (ICCA) method is proposed to deal with the tension output fluctuations and some uncertainties. The allocation strategies for coupled stretching ratios at different levels are implemented in the ICCA to achieve the best stable tension performance. The stretching ratio of single level is determined by minimizing the error between the proposed reference model and the actual stretching plant. Compared with distributed control for individual sub-processes, the reversing dynamic programming on each level is introduced which is operated from the last level sequentially. The gain-tuning strategy is directly driven by the optimization result, namely, the self-adaptive allocation algorithm, is just the execution level for operating the solutions of reversing optimization. The optimization and self-adaptive controller are designed to cope with the presence of actuator imperfections and tension tracking fluctuations in the neighboring non-linear process. In addition, the criterion is an important factor in evaluating the control performance of this system, which consists of the objective function. Simulation results show that the ICCA method exhibits better performances than the centralized PI control and the cytokine network-inspired cooperative control in dealing with the desired tension tracking and fluctuations reducing by the control algorithm.

1. Introduction

In large-scale industrial production lines, the multiple sub-processes are complicated with non-linear dynamics, and many control variables are coupled with each other, for example, the multi-level stretching processes in large chemical fiber production lines [7]. In this production line, a precursor handling system refers to the physical and mechanical operation, which completes the control of tension and influences directly the quality of finished fibers. In particular, for the strong coupling between driving velocity and precursor tension, there are many sources of disturbances on these two variables. In such multi-level process, allocation of the stretching ratio at each level determines each stable tension condition on precursor, which is the primary reason for the final fiber break or fold. In normal conditions of industrial environment, the stretching

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ratios are often determined empirically and pre-fixed offline by using preliminary experimental studies. Consequently, from the control point of view, during the system operation, the stretching ratios are interrupted and varied with the coupling effects of tensions in neighboring levels, which is the primary reason leading to the fluctuation in tension response [18,28]. For the traditional PI control strategies, the determined stretching ratios only ensure the stabilization of independent inner-loops where the stretching ratio can be reached easily, but the final tension values cannot be always kept in desired ranges. The tension fluctuation directly leads to the fiber break or fold, and a series of gradient increasing tensions for precursors at different levels are guaranteed for a high fiber strength grade. In this case, an on-line re-allocation and distributed control of the stretching ratios become indispensable to achieve accurate and smooth tension tracking and especially driving the motor load torque disturbance rejection [7,18].

Generally speaking, the servo drive system is composed of the electrical control and mechanical actuators. Under the actual working conditions, the mechanical-electric coupling system often presents various disturbances in the driving motors due to the uncertainties of materials, such as changes of unit weight [1,6,19]. For the traditional control methods including PID and robust control, the accurate model is necessary [3,14,35]. In these methods, the dynamic model is introduced for the behavior of pliable material tension variations in machinery. Differential equations are used to describe the relationship between tension of elastic webs and velocity of each roller based on the general laws of physics [12,13,26]. An improved dynamic model for the wholly elastic material is proposed for distinguishing among multiple sub-processes or different tension zones [3,21], then a decentralized controller is designed based on this proposed model [11,12]. Starting from the mathematical models designed for longitudinal dynamics of a web stretching, decentralized *H*-infinity control methods for reducing the coupling effects between tension and motor velocities are proposed [11,39]. For the aforementioned methods, due to the lacking of the proper stretching ratios in all sub-processes, the decentralized control also may not lead to a collaborative regulation of these sub-units [14,16,27].

To solve this type of problem, the gain-tuning control strategies are addressed based on the mathematical model and some assumed conditions with rarely varying systematic parameters [15,28,36], and the gain-tuning control is designed to treat the dynamics without mathematical model. Furthermore, the model-free gain-tuning method is proposed in order to adapt with the varying conditions to the non-linear parameters, such as process noises and parameter disturbances, it can operates effectively by tuning the gains. The critical issue is how to systematically and simultaneously operate the online tuning for relevant driving actuators. The adaptive control is proposed to solve the coupling effects [26,30]. Using the gain-tuning controllers for the speed online setting of two neighboring permanent magnet synchronous driving motors, the control of desired stretching ratio in each stretching zone and the tension response are attainable [15,30,34]. In addition, Su and Wu proposed an output feedback control for solving the Markovian jump scalar nonlinear system [7,11,17]. The interconnected control problem was also addressed by decentralized adaptive fuzzy output feedback control to deal with dynamic uncertainties.

It is the most important problem for the decentralized control structure to attain the optimal solution of online gain-tuning. For achieving the gain-tuning in large scale systems, an improvement of the transient collaborative performance has been addressed by control allocation [15]. Moreover, control allocation for online optimization is proposed to combine the gain-tuning controller for the stretching ratios reallocation [3,20,33]. Using the dynamical programming for approximating the real-time sub-models, the manipulations of the driving motor velocities within a feasible range are used as manipulated control variables [17,24], and then the dynamical programming is used to reversing optimization for minimizing the tracking error from reference sub-models [2,4,29,32]. Decentralized adaptive fuzzy control for a class of large-scale MIMO nonlinear systems is proposed and its application is expanded to industrial systems [5,22,38]. Based on a self-tuning controller capable of handling with error tracking, the motor speeds can be regulated by online regulation according to the fiber overall tension requirement aforementioned. The reconfigurable control is also one of those control strategies to solve the online regulations [23].

In this paper, we propose a novel immune-based self-adaptive cooperative control allocation (ICCA) method for the multi-level stretching processes [12,31], and the ICCA method optimizes the coupled stretching ratios allocation at different levels. In order to demonstrate the effectiveness of the proposed method, the ICCA is applied to the multi-level stretching systems in PANCF production line, and compared with the conventional centralized PI control method and the cytokine network-inspired cooperative control (CNCC) method proposed in [37,39]. The centralized PI control method performs very well for each single-level stretching process but not the overall performance. The CNCC method has considered more in the coupling effects of tensions between neighboring stretching zones existing in an actual system. Simulation results show that ICCA has better performances in tracking the desired tension, reducing fluctuations, and rejecting disturbances of coupling variables between tensions and driving motor speeds [18,19,34].

The main contributions of this paper are as follows: (1) A novel and practical immune mechanism inspired self-adaptive control law with stretching ratios allocation algorithm is proposed for the multi-level stretching systems. It includes an error-driven optimization and a self-adaptive tracking controller. (2) The proposed ICCA method is capable of readjusting the stretching ratios online in the permissible redundant ranges, and can be used for attaining eligible tension instead of pre-defined set-points. (3) The ICCA includes the conventional feedback control and the gain-tuning regulating control for the stretching ratios by re-allocation algorithm. Based on the real-time dynamical tracking error, the control structure is specifically designed to implement the online optimization solutions.

The paper is organized as follows. Section 2 introduces the structure of the multi-level stretching process, and formulates a multi-level stretching model of the fiber production line. Section 3 proposes the construction of the immune mechanism