**A Cytokine Network Inspired Cooperative Control System for Multi-Stage Stretching Processes in Fiber Production**

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*[[1]](#footnote-2)* ***Abstract* — The quality and stability of stretching processes during the polyacrylonitrile (PAN)-based precursor preparation could have strong influence on the properties of carbon fibers and subsequent processes efficiency. The distributed units existing in the stretching processes pose a serious challenge to the cooperative regulation of the whole process to achieve a proper ratio distribution among the different stretching units, each of which having a specific technological characteristics. In this paper, a novel Cytokine-Network-based Stretching Network (CNSN) is proposed to achieve the desired ratio distribution and control performance in large production lines composed of interconnected yet distributed units organized as nodes in both spatial and temporal layers. Based on the mechanism of the multi-layered cytokine network for regulating the whole immune system in human bodies, a dynamical model of stretching network is suggested in order to describe interaction between stretching units. The model consists of a control allocation layer, a distributed controller layer and an actuator layer. An allocation algorithm based on quadratic optimization has also been successfully proposed to enhance the system’s ability to redistribute stretching ratios to ensure the quality requirement of the final fiber. Numerical results show that the CNSN outperforms traditional control strategies for the multi-stage stretching process in fiber production lines. As the main components of the proposed CNSN are very generic, it can easily be extended to other large scale production lines having multiple interconnected processes.**

*Index Terms*—PAN fiber production; stretching processes; artificial cytokine networks; stretching networks; multi-layer regulation networks; control allocation; distributed systems

# INTRODUCTION

T

HE rapid development of the manufacturing industry has resulted in a rapidly growing demand for high tensile, light-weight and high modulus polyacrylonitrile carbon fibers (PANCFs) [1]. PANCFs are now used in a wide range of applications such as aircraft, space structures, sport facilities, and structural reinforcement in construction materials. Polyacrylonitrile (PAN) precursor properties mainly depend on the physical and chemical operations of precursor fiber, such as plasticization, oxidation, coagulation and stretching process, all of which are critical in accomplishing high performance fiber productions. PAN filament has been well known as the perfect precursors for preparing high-performance carbon fibers after a set of primary processing steps including thermal stabilization treatment, carbonization and stretching process. Particularly, the stretching process plays a crucial role in improving the overall properties of entire production line, which mainly consists of a cold-stretched process and a hot-stretched process [2][3]. The mechanical properties of PANCFs become superior only after they undergo the stretching process. This raises a challenging demand for innovative stretching control techniques, which are able to not only smoothly and accurately track the preset stretching ratios but also to achieve a cooperative regulation between two processes, thereby realizing the desired tension of fiber precursors in the presence of various disturbances [4].

In PANCF manufacturing processes, the classical control objective in machining operations focuses only on achieving the performance of each individual component. To meet the requirements of high performance fibers, a collaborative regulation of the stretching ratios highly is in demand. However, achieving high overall control performance in various stretching processes is extraordinarily challenging. For instance, the extent to which the different stretching ratios affect the quality of the fibers depends on the combination of them in different environmental temperatures. Therefore, it is essential for the system to be able to re-allocate the stretching ratios online so as to realize a cooperative ratio regulation among the units.

Traditional control systems for complex industrial processes are composed of multi-stage, interconnected units. For example, the control system in PAN fiber production often consists of a centralized twin direct-driven, typically multi-variable PID controller. This control strategy offers global optimum control, which, however, requires a detailed mathematical model of the whole system. In practice, it is very difficult, if not impossible to obtain an accurate model. Therefore, this kind of controllers often fail to achieve high performance fiber production, partly due to inaccurate models and partly due to the lack of online optimization in the inner-loop controllers [5][6][7]. To address the weaknesses of the PID controllers, more advanced control schemes, such as decentralized control, multi-layered feedback control, and robust control, sliding-mode control have been proposed. A major remaining issue in these methods is the requirement for an accurate mathematical model of the controlled plant. To control the processing lines of fibers, Pagillaet al. [8] analyzed the dynamic model by taking into account the time-varying nature of the roll inertia and radius, and proposed a decentralized controller [9][10]. To reduce the coupling between tension and velocity and to enhance the robustness to radius variations in the web transport and stretching system, a robust control strategy has been proposed [11][12]. Multi-variable tension control in the multi-stage winding systems has also been reported, in which the coupling between these variables is considered in the design of the controller. A sliding-mode controller is implemented for solving coupled multi-motor web-winding system [13][14]. A multi-variable PID controller for discrete-time systems based on linear matrix inequalities is developed in [15][16], and an improved multi-loop PID controller is designed for multi-variable process to satisfy multiple objectives simultaneously [17]. Although these schemes have successfully been used to solve some specific problems existing in interconnected processes, they mostly rely on an accurate mathematical model of the plant. On the other hand, some *ad hoc* control strategies are designed, which cannot be easily extended to other large scale systems [18].

In addition to the conventional decoupling strategies discussed above, intelligent cooperative strategies have been proposed. Ding and Liu proposed a bi-cooperative decoupling control approach to achieve better multi-variable performance [19], in which a more general and easy implementing method suited for all these sorts of reconfigurable problems is proposed. Liang et al. proposed an intelligent cooperative controller based on the regulation network in human body for coordinated and synchronous regulation in stretching system [20][21]. There is also research work that focuses on adaptive cooperative strategies. For example, Rashed et al. suggested an adaptive control scheme in speed regulation of voltage-fed induction multi-motor and Gren et al. reported an adaptive cooperative control of mobile sensor networks in a distributed environment [22]. All of these papers provide a new thought for combination of online optimization and distributed control.

Therefore, control allocation of the stretching ratios opens up a new avenue for cooperative control of multi-stage processes involved in large scale production lines [23][24]. The central idea of this approach is to map the alterable desired virtual inputs given the condition of output fiber performance onto real-time set-points of the controllers. The purpose of this strategy is to build a structure including interconnections of all stages in resource, information sharing and control deployment optimizations according to the corresponding control allocation algorithms. A stretching process with many interconnected units being integrated as a complete network based on an Artificial Cytokine Network (ACN) in human has been constructed [25], and a specific control allocation algorithm is proposed and implemented [26]. The control allocation algorithm here refers to an algorithm that allocates desired stretching ratios to each controller according to the feedback of the fiber tension value and the change of control.

Control allocation deals with the problem of unalterable control demands for distributed multi-level sub-processes, leading to a restricted performance, which changes the pre-fixed inner-loops conditions and improves the optimization oriented operations. A control allocation problem in the stretching process can be formulated as an optimization problem for the final fiber quality, where the objective is typically to search for the best combination of control efforts (or power) subject to actuator constrains and other operational constraints [29]. Conventional methods for solving the reconfigurable issue include the unconstrained least-square method, linear programming and quadratic programming [30]. Most recently, intelligent optimization methods inspired from nature have been developed to address the weaknesses in traditional control allocation algorithms to achieve faster and more accurate global search [31].

Traditionally, tension control has been performed by adjusting the stretching ratio set-points of each unit and cannot be changed, mostly using separate PID feedback controllers. These separately designed closed-loop control systems can enable the deflection of single stretching levels to track a desired value of tension requirement. However, there is little consideration of interactions among different stretching units, let alone an optimized distribution of stretching ratios for obtaining high performance PANCFs. As we know, traditional PID controllers were designed to speed up the tracking response of the roller system without a steady-state error. However, this control strategy does not take interactions between the various units into account. To achieve high performance fibers, the key is to improve ratio allocation, for which it is critical to coordinate the multiple stretching units in different environments to achieve more reliable and accurate control.

The immune system in the human body has attracted increasing interest in constructing computational models to simulate interactions between immune lymphocyte cells, such as B-cell and T-cell. Jerne first used an immune theory to construct an idiotypic network of immune cells so as to recognize each other and external antigen as well [33]. In addition, Farmer et al. proposed a self-adaptive immune network mathematical model to represent a large scale chemical process [32]. Subsequently, a number of immune algorithms were introduced to solve optimization problems in the system [27][28]. In recent years, the immune agent network system in the human body has been studied and simulated in designing distributed controllers for autonomous agent systems and complex industrial networks. An ACN was first proposed by Hone for modeling the cytokine network in the human body, in which each of these immune B-cells are interconnected with others through a kind of messengers-cytokines [25][26].

In this paper, we introduce an ACN model based on the interaction mechanisms in the human cytokine network for coordinated control of the multiple stretching processes for high performance fiber production. Then we propose a computational framework for optimization of stretching ratios among the multilayered stretching controllers, which is crucial in the whole stretching processes. The regulation of stretching controllers is driven by the environment, including sensory input, external or internal disturbance, and the control performance. The data collected from different units can be shared and the control signals can be easily transmitted within the network, all of which facilitates an adaptive and optimal allocation of the stretching ratios. The experimental results confirm that the system is able to accurately track the set fiber tension and is robust to internal and external disturbances.

The main contributions of this paper are as follows:1) On the basis of the ACN model, a novel decentralized control framework for multi-level stretching systems, termed CNSN, is proposed. This framework includes a multilayered feedback structure for finding the optimal trade-off between multi-stage stretching units and entire performance. 2) Simulation studies have been performed to compare the proposed CNSN with traditional PID controllers that independently regulate the ratios in different subsystems. Our results have demonstrated that the CNSN outperforms the traditional PID controllers in tension tracking and have higher robustness to disturbances.

This paper is organized as follows. In Section 2, we introduce the mechanical properties of as-spun fibers and the control requirements of stretching process. In Section 3, we propose the CNSN model based on cytokine network while its logical structure and working mechanism are established, and the intelligent stretching unit in this model is introduced. Section 4 describes optimization algorithm for stretching ratio allocation, which is also implemented successfully in the CNSN. Numerical simulations and analysis of the model are given in Section 5. Section 6 concludes the paper and further work is suggested.

# The Stretching Process and its Control Requirements

## Stretching Process on fiber production

The PANCF precursors are made through the multi-stage stretching process in different situations, such as cold-stretched and hot-stretched processes. In the cold-stretched process, the mechanical properties such as modulus and tensile strength are enhanced. The filaments are not yet in perfect alignment with respect to the molecular orientation and crystallinity. Therefore, the high active molecules reaction in precursors, along with an appropriate stretching ratio in hot-stretched process, are believed to contribute to the more effective treatment for attaining high performance PAN fibers [2][3]. The schematic flow of stretching process in carbon fiber production is as shown in Fig. 1.



Fig. 1. The stretching process on carbon fiber production

After the molten polymer changes into filaments in coagulating bath, filaments are uniaxially stretched into the solidified filaments. In different stretching situations, the aggregated state microstructure and orientation degree of macromolecule chains of as-spun PAN fibers become sufficiently stretched and regularly oriented along with fiber axis, which is designed to produce filaments with a desired strength. At the same time, the increase of the number of molecule chains, which can hold more external tension, leads to the improvement of the fracture strength [1][2].

The tensile strength and the breaking elongation ratio of the precursors depend on the combination of individual stretching ratios of sub-processes in different environments. Table I shows the tension values of the same test sample in one experiment ranging from 320 to 335 cN with varying stretching ratios in the cold-water-stretched process and the almost same situation in hot-water-stretched processes. On the contrary, another consequence is obtained by comparing the values in hot-stretched process, where the tension value of precursors changes in the range of 257 to 325 cN depending on various stretch ratio of 1.16 to 6.17 at the different test samples. In addition, we can observe from table that plastic deformation in as-spun fibers increases as the temperature of fiber precursors becomes higher. These cases indicate that we should find the best combination of these ratios online of two stretching process.

We can also see from the table that the properties of PAN as-spun fibers heavily depend on the real-time adaptive allocation of the stretching ratios in different units because different stretching processes have different influences on the orientation degree and the physical relaxation or shrinkage of PAN molecule chains. This is mainly due to the thermal treatment that aims to improve the orientation degree, extension ability and molecule activity of the PAN molecule chains, leading to carbon fibers of higher strength, better elasticity and less elongation [4].

Table I．Tension and stretch ratio at different measuring points during preoxidation process

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| *Test sample* | *Cold-stretched process* | | | *Hot-stretched process* | |
| Tension/cN | *Stretch ratio* | Tension/cN | | *Stretch ratio* |
| 1 | 320 | 1.65 | 257 | | 1.25 |
| 2 | 335 | 5.38 | 325 | | 6.17 |
| 3 | 238 | 0.769 | 272 | | 1.16 |
| 4 | 190 | 0.57 | 221 | | 0.85 |

## Control Requirements of the Stretching Process

In coagulating process, the polymer material is extruded from the spinneret hole and formed the precursor in the form of filaments. Therefore, for the different concentration and temperature of polymeric melt, the extruding rate, thickness, modulus and also cross-sectional area of filaments may be changed, which regarded as the disturbances to the wholly system, yield the deterioration of pre-defined PI gains and further the unacceptable tensile force of fibers. Moreover, the PI parameters of inner velocity loop and the outer tension loop are difficult to determine and need a lot of experiments. Due to these special situations, especially the variable elastic modulus of as-spun fibers attached onto the rollers, the best combination of the P and I gains of these inner-loops in the normal conditions may be deteriorated and could not adapt to new circumstance anymore. From Fig. 1, the different selection of two-level stretching ratios will lead to the different mechanical properties of precursors on stretching zones. With more than one desired control objections and two distributed control effectors to generate the appropriate solutions for these inner-loops, control modes and combination of both control surfaces are of great importance and should be carefully selected for the tension control performance. In this case, comparing with traditional methods, by means of optimization, namely, the compensation of controller gains for individually tension and velocity error corrections, the systematic disturbances can be eliminated easily and precisely.

Therefore, during this stretching process, two aspects are important for precursor properties:

*Control performance:* As mentioned above, the main difficulty that results in inaccurate tension tracking and high sensitivity to disturbances can mainly be attributed to the nonlinear speed coupling between these neighboring driving motors. In most related controller design, the ratios in different units (subsystems) are specified separately in advance. For achieving high performance precursors, more efficient control strategies must be designed.

*The stretching mechanism:* The tension of the precursors after the second driving roller should be maintained at a normal and desired value, which is the most important requirement in production, because the deviation from it will introduce fluctuations in elongations at break of filaments, and may decrease the crystallization and orientation of fibers. In order to guarantee the quality of PANCF, the precursor tension value should be maintained at a desired value during operation.

To optimize the stretching ratios, we first construct a Stretching Network based on an ACN that enables us to simulate the interconnection of the units and then develop a control algorithm for online allocation of the stretch ratios in multiple sub-processes. With the help of online optimization based on the predicted error and control output variations, the input of the controllers can be reallocated if the deviation of the measured tension from the desired value exceeds a given threshold. These are two main functions of the proposed CNSN.

We take into account the following two properties.

*Tension tracking:* Once the stress value of filament tension is set to a desired value in order to regulate both mechanical properties and surface roughness, stretching controllers should interact with each other to maintain the desired tension value in different conditions.

*Disturbance rejection*: Since the stretching network is expected to be robust to disturbances, the system should be able to detect abnormal conditions with the help of multi-layered feedback loops within the network and then reallocate the stretching ratios accordingly to these stretching units to maintain the desired tension.

# Construction of cytokine-network-based stretching network

In the following, we present the details of the CNSN that aims to achieve the ability for accurate tension tracking and disturbance rejection in multiple stretching zones.

## Cytokine network theory and its computational model

The human immune system has several useful mechanisms from the viewpoint of information collection, processing and communication. The system is able to autonomously respond to internal and external changes and maintain the most important states at a normal value without a direct interference of the nervous system. This phenomenon is known as self-adaption. These properties are very important for designing adaptive artificial immune systems.

The cytokine network is a typical immune network in the human body [25]. Cytokines are small molecules, usually soluble proteins and peptides less than 30kDa that play an essential role in the immune response to infectious agents. They are messengers that carry information from one immune cell to another, along with these immune cells, constitute the cytokine network, which is one of the complex network existing in micro-environment. In this network, varieties of biological entities - immune cells communicate with each other via information exchange and control signal transmitting, resulting in the immunological network, in which cytokine works as signals to convey antibody proliferation information. This immune network can autonomously and accurately detect and identify antigens, and then the immune cells interact with other agents through the messengers, i.e., cytokines, and stimulate corresponding antibodies together against specified antigen.

According to biological findings, the relationship between internal or external antigen and immune cells is very complicated, as shown in Fig. 2. The secretion of specified antibodies is an effective defense against antigen, and cytokines as a kind of messenger synthesized for the communication of immune B-cells for finally stimulation of the proliferation of specified antibodies. To simplify this process in engineering applications, we can define a one-to-many relationship among them, namely, several classes antibodies that are secreted by related kinds of locally relevant B-cells including itself can combine with the corresponding antigen. B-cell receptor is an important part in B-cell ontogeny that enables it to specifically recognize antigen type and eventually help to eliminate this kind antigen through interaction of corresponding B-cells with each other.



Fig. 2. Schematic diagram of immune cells interact ion.

## The feasibility of adapting the immune system model to simulating complex stretching processes

An immune agent consists of three parts: competent cells which provide environment perception, B-cells which produce cytokines as signal messengers communicated with other agents, as well as effector cells within B-cell which respond to external antigens against invasion by secreting antibodies [26]. These properties are very desirable for control of the stretching system containing multiple coupled units.

Therefore, the proposed CNSN consists of several components: sensors, communication modules, a controller as well as actuators. The mapping relationship between immune system and stretching network is shown in Table II. The effectiveness of the proposed CNSN will be discussed as follows.

## The construction of the entire Stretching Network based on the Artificial Cytokine Network

The control allocation of stretching ratios is crucial to the production of high performance carbon fiber. The CNSN is proposed to achieve coordinated control of the coupled units, which aims to adaptively allocate the optimal ratios combination to different stretching units for

Table II. The mapping relationship between immune system and stretching network

|  |  |
| --- | --- |
| *Human Immune System* | *Stretching Network* |
| Immune competent cell (ICC,T cell,B cell) | Stretching unit |
| Antigen | External and internal disturbances |
| Lymphocyte | Detection of tension disturbance |
| Specific activation | Modulation of stretching process response |
| Cell clones and disappearance | The increase and decrease of antibody |
| Cytokines | Medium of competent cells’ communication |
| Antibodies | The control of multilayered stretching units |

continuous and steady stretching processes.

Human immune system regulates information exchange by means of an interaction network consisting of various immune cells which mutually influence each other via hormone-like intercellular molecule messengers called cytokines. CNSN adopts a similar structure of an ACN. On top of that, CNSN has the ability of online optimization that can adaptively reallocate an optimal stretching ratio to each unit in response to environmental changes. In the following, we present this network model and describe the details of the optimization algorithm that determines the set-point of each stretching ratio controller in each unit.

ACN is a new computational framework for simulating the interactions of signaling molecules (cytokines) with immune cells. Ordinary differential equations are used for describing the interactions between immune cells, cytokines, and external stimulus (antigen). Considering each stretching controller input as the information in cytokine network waiting to be optimized between the units by this optimization algorithm, in order to obtain an accurate allocation of these ratios, a specified mathematical function for describing the interactions between these units to compute the re-distributing deviation is presented.

The whole network system is composed of several layers to simulate the multilayered feedback stretching processes. As illustrated in Fig. 3, the upper layer is the network layer, which is the most important and capable of receiving all the states, carrying out stretching ratio re-allocation and passing the real-time optimized ratios to the stretching ratio controllers. The next layer is the distributed control layer, which is composed of sensors, inference modules and controllers. The lower layer are the actuators, each composed of one driving roller and one driven roller for regulating the fiber tension in each of the stretching zones and receiving control commands from the network layer. Such a network structure makes it possible to realize a cooperative control of the different stretching units, which is critical for achieving high-performance dynamic of the whole system.



Fig. 3. Regulation network of the stretching agents

In the following, from the relationship between the general ACN and the stretching network, the stretching controller inputs can be defined as the different antibody concentrations, which are the result of interactions of multiple type cytokines and feedback antigen concentrations. In other words, the controller input deviation can be manipulated from minimizing an objective function that is related to the cytokine concentrations and error between the antigen real-time concentration and the required normal value in human body. In this way, the speed of each driving motor can be regulated at each interval for accurately tracking the final tensile force setting points, which is inspired by this self-adaptive ability of immune system.

 (1)

 (2)

 (3)

 (4)

 (5)

 (6)

In this modified ACN model, two types antibodies are considered, and,represent the concentration changes of antibodies for eliminating the same invading antigen, is the concentration of this type invading antigens, which should be eliminated by related antibodies. represents the independent cytokine concentration secreted by related immune antigen-presenting cells regarding to invading antigen type, which means the objective function. The final output of this immune system is related to the states ofand, which represents different elimination abilities against this same antigen. The functionexpresses the effect to the -th cytokine that is stimulated by the antigen type and concentrations, and proliferation rate and concentration of corresponding type antibodies. is the required threshold of the *j-*th type antigen. A sigmoid function is used in to describe the trend of change of the cytokine concentration according to the elimination requirement of antigens, which is slightly higher than 0 in normal condition for considering the cytokine degradation, where is the degradation of *j*-th cytokine, and,represent the effect to cytokine stimulation by antibodies, respectively.

To summarize, the regulation of the elimination of the invading antigens is mainly based on the optimization of, in which, the error between measured antigen quantities and the required threshold, plays a key role. Two types of antibodies concentrations are determined and optimized byrespectively, and different representations of  leads to the different information allocation results, which also means the different effects on the corresponding antibodies proliferations. These functions facilitate to obtain related cellular immunity elimination against specified antigen. ,shows the final effect of re-allocation antibody cell concentrations, respectively, in order to the minimize the antigen concentration, which is inspired from biology.

 (7)

 (8)

In short, in the immune network, the antigen-presenting cell produces one type of cytokines that can stimulate specific antibodies (usually more than two types and different proliferation rates) proliferation by different type immune cells. In the application of Stretching Network, two different types of immune cells can eliminate one type antigen by means of the related cytokines proliferation, in which two immune cells mean two neighboring driving motors on both sides of a stretching zone, the error between concentration of antigens and the setting value is considered as the tension feedback error, and the distributed control input of two neighboring actuators is modified by this real-time cytokine proliferation rate. The antibody concentration by related immune cells represents the speed of driving motors. The objective function is defined by the feedback error of setting tension value and actual response. To minimize this function, the gradient-based method is used to regulate the two actuators.

In the actual system, the cytokine proliferation raterepresents the modified allocation law on these two levels of motor controllers, represents the tension response in each sub-process, and the square of the feedback error is considered as the objective function to regulate the speed of driving motors, which represents the information allocation in these immune cells, specifically, the different dynamics of driving system in the stretching process. For the performance index in (8), considering,,,, the controller inputs are also specified for achieving the minimum function value.

The dynamics of network model can be described by a set of differential equations (1~7), which can also be used to describe the dynamics of stretching system. We consider this intercellular medium distinct chemical material - cytokines, as the real-time modified states to each sub-process controller at each interval. Generally, we can defineas the modified inputs of each driving actuator, whererepresents the input voltage of driving motor. The control vector of the sub-processes is independently determined by the control allocation strategy, which is different from the conventional PI controller. Therefore, all the control inputs of driving motors are optimized and determined by the control allocation layer for the sake of minimizing of tension feedback error in all sub-processes at the same time, which also bring the final system output  to a desired target value.

Here we will introduce the operational mechanism of the ACN to be used for the stretching system. Cytokine production is stimulated by the concentration of real-time invading antigens. The density and proliferation rate of this communication medium will also affect the antibody production, which indicates the ability of real-time modification of the corresponding antibody concentrations, and the combined action of antibodies leads to the current antigens elimination. Similarly, considering the interconnections of two driving motors in each process, with the traditional PI control strategy, we can define  andas the modified control inputs of current -th stretching zone capable of achieving the real-time optimization for this nonlinear stretching dynamics. This regulation network expresses the iterative effects between multiple types of antibodies and finally antigen elimination based on the proliferation rate of *k*-th cytokine concentration by means of the production of the corresponding antibodies. So the network control allocation for each unit can be described and implemented in the following form (9):

 (9)

whereare the real-time control allocation and the PI control law, respectively, both of which comprise of the control input of each stretching sub-process.

To summarize, this network control strategy performs on-line multi-objective optimization to eliminate the tracking errors in all sub-processes at the same time by coordinating the control inputs in each stretching actuator. That is, the modification of each controller input considers the stability and tracking accuracy of the tension on each stretching zone by taking into account of the coupling between the neighboring driving motors,



The network behaves essentially like a look-up table which will evolve itself over time, depending on the feedback error and allocation control. In short, Equation (1~5) are used as a platform on which optimization of the inner-loops is implemented and more sub-units can be introduced for collaborated control in the whole system. The optimization method for further re-allocating the set-point of the ratio in each unit will be introduced in the following section.

# allocation Control and its optimization based on the cytokine network

In this section, we discuss in detail the online optimization for control allocation, including the problem formulation in the context of stretching processes and control law for each driving actuator. We will show that ratio allocation can be seen as a constrained quadratic optimization and two driving motors on both sides of the stretching zone as directly actuators to realize these stretching ratios.

## Allocation control and its application in stretching processes

There are many important factors in the stretching process that determine the final fiber quality, such as temperature, pressure, stretching ratios applied in different stretching zones. Traditionally, the stretching ratios are controlled separately, which is not able to be tuned according to the tension requirement for high performance filaments on each level, since various stretching environments require different optimal stretching ratios combination. Without a coordinated regulation of the ratios in these different units only limited performance improvement can be achieved. To resolve this problem, instead of allocating a set of predefined stretching ratios beforehand, online re-allocation of the stretching ratios is necessary to maximize the performance enhancement. In this way, the interaction between the two stretching units can be considered together, and two layers are also defined as the regulation mechanisms in the allocation algorithm within the hardware framework, including network layer in a slower time-scale for modifying the set-points of ratio controllers and the controller layer in a fast time-scale in order to ensure desired overall performance. The primary aim of developing a cooperative ratio control is to allocate the set-points of the control units by optimizing an objective function.

The objectives of the online optimization and control of the stretching ratios include [15][27]:

1) Ensuring the speed of the inner-loop driving motor close to the desired dynamical states;

2) Restricting the change in the control input compared to the previous sampling instant;

3) After the cooperation of multiple level processes, without affecting the system dynamics, all of which make the system behave the same way as manually regulating the PI coefficients and off-line adjustment of tension tracking.

In this work, we adopt the quadratic programming to describe the optimization problem defined in Equation (10). The above objectives can be mathematically formulated using the following equations [27][28]:

 (10a)

subject to

 (10b)

 (10c)

where the weighting matrixrepresents the transform matrix, in which *m* = 2 is the number of related stretching zones, *n*=2 is the number of driving actuators in each process which directly regulated by control allocation and can be used to approximately evaluate all desired control inputs with the final tension value. *T* is the sampling interval. In this case, is the desired tension value of the first stretching zone that should be pre-determined, which can be varied once the tension set-point changes, andis the measured tension, is a constant used to evaluate the matching degree of control effect and feedback error.

 (11)

whereis the real control vector for each driving motor, which is feasible with respect to the constraints (10c), and will be computed at each sampling instant to minimize the cost function in (10a).

The trade-off between the two terms in (10a) is determined by the weights and, in which aims a faster convergence of the corresponding actuator to its desired position, while  ensures a reasonable moving velocity of actuators.

Hence, it is highly important to determine constrained by (10c). Using the gradient-based method, and finding a group of online compensation results satisfying (10a) as the dynamic regulated gains of each driving unit of multiple levels. Tuning of these inputs of the driving motor controllers in the inner loops restricting between -10% and 10% are introduced to prevent the vibration response of system dynamics.

Note that the tension can be approximately considered to be proportional to the combination of control variable of driving motor speeds, which also are regulated by these inner control loops of each driving unit. Based on this assumption, for solving the optimization problem, the resulting control gains in each level stretching can be expressed in the following form:

 (12)

For this discrete time dynamic optimization system,  can be found analytically according to the stretching ratio requirement and temperature or pressure. It is also important to point out that although the set-points for the ratios are determined online, no extra time lag will be introduced in solving the optimization problem defined in (10). Consequently, the resulting control input has a linear form as follows [27][28]:

(13)



(14)

Where,, is the feedback tension error of *r*-th process, andare the inner-loop control error of driving motor velocities. andare the related coefficients of two driving motors respectively according to the stretching ratio of current chemical requirements.is 2-D vector representing two driving motor velocity revision factors of *r*-th stretching zone from the minimization of objective function . ,are also the 2-D vectors. is the inner-loop control law of *i*-th driving actuator respectively.  including  and can be updated if needed, namely, especially when the current tension tracking performance is not acceptable. This control method with both self-tuning and conventional PID features is applied in this two-actuator system. In this way, given the desired tension set-point, the continuous or appropriate calculation of valid control inputs for distributed actuators can be determined and simultaneously the collaborative compensation of next level processes are also considered, all of which will be provided with appropriate control inputs and will lead to an approach for overall fiber mechanical performance. This has been demonstrated by the simulation results.

The stretching system frame diagram for realizing this allocation method is shown in Fig. 4, including the control allocation block.



Fig. 4 The block diagram of the stretching system.

## Optimization of control allocation in the Cytokine Network model

As mentioned above, thanks to the online adaptation of the desired stretching ratios, an optimal control of the stretching process can be accomplished, which will result in enhanced fiber quality. This control strategy is easily implemented within the ACN, which has a very similar structure to that of the stretching system.

Moreover, the optimized single stage response can be completely fit into the Cytokine Network framework, which is described by (1~5), where the interaction functionincludes a control allocation optimization of the input vectorfor achieving theoptimization results in (3) and (4). The objective is reformulated in a discrete form as in (10), which aims to ensure smooth operation and accurate tracking of desired tension.

Therefore, the corresponding descriptive functions of each driving motor in the framework of cytokine network can be described as follows [15]:

 (15)

 (16)

whererepresents the number of driving actuator controller, or in the Cytokine Network, the type of antibody in the human body. The function describes the specific and important control law of each driving motors and considers the coupling between the neighboring stretching zones both spatially and temporally, all of which mainly to maintain the tensions of each stretching zone within a certain range.

In this work, the online allocation of the stretching ratios is realized by using the quadratic programming. The obtained ratios are then applied to driving actuators of stretching network model. In the following, the effectiveness of this optimization method embedded in the Cytokine Network will be empirically examined in computer simulations.

# Simulation results on stretching network

In order to verify the performance of the proposed CNSN, in particular the online allocation algorithm, we have chosen a widely used stretching model including cold-stretched and hot-stretched processes [30].

To demonstrate the performance of the proposed method, it has been compared with a conventional centralized control method given the same initial conditions. It is expected that the conventional method with two independent controllers can also achieve the desired tension response to a certain degree. However, for a more accurate tension value and especially in the presence of various disturbances in stretching production line, the conventional independent control method will no longer be able to satisfy the requirements. A detailed description of the performance comparison of two control strategies will be given below.

## The stretching process model

The SIMULINK platform for the stretching process is composed of two main parts: an allocation control algorithm and the network model, as shown in Fig. 5.



Fig. 5. The diagram of simulation platform

The state-space representation of the DC motor used for driving the stretching roller can be described as follows:  (17)

Where, *i* is the current, ω is the angular rate, vapp is the applied voltage, *R* is the resistance, and *L* is the self-induction.

The parameter settings of the DC motor used in this work are shown in Table III. Given these parameters, we can get the transfer function representation of the DC motor as follows:

 (18)

TABLE III. Parameter list of DC motor

|  |  |  |
| --- | --- | --- |
| *PARAMETER* | *VALUE* | *UNIT* |
| R | 2.0 | Ohms |
| L | 0.5 | Henrys |
| Km | 0.015 | torque constant |
| Kb | 0.015 | emf constant |
| Kf | 0.2 | Nms |
| J | 0.02 | kg.m2 |

The motion control model has four motors in the stretching system. In this experiment, the two stretch ratios are originally fixed to 1.50 and 3.50, respectively.

In this constant stretching ratio control system, we consider that the whole stretching system consists of two spatially separately distributed units with cooperated controllers, and these controllers share the corresponding input instructions from control allocation block. For example, we take the structure of the cold-water stretching process in Fig. 6, which is almost the same as the hot-water unit except the environment parameters representing the temperature. The driving roller R1 handles the filaments waiting for stretching. The roller R2 controls the stretching ratio of the filaments by taking a motor as its driver. The velocity ratio of the two motors viewed as the stretching ratio the process needs. The dynamic ratio of the filaments can be maintained by such a feedback loop. The diagram of feedback inner-loops of the separate units with gains allocation is shown in Fig.7 and the closed-loop transfer function of the wholly tension control system can be written as

 (19)

wherein Eq. (19) represents the reference input of stretching unit #1, which further denotes the speed of two driving rollers, is the interference input, and

,

,

, and



represent the transfer function of the driving motor R2 and driving motor R1, stretching roller, and fiber tension dynamics, respectively.



Fig. 6 Speed control system of stretching unit for fiber production



Fig. 7 Control diagram of the inner-loop speed regulation system.

In the fiber stretching system, for attaining the fiber tension dynamics, according to the Hooke’s law and Coulomb’s law and considering the special condition of PAN precursors, the transfer function of  is derived from Eq. (20) for different fiber spans, temperatures inside the water bath and stretching ratios. The transfer functions for describing precursor dynamics are derived based on hydromechanics of fiber behavior and the dynamics of driving motors used for stretching process. Therefore, the change regularities of the precursor structure and tension properties versus stretching ratios on each level stretching zone are described clearly. For the tension to change slowly, we have specifiedas a constant in the calculation of, and the variations velocityas a constant value, because it has no significant changes in normal operations [8][9]. However,  is also one source of disturbances in velocity variations of two successive driving motors, which may affect the whole transfer function and the system dynamics:

 (20)

 (21)

where

,  

For this general expression of web stretching system, the modulus of elasticityandmay change along with the same certain probabilities, the product of both is regarded as parameter disturbance.  is the length of span between two successive driving rollers in one single stretching zone. To eliminate the variations ofand of precursors in the plant during the dynamic response, the traditional control strategy that cannot change the PI gains of two driving motor control loops is not enough. Therefore, this novel method has significantly improved the tension tracking performance by gain-tuning in these driving actuators. The complete stretching model including two feedback loops of above system is shown in Fig. 8. First, when the cold-water and hot-water stretching units are considered separately, the inner-loop of each unit is independent, and each has its own influence on the output tension. In this case, the controller for each unit can be designed separately. In classical approaches, no coordination between the two units is taken into account, and thus, less accurate tension tracking can be obtained. However, this proposed online optimization method considers the model of velocity set-points reconfiguration of two-level driving motor versus the final fiber tension response for regulation mechanism of this distributed inner-loops allocation. Based on this descriptive optimization model and distributed control of multi-span precursor stretching zones, the inter-connected stretching ratios can be determined for the final tension requirement.



Fig. 8 The simulated diagram of overall stretching system

In the simulations, we assume that the roll inertia *J*k and roll radius *R*k remain constant, and a sticking zone between fibers and the rollers always exists.

## Real-time optimization experiments and analysis of the dynamics of the stretching network

In this section, experiments of using the proposed CNSN with the optimized stretching ratios allocated to each unit are performed to compare its performance with that of a conventional centralized PID method. In the traditional method, the stretching ratios are often predefined and remain unchanged, and tracking control in the different units is excised separately. Because of the fixed stretching ratios, the traditional method cannot reject disturbances often seen in the system completely, which will degrade the performance of tension tracking. In the proposed method, the stretching ratios are optimized real-time, which enables accurate tracking even in the presence of disturbances.

To demonstrate the effectiveness of the proposed controller, several simulations are conducted. The output responses of the system controlled by the proposed CNSN and the conventional control method are shown in Figs. 9-13. Simulations for examining the ability of disturbance rejection of the CNSN are carried out by applying perturbations to the parameters of tension dynamic. Such disturbances are often seen in practical systems, where the states of the stretching system may experience small fluctuations even under normal conditions [20][21].

### Phase I- Tracking Performance

In each simulation, 600 sampling periods are given as the total time in one run and the sampling time *T*=0.05s, which is the same as in Phase II presented below. The optimization process can be observed through the experiments, which demonstrates the reason for CNSN to be able to achieve acceptable control performance in normal condition. This also indicates that the introduced online ratio allocation algorithm works very well. Both the proposed CNSN and the conventional controller adopt PID control in each inner-loop unit. The system will first regulate the tension to a stable status with an initial preset final tension. That is to say, the simulation of this phase is regarded as verifying the tracking performance of the two control schemes.

Fig. 9 shows the response curves of the two controllers, which are almost the same. The actual optimized set-points of stretching ratios are almost the same as the predefined ones. Both outputs satisfy the constraints and produce acceptable tracking of the required tension. So both control methods can achieve acceptable performance in the absence of disturbances.



Fig. 9. The system response of two control strategy in normal condition



Fig. 10 The system response of two control strategies in the presence of disturbances

Then we perturb the parameter  with 80% intensity in system model, which is a combination of the velocities of two successive driving motors. As we can see, it seriously affects the tracking performance. In this case, although the tracking response in each separate control loop can be maintained at a desired value, the final performance may not be achieved, which is the most straightforward way to verify the performance of two methods in the presence of disturbances. As seen from Fig. 10, compared with the conventional PID controller, the final tension response of the CNSN with coordinated stretching ratio control has exhibited much better tracking accuracy, in which the set-points for the ratio controllers of inner-loops are recalculated according to the objective function and are proved to be an appropriate allocation.

The purpose of the experiments in Phase I is to demonstrate the advantage of the online reallocation of the stretching ratios and show the capability of distribution of cooperative control instructions on these direct driving motors in two-level stretching processes offered by the proposed CNSN in comparison with the conventional PID controller.

### Phase II - Disturbance Rejection

Each experimental period for a control loop was chosen to be 1200 simulation time. Three experiments in the presence of different levels of disturbances, namely, 10%, 20% and 50%, to the fiber tension dynamics of the cold-water stretching process were conducted using the centralized PID controllers and proposed method, respectively. In these experiments, the driving motor speeds are correspondingly changed for achieving the current level tensile force set-point in the proposed method. In this set of simulations, the initial system state is in a steady state before the regulation begins. Disturbances are then added into the stretching system at the 600-th sampling period to test the robustness properties of the proposed system. In practical fiber production systems, the precursor line is subject to various disturbances. Two types of disturbances can often be found during the normal operation. The first one exists in the inner-loops caused by changing motor loads or unpredictable parameter variations since the radii, fiber material properties and inertia are time-varying. The inner-loop controllers are just used to keep the corresponding stretching ratios stable. The second one is that it leads to tension fluctuations or excess of the allowed maximal tension, the focus of this control allocation is to maintain precursor tension within the pre-set range. Three simulations will be carried out for checking the system response against the second type of disturbances. The aim is to verify the ability of disturbance rejection on two-level tension responses when each inner-loop set-point is online reallocated according to optimization algorithm. Note that in Figs. 11, 12 and 13, the steady-state of fiber tension is closely related to the posed control set-points, and their respective responses against disturbance appeared at the 600-th sampling period all have a sharp and quick decrease. These figures show that the control strategy both in the centralized control strategy and in CNSN result in stable and accurate tension tracking, but the former cannot satisfy the tension requirements. This means that the PID controller is able to reject the first type disturbances in the system, but lacks the ability to reject the second type. We will show, however, that the situation will change in the second method, whose results are also given. From these results, we can see that the tracking performance deteriorates due to the fixed ratios in the classical control method after disturbances are introduced, while the CNSN can maintain the steady-state tracking accuracy even in the presence of the disturbances due to the online reallocation of the desired stretching ratios. From the second level stretching process dynamic response in (b) of these figures, the final tensile forces of the two methods also show the different tracking performances, which can also be attributed to the fact that the inner-loop feedback in the classical method just regulates the velocity of their owns, but the influence of driving motor velocity fluctuations in the upper level cannot be eliminated. Although both methods can be regulate the tension after disturbances, but the steady-state tension tracking error of the centralized PI control strategy is much larger. Refer to Fig. 11, Fig. 12, and Fig. 13 for detailed tracking performances of the PID and the proposed controller.

0

200

400

600

800

1000

1200

0

5

10

15

time(s)

(b)

Tension value ( x100cN)

0

200

400

600

800

1000

1200

0

2

4

6

8

Disturbance rejecting response with 10% intensity added in first level model at 600sampling period

time(s)

(a)

Tension value ( x100cN)

Conventional centralized control

Reference input

CNSN

Conventional centralized control

Reference input

CNSN

Fig. 11 The response curve of 10% disturbance rejection

(a) the first level response, (b) the second level response.

0

200

400

600

800

1000

1200

0

2

4

6

8

Disturbance rejecting response with 20% intensity added in first level model at 600sampling period

time(s)

(a)

Tension value ( x100cN)

Conventional centralized control

Reference input

CNSN

0

200

400

600

800

1000

1200

0

2

4

6

8

10

time(s)

(b)

Tension value ( x100cN)

Conventional centralized control

Reference input

CNSN

Fig. 12 The response curve of 20% disturbance attached.

(a) the first level response; (b) the second level response.

0

200

400

600

800

1000

1200

0

2

4

6

8

Disturbance rejecting response with 50% intensity added in first level model at 600sampling period

time(s)

(a)

Tension value ( x100cN)

0

200

400

600

800

1000

1200

0

2

4

6

8

10

time(s)

(b)

Tension value ( x100cN)

Conventional centralized control

Reference input

CNSN

Conventional centralized control

Reference input

CNSN

Fig. 13 The response curve of 50% disturbance

(a) the first level response; (b) the second level response.

Table IV and Table V show additional results that compare the tracking and disturbance rejection performance of the two control schemes, including the overshoot percentage, recovering time and the settling time. The results indicate that both the conventional PID control and the proposed CNSN show very good tracking of the initial setup value and have obtained almost the same overshoot percentage and settling time. But the conventional PID control is more sensitive to the disturbances, especially in the tension tracking. Due to the lack of ability to coordinate the two sub-processes, the conventional PID controller exhibits much weaker disturbance rejection performance, especially when the second type disturbances are present. By contrast, the regulation time and the accuracy of set-point tracking of the CNSN are much better than that of the PID controller. Note, however, that this performance gain is at the price of a slightly higher overshoot, more tension fluctuations and a slightly longer recovering time during the redistribution period.

To summarize, the proposed CNSN aims to online reallocate the set-points of the stretching ratios in the different units in the presence of disturbances, which leads to more accurate tracking performance and a stronger ability for disturbance rejection.

TABLE IV. NUMERICAL PERFORMANCE COMPARISON BETWEEN TWO CONTROL SCHEMES IN NORMAL CONDITION AND 80% PARAMETER DISTURBANCE ATTATCHED

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | *Tracking performance* | | *System parameters interference* | | | |
| *CNSN* | *CC-PID* | | *CNSN* | *CC-PID* |
| Initial overshoot/% | 12.7 | 10.1 | | 12.53 | 12.58 |
| Settling Time/s | 300.00 | 290.00 | | 300.00 | 290.5 |
| Recover Time/s | 304 | 288 | | 300 | 290 |
| Steady State Error/|·| | 0.30 | 0.33 | | 0.31 | 0.61 |

TABLE V. NUMERICAL PERFORMANCE COMPARISON AT FIRST LEVEL BETWEEN TWO CONTROL SCHEMES IN ABNORMAL CONDITION OF 10%, 20% and 50% DISTURBANCE ATTACHED

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | *10% Disturbance rejection* | | *20% Disturbance*  *rejection* | | |
| *CNSN* | *CC-PID* | | *CNSN* | *CC-PID* |
| Initial overshoot/% | 12.9 | 11.1 | | 12.8 | 12.7 |
| Settling Time/s | 213 | 210 | | 232.0 | 231.0 |
| Disturbance Overshoot/% | 21.6 | 21.3 | | 23.9 | 24.5 |
| Recover Time/s | 220 | 210 | | 220 | 240 |
| Steady State Error/|·| | 0.33 | 0.42 | | 0.32 | 2.92 |

|  |  |  |
| --- | --- | --- |
|  | *50% Disturbance rejection* | |
| *CNSN* | *CC-PID* | |
| Initial overshoot/% | 12.9 | 12.9 | |
| Settling Time/s | 215 | 216 | |
| Disturbance Overshoot/% | 22.4 | 24.3 | |
| Recover Time/s | 220 | 230 | |
| Steady State Error/|·| | 0.33 | 5.12 | |

# Conclusions

This paper presents a novel stretching network based on the cytokine network in human body for cooperative online re-allocation of the desired ratios in multi-stage stretching systems, resulting in a much smaller steady-state tracking error and better ability to reject disturbances. The proposed controller, termed CNSN, is inspired from the autonomous immune system in the human body and plays a crucial role in perception of environment, coordination within the sub-processes, as well as accurate tracking of the desired states. An optimization algorithm is adopted to tune the set-up points of the stretching ratios in different stretching units. To the best of our knowledge, online reallocation of the stretching rations has not been reported in the literature.

The cytokine network system has also a high degree of flexibility and can be extended to other complex chemical processes consisting of multiple layers. In the future, we will not only work on further improvement of online allocation of the stretching ratios, but also on the development of more effective and intelligent control structure based on the cytokine network and immune mechanisms for reducing the difficulty of design and modeling for high performance requirements and more complex production systems.

References

1. R. Sedghi, I. Farsani, and A. Shokufar, “The effect of commercial polyacrylonitrile fibers characterizations on the produced carbon fibers properties”[J], *J. Mater. Process. Tech.*, vol. 198, no. 1-3, pp. 60-67, Mar. 2008.
2. L.-J. Tan, H.-F. Chen, D. Pan, and N. Pan, “Investigating the spin ability in the dry-jet wet spinning of PAN precursor fiber”[J], *Journal of Applied Polymer Science*, vol. 110, pp. 1997-2000, 2008.
3. S. Wang, Z.-H. Chen, W.-J. Ma, and Q.-S. Ma, “Influence of heat treatment on physicalchemical properties of PAN-based carbon fiber”[J], *Ceramics International*, vol. 32, no. 3, pp. 291-295, Mar. 2006.
4. J. C. Chen, I. R. Harrison, “Modification of polyacrylonitrile (PAN) carbon fiber precursor via post-spinning plasticization and stretching in dimethyl formamide (DMF)”[J], [*Carbon*](http://www.sciencedirect.com/science/journal/00086223), vol. 40, no. 1, pp. 25-45.Jan. 2002.
5. C. Mitsantisuk, K. Ohishi, and S. Katsura, "Control of interaction force of twin direct-drive motor system using variable wire rope tension with multisensor integration"[J], *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 498-510, Jan. 2012.
6. J. G. Juang, M.-T. Huang, and W.-K. Liu, “PID control using presearched genetic algorithms for a MIMO system”[J], *IEEE Trans. Systems, Man, and Cybernetic- Part C, Appli**cations and Reviews*, vol. 38, no. 5, pp. 716-727, Sept. 2008.
7. J. Q. Han, “From PID to active disturbance rejection control”[J], *IEEE Trans. Industrial Electronics*, vol. 56, no. 3, pp. 900-906, Mar. 2009.
8. P. R. Pagilla, N. B. Siraskar, R. V. Dwivedula, “Decentralized control of Web processing lines”[J], *IEEE Transactions on Control Systems Technology*, vol. 15, no. 1, Jan. 2007.
9. S. Mehraeen and S. Jagannathan, "Decentralized optimal control of a class of interconnected nonlinear discrete-time systems by using online Hamilton-Jacobi-Bellman formulation"[J],  *IEEE Trans. Neural Netw.*, vol. 22, no. 11, pp.1757-1769, 2011.
10. P. Li and J. Lam, "Decentralized control of compartmental networks with h-infty tracking performance"[J], *IEEE Trans. Industrial Electronics,* vol. 60, no. 2,pp. 546 – 553, Feb. 2013.
11. H. Koc, D. Knittel, M. de Mathelin, and G. Abba, "Modeling and robust control of winding systems for elastic webs"[J], *IEEE Transactions on Control Systems Technology*, vol. 10, no. 2, pp. 197-208, 2002.
12. R.-J. Wai, “Robust control for nonlinear motor-mechanism coupling system using wavelet neural network”[J], *IEEE Trans. Syst., Man, Cybern., PartB: Cybern*., vol. 33, no. 3, pp. 489-497, Jun. 2003.
13. N. R. Abjadi, J. Soltain, J. Askari, and G. R. A. Markadeh, “Nonlinear sliding-mode control of a multi-motor web-winding system without tension control”[J], *IET Control Theory Applications*, vol. 3, no. 4, pp. 419-427, Mar. 2008.
14. R. A. Hess and S. R. Wells, “Sliding mode control applied to reconfigurable flight control design”[J], *Journal of Guidance, Control, and Dynamics*, vol. 26, no. 3, pp. 452-462, 2003.
15. C.-L.Wang. “Multivariable adaptive backstepping control: A norm estimation approach”[J], *IEEE Trans. Automatic Control*, vol. 57, no. 4, pp. 989-995, April 2012.
16. Z. Z. Wuand and A. Iqbal, “LMI-based multivariable PID controller design and its application to the control of the surface shape of magnetic fluid deformable mirrors”[J], *IEEE Transactions on Control Systems Technology*, vol. 19, no. 4, pp. 717-729, July. 2011.
17. T. N. Luan. Vu and M. Lee, “Multi-loop PI controller design based on the direct synthesis for interacting multi-time delay processes”[J], *The International Society of Automation Transactions,* vol. 49, no. 1, Jan. 2010.
18. T.-L. Chien, C.-C. Chen, and C.-J. Huang, “Feedback linearization control and its application to MIMO cancer immunotherapy”[J], *IEEE Trans. on Control Syst. Technol*., vol. 18, no 4, pp. 953-961, July. 2010.
19. Y.-S. Ding and B. Liu, “An intelligent bi-cooperative decoupling control approach based on modulation mechanism of internal environment in body”[J], *IEEE Transactions on Control Systems Technology*, vol. 19, no. 3, pp. 692-698, Mar. 2011.
20. X. Liang, Y.-S. Ding, L.-H. Ren, K.-R. Hao, H.-P. Wang, and J.-J. Chen, “A bio-inspired multilayered intelligent cooperative controller for stretching process of fiber production”[J], *IEEE Trans. Systems, man, and cybernetics-Part C: Applications and reviews*, vol. 42, no. 3, pp. 367–377, May. 2012.
21. Y.-S. Ding, X. Liang, K.-R. Hao, and H.-P. Wang, “An intelligent cooperative decoupling controller for coagulation bath in polyacrylonitrile carbon fiber production”[J], *IEEE Trans. Control Systems Technology*, 2013, 21(2): 467-479.
22. J. Chen , X. Cao , P. Cheng , Y. Xiao and Y. Sun,  "Distributed collaborative control for industrial automation with wireless sensor and actuator networks"[J],  *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp.4219 -4230, 2010.
23. T. N. Nguyen, S. Su, and H. Nguyen, "Robust neuro-sliding mode multivariable control strategy for powered wheelchairs"[J], *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 19, no. 1, pp. 105 -111, Feb. 2011.
24. [Z.-Z. Wu](http://ieeexplore.ieee.org/search/searchresult.jsp?searchWithin=p_Authors:.QT.Zhizheng%20Wu.QT.&searchWithin=p_Author_Ids:37291503100&newsearch=true), “LMI-Based Multivariable PID controller design and its application to the control of the surface shape of magnetic fluid deformable mirrors”[J], *IEEE Trans. Control Systems Technology*, vol. 19, no. 4, pp. 717-729., July. 2011.
25. L. S. Farhy, “Modeling of oscillations of endocrine networks with feedback”[C], *Methods Enzymol*, vol. 384, pp. 54-81, 2004.
26. A. Hone, “Modeling a cytokine network”[C], *2007 IEEE Symposium on* [*Foundations of Computational Intelligence,*](http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=4233874) pp. 389 - 393, April. 2007
27. M. Bodson, "Evaluation of Optimization Methods for Control Allocation”[J], *Journal of Guidance, Control and Dynamics*, vol. 25, no. 4, pp. 703-711,2002.
28. J. Tjonnas and T. A. Johansen  "Stabilization of automotive vehicles using active steering and adaptive brake control allocation”,[J]  *IEEE Trans. Control Syst. Technol.*, vol. 18, no. 3, pp.545 -558, 2010.
29. Y.-F. Hu, Y.-S. Ding, and K.-R. Hao, “An immune cooperative particle swarm optimization algorithm for fault-tolerant routing optimization in heterogeneous wireless sensor networks”[J], *Mathematical Problems in Engineering*, vol. 2012, pp.1-19, 2012.
30. X.-H. Cao, P. Cheng, J.-M.Chen, and Y.-X. Sun, "An online optimization approach for control and communication codesign in networked cyber-physical systems”,[J].*IEEE Trans. Industrial Informatics*,vol. 9, no. 1, pp. 439 – 450, Feb. 2013.
31. S. Skogestad, “Self-optimizing control: The missing link between steady-state optimization and control”[J], *Computers & Chemical Engineering*, vol. 24, no. 2, pp. 569-575, May. 2000.
32. N. K. Jerne and J. Cocteau, “Idiotypic networks and other preconceived ideas”[J], *Immunological reviews*, vol. 79, no. 1, pp. 5-24, June. 1984.
33. J. D. Farmer, S. A. Kauffman, N. H. Packard, et al. “Adaptive dynamic networks as models for the immune system and autocatalytic sets”[J], *Annals of the New York Academy of Science,* vol. 504, no. 1, pp. 118-131, June. 1987.
34. Y.-F. Hu, Y.-S. Ding, K.-R. Hao, L.-H. Ren and H. Han. “An immune orthogonal learning particle swarm optimization algorithm for routing recovery of wireless sensor networks with mobile sink“[J]. International Journal of Systems Science, 2014, 45 (3): 337-350.

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