Recent Advances in Industrial Control

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***Abstract*—The paper presents the state-of-the-art study on the recently published literatures subjected to industrial control in various industrial applications. Controllers are classified into several types according to different control technologies, including PID algorithm, Kalman filter, least squares regression, network-based automation, fuzzy inference systems, neural networks, radial basis function networks, sliding-mode based control and so on. For each paper, a brief summary is given to introduce the related control technologies and applications.**

***Index Terms*—Industrial Control, PID algorithm, neural networks, fuzzy inference systems, sliding-mode control**

I. INTRODUCTION

A controller acts as an estimator which provides proper key parameters in order to maintain the good functionalities of the whole system. With decades of research and development, industrial control has already been recognized as a complete discipline, and it tends to become an interdisciplinary field with many subjects, such as software computing and communication technologies. In this paper, we will study the recently published literatures and give an overview about the current research interest in industrial control realm. The literatures are classified by different control technologies as follows.

II. CLASSICAL METHODS

A. PID Controllers

The proportional-Integral-Differential (PID) algorithm is the most popular control technology and can be easily implemented in both software and hardware.

Khan *et al.* [1] proposed a wavelet-based multiresolution proportional-integral-derivative (PID) (MRPID) controller for temperature control. The temperature error of actual and command temperatures of a thermal system was decomposed into different frequency components at various scales of the discrete wavelet transform (DWT). The temperature-control signal was generated from the second-level wavelet-transformed details and approximation coefficients of temperature error of the DWT. Theoretical simulation and experimental results showed that the proposed wavelet-based MRPID controller was superior to both the conventional PID controller and adaptive neural network controller for temperature control of the thermal systems.

Wai *et al.* [2] presented the design of a real-time particle swarm optimization (PSO) based proportional integral differential (PID) control scheme for the levitated balancing and propulsive positioning of a magnetic-levitation (maglev) transportation system. The proposed controller incorporated the real-time PID control methodology and PSO gain selections, which ensured the stability of the controlled system without the requirement of strict constraints, detailed system information, and auxiliary compensated controllers despite the existence of uncertainties. Experimental results showed that the proposed PSO-PID control scheme for the maglev transportation system was superior to both fixed-gain PSO-PID control and conventional sliding-mode control strategies.

Solid oxide fuel cells (SOFC) could be considered as a promising alternative for large-scale electricity production. Sendjaja *et al.* [3] systematically designed a simple and reliable decentralized proportional-integral-derivative (PID) controller based on a benchmark nonlinear dynamic model of SOFC. The controlled variables were maintained at constant setpoints so as to facilitate constraint satisfaction for all key variables. Close-loop simulations showed that the proposed decentralized PI controllers were able to closely meet the control objects of SOFC even in the presence of changing operating conditions.

Efe *et al*. [4] proposed a proportional-integral-derivative (PID) based controller for unmanned aerial vehicles (UAVs) control. Neural networks were adopted in the proposed PID controller to provide the coefficients of a finite impulse response (FIR) type approximator. Experimental results showed that the neural network aided FIR type PID controller was very successful in driving the vehicle to prescribed trajectories accurately.

B. Kalman Filter

Kim *el al.* [5] studied the fault tolerance of electronic devices in intelligent vehicles and proposed a fault-detection algorithm based on the Kalman filter concept. The proposed algorithm was modeled in the Kalman predictive redundancy system which was capable of eliminating the effect of faults. The Kalman predictive redundancy system was implemented using an embedded microcontroller. Experimental results show that the Kalman predictive redundancy system can ensure the fault-tolerance of safety-critical systems over well-known average and median voters.

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Jana [6] proposed a nonlinear feedback linearizing control (FLC) strategy within the differential geometric framework for temperature control of a refinery debutanizer column. In the proposed controller, the extended Kalman filter (EKF) and short-cut model-based open-loop estimator (SMBOLE) had been developed using an ideal binary distillation model to device the hybrid FLC-EKF and FLC-SMBOLE control systems, respectively. Experimental results demonstrated that the proposed FLC controllers performed better than the traditional PID control scheme despite the significant process/model mismatch.

C. Least Squares Regression

Wang *et al.* [7] introduced a novel soft sensor technology based on partial least squares (PLS) regression with online prediction ability and enhanced dynamics in data process. The modeling is mainly concerned on data preprocessing, multivariate-outlier detection, and variables selection. The proposed approach was applied to data from a refining process for quality prediction and evaluated by comparing with neural network (NN) based soft sensor. The experimental results show that the proposed PLS soft sensor got very similar precision with NN-based soft sensor, but the former one was more suitable for online deployment.

Zhang *et al.* [8] proposed a decentralized fault diagnosis approach of complex process based on multiblock kernel partial least squares (MBKPLS) used to monitor large-scale processes. The advantages of the proposed MBKPLS were demonstrated by comparing with other methods, such as partial least squares (PLS), kernel partial least squares (KPLS), and multiblock partial least squares (MBPLS). The proposed was applied to process monitoring of a continuous annealing process and the experimental results showed that the proposed decentralized monitoring scheme effectively captured the complex relations in the process and improved the diagnosis ability tremendously.

Zhou *et al.* [9] introduced a formal decision software tool based on a formal mathematical approach that selects dominant features using the singular value decomposition of real-time measurements from the sensors of an industrial cutting tool. The tool was used to extract the dominant features enabling tool wear prediction. Also the identified dominant features were used with the recursive least squares (RLS) algorithm to identify parameters in forecasting the time series of cutting tool wear. Experimental results on an industrial high-speed milling machine demonstrated the effectiveness in predicting the tool wear using only the dominant features.

III. Network Based Control

Networked control systems consist of different devices, such as sensors, actuators and controllers, which are connected under a shared communication medium.

Huang *et al.* [10] studied the network-induced delay in networked cascade control systems (NCCSs) with state feedback controllers. They proposed the sufficient conditions for the asymptotically stability of the NCCSs with or without disturbances, and derived the state feedback stabilization control laws via Lyapunov stability theory and linear matrix inequality (LMI) approach. The proposed approaches were applied to simulate the main steam temperature in a power plant and their effectiveness was demonstrated.

Lai *et al.* [11] proposed a remote network control system (NCS) structure by implementing the adaptive Smith predictor using an online time-delay estimator. The key issue, time-delay in NCS, was estimated online by measuring he round-trip time (RTT) between the application layers of the server and the client. The adaptive Smith predictor control scheme is developed based on the estimated time-delay. The proposed design was applied to an AC 400 W servo motor tested from a 15 km distance, and the experimental results shows the significantly improved stability and motion accuracy by using the proposed approach.

Cuenca *et al.* [12] introduced a methodology to design controllers which were capable of coping with different load conditions on an Ethernet network. Delay-dependent gain scheduling law was used to handle the time-varying delays between measurements and control induced by load conditions. An event-based control approach was applied to solve the synchronization problem, and the stability was proved in terms of probabilistic linear matrix inequalities. The proposed control scheme was validated by both simulations and experiments on an Ethernet test-bed.

Marti *et al.* [13] presented a novel approach to networked control systems (NCSs) analysis and design which provided increased control performance for a set of control loops that share a single controller area network (CAN). In each control loop, standard periodic messaging was guaranteed to ensure stability; then non-periodic additional messaging was added whenever bandwidth was available. The proposed approach was validated based on a proof-of-concept implementation, and experimental results showed that the proposed approach could be implemented in practice.

IV. Methods of Computational Intelligence

A. Fuzzy Controllers

Li *et al.* [14] presented the dynamic fuzzy controller combined with two synergic PID controllers to simultaneously control both fluid- and radiation-based cooling mechanisms, in order to dissipate exhaust heat of onboard electronic components inside spacecraft to the outer space environment. By numerical evaluation, the proposed fuzzy coordination controller was demonstrated to have a better performance than single-input PID controllers in terms of its ability to leverage between two actuators in rejecting disturbances and preventing over-manipulations.

Suetake *et al.* [15] presented a compact embedded fuzzy system for three-phase induction-motor scalar speed control. The control strategy was to keep constant the voltage-frequency ratio of the induction-motor supply source. Using speed error and speed-error variation, the proposed fuzzy controller changed both the fundamental voltage amplitude and frequency of a sinusoidal pulse-width-modulation (PWM) inverter. A comparative study was performed by implementing the proposed fuzzy controller, PID controller, and PI controller on digital signal processors.

Abiyev *et al.* [16] presented a type 2 Takagi-Sugeno-Kang fuzzy neural system with a parameter update rule derived based on fuzzy clustering and gradient learning algorithm. The performance of the proposed type 2 TSK system was evaluated and compared with other approaches based on sufficient literature study. The simulation results indicated the potentially good performance of the proposed structure for identification and control of dynamics plants.

Orlowska-Kowalska *et al.* [17] developed an adaptive speed controller based on a fuzzy neural network model. Connective weights of the hybrid neuro-fuzzy controller were tuned online according to the error between the estimated motor speed and the speed given by the reference model. The proposed controller was applied for speed estimation in a sensorless induction motor (IM) drive with elastic joint. Experimental results showed that, the proposed neuro-fuzzy controller performed smooth control, even without mechanical speed sensor in the two-mass induction motor drive.

B. Neural Networks based Control

By analyzing the architectures of traditional fuzzy inference systems, neuro-fuzzy systems, and neural networks, Xie *et al.* [18] interpreted the architecture of fuzzy inference systems by specially structured neural networks: (1) fuzzy membership function was decomposed as the sum of two neural activation functions; (2) fuzzy rules was transformed as an area selection by neurons; (3) defuzzification process was replaced by linear output neurons with weighted inputs. The equivalence of fuzzy inference systems and the specially designed neural networks was demonstrated by a case study.

Monmasson *et al.* [19] presented a survey on field programmable gate arrays (FPGAs) in industrial control applications. As a case study, an Extended Kalman filter based controller was designed and implemented in Xilinx FPGA in order to control a sensorless motor. A dedicated design methodology was discussed. Also, another two case studies of neural network control systems were designed and implemented in FPGA for induction motor control and electronics nose for pattern recognition, respectively. Feedforward backpropagation networks were applied for network construction and trained online.

Orlowska-Kowalska *et al.* [20] presented a practical realization of a neural network (NN)-based estimator of the load machine speed for a drive system with elastic coupling. The multilayer perceptron (MLP) networks were implemented in the FPGA placed inside the NI CompactRIO controller. Levenberg Marquardt algorithm [21] was applied for neural network training. The neural estimators were tested both offline (based on the measured testing dataset) and online (in the closed-loop control structure). Those estimators were also tested for changeable inertia moment of the load machine of the drive system with elastic joint. Experimental results showed that the proposed MLP network based estimators performed a high-quality state variable estimation of the two-mass drive system.

The recently developed neuron-by-neuron (NBN) algorithm [22-23] makes it possible to design more powerful network architectures with improved performance for control surface approximation [24]. Cotton *et al.* [25] implanted arbitrarily connected neural (ACN) networks in microcontrollers used for nonlinear compensation in dynamic system design. The ACN networks were trained by NBN algorithm. Malinowski *et al.* [26] presents a comparison study between neural networks and fuzzy inference systems from the points of computation complexity and quality of performance. Powerful fully connected cascade neural (FCC) networks designed by NBN algorithm were implemented in a microprocessor and applied to solve the two-dimension forward kinematics problem.

C. Radial Basis Function Networks

Yu *et al.* [27] present a survey study on radial basis function (RBF) networks, including network construction and training algorithms. In this literature, neural networks and fuzzy inference systems were compared with RBF networks from the points of design and functionality. Experimental results showed that RBF networks were more proper for dynamic system design because of the simple design process, strong tolerance to input noise, and good generalization ability.

Lin *et al.* [28] proposed a hybrid self-organizing fuzzy and radial basis function neural network controller (HSFRBNC). The parameter selection problem in a traditional self-organizing fuzzy controller (SOFC) was solved by incorporating radial basis function neural networks. The proposed HSFRBNC was applied in manipulating an active suspension system, and the simulation results showed that the proposed controller performed better than the SOFC in improving the service life of the suspension system and the ride comfort of a car.

Cai *et al.* [29] presented a fuzzy radial basis function network (FRBFN) longitudinal controller for intelligent cruise control of semiautonomous vehicles. The proposed FRBFN controller inherited the advantages of fuzzy logic, such as easy design, and radial basis function networks, such as accurate approximation. The proposed control algorithm was tested by a small-scaled vehicle with computer and sensors onboard. The experimental results showed that the proposed controller was able to perform a smoother control process than traditional PID controller.

Tsai *et al.* [30] introduced an adaptive controller using radial-basis-function neural networks (RBFNNs). The proposed control system was decomposed into two subsystems, yaw motion and mobile inverted pendulum, controlled by two separated RBFNN controllers which achieved self-balancing and yaw control, respectively. The proposed control algorithm was implemented in a two-wheeled self-balancing scooter. Experimental results showed that the proposed controller was useful and effective in providing appropriate control action to steer the vehicle at slow speeds.

D. *Genetic Algorithm*

Lo *et al.* [31] proposed a hybrid technique based on fuzzy logic and genetic algorithm for automatically detecting failures in aircraft. The fault detection system was constructed by the proposed fuzzy-genetic algorithm for monitoring aircraft behaviors. Fuzzy-based classifier was employed to estimate the time of occurrence and types of actuator failure; while genetic algorithm provided an efficient and effective way to generate optimal fuzzy rules. The proposed fault detection system was validated by different actuator failures of the nonlinear F-16 aircraft model.

V. SLIDING-MODE CONTROL

Sliding-mode control (SMC) has been studied extensively for over 50 years and widely used in practical applications due to its simplicity and robustness against parameter variations and disturbances. In [32], Yu and Kaynak provided the state-of-the- art of recent developments in SMC system with software computing, examining key technical research issues, and future perspectives.

Mehta *et al.* [33] presented a method for a frequency-shaped sliding mode control using output feedback. A compensator was designed in the sliding surface to attenuate the certain component of the sliding mode dynamics. The output of the controller was measured at a faster rate than the control input used to estimate the states of the system. The proposed output feedback frequency-shaped sliding mode controller was tested in the vibration suppression of intelligence structure, and the experimental results demonstrated the efficacy of the method.

Zhang *et al.* [34] designed a second-order sliding mode controller based on the integrated dynamic congestion control strategy and a leader-follower control scheme. The analyzed control laws were continuous without the chattering effect and more acceptable in applications. The proposed controller was applied to control DiffServ Network, and its performance was verified by the simulation results.

Defoort *et al.* [35] developed a controller based on third-order sliding-mode control with which a desired angular motor position was accurately tracked. The measurement or the estimation of the motor speed and acceleration were considered as feedback in the proposed control scheme. By introducing a robust second-order sliding-mode observer, tachometers and accelerometers were removed in the control system so as to reduce the cost and energy consumption. Experimental results validated the advantages of the proposed controller.

Rao *et al.* [36] proposed an observer-based solution to control the speed of induction motors without speed and flux sensors. Two observers were designed with inputs that enforced first- and second-order sliding models, respectively, in order to provide motor speed, flux, and rotor resistance estimation simultaneously. Experimental results demonstrated that only current and input voltage measurements were required for accurate speed and flux estimation even in the presence of unknown parameters.

Considering the geometric-stabilization mechanisms due to a bicycle trial, Defoort *et al.* [37] presented a dynamic model of an autonomous bicycle. First, a posture controller was designed by combining second-order sliding-mode control and disturbance observer. Then, an innovative tracking controller was designed based on the posture controller and the dynamic-inversion framework. Simulation and experimental results verified the performances of the proposed strategies for the stabilization and tracking problems.

Ghanes *et al.* [38] designed a sensorless output feedback controller in order to drive the induction motor (IM) without the use of flux and speed sensors. First, a novel sliding-mode observer was synthesized to estimate the speed, flux, and load torque. Then, a current-based field-oriented sliding-mode control scheme was developed to steer the estimated speed and flux magnitude to the desired references. The stability analysis of the proposed control system was derived based on Lyapunov theory. Two experimental results for a 1.5 kW IM validated the performances of the proposed controller.

Silva *et al.* [39] proposed the static-output-feedback (SOF) and compensator-based sliding-mode controllers for plants with matched and mismatched uncertainties. The control law consisted of both linear and nonlinear components: the linear component was synthesized numerically using linear matrix inequalities (LMIs) through a polytopic formulation; the nonlinear component took into count matched uncertainties or nonlinearities. Experimental results demonstrated the efficacy of the proposed controllers.

Liang *et al.* [40] proposed a control scheme by combining the Takagi-Sugeno (T-S) fuzzy system modeling method and the sliding-mode control (SMC) technique. Inheriting the merits of both approaches, the proposed controller not only alleviated the online computational burden, but also preserved the advantages of the SMC schemes, such as rapid response and robustness. Both the active and the passive reliable designs were presented and applied to the attitude control of a spacescraft. The experimental results showed the promised benefits of the proposed controller.

Wang *et al.* [41] proposed a neural-network-based terminal sliding-mode control (SMC) scheme for robotic manipulators including actuator dynamics. The proposed terminal SMC (TSMC) alleviated some main drawbacks in the linear SMC while maintaining its robustness to the uncertainties. A radial basis function neural network with a robust error estimator was adopted to approximate the nonlinear dynamics of the robotic manipulator. Experimental results demonstrated the validity of the proposed control scheme by comparing it with other control strategies.

Beltran *et al.* [42] proposed a high-order sliding-mode control strategy to ensure stability in both two operation regions and to impose the ideal feedback control solution in spite of model uncertainties. The proposed sliding-mode control approach was validated on a 1.5-MW three-blade wind turbine using the National Renewable Energy Laboratory wind turbine simulator FAST (Fatigue, Aerodynamics, Structures and Turbulence) code. Experimental results showed that the proposed control strategy was effective in terms of power regulation and produced no chattering in the generated torque.

Feng *et al.* [43] proposed a hybrid terminal sliding-mode observer based on the nonsingular terminal sliding-mode (NTSM) and the high-order sliding-mode (HOSM) for the rotor position and speed estimation in the permanent-magnet synchronous motor control system. The NTSM manifold was utilized to realize both fast convergence and better tracking precision; the HOSM control law was designed to guarantee the stability of the observer and eliminated the chattering. Simulation and experimental results verified the proposed method.

VI. Other Methods

Ebiere *et al.* [44] proposed a novel monitoring technique using the canonical variate analysis (CAV) with the upper control limits (UCLs) which was derived from the estimated probability density function through kernel density estimations (KDEs). Several approaches were applied to monitor the simulated nonlinear Tennessee Eastman Process Plant. Comparing with traditional CAV approaches, the proposed CAV with KDE approach significantly improved the monitoring performance: higher reliability and earlier fault detection.

Zheng *et al.* [45] studied the performance, stability conditions, and the large deviation issue of the exponential weighted moving average (EWMA) run-to-run control, based on which a cycled resetting (CR) algorithm for discount factor was proposed in order to reduce the large deviations, as well as to achieve the minimum asymptotic variance control. Simulation study was provided to verify the effectiveness of the proposed approach.

Hur *et al.* [46] proposed a novel model-based cross-directional (CD) controller to control a plastic file manufacturing web process. The proposed controller had similar structure with internal model control (IMC) but with an additional observer. The gain of the observer was selected to minimize process and model mismatch by solving a multiobjective optimization problem through a genetic algorithm. Simulation results showed that the proposed controller was superior over two existing CD controllers.

Ling *et al.* [47] derived a formula to calculate the integral-square-error (ISE) performance of a multiplexed model predictive control (MMPC) controlled system. With a given plant and disturbance models, the ISE formula allowed one to investigate how the ISE changed with control design parameters. Suitable sampling interval for the MMPC design could be selected to achieve the desired ISE performance. The proposed ISE formula was validated on a multizone semiconductor manufacturing thermal process.

Based on the study of the kinetic and dynamic behaviors of haptic communication system for cardiac surgery, Sakaino *et al.* [48] proposed a novel hybrid controller for the decoupling of the responses and analyzed its performance, stability and robustness. Simulations and experimental results showed that the proposed method could perform effective control toward cardiac surgery.

Wang *et al.* [49] presented a two-layer coordinated CPU utilization architecture with theoretically guaranteed control accuracy and system stability. The primary control loop used frequency scaling to locally control the CPU utilization of each processor; the secondary control loop adopted rate adaption to control the utilizations of all the processors at the cluster level on a finer timescale. The experimental results showed that the proposed controller achieved higher accuracy and less power consumption than a state-of-the-art utilization control algorithm. Also, the feasibility of utilization control was significantly improved using the proposed control solution.

VII. Concluding Remarks

The paper introduced the recent research work of industrial control in various industrial applications. As an interdiscipline connected to computer and communication realms, industrial control is embracing cutting-edge informatics technology. More and more novel applications are opened up, and they significantly impact the continuous development of industrial control technologies.

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