Guest Editorial
Special Section on Data-Driven Approaches for Complex Industrial Systems

TODAY'S industry processes, for instance, those in heavy industries (e.g., papermaking, steelmaking, petrochemical and power generation), are becoming more and more complex. In order to operate the processes efficiently, improved understanding of the intricate interactions between process variables is required. Mathematical modeling offers ways to gain deeper understanding of the interdependence between variables of the processes. However, if the system studied is excessively complex, stochastic, hybrid, time-varying or highly nonlinear, it may not be possible or feasible to develop a first-principle model. In such cases data-driven models, based on novel nonlinear signal processing and data analysis techniques, may provide an attractive alternative.

Data-driven methods are a potential technique to describe complex behavior, and have proven to be a powerful modeling alternative for many industrial systems. A distinct feature of data-driven methods is that no prior information about the process is necessary. Due to this, such methods are today playing an important role in the modeling, control and optimization of complex industrial systems since the mechanism-based methods often fail to work due to difficulty in describing unexpected disturbances and weak real-time service. Along with the development of computer hardware and software and sensor technology, it is today common in industrial processes to record and store thousands or tens of thousands of various online measurements, which greatly stimulate the research and development for modeling, monitoring, control, and optimization by using data-based methods.

It is our pleasure to present this Special Issue on "Data-Driven Approaches for Complex Industrial Systems" of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, which provides a forum for researchers and practitioners to report recent results on data-driven methods with applications to complex industrial systems, and to identify critical issues and challenges for future investigations in this field.

Roughly, data-driven methods can be categorized into three sets, i.e., data-driven modeling, data-driven monitoring and fault diagnosis, and data-driven control and optimization (cf. Fig. 1). In this Special Issue, 13 papers are selected with novel contributions in data-driven modeling, data-driven monitoring and diagnosis, data-driven control and their industrial applications, respectively.

This Special Issue is initiated by two survey papers. The paper contributed by Saxén *et al.* [1], reviews discrete-time black-box models particularly for short-term time discrete prediction of the silicon content of hot metal produced in blast furnaces. Linear and nonlinear models are treated separately, and within each group a rough subdivision according to the model type is made. The principles behind the modeling approaches, the signals used and the main findings in terms of accuracy and usefulness are revisited and commented. Some potential lines of future research of data-driven modeling are also proposed.

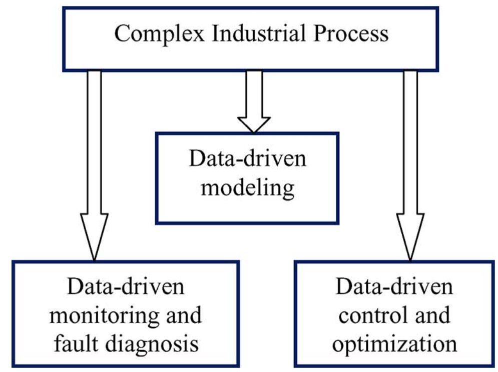

Fig. 1. Data-driven methods.

The second survey paper contributed by Dai and Gao[2], gives an overview of fault detection and diagnosis (FDD) in complex systems from the perspective of data processing. A variety of FDD techniques are reviewed within the unified data-processing framework to give a full picture of FDD and achieve a new level of understanding. According to the type of data and how the data are processed, the FDD methods are classified into three categories: model-based online data driven methods, signal-based methods and knowledge-based history data driven methods. An outlook to the possible evolution of FDD in industrial automation, including the hybrid FDD and the emerging networked FDD, is also presented to predict the future development direction in this field.

In the paper by Ding *et al.*[3], a data-driven approach of key performance indicator (KPI) prediction and diagnosis is proposed for complex industrial processes. By means of a data-driven realization of the so-called left co-prime factorization of a process, efficient KPI prediction and diagnosis algorithms are developed for dynamic processes, respectively, with and without measurable KPIs. The proposed KPI prediction and diagnosis scheme is applied to an industrial hot strip mill, demonstrating its effectiveness.

The electro-fused magnesia furnace (EFMF) has complex characteristics, such as strong nonlinearity and multi-modes. In

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the paper by Zhang and Li [4], a new method is proposed for between-mode part to establish an integrated monitoring system, which would simplify the monitoring model structure and enhance its robustness. Based on subspace separation, process information is captured across modes and between-mode transition regions are distinguished from two modes. Two modes and between-mode transition models are developed, respectively, for multimode processes monitoring with experiments verification.

On the basis of classification techniques, the paper by Cococcioni *et al.* [5] presents a method for automatic detection and diagnosis of defects of rolling element bearings. Using the experimental data set and the proposed algorithm, the authors report that classification accuracy higher than 99% was achieved in all the experiments performed on the vibration signals represented in the frequency domain, thus proving the high sensitivity of the method to different types of defects and to different degrees of fault severity. The degree of robustness of the method to noise is also assessed by analyzing how the classification performance varies with the signal-to-noise ratio and using statistical classifiers and neural networks.

In the paper by Grbovic *et al.* [6], cold start learning problem in data-driven fault detection is investigated, where at the beginning only normal operation data are available and faulty operation data become available as the faults occur. The authors explore how to leverage strengths of unsupervised and supervised approaches to build a model capable of detecting faults effectively. The proposed framework was evaluated on the benchmark Tennessee Eastman Process data, indicating that the proposed fusion model performed better on both unseen and seen faults compared with the standalone unsupervised and supervised models.

Da Silva *et al.* [7] present a robust method to monitor the operating conditions of induction motors, which utilizes the data analysis of the air-gap torque profile in conjunction with a Bayesian classifier for determining the operating condition of an induction motor as either healthy or faulty. This method is trained offline with data sets generated either from an induction motor modeled by a time-stepping finite-element method or experimental data, which can effectively monitor the operating conditions of induction motors that are different in frame/class, ratings, or design from the motor used in the training stage. The experimental results validate the robustness and efficacy of the method.

In the paper by Wang and Liu [8], a data-based real-time state feedback control method is developed for a class of nonlinear systems. A fast sampling technique is applied to sample the state signal, and the zero-order hold (ZOH) and the control switch are used to obtain system information. The feedback gain matrix is calculated and adjusted according to these sampled data, and the method is demonstrated by convergence analysis and simulated results.

The paper by Formentin and Karimi [9] presents a data-driven approach to tune fixed-order controllers for unknown stable linear-time invariant plants in a mixed-sensitivity loop-shaping framework. The method requires a single set of input-output sampled data, and utilizes convex optimization techniques and internal stability analysis. The effectiveness of the method is illustrated with application to the control of an active suspension system.

In the paper by Hou and Zhu [10], a new type of model free adaptive control (MFAC) method is presented for a class of discrete-time single-input-single-output nonlinear systems. The proposed method is a pure data driven control method since the controller is independent of the model of the controlled plant, and controller parameter tuning is merely based on the measured input/output data of the controlled plant in closed loop. Differing from the MFAC prototype, the proposed method uses the dynamic linearization approach not only on ideal controller but also on the plant. The effectiveness is evaluated on simulation examples and a three-tank liquid control experimental system.

The paper contributed by *Chi et al.* [11] presents a new data-driven iterative feedback tuning approach to tune ALINEA controller gain automatically when there is not enough prior information available to select a proper feedback gain of ALINEA. To mimic a real traffic environment, a simulator is built on the PARAMICS platform, and the effectiveness of the proposed method is verified through PARAMICS-based simulations.

In the paper by Zheng *et al.* [12], a data-driven particle PHD filter is developed for real-time multitarget tracking of nonlinear/non-Gaussian system in dense clutter environment. Extensive simulations validate the improvement of both the real-time performance and tracking performance of the proposed data-driven particle PHD filter in comparison with the traditional particle PHD filter.

This Special Issue ends with a paper by Badac *et al.* [13], which proposes a data-driven algorithm that solves a reference trajectory tracking problem defined as an optimization problem. The new data-driven reference trajectory tracking algorithm solves the optimization problem in the framework of Iterative Learning Control. The tracking algorithm updates the reference input sequence using an experiment-based approach which accounts for operational constraints and employs an interior point barrier algorithm. A case study is included to validate the proposed algorithm by experimental and simulation results.

Data-driven methods are a powerful tool for complex industrial automation processes. The 13 selected papers have reflected recent progress in this research field to some extent and profundity. We hope this special issue may further stimulate the research interests in this direction from a variety of societies, particularly from the IEEE Industrial Electronics Society, and the Industrial Community. More effective data-driven research methods/algorithms and successful applications are expected.

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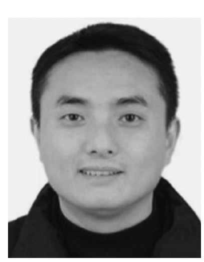

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