Guest Editorial
Special Issue on Current Research Trends and Open Challenges for Industrial Internet of Things

THE success of the Internet of Things has recently spread to the industrial sector, commonly referred to as Industrial IoT (IIoT). IIoT, which has a far-reaching impact on the operation of industries around the world, is recognized as a key enabler for the fourth industrial revolution. It has the potential to prompt economic growth and global competitiveness, in terms of improving productivity, efficiency, and so on.

Considering the massive-devices deployment, ubiquitous connectivity, heterogeneous traffic and quality-of-service requirements, and complex and dynamic transmission environment in IIoT, the full potential of IIoT is yet to be realized. This special issue presents emerging areas that can potentially be used to support and assist to solve open challenges in IIoT. Specifically, we dive deep into communications, sensing, computing, and control technologies that directly enhance the digitization, intelligence, and controllability of IIoT; we sought articles from the research community working in trustworthy IIoT, that are used for increasing the security and privacy levels of IIoT; we collected works on the topics of modeling, field trials, prototypes, and hardware realization of devices in IIoT.

Our special issue brought together researchers in these areas resulting in 29 high-quality accepted articles that were subdivided into the following categories: 1) communication, sensing, computing, and control in smart IIoT; 2) security and privacy in trustworthy IIoT; and 3) modeling, prototype, and field trials in IIoT.

I. Communication, Sensing, Computing, and Control in Smart IIoT

The emerging intelligent services of IIoT rely on ubiquitous connections, multidimensional information perception, supercomputing power, and deterministic-latency control. It puts forward high requirements for communication, sensing, computing, and control designs in IIoT.

Ultrareliable low-latency communication (URLLC) has been envisioned as the paradigm shift for wireless industrial automation in the coming Industry 4.0. However, despite its stringent latency and reliability requirements, URLLC still lacks deterministic low-jitter delivery in IIoT. Li et al. [A1] study low-latency and bandwidth-saving scheduling of time-triggered traffic in IIoT. The challenge lies in achieving deterministic scheduling with bounded end-to-end latency and low loss probability, due to queuing congestion and wireless link fluctuations. To ensure determinism and schedulability, the authors proposed to jointly optimize transmission delay, offset, bandwidth, and the number of subchannels.

In [A2], Zhao et al. investigate the problem of maximizing the sum semantic-aware transmission rate in an IIoT system with multiple reconfigurable intelligent surfaces (RISs) serving multiple users. The article considers the compute-then-transmit protocol for probabilistic semantic communication to reduce the transmission data size. The optimization problem involves jointly optimizing the semantic compression ratio, transmit power allocation, and distributed RIS deployment under various constraints. To solve this problem, the authors propose a many-to-many matching scheme for RIS–user association, a greedy policy for semantic compression ratio, and tensor-based beamforming for RIS phase shift optimization.

The integrated satellite–air–terrestrial network architecture is a promising solution to provide ubiquitous and seamless services, especially for outdoor IIoT applications. In [A3], Zhu et al. investigate a delay-optimized edge caching with diverse content popularity and user access modes. The authors propose a three-layer caching architecture, utilizing base stations, the satellite, and the gateway, to provide content services. To minimize the average content retrieving delay, the authors formulate a content placement problem, considering diverse content preferences in different areas.

In [A4], Xu et al. propose to use unmanned aerial vehicles (UAVs) and RIS to establish robust air-to-ground links and enhance wireless channels. The authors introduce device-to-device (D2D) communication techniques to enable direct information exchange between IoT devices. They prioritize optimizing energy efficiency for D2D users while ensuring quality of service for cellular users through joint optimization of transmit power, channel allocation, and RIS reflection coefficients, employing both centralized and distributed deep neural network-based algorithms.

In [A5], Cao et al. investigate a UAV-based emergency communication system where a terrestrial vehicle deploys multiple UAVs as aerial base stations (UAV-BSs) to cover a disaster-stricken area. The authors formulate a joint optimization problem to maximize throughput and coverage by considering UAV-BSs' dynamic deployment positions and the association policy between user equipment and base stations. In [A6], Yan et al. consider the fault-tolerant issue for UAV-aided data collection scenarios. Based on a three-layer data collection model, the proposed multiobjective algorithm

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optimizes the data throughput and load balancing of data collection.

Apart from URLLC, massive machine-type communication typically serves noncritical applications in IIoT. In [A7], Liu et al. design approximately mutually unbiased base (AMUB) sequences for massive connection in IIoT. The proposed approach addresses the limitations of existing orthogonal sequences, which often have small family sizes or strict length requirements. The authors modify the original MUB sequence generator from a quadratic to a cubic polynomial, increasing the number of available sequences by a factor of M (the MUB dimension). Theoretical analysis and numerical results confirm the low correlation properties of the proposed sequences, making them suitable for massive connection scenarios.

To address the remaining useful life prediction demand in multivariate time series, Li et al. [A8] propose an encoder–decoder model called DSFormer, built upon the transformer architecture. The encoder incorporates a dual-attention module to extract weight features from both sensor and time-series dimensions, compensating for the diverse impacts of different sensors on the prediction process. Additionally, a temporal convolutional network module is introduced to capture sequence features and mitigate the loss of positional information caused by stacking blocks. In the decoder, a feature decomposition module extracts trend features from sequences, providing the model with supplementary sequence information.

The combination of sensing and IIoT represents enabling the capability of converting environmental inputs (e.g., humidity, weight, liquid detection, and temperature) into readable data and transmitting the data to a centralized repository. It is a key enabler for smart IIoT. In [A9], Jia et al. deploy a lightweight spatial difference attention-based dynamic fusion module for edge data collection devices in IIoT. The proposed design empowers the capability of adaptive detection of salient objects of varying scales. In [A10], Alsattar et al. try to model IoT real-time monitoring devices, in order to minimize food loss and waste in supply chain systems. In [A11], Li et al. propose a lightweight fire target detection and precision segmentation model that can be used on UAVs, which enables accurate, flexible, and cost-effective detection performance of forest fires.

In [A12], Gao et al. attempt to address the challenges of handling missing data and capturing correlations between views in incomplete multiview clustering for IoT data. The proposed clustering network utilizes an unsupervised multiview information bottleneck and dual consistencies to improve pattern mining accuracy, particularly in extreme view missing scenarios.

Edge computing is able to analyze and process a portion of data using the computing, storage, and network resources distributed on the paths between data sources and the cloud computing center. Edge computing uses edge devices with sufficient computing power to implement local preprocessing of source data, thus enabling fast decision, reduced operational costs, and improved system performance for IIoT. In [A13], Liao et al. propose a RIS-assisted mobile-edge computing (MEC) network to enable low-latency data computation. To enhance task processing efficiency, the authors formulate an optimization problem that minimizes task processing time by jointly considering UAV flight route selection, USV execution mode selection, UAV hovering coordinates, and RIS phase shift vector. The authors then propose a heuristic solution that iteratively tackles this challenging problem by decoupling it into three subproblems.

In [A14], Lin et al. propose a Stackelberg-game-based computation offloading scheme for MEC in IIoT. While the mobile devices offload data for edge computing, the edge servers can gain revenue through a proposed resource pricing strategies.

In [A15], Yan et al. focus on the scenarios where the service provisioning capability of IIoT is impaired due to extreme events. They propose a UAV-aided service caching scheme based on the game theory, together with a deep Q-network-aided UAV position update scheme.

Smart manufacturing is a keyword in IIoT, which uses digital technologies to improve operational efficiency, productivity, and quality. In [A16], Ren et al. investigate monitoring accuracy-oriented task scheduling in the flight control system testing (FCST) process, where multiple factors in the testing process are identified for enabling a digital twin FCST.

Zhao et al. [A17] propose a reinforcement-learning-assisted framework to address the challenges in a warehouse cargo inspection scenario with multiple heterogeneous UAVs. As the existing heuristic algorithms struggle to balance solution time and quality, the authors propose a framework that utilizes a multiple traveling salesman transformation algorithm for task allocation and a multiagent reinforcement learning algorithm for conflict-free path finding.

II. Security and Privacy in Trustworthy IIoT

The rise of collaborative manufacturing and IIoT technologies has enhanced industrial agility and productivity but also increased vulnerabilities. The world's major information technology companies and standard organizations have stated the need for trustworthy IIoT. Many researchers have also proposed various techniques for constructing the trustworthiness of IIoT.

In [A18], Zeng et al. propose a cross-domain data-sharing scheme for data governance in IIoT. A zero-knowledge proof scheme is designed to verify data ownership confidentially and anonymously, together with a key agreement protocol for the purpose of security in data sharing.

In [A19], Jiang et al. propose a blockchain-reinforced federated learning architecture for cooperative intrusion detection in IIoT. It can secure the federated training process against man-in-the-middle attacks trying to disturb the client model.

In [A20], Wang et al. propose a secure cross-domain authentication scheme for space TT&C networks, aided by blockchain techniques for distributed key management. The proposed scheme can authenticate requests from different domains, achieve conditional privacy-preserving, and track malicious users.

In [A21], Chen et al. investigate the issue of jammer attacking in ambient backscatter communications. The proposed posterior probability detector and energy-threshold determination detector help receivers maintain a high level of symbol error rate performance against external jamming.

Deep learning (DL) and graph neural networks (GNNs) have become powerful tools for malware classification using control flow graphs (CFGs). However, the threat of adversarial attacks on these classifiers necessitates robust detection mechanisms. In [A22], Esmaeili et al. propose a GNN-based adversarial detector that learns normal data distribution to identify and filter out adversarial CFGs before classification, improving detection rates and reducing false positives compared to previous methods. In [A23], Zhang et al. focus on detecting malware on a large-scale sample set and identifying zero-day or new malware variants. The proposed malware retrieval and malware classification achieve enhanced malware classification and identification accuracy performance.

In [A24], Yin and Gong propose a lightweight certificateless signature scheme. The lightweight certificateless mutual authentication scheme proposed for IIoT is capable of key agreement and batch authentication, which demonstrates strong security properties and exhibits superior computational and communication efficiency compared to existing solutions.

In [A25], Javeed et al. investigate a DL-based intrusion detection design against distributed denial-of-service attacks in smart agricultures. The proposed design combines bidirectional gated recurrent unit and long short-term memory to detect attacks at the edge of the network, where the detection performance is verified with publicly available data sets.

III. Modeling, Prototype, and Hardware Design in IIoT

Evaluating system performance through modeling, prototype, and testing trials is an essential part of most early stage, exploratory, product development processes. The outcome also prompts a better understanding for developing IIoT-related technologies.

In [A26], Wan et al. propose the concept of RIS partition for the purpose of joint communication and security design. A 4.9-GHz RIS physical-layer key generation prototype system is developed, showing enhanced performance of average received power and key generation rate.

In [A27], Zhang et al. formulate 3-D nonstationary channel models for UAV-based IIoT networks in the sub-THz band. The model analyzes statistical channel properties, such as propagation gain, atmospheric absorption gain, and temporal auto-correlation function at 140 GHz.

In [A28], Xu et al. propose a spectrally efficient irregular Sinc (irSinc) shaping technique, with the aim of enhancing low-latency and time-jitter tolerance in IIoT. The utilization of irSinc yields a single-carrier nonorthogonal frequency shaping waveform, demonstrated by software-defined radio. It achieves increased spectral efficiency without sacrificing bit error performance and is compatible with 5G standards.

In [A29], Wang et al. investigate ambient radio frequency (RF) energy harvesting for powering sensors in IIoT. The fabricated meta-lens-assisted technique can achieve 30% conversion efficiency enhancement across a frequency band ranging from 2.9 to 3.63 GHz, even when the received RF power is on the level of −20 dBm.

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Appendix: Related Articles

[A1] K. Li, P. Zhu, Y. Wang, J. Wang, and X. You, "Scheduling of time-triggered traffic for deterministic URLLC in industrial automation," *IEEE Internet Things J.*, vol. 11, no. 16, pp. 26552–26567, Aug. 2024.

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