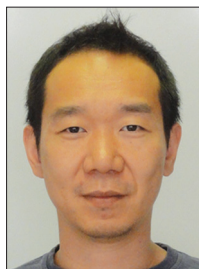# Edge Intelligence for the Industrial Internet of Things

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The Industrial Internet of Things (IIoT) is deemed to be the revolutionary progress in the new Industry 4.0 era. With the development of machine sensors, computer systems, and modern telematics, IIoT provides comprehensive insight into wide productivity areas including manufacturing, energy management, and other industrial processes, which can reduce costs, improve efficiency, and ultimately gain business profits. The growth of the industrial machines and network scale has brought excessive burden on the automation and intellectualization of the industrial process, and consequently voluminous quantities of big data.

The traditional cloud model provides advanced analytics performed in powerful central servers by gathering massive data and sending the processed results back. Although the model has proved to be effective and successful for legacy applications, it leaves a dilemma of the communication latency in the cloud-host services for IIoT applications, which often require prompt response and mobility support. The data traffic that has to be routed to remote cloud servers via uncontrolled network paths also increases the risks of compromised data confidentiality and privacy leakage.

Edge computing provides a solution to the dilemma by providing an infrastructure close to the network edge between the IIoT devices and cloud servers that can provide similar services as the cloud model, such as auxiliary computing and storage capacity. The edge differs from the cloud by reducing the latency as it is much closer to the data source, and thus can improve the quality of service (QoS) for IIoT applications.

The latest innovation in artificial intelligence, blockchain and other big data techniques further envision the future IIoT to create inherent intelligence that machines can work and adapt to the environment without human intervention. To upgrade the current IIoT ecosystem with these kinds of new capabilities (e.g., self-monitoring, autonomous operation), this Special Issue (SI) proposes to present and highlight the advances and the latest intelligent technologies, implementations, and applications in the field of edge-based IIoT, so as to move the theoretical and practical frontiers forward for a deeper understanding from both the academic and industrial viewpoints. In response to the Call for Papers, 14 outstanding articles have been selected for this SI after a careful review process.

The articles in this SI are classified into three categories:
• Security and privacy in edge intelligent IIoT
• Analytics architectures, frameworks, and models for intelligent edge-based IIoT
• Machine-learning-based optimization methods for edge intelligent IIoT

In the first article, "Edge Intelligence and Blockchain Empowered 5G Beyond for Industrial Internet of Things," the authors create an intelligent and secure edge intelligence framework for fifth generation (5G) beyond, which is further applied in IIoT. The study mainly realizes the collaboration of edge resources in a novel cross-domain sharing approach. Moreover, deep learning methods and algorithms are also exploited in the proposed edge intelligence framework to help system managers recognize industrial environments, understand application requirements, and optimize resource scheduling strategies. To ensure secure edge services, blockchain is utilized with a newly devised credit-differentiated transaction approval mechanism, which significantly improves the efficiency and flexibility of the blockchain consensus process. This article is a pioneering study in leveraging edge intelligence and blockchain for 5G beyond wireless communications (also called 6G). The proposed resource sharing mechanism is truly superior in tackling the resource constraints in terms of types, geographical distributions, and service capacities. The study will have high impact on the technology advancement of 5G beyond and 6G wireless communications.

In the second article, "Toward Data Security in Edge Intelligent IIoT," the authors aim at data security in IIoT and analyze four main challenges in this scenario, including reliable storage, convenient usage, efficient search, and secure deletion. They then address the issues by presenting corresponding solutions to each challenge. An optimized framework, facilitating the underlying IIoT in data acquisition, processing, and transition, is proposed, which enjoys stronger security and better efficiency. The authors also implement the instantiations to each possible solution on both a laptop and a Raspberry Pi to show the efficiency.

In the third article, "Privacy-Preserving Image Retrieval for Medical IoT Systems: A Blockchain-Based Approach," the authors focus on the limitations of existing studies on retrieval of medical data, which either fail to protect sensitive information of medical images or are limited to a single image data provider. In this article, the authors propose a blockchain-based system for medical image retrieval with privacy protection. Using the emerging blockchain techniques, they present the layered architecture and threat model of the proposed system. In order to accommodate large-size images with storage-constrained blocks, the authors capture a carefully selected feature vector to represent a medical image. They also design a customized transaction structure to record feature vectors on blockchain, which protects the privacy of both medical images and image features.

The IIoT ecosystem can efficiently optimize several relevant computational factors such as execution time, price or economic cost, and energy consumption in edge computing to improve productivity, efficiency, and reliability.

In the fourth article, "PMS: Intelligent Pollution Monitoring System Based on the Industrial Internet of Things for a Healthier City," the authors propose an intelligent pollution monitoring system (PMS) based on IIoT to prevent the direct emission of harmful substances. The PMS has three main parts: 1) real-time pollutant monitoring equipment, consisting of many kinds of sensors, including position sensors, PM 2.5 sensors, and so on, to monitor harmful substances in the gas and water in real time; 2) a real-time alarm system, storing all the data of the components in the gas and water receiving data from the pollutant monitoring equipment, and detecting periodically whether these data are abnormal. If the received data is abnormal, the system will issue an alarm; 3) an intelligent and fast response system, which sends management people to the place where the abnormality occurred to find out the reason. Moreover, based on the received big data, the system can be intelligent enough to predict and analyze the healthy events of the city. The proposed PMS can improve response efficiency to 15 minutes on average.

In the fifth article, "Serious Challenges and Potential Solutions for Industrial Internet of Things with Edge Intelligence," the authors focus on the design related risks and challenges of data security, energy consumption, and complexity in the edge intelligent IIoT. Then they provide potential solutions for the edge intelligent IIoT toward privacy preservation, high-power dissipation, and complexity issues. In particular, edge intelligence based on privacy preservation, whose purpose is to improve security through the encryption operation and hash function, is discussed. The potential solutions for the edge intelligent IIoT that require the lowest cost in versatility, security features, and real-time assurance are proposed to address these types of conundrums.

In the sixth article, "Demand-Response Management Using a Fleet of Electric Vehicles: An Opportunistic-SDN-Based Edge-Cloud Framework for Smart Grids," the authors set up an edge-cloud framework where cooperation among cloud and edge devices is realized to make intelligent decisions related to electricity vehicles' (EVs') charging and discharging in addition to achieving the expected demand-supply balance. However, one of the fundamental challenges of this setup is induced due to a large number of migrations in the edge-cloud setup primarily due to network congestion and an EV's mobility pattern. An amalgamation of software-defined networking (SDN) with opportunistic networks (OppNetworks), which is referred to as opportunistic SDN (Opp-SDN), is applied to handle this challenge. In detail, the proposed work exploits the use of EVs in two forms, namely as energy reservoirs for instantaneous DRM and as forwarding nodes in Opp-SDN. To realize EVs' activities in both roles, the work formulates dedicated Stackelberg game-based approaches for DRM and Opp-SDN, respectively. The obtained results indicate superior performance of the proposed scheme in contrast to the existing state-of-the-art schemes.

The remaining articles discuss the technical challenges and recent results related to machine learning methods on IIoT.

The seventh article, "Trust-Evaluation-Based Intrusion Detection and Reinforcement Learning in Autonomous Driving," proposes a novel trust evaluation model for autonomous driving vehicles (ADVs), in which all the trust evaluation information of a given ADV is utilized to compute its trust value. Then, based on this trust evaluation model, a two-level intrusion detection framework is presented. In the framework, the trust in an accident or attack warning is established based on not only the trust evaluation with the coverage of a roadside unit (RSU), but also the information exchanged between RSUs through the cloud server. Afterward, a reinforcement-learning-based incentive mechanism is proposed to stimulate ADVs to report warnings. Through the case study, the proposed framework outperforms the conventional mechanism and can reach a higher warning detection ratio than the conventional methods.

In the eighth article, "Improving the Cognitive Ability of Edge Intelligent IIoT through Machine Learning," B. Chen *et al.* realize the novel intelligent applications of edge-enhanced IIoT. First, a machine learning (ML)-enabled framework of cognitive IIoT is proposed. Then the ML methods are presented to enhance the cognitive ability of IIoT including ML model of IIoT, data-driven learning and reasoning, and coordination with cognitive methods. Finally, with a focus on the reconfigurable production line, scenario-aware dynamic adaptive planning (DAP) with deep reinforcement learning (DRL) was conducted. The experimental results show that the DRL-based dynamic adaptive planning (DRL-based DAP) had good performance in an observable IIoT environment.

In the ninth article, "AI-Enhanced Offloading in Edge Computing: When Machine Learning Meets Industrial IoT," the authors explore the potential of deploying computational-intensive artificial intelligence (AI)-based applications on edge servers and the offloading framework for mobile users to heterogeneous edge resources. The authors design an intelligent computing architecture with cooperative edge and cloud computing for IIoT. Due to the heterogeneous computing capabilities, edge servers also exhibit heterogeneity in terms of provided accuracy. Based on the computing architecture, an AI-enhanced offloading framework is proposed for service accuracy maximization, and intelligently disseminates the traffic to edge servers or through an appropriate path to remote cloud. The article for the first time considers service accuracy as a new metric, despite the typically used metrics such as delay and energy, to capture the intrinsic characteristics of AI-enhanced edge computing architecture.

In the 10th article, "Hybrid Intrusion Detection System for Edge-Based IIoT Relying on Machine Learning Aided Detection," the authors highlight the importance of the data traffic intrusion detection system (IDS) in IIoT scenarios. However, due to the computing power and computing resources of equipment in edge-based IIoT, the traffic classification effect of the IDS still has room for improvement. The authors survey the typical state-of-the-art studies about detection methods and system structure of IDS, and propose an ML-aided detection method and a hybrid IDS architecture for edge-based IIoT. The ML-aided detection method reduces the training time and increases detection accuracy, while the hybrid architecture effectively utilizes the computing power and computing resources of the edge-based IIoT. The article, persuasively emphasizing the role of IDS in edge-based IIoT, proposes AN intrusion detection method and hybrid IDS architecture, which captures a new perspective for future application.

In the 11th article, "iTaskOffloading: AI-Enabled Task Offloading over Smart Edge," the authors propose AI-enabled task offloading (iTaskOffloading) scheme for personalized task offloading, which provides a global view to reach an optimal decision under the cloud computing framework. This scheme focuses on the requirements of ultra-low latency, ultra-high reliability, and the user's quality of experience (QoE). The authors propose the architecture of AI-enabled task offloading over smart edge that includes local layer, edge layer, cloud layer, and cognitive engine. Furthermore, it takes emotion detection as an example to explain the advantage of this framework for satisfying the strict requirements of AI applications. Fine-grained computing and software-defined computing are proposed in the scheme. Evaluation results show that iTaskOffloading is more effective when the task complexity and task load increase.

In the 12th article, "Crowdtraining: Architecture and Incentive Mechanism for Deep Learning Training in the Internet of Things," the authors propose a concept of crowdtraining that employs edge computing units (ECUs) for big data training in IoT and pays rewards to ECUs using a game-based incentive mechanism. Simulations have been performed to evaluate the performance of a crowdtraining game.

In the 13th article, "Boomerang: On-Demand Cooperative Deep Neural Network Inference for Edge Intelligence on Industrial Internet of Things," the authors propose a framework called Boomerang for on-demand cooperative deep neural network (DNN) inference for IIoT applications. Boomerang exploits DNN right-sizing and partition to execute DNN inference tasks with low latency as well as high accuracy. DNN right-sizing reshapes the amount of DNN computation via the early-exit mechanism so as to reduce the total runtime of DNN inference, while DNN partition adaptively segments DNN computation between the IIoT devices and the edge server in order to leverage hybrid computation resources to speed up. Combining these two keys, Boomerang carefully selects the partition point and the exit point to maximize the inference accuracy while promising the latency requirements of IIoT applications. Furthermore, an advanced version of Boomerang integrated with a deep reinforcement learning mechanism is developed, for achieving end-to-end automatic DNN inference plan generation. Overall, this article advocates a novel design paradigm of enabling on-demand balance between DNN accuracy and latency for provisioning agile edge intelligence services.

Finally, the 14th article, "Opportunities and Challenges of Wireless Human Sensing for the Smart IoT World: A Survey," presents a comprehensive survey of the existing wireless human sensing approaches. Specifically, the authors discuss promising human sensing applications and partition them into three categories: vital sign monitoring, gesture recognition, and activity recognition. For each category of applications, they further conduct a taxonomy of the existing solutions and summarize their ideas, characteristics, pros, and cons from various perspectives, such as design approaches, system configuration, wireless technology, and used information. Finally, they discuss some technical challenges and problems that have not been noticed previously and point out the potential opportunities in the future study of wireless human sensing.

In closing, we would like to extend our sincere gratitude to all the authors who submitted their research to this SI. We would like to thank all the experts in this field who reviewed these articles and provided suggestions to help the authors improve their research. Especially, we express our gratitude to the publishing team and editors for their helpful suggestions and great support for this SI.

Biographies

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