Edge Computing Applications in Industrial IoT: A Literature Review

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Abstract. The Industrial Internet of Things (IIoT) covers many computing devices and sensors constantly generating and exchanging data in a complicated network. Ongoing research tries to fit decentralized edge computing architectures in IIoT environments with urgent computation and action requirements. This paper investigates state-of-the-art edge computing applications based on security, latency, resource utilization, and energy efficiency aspects as well as application domains. Accordingly, a set of case studies for researchers and practitioners to explore or develop applications of edge structures in industrial environments are presented. It is identified that socio-technical issues related to organizations going through digital transformation can point to a possible future research area.

Keywords: Edge Computing, Internet of Things, Industrial IoT, Industrial Use Cases

1 Introduction

Internet of things (IoT) is a term coined by Kevin Ashton in 1999, enabling objects to manage their tasks without human intervention through the data gathered from their sensors and actuators. Industrial IoT (IIoT) refers to IoT applications in industrial domains [1]. IIoT data are traditionally sent and processed in cloud-based central computing architectures. As the volume and velocity of data increase, transmitting all the data to a central cloud for processing becomes costly in terms of time and network resources. Gartner predicts that around 75% of business data will be generated outside a traditional central cloud architecture by 2025. This number was around 10% in 2021 [2]. In critical IIoT environments where a business decision requires immediate computation and action, edge computing as a new paradigm brings faster response times. It reduces network congestion by moving computing and storage near where data is generated.

Edge computing is a paradigm where computations occur closer to the data source. The term edge refers to the node in the opposite direction of the cloud data center [2]. Fog computing is a similar concept introduced by Cisco, focusing more on the infrastructure between edge devices and central cloud servers [3]. Fog and Edge terms are used interchangeably in this study because they try to achieve the same from the perspective of business objectives. Investigating available real-life applications and understanding the edge architectures is significant for organizations since practitioners can understand the technology trends and architectures for a particular IIoT edge computing use case. While paradigms such as edge computing emerge, there is a research gap in related work [4–8] on guiding digitally transforming organizations to utilize them strategically. These studies review existing edge architectures, possible application domains, and objectives; however, they lack a business strategy perspective. Accordingly, the research questions of the study are formed:

- What kind of real-life applications of edge computing and case studies are used in the industry regarding an IIoT environment?
- What are the main objectives of real-life edge computing applications?
- How do these objectives shape edge computing technology trends and architectures?

This paper investigates applications of edge architectures in the industry and groups them according to their objectives and application areas. It aims to present the current implementation status of edge technologies and trends to assist organizations in reaching their business objectives. The paper is structured as follows: Chapter 2 presents the motivation, challenges behind using edge computing in IIoT, and market trends. The literature review methodology is explained in Chapter 3, while Chapter 4 presents the real-life applications and case studies. Lastly, discussion and conclusion are stated.

2 Edge Computing in IIoT

This paper groups edge computing studies in IIoT according to four main objectives: **latency**, **security**, **energy efficiency**, and **resource utilization**. **Latency** is a common concern between edge applications. In an experiment [9] on a face recognition task, it has been shown that moving applications from the cloud to the edge reduces 900 to 160 msec. in response time. With less latency, edge nodes can help monitor and control processes [10] or machine status [11], make forecasts under uncertainty [12]. Edge computing platforms are heterogeneous considering data communication, protocols, policies, platforms, and energy consumption, and these differences result in interoperability challenges [5]. Using computationally less complex heterogeneous devices at the edge brings vulnerabilities regarding privacy and **security** in the network [13], which is the second objective the literature focuses on. For efficiently managing these platforms, there are solutions to increase flexibility, scalability, and availability of edge devices stated as **resource utilization** objectives. Finally, **energy efficiency** is a vital aspect to consider in edge architecture s while utilizing edge nodes, referring to the energy consumption of edge devices [14]. Report in [15] identifies deployment strategies as full edge provider, partner edge provider, aggregator edge provider, and limited edge provider [15]. Knowing these roles and strategies in the market is essential to achieve business goals and forming an edge computing adoption strategy.

3 Research Method

This study has been structured based on Kitchenham's guidelines [16] in order to find case studies and real-life examples of edge computing applications regarding IIoT environments. Snowballing approach is combined with a database search. The following keywords are determined as a starting point of the search: "Edge," "Fog," "Computing," "Industrial," and "IoT." Web of Science and IEEE Explore are selected for search databases. Search results are stored in MS Excel. 67 initial results were found after searching the Web of Science Core Collection. Only four of them were released before 2017, and the number of published papers had increased by the year of 2021. 15 studies were selected after the initial elimination. After fully reading these articles, and including references of the references of those studies, 28 papers were selected as **Primary Studies** (PS). The studies focusing on edge computing use cases, applications, and architectures in IIoT, covering on algorithms, tools, benefits, and implementation challenges were regarded as PS, and 16 of them are journal articles, while 11 studies are conference papers, and one is a book chapter. Authors conducted iterative meetings for identifying main objectives and trends for grouping papers. Domain-specific IoT articles with no edge computing implementation were excluded from the search. Studies targeting domains other than manufacturing such as smart cities, autonomous driving, and healthcare, were excluded. The papers that include technical solutions were included if they explain a particular case study application in IIoT domain.

4 Case Studies and Applications

This section reviews applications of edge architectures in the industry and groups them according to objective and application areas. Studies are explained regarding how the architectures and trends are shaped to fulfill the objectives, allowing practitioners to have an idea while developing implementations for their cases. Studies focusing on security, latency, resource utilization, and energy efficiency are presented in Table 1. Objectives are shown in **bold,** while trends are shown in *italic*.

Table 1. Papers are grouped by their objective and applications

Papers	Main Objective	Application Domain
[17]	Security	Agricultural Monitoring
[18]	Security	Additive Manufacturing
[19]	Security	Simulated Factory
[20]	Resource Utilization	Real-Time Gas Pressure Control
[21]	Resource Utilization	Predictive Maintenance
[8]	Latency+ Energy Efficiency	Active Maintenance
[14]	Latency+ Energy Efficiency	Software Defined Network
[22]	Energy Efficiency+ Resource Utilization	Air Quality Monitoring
[23]	Energy Efficiency+ Resource Utilization	Smart Manufacturing System

[7]	Security+ Latency	Active Maintenance
[24]	Security+ Latency	Smart Grid
[25]	Security+ Latency	Simulation
[26]	Security+ Resource Utilization	Factory Temperature Monitoring
[27]	Latency+ Security+ Resource Utilization	Conveyor Routing, Distributed Predictive Maintenance
[28]	Latency+ Resource Utilization	Simulation with real IIoT Data
[29]	Security+ Resource Utilization	Real-Time Machine Data Analytics
[30]	Latency+ Resource Utilization	Image Classification Simulation
[31]	Latency+ Resource Utilization	Real-Time Anomaly Detection
[32]	Latency+ Resource Utilization	Numerical Experiments
[33]	Latency+ Resource Utilization	Vertical Plant Wall System
[34]	Latency+ Resource Utilization	Industrial Robotics
[35]	Latency+ Resource Utilization + Energy Efficiency	Smart Manufacturing

There are many studies related to *blockchain* and edge computing convergence in the literature concerning the **security** of IIoT systems, such as [25], [32], [13]. An approach that uses blockchain and context-aware security for IIoT environments was proposed in [18], and implementation in an additive manufacturing site was presented. When data is provided with blockchain instead of cloud, it reduces communication costs and increases bandwidth efficiency. [17] integrates blockchain for increasing security in an agroindustry platform to monitor and support decisions in a dairy farm. ZigBee was used to connect IoT gateways and sensors and a Raspberry Pi as edge node for preprocessing IoT data and forwarding it to the cloud. A data processing framework is proposed in [26], enabling secure data storage using edge in IIoT systems. Data management and encryption challenges are summarized, and solutions proposed were evaluated using simulations in a prototype to monitor the temperature in a factory. [19] implemented security application in a simulated smart factory to observe the effectiveness under cyber security scenarios. An edge computing smart grid architecture has been proposed in [28], where data load balancing can be achieved with low **latency** and increased **security**.

Energy efficiency and **resource utilization** in terms of computational workload are vital aspects to consider while utilizing edge nodes. *Software Defined Networking* is widely used for managing a network of middleware devices, as reviewed in [14], where the trade-off between energy efficiency and **latency** is evaluated. [36] proposes a technical architecture that leverages SDN with Network Function Virtualization (NFV) and serverless architectures to reduce the high energy consumption of edge architectures. An adaptive data transmission algorithm using SDN in edge computing for IIoT is proposed in [35] to find an optimal route for traffic load, task deadlines, and energy consumption. To achieve an industrial internet, [23] proposed a framework consisting of high-level embedded microcontrollers and gateway systems. With the help of distributed computing, the gateway efficiently performs network management, data collection, and communication, considering power consumption and providing better **scalability** than traditional IIoT solutions. A similar problem is addressed in [28], which obtains optimized scheduling of IIoT data according to priorities. [8] proposes an architecture to resolve latency and boost energy efficiency in manufacturing utilizes SDN in the network domain. In the proposed architecture, application domain provides monitoring and control services; data domain provides data cleaning and feature extraction using Hadoop; and the network domain utilizes SDN and Time Sensitive Networking (TSN) to manage devices such as Raspberry Pi connected with OPC UA. This edge architecture is compared to the existing private cloud on a candy packaging production line in terms of productivity [7]. Although the network's speed decreased from 16MB/s to 6 MB/s after switching to edge, the results show that edge provides more productivity in high volume mass production. To monitor the real-time status of machinery and conduct predictive maintenance, a database is created in [21], small enough to fit in memories of edge devices using Python SQLite.

Containerized edge architectures are evaluated in [33] regarding industrial requirements, measuring round trip time, bandwidth, processing capabilities, and **latency** while doing machine learning tasks for predictive maintenance. Microsoft Azure IoT Edge is utilized for running container applications on Raspberry Pi. Results show that containerization does not decrease performance while **increasing flexibility and scalability**. A manufacturing process control system has been proposed in [37] to monitor production lines and collect and analyze data to increase efficiency. Stream data were collected from sensors through communication adapters working on OPC UA and MTConnect protocols. Edge node, streaming data in real-time, provides control signals. [22] implemented an air quality monitoring system using data from Arduino sensors spread across a university campus. Low Power Wide Area Network (LoRA) gets data from sensors, transmits data to the LoRa gateway, then to an edge gateway of Kubernetes minion installed on a Raspberry Pi for final unified delivery to the data center. MQTT protocol enables sending alerts to devices if there are anomalies in the data. An open-source architecture for industrial networks called IFog4.0 is proposed in [20] with case studies in an emulated gas regulation station environment. A Fog-Management module has been developed to manage Docker containers. Fog Computing Platform reference architecture is proposed for IIoT applications in [27], using open standards, OPC UA and TSN. A machine is provided with packages containing tags, and the system delivers them to the destination by accessing a database through reading the tag. Network configurations and the benefits of using an edge architecture in different use cases of the same architecture are explained in detail in [38]. Similar fog-based industrial robotic systems are proposed in [34] and [29].

Utilizing *deep learning* requires high computation power and bandwidth. In an edge architecture tailored for deep learning [30], complexity is optimized in line with the computational capacity of edge devices. To evaluate the solution, authors formed a convolutional neural network using real-world IIoT data. They applied experiments that reduce network traffic while maintaining the model's classification accuracy in an object identification task of 30 different components. One way of processing deep learning in the edge is by inferencing, executing pre-trained models with newly generated visual content from mobile edge devices. [39] formulated the inference offloading problem to **minimize energy consumption** and evaluated the performance using simulations. In order to use deep learning for anomaly detection, performance of different architectures are tested in [31]. Trade-off of choosing the architecture considering scalability, bandwidth, and delay have been presented. The author concludes that scaling cloud computation power results in full cloud outperforming the edge.

5 Discussion and Conclusion

In this study, a comprehensive literature review was conducted for edge computing architecture and applications to business cases in IIoT. The main contributions of this paper are stated as follows: (I) Explanations of case studies retrieved from the literature are provided as guidance for organizations and (II) Different application domains are investigated regarding security, latency, resource utilization, and energy efficiency objectives. Additionally, trends, motivation, and implementation challenges of edge computing are explained for both researchers and professionals. Furthermore, this study presents tailored approaches for effective resource utilization in terms of efficient computation needs of the businesses such as complex deep learning applications or simpler monitoring tasks. Although there are plenty of studies focusing on when and why to implement edge architectures, all example applications are experimental. The main research highlights are explained as below:

- While integrating different approaches, there is a trade-off between increasing security, reducing latency, increasing energy consumption, and making the network more complex with potential interoperability problems [25]. For example, deploying blockchain to increase security results in more energy consumption.
- Further trends of edge computing are identified: Blockchain has been incorporated into IIoT networks for security. Approaches such as SDN, containerization, and offloading algorithms are used to increase resource utilization and energy efficiency.

There are some limitations of this study. First, snowballing may have reduced the reproducibility of the search process, and it is likely to obtain further examples. Secondly, a limited number of non-academic resources, such as reports of institutes or consulting agencies, have been reviewed to present trends in edge computing. Also, grouping papers by their objectives and identified trends may contain subjectivity.

Findings show that there is no framework or guidance for selecting and implementing an appropriate edge computing architecture. In future work, we plan to investigate technology management approaches to bridge the socio-technical knowledge gaps in the literature.

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