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Microservices for Data Analytics in IoT Applications: Current Solutions, Open Challenges, and Future Research Directions

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Abstract

The synergy between the Internet of Things (IoT) and big data technologies has resulted in the great development of multiple smart applications in varied fields such as energy management, environmental monitoring, elderly healthcare, etc. Due to the increasing demand for smart applications, opting for a flexible and scalable software architecture that supports and accelerates the development of these applications is in dire need nowadays. As an effective solution to continuously maintain, upgrade, and scale IoT-based applications, the microservices paradigm has been adopted as an architectural style allowing to provide several enhancements in terms of independent deployment, modularity, containerization, loose coupling, etc. These advantages provided by microservices impact also the efficiency of the analytics conducted by the IoT-based systems. In this view, the current research aims to address a survey about the adoption of the microservices paradigm for supporting data analytics in IoT applications. For this purpose, first of all, the theoretical concepts related to IoT, data analytics, and microservices are briefly presented. Second, relevant microservices-based solutions for data analytics in IoT applications are reviewed and discussed. Third, the challenges and opportunities offered by the microservices paradigm in the IoT context are outlined and explained. The present study will pave the way for promising future research on the issues of integrating the emerging microservices technology in data analytics and IoT applications.

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Keywords: Internet of Things; Data Analytics; Microservices; Review.

1. Introduction

With different descriptions from various viewpoints, the Internet of Things (IoT) has stood up as a novel paradigm for the rapid development of information and communication technologies. IoT is a network of interconnected smart devices exchanging data with each other or with external systems via internet communication protocols [1]. This

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technology transforms the physical objects into intelligent actors that could communicate with each other, exchange information, and orchestrate actions. The rapid evolution of the IoT has shown a significant advance in big data techniques. Harnessing IoT data for analytics is an effective solution to extract features, learn knowledge, and aid decision-making in different applications developed in various fields such as healthcare, smart cities, and energy management [2].

Nowadays, IoT and big data analytics have become extremely hot research topics. However, a big gap still exists between the IoT's ability to collect environment related information and the analytics capabilities used to interpret that information. Therefore, there are several challenges that make exploiting data analytics in IoT systems a complex task. Some of the main challenges include how to manage heterogeneous IoT data, how to analyze collected data efficiently, and how to develop and maintain scalable and modular functionalities that can be reused in other contexts and applications. To face these challenges, adopting flexible and extensible software architecture instead of monolithic ones is the most appropriate solution. In this context, several recent works have opted for the microservices-based development paradigm. The microservices paradigm has ushered in a new era of software application development. It has grown in popularity as a methodology of producing flexible and distributed software applications [3]. In a microservices-based design, tiny services are designed totally independently of one another, with lightweight communication methods and protocols to meet business needs. In a constrained computing environment like IoT, the microservices approach ensures the implementation of a modular architecture, which is fundamental for supporting different types of analytical features. Unlike monolithic solutions, the suggested architecture considers each service to handle, from the analytic process, specific functionality that is deployed, scaled, and maintained independently of other services, resulting in increased efficiency and higher resilience to failures in the IoT environment.

In this article, we present a review of relevant works that are proposed to couple between IoT data analytics techniques and the microservices' architectural style. This review will assist practitioners in better understanding tough issues and exploring new and exciting research prospects in the field of IoT analytics. To the best of our knowledge, this work presents the first review paper that discusses how microservices technology is being used in IoT applications. This paper is organized as follows. Section 2 gives a brief overview of IoT, data analytics, and microservices. Section 3 discussed the microservices-based solutions for data analytics in IoT applications. In Section 4, the challenges and the future research directions concerning the adoption of microservices for IoT applications are highlighted. Finally, our conclusions are drawn in Section 5.

2. Background

In this section, the theoretical concepts that will be employed throughout the paper are defined. An overview of the IoT ecosystem is presented. The different types of data analytics are detailed. Moreover, the microservices' architectural style and its essential benefits are outlined.

2.1. Internet of Things: Definition, Architecture, and Requirements

Over the last few years, IoT has stood out as a breakthrough technology by developing smart services in multiple and various areas. The IoT is defined as the linking of billions of objects, called also things, on the Internet [4, 5]. These objects communicate via standardized communication protocols, share data, and exchange information over heterogeneous platforms. The IoT has made it possible to improve the efficiency and performance of various infrastructures such as those used in transportation, security, education, agriculture, and healthcare [2]. Figure 1 presents the IoT architectural stack, which includes five layers: the business layer, application layer, processing layer, and perception layer [6]. The roles of these layers are briefly detailed in the following points:

- **Business layer:** the entire IoT system, its functionalities, applications, and business models are managed and organized in this layer;
- **Application layer:** manages the processed data obtained from the processing layer to solve specific problems;
- **Processing layer:** in this layer, the gathered data are processed and analyzed to extract valuable knowledge and insights;

- **Transport layer:** is responsible for the communication and the transfer of data from IoT smart devices to the upper layers;
- **Perception layer:** the role of this layer is to capture and collect data. This layer comprises various smart devices, including sensors and actuators.

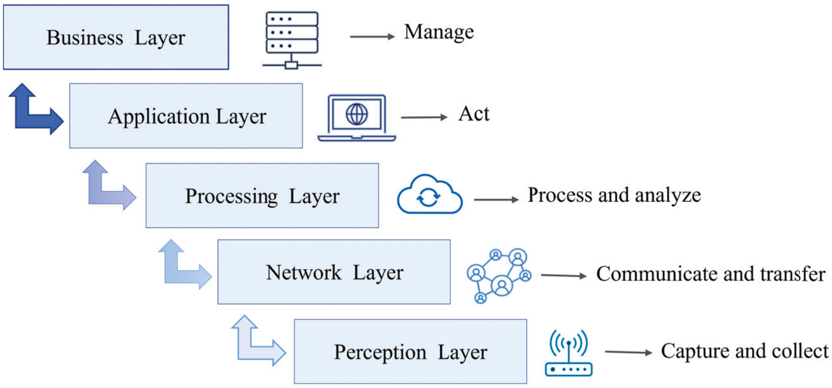

Fig. 1. IoT architecture.

The volume of data generated by IoT smart devices and sensors is continuously increasing encapsulating huge amounts of structured and unstructured data. This massive data generation needs more advanced technologies to be processed and analyzed in order to extract valuable insights that help to improve the performance of IoT applications. In this context, satisfying (i) user-oriented, (ii) solution-oriented, and (iii) Quality of Service (QoS) requirements plays a major role in improving operational efficiency and increasing productivity of the IoT applications [7]. The user-oriented requirements define the characteristics of the IoT application that will increase its usability, such as personalization and contextualization, improved onboarding, and seamless cross-device design and interaction. The essential criteria of processes and practices that should be part of every IoT implementation are captured in solution-oriented requirements. Distributed computing and analytics, data ingestion and stream processing, and device management are three such criteria. Meeting QoS-based criteria improves the overall IoT application's performance. Data's accuracy, security, and privacy are considered the most significant QoS requirements. To meet this panoply of essential requirements, it is crucial to review the architectural style of the developed IoT application and carefully choose the most appropriate one, ensuring a satisfactory implementation.

2.2. Data Analytics

The recent growth of IoT data has led to the appearance and development of different types of data analytics. Big data analytics is defined as the examination stage of large and heterogeneous data to extract unseen patterns, find hidden correlations, reveal market trends, and discover customer preferences [8].
Recently, IoT big data analytics have become an attractive research domain, particularly because traditional methods of data processing have demonstrated various limitations, especially when working with a huge volume of heterogeneous data. The data analytics process consists of five main stages. Before getting into the analytics process, the first step is requirements understanding. Determining the problem, business needs, and why you need data analytics should be well investigated at the first step of the data analytics process. This stage may take a long time and be arduous, but it is critical to be ready for the next stages. After drawing a clear image of the needs, the next stage aims to collect data. The collected data should be cleaned, filtered, and sorted. This stage should be conducted with attention because it directly affects the effectiveness of the obtained results. After that, the data is ready to be analyzed and manipulated through the appropriate analytics techniques. The final step is about interpreting the results and outputs obtained from the data analytics step.

There are mainly four different types of data analytics [9]: descriptive, diagnostic, predictive, and prescriptive, as it is illustrated in Figure 2. These types are briefly defined in the following points:

- **Descriptive analytics:** is the general form of analytics, helps in the enhancement of decision-making by analyzing and learning from past achievements to improve the current performance;
- **Diagnostic analytics:** helps to find and understand the main causes of the events and determine what factors contributed to the outcome;
- **Predictive analytics:** is used to get knowledge and helpful insights about the future from the raw data. Both historical and current statistics are used in this type of analytics to predict behaviours and events;
- **Prescriptive analytics:** is the most advanced form of analytics, applied to determine the best solution among different options and suggest decision choices to bring advantages of the future opportunities or eliminate the future risks.

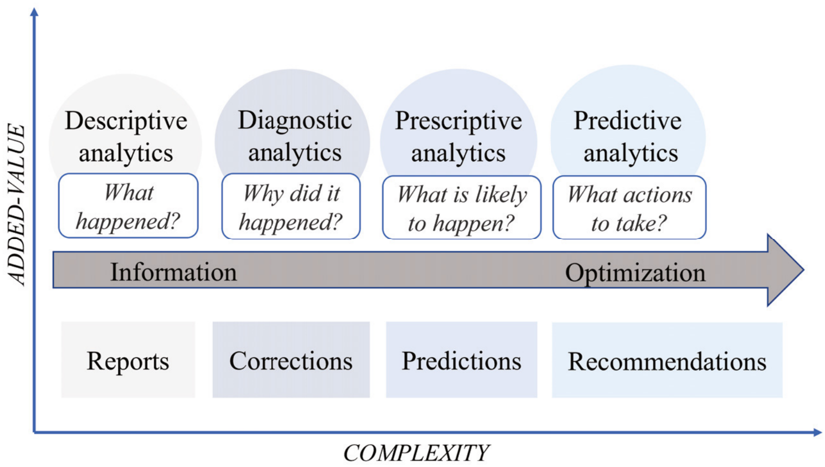

Fig. 2. The different types of data analytics.

Different techniques of analytics have been proposed to achieve various analytical tasks [8], including: classification used to distinguish the category of a new observation, clustering used to create and identify groups of similar items based on certain distinctive features, recognition used to identify and categorize objects, detection used to analyze images and videos to discover objects or find states, prediction used to reveal patterns about events in the future and identify the right actions to be taken, analysis which is the act of cleaning and processing data to supports decision-making, and recommendation which provides customers with services suggestions on the best course of actions.
Despite the various advantages afforded by data analytics approaches, there are certain downsides, mostly in terms of complexity and bias [10]. Some analytics solutions are more equivalent to a black box design. What's inside the black box is an enigma, as is the logic the system employs to learn from data and build learning models. Although the use of these tools is simple, the reasoning behind and how decisions are made are not. To get over this limitation, it's important to rethink the design of these tools so that they may be customized, improved, and reused in other contexts and applications.

2.3. Microservices: Architecture and Essential Benefits for IoT Data Analytics

Microservices technology is a Web services' variation that allows the construction of distributed software applications utilizing a collection of entities. These entities are fine-grained, loosely coupled, and reusable software components that collaborate to accomplish the system's goals. In a microservices-based architecture, each microservice runs in its own process and exchanges data with others. Using the monolithic development approach, a single block of code is used to design and build the traditional programs. However, a microservices architecture describes an application

as a collection of separate but interconnected entities that can be built, tested, and deployed individually, or even as separate software projects. Typical entities of a microservices architecture include a number of key features or functions. APIs, containers, a service mesh, service-oriented architectural principles, and the cloud are the main typical entities of a microservices architecture, in addition to the individual services [3]. Microservices' modular and loosely coupled architecture makes IoT software lightweight and more distributable across various computing environments. The IoT application may be subdivided into smaller components using this approach, resulting in decreased coupling and greater flexibility for change. Microservices can also be utilized to help IoT systems deal with the diversification that comes with the different devices and protocols that can be used, and this by assuring an interoperable information transmission using different techniques such as semantic web models and tools.
There are good reasons for adopting the microservices' architecture for IoT systems. In the following, we summarize the main benefits of this promising development style [11]:

- **Availability:** The microservices architecture ensures the availability of software applications with reduced downtime due to the independence of the services, which contributes significantly to improving and increasing the overall performance. Indeed, even if there is a failure, it only affects the concerned entities which can be replaced by applying dedicated compensation mechanisms;
- **Dynamism:** microservice architecture is a DevOps-based methodology that uses modular components rather than a monolithic structure to ensure a more dynamic and agile approach to designing, executing, and maintaining software applications;
- **Modularity:** Microservices provides applications with a strong encapsulation, well-defined interfaces, and clear dependencies. A microservice can be built in any fashion that provides a well-defined interface to other services. Dependencies between microservices are explicit since they are specified using orchestration and choreography standards;
- **Scalability:** Because each service may be developed in a different language, or technology, software development teams can pick the best technology stack for each module without worrying about inconsistency and incompatibility issues. Individual services can be extended and upgraded individually, and new components can be introduced without the need for system downtime or re-deployment;
- **Functionalities' Optimization:** It's simpler to tailor the demands of each service to improve and optimize business functionality when the focus is on a single service rather than the entire application. Existing services may thus be modified for use in a variety of contexts rather than having to reimplement new services from scratch;
- **Resilience:** The process of identifying and fixing the main cause of performance issues is made easier using microservice-based architecture. Because independent service deployment provides better fault isolation, complex applications are unaffected by a single failure. As a result, developers may roll back an update or make changes to a service, reducing thus the possibility of downtime.

3. Related Works: Microservices-Based Solutions For Data Analytics in IoT Applications

The rapid evolution of efficient and cost-effective distributed applications that offer enhanced and value-added functionalities has been fueled by the explosive growth in IoT and data analytics technologies. To ensure better overall performance and analytic capabilities, these applications must be built using a flexible and scalable architecture. Several research studies have recently been published that investigate the potential of the microservices paradigm for the development of IoT applications. In this context, we discuss, in the following paragraphs, the most recent and relevant works that leverage microservices technology to make the development of IoT applications more adaptive and agile.
In [12], The authors proposed a new federated DL model (Fed-TH) for detecting and classifying cyber threats in industrial IoT. The Fed-TH is built in the form of reusable blocks using microservices technology to enable efficient latency of cyber threats detection at the network's edge. The proposed model is based on different DL methods, including the multiscale convolution networks and the gated recurrent unit (GRU)-based Autoencoder (AE) to capture and analyze the spatial and temporal representations. In [13], Ali et al. proposed a microservices-based methodology that provides efficient data analytics services as modular microservices. They divided the data analytics process

into a set of major steps and developed them as microservices. To enhance the application's scalability, the different functions are deployed as microservices, composed, and orchestrated with each other. In [14], Li et al. proposed to develop a microservice-based platform to support IoT-oriented big data analytics. The proposed platform focused on the microservice level to abstract the IoT data analytics in a friendly way. The different tasks of the data analytics were implemented as loosely coupled and distributable microservices.

To provide smart transportation services that are required for smart cities implementation, Asaithambi et al. [15] designed a Microservice-Oriented Big Data Architecture (MOBDA), which implements different data processing and predictive techniques. In [16], Ardagnawe et al. developed a system based on the idea of Model-Based Big Data Analytics-as-a-Service (MBDAaaS). The system serves as an interoperable solution for deploying different IoT analytics applications to meet the user and solution requirements.

Lue et al. [17] presented a novel topology platform constructed as a set of basic services. The proposed data analysis architecture is able to improve the analysis outcomes cognitively, quickly integrate different analytics algorithms, and meet the diverse demands of users via the deployment of microservices. Dineva et al. [18] presented a microservices-based architectural framework that provides Machine Learning (ML) solutions as services. The IoT data analytics are enabled through a set of microservices; each of them offers a single analytics function. The microservices composed in the proposed architecture are: identity service, data acquisition, transformation, machine learning, device management, and logging service. A customizable framework based on microservices and visualization technologies has been proposed in [19] to support smart predictive analytics and maintenance operations in industrial contexts. The design of this platform was structured as a set of microservices, where every service performs a specific function. [20] introduced an IoT platform for smart dairy farming that allows the analysis of animal behaviour and the monitoring of their health. The design of this platform was based on microservices and fog computing to address the major issues related to the constrained Internet connectivity in remote farm locations. Trilles et al. suggested an IoT architecture that united various IoT tools and devices into a single ecosystem [21]. The proposed architecture was based on microservices and serverless technologies to ensure scalability, stability, and reusability. A scalable architecture based on microservices was presented in [22] to improve the facial recognition process. The proposed architecture deployed a Deep Learning (DL)-based facial recognition algorithm.

From the comparison provided in Table 1, it is clear that most of the proposed works use microservices primarily in the analytical layer of the IoT stack. As mentioned above, most of these works aim to enhance the data analytics features and services through the use of microservices architectural style. In [14, 13], the authors proposed solutions that breakdown the data analytics process into a series of steps and implement them using composable microservices that may be utilized in a variety of scenarios/case studies. This type of implementation enhances the efficiency of the developed smart data analytics services, gives them the ability to manage heterogeneous IoT data coming from different sources, and makes the analytics feasible on huge volumes of data. Moreover, these services are modular and flexible which enables the IoT systems to scale well with analytic features. The goal of the remaining works that were reviewed was to improve specific IoT data analytics case studies related to particular application domains, such as smart surveillance, smart city, manufacturing, and smart farming.

In addition to the benefits already mentioned, the utilization of microservices-based architecture is primarily employed to meet user-oriented requirements. Indeed, this architectural style allows improving the features of IoT applications by boosting usability, personalization, and contextualization. All the reviewed works that are presented in this study utilize the microservices-based architecture to satisfy the user-oriented requirements. Some of the examined works, such as [15, 21], have explored the QoS-oriented requirements that should be fulfilled by microservice-based architectures. Because these architectures are scalable and dynamic, different QoS assurance mechanisms are developed to preserve the application's performance, security, and privacy throughout executions. The solution-oriented criteria have been investigated in some works, such as [12, 19] to enable distributed computing and stream processing, and facilitate device management. The use of the microservices development paradigm for IoT applications has yielded several benefits and advantages. Essentially, the development process is broken down into a series of steps that allow mainly the flexible deployment of IoT applications as well as the creation of scalable, reusable, and robust infrastructures. Based on the comparative analysis presented in table 1, it is clear that additional in-depth research should be undertaken to further investigate the potential and promising capabilities of microservices technology to boost data analytics in IoT applications.

Table 1. Comparison between related works.

Work	Case Study	Type of analytics	Analytics' task	IoT requirements	Analytics' techniques
[12]	Threat intelligence	Predictive	Classification+ Prediction	User-oriented+ Solution-oriented requirements	DL models
[13]	High abstract conceptual approach	Predictive	Classification+ Prediction+ Recommendation	User-oriented+ Solution-oriented+ QoS requirements	SVM+LDA + KNN +DT + LR
[14]	High abstract conceptual approach	Predictive	None	User-oriented requirements	MapReduce converger
[15]	Smart transportation	Descriptive+ Predictive	Prediction	Solution-oriented+ QoS requirements	Linear regression+ Random forest regression
[16]	Heterogeneous IoT domains	Predictive	Prediction+ classification	User-oriented+ Solution-oriented+ QoS requirements	ML models
[17]	Data analytics applications	Descriptive	None	User-oriented+ Solution-oriented+ QoS requirements	Analysis algorithms
[18]	IoT applications	Predictive	Detection+ Classification	User- oriented+ QoS requirements	ML models
[19]	Manufacturing	Predictive	Prediction+ Classification	User-oriented+ Solution-oriented+ QoS requirements	ML models
[20]	Smart dairy farming	Predictive	Classification+ Clustering	User- oriented+ QoS requirements	Random forest+ KNN
[21]	Smart farming	Descriptive+ Predictive	Detection+ Prediction	User-oriented+ QoS requirements	Data analytics methods
[22]	Face recognition	Predictive	Recognition	User-oriented	CNN

To that end, in the following section, we highlight the ongoing challenges that still face the adoption of the microservices development paradigm in IoT environments, and we propose a number of new lines of research to be pursued in order to strengthen the analytical solutions implemented with microservices technology.

4. Adoption of Microservices Paradigm For IoT Applications: Challenges and Future Research Directions

4.1. Challenges

Even though there exist different benefits gained from the convergence of the microservices paradigm with IoT data analytics, there are also several challenges.In this section, we present the key ongoing challenges that still need to be resolved to utilize the full potential of the microservices paradigm for IoT data analytics. These challenges are discussed in the following points:

- **Microservices-based IoT applications are often more complex to design, implement, and maintain:** generally, software development teams encounter higher complexity when designing, implementing, and maintaining microservices compared to monolithic programs. Indeed, if they are unfamiliar with the microservices development paradigm, they could find it extremely difficult to understand how to determine: i) the size of each microservice, ii) each microservice's connecting points, and iii) the service coordination and integration [23]. Designing and implementing microservices necessitate doing them inside a defined domain/environment. As a result, each microservice should identify, specify, and encapsulate a single task. When modelling a domain, developers often utilize a data-centric approach to accomplish this task for each function/service. The main problem with this approach is that data that is not logical (i.e.,doesn't have a predefined structure) is meaningless. However, in heterogeneous computing environments like IoT, raw data can provide interesting insights after performing appropriate preprocessing and analytical techniques. Besides extending behaviours to a system and expanding the issues it solves necessitates the integration of more features and capabilities in the microservice architecture. The maintenance of this architecture may become a serious issue. The correct DevOps and automation technologies can manage a lot of this added complexity. However, without them, the maintenance may quickly turn into a headache [24].

- **Microservices-based IoT applications can present security vulnerabilities:** security is a critical requirement in any IoT environment. IoT devices handle a wide range of sensitive data related to IoT users, including their movement information, contacts, purchase preferences, etc. Furthermore, as more devices are connected to IoT networks, security threats to IoT devices are increasing. Because of this, IoT ecosystems are vulnerable to serious security risks. IoT security attacks can be categorized into four types [25]: i) physical attacks: occur when attackers reach the IoT network or devices physically, ii) network attacks: occur when attackers target the IoT network systems to inflict harm, iii) software attacks: are carried out by focusing on the security software or bugs in an IoT application, and finally iv) data attacks: target the computational resources that enable the management of communication across multiple IoT nodes as well as the data collecting that IoT resources and devices demand. Adopting a microservices-based architecture for IoT systems poses several serious security challenges when compared to the monolithic development approach. Because the major components of the IoT system are accessible to the network and data is shared across several small containers, different types of attacks, namely network, software, and data attacks, can occur. It's also worth mentioning that, because containers are highly replicable, a vulnerability in one module may quickly escalate into a larger issue. Besides, since the source code of microservices is frequently reused across several applications, hackers can have simple access to it to cause damage to the whole IoT system [26].
- **Microservices-based IoT applications require organizational culture changes:** any microservices adoption strategy necessitates a shift in organizational culture. An Agile and DevOps culture should already be in place before beginning the reengineering process. Adopting a microservices-based architecture for IoT applications has the drawback of requiring from each development team to manage the whole service lifecycle, including maintaining reliable APIs and managing testing iterations and releases. Organizations that decide to use this development approach must also assess if their developers have the necessary experience to build a microservices-based IoT solution [27]. Developers should have a complete grasp of the entire process, as well as the ability to create, deploy, test, and monitor such applications. Transferring expertise and decision-making authority from managers and architects to individual teams is a fundamental part of the transition to a microservices-based architecture. Finally, organizations must examine the communication problems that this adoption may entail. Microservices' independence implies that developers won't always have the same global visibility as they would with a monolithic model. To construct a working IoT application, several development teams must collaborate, and the inherent isolation between teams may make it difficult to generate a unified final result.

4.2. Future Research Directions

This section details a list of potential future research topics that may be explored further to improve the adoption of the microservices development paradigm for IoT applications.

- **Cloud-native technologies:** microservices-native applications involve employing cloud microservices to be built and hosted. This development approach presents several advantages that are convenient for IoT ecosystems. Across different types of clouds, the cloud-native application platforms deliver a unified development and administration experience. They bring improvements in terms of manageability, scalability, cost reduction, development automation, etc. Cloud-native technologies adoption gives IoT applications the ability to benefit from big data analytics services and gain better business insights.

- **Privacy-preserving in microservices-based IoT applications:** the privacy of microservice-based architecture is regarded as the primary difficulty that has sparked a great deal of research interest in order to improve it. Various efforts have concentrated on the ability to create a flexible architecture that fulfills the appropriate roles with the proper design and required privacy in different IoT use cases. Adopting blockchain technology in the creation of such architecture is critical to maintaining the confidentiality of recoded IoT data [28]. The integration of artificial intelligence, blockchain, and microservices technologies will result in a predictive, scalable, and privacy-preserving architecture suitable for different IoT applications.
- **Adopting best practices for the development of microservices-based applications:** best practices are methods that have been shown to be successful in attaining their goals and that may be used and adapted for usage in other contexts. Using a tried-and-true method increases the chances that the organizational targets will be met and the expected outcomes will be realized. Different best practices for microservices-based architectures for IoT applications have been established and categorized, where microservice adoption experiences are collected, best actions are documented, and migration to microservices architecture difficulties are determined [29].
- **Data management in microservices-based IoT applications:** the employment of microservices-based architecture can ensure the improvement of IoT applications' quality and make their deployment easier. However, before starting the design of a microservices-based application, the management of data must be taken into account. The data collected should be carefully handled to ensure that the application's performance and security fulfill expectations and requirements. Data should be effectively organized and structured to enhance the overall application scalability, availability, communication, and agility [30]. To this end, Appropriate representations must be specified to guarantee knowledge acquisition from data management logic and the complex interactions of microservices.

5. Conclusion

The IoT environment is made up of a huge number of objects in the form of smart devices and sensors. These objects are linked together and allow for the capture and gathering of massive volumes of data, which is then transferred to the cloud for analysis. The use of data analytics for IoT applications has risen in prominence, opening up a plethora of new prospects. However, several challenges still need to be solved to effectively utilize the full potential of IoT data analytics. To address these issues, the microservices paradigm is adopted to enable the development of modular and extensible architectures, resulting in significant gains in terms of performance, dynamism, and resilience. Several studies relating to the use of microservices technology for IoT data analytics have been examined in this article. These studies have demonstrated the perfect harmony between microservices and intelligent IoT services. Furthermore, in this article, we highlighted the key challenges and future research directions regarding the adoption of microservices-based architecture for the development of IoT applications. This would broaden the boundaries for promising new research in this field, leading to the proposal of predefined and reusable modules in the form of analytics-as-a-microservice guaranteeing the acceleration of the development of IoT applications and widespread adoption in most aspects of daily life.

References

[1] Hajjaji, Yosra, Wadii Boulila, Imed Riadh Farah, Imed Romdhani, and Amir Hussain. (2021) "Big data and IoT-based applications in smart environments: A systematic review." *Computer Science Review* **39**: 100318.

[2] Ben Atitallah, Safa , Maha Driss, Wadii Boulila, and Henda Ben Ghézala. (2020) "Leveraging deep learning and IoT big data analytics to support the smart cities development: Review and future directions." *Computer Science Review* **38**: 100303.

[3] Surianarayanan, Chellammal, Gopinath Ganapathy, and Raj Pethuru. (2019) "Essentials of microservices architecture: Paradigms, applications, and techniques." *Taylor & Francis*.

[4] Laghari, Asif Ali, Kaishan Wu, Rashid Ali Laghari, Mureed Ali, and Abdullah Ayub Khan. (2021) "A review and state of art of Internet of Things (IoT)," *Archives of Computational Methods in Engineering*: 1–19.

[5] Aboubakar, Moussa, Mounir Kellil, and Pierre Roux. (2021) "A review of IoT network management: Current status and perspectives." *Journal of King Saud University-Computer and Information Sciences*.

[6] Abdmeziem, Mohammed Riyadh, Djamel Tandjaoui, and Imed Romdhani. (2016) "Architecting the Internet of Things: State of the art." *Robots and Sensor Clouds*: 55-75.

[7] Pattar, Santosh, Rajkumar Buyya, Kuppanna Rajuk Venugopal, SS Iyengar, and LM Patnaik. (2018) "Searching for the IoT resources: Fundamentals, requirements, comprehensive review, and future directions." *IEEE Communications Surveys & Tutorials*. **20** (3): 2101-2132.

[8] Marjani, Mohsen, Fariza Nasaruddin, Abdullah Gani, Ahmad Karim, Ibrahizm Abaker Targio Hashem, Aisha Siddiqa, and Ibrar Yaqoob. (2017) "Big IoT data analytics: Architecture, opportunities, and open research challenges." *IEEE Access* **5**: 5247-5261.

[9] Deshpande, Prachi S., Subhash C. Sharma, and Sateesh K. Peddoju. (2019) "Predictive and prescriptive analytics in big-data era." in *Security and data storage aspect in cloud computing*: 71-81. Springer.

[10] Runkler, Thomas A. (2020) "Data analytics." *Springer Fachmedien Wiesbaden*.

[11] Wolff, Eberhard. (2016) "Microservices: Flexible software architecture." *Addison-Wesley Professional*.

[12] Abdel-Basset, Mohamed, Hossam Hawash, and Karam Sallam. (2021) "Federated threat-hunting approach for microservice-based industrial cyber-physical system." *IEEE Transactions on Industrial Informatics* **18** (3): 1905-1917.

[13] Ali, Sajjad, Muhammad Aslam Jarwar, and Ilyoung Chong. (2018) "Design methodology of microservices to support predictive analytics for IoT applications." *Sensors* **18** (12): 4226.

[14] Li, Zheng, Diego Seco, and Alexis Eloy Sánchez Rodríguez. (2019) "Microservice-oriented platform for Internet of big data analytics: A proof of concept." *Sensors* **19** (5): 1134.

[15] Asaithambi, Suriya Priya R., Ramanathan Venkatraman, and Sitalakshmi Venkatraman. (2020) "MOBDA: Microservice-oriented big data architecture for smart city transport systems." *Big Data and Cognitive Computing* **4** (3): 17.

[16] Ardagna, Claudio A., Valerio Bellandi, Ernesto Damiani, Michele Bezzi, and Cedric Hebert. (2021) "Big data analytics-as-a-Service: Bridging the gap between security experts and data scientists." *Computers & Electrical Engineering* **93**: 107215.

[17] Lu, Wanjie, Qing Xu, Chaozhen Lan, Liang Lyu, Yang Zhou, Qunshan Shi, and Yinghao Zhao. (2020) "Microservice-based platform for space situational awareness data analytics." *International Journal of Aerospace Engineering*.

[18] Dineva, Kristina, and Tatiana Atanasova. (2020) "Architectural ML framework for IoT services delivery based on microservices." in *International Conference on Distributed Computer and Communication Networks.* Springer, Cham.

[19] Nikolakis, N., A. Marguglio, G. Veneziano, P. Greco, S. Panicucci, T. Cerquitelli, E. Macii, S. Andolina, and K. Alexopoulos. (2020) "A microservice architecture for predictive analytics in manufacturing." *Procedia Manufacturing* **51**: 1091-1097.

[20] Taneja, Mohit, Nikita Jalodia, John Byabazaire, Alan Davy, and Cristian Olariu. (2019) "SmartHerd management: A microservices-based fog computing–assisted IoT platform towards data-driven smart dairy farming." *Software: practice and experience* **49** (7): 1055-1078.

[21] Trilles, Sergio, Alberto González-Pérez, and Joaquín Huerta. (2020) "An IoT platform based on microservices and serverless paradigms for smart farming purposes." *Sensors* **20** (8): 2418.

[22] Timur, Tahta D., I. Ketut Eddy Purnama, and Supeno Mardi Susiki Nugroho. (2019) "Deploying scalable face recognition pipeline using distributed microservices." in *2019 International Conference on Computer Engineering, Network, and Intelligent Multimedia (CENIM)*: 1-5. IEEE.

[23] Wang, Yingying, Harshavardhan Kadiyala, and Julia Rubin. (2021) "Promises and challenges of microservices: an exploratory study." *Empirical Software Engineering* **26** (4): 1-44.

[24] Jamshidi, Pooyan, Claus Pahl, Nabor C Mendonça, James Lewis, and Stefan Tilkov. (2018) "Microservices: The journey so far and challenges ahead." *IEEE Software* **35** (3): 24-35.

[25] Driss, Maha, Daniah Hasan, Wadii Boulila, and Jawad Ahmad. (2021) "Microservices in IoT security: Current solutions, research challenges, and future directions." *Procedia Computer Science* **192**: 2385-2395.

[26] Hameed, Ali, and Alauddin Alomary. (2019) "Security issues in IoT: a survey." in *2019 International conference on innovation and intelligence for informatics, computing, and technologies (3ICT)*: 1-5. IEEE.

[27] Bogner, Justus, Stefan Wagner, and Alfred Zimmermann. (2017) "Automatically measuring the maintainability of service-and microservice-based systems: A literature review." in *Proceedings of the 27th International Workshop on Software Measurement and 12th International Conference on Software Process and Product Measurement*: 107–115.

[28] Jamil, Faisal, Faiza Qayyum, Soha Alhelaly, Farjeel Javed, and Ammar Muthanna. (2021) "Intelligent microservice based on blockchain for healthcare applications." *CMC-Comput. Mater. Contin* **69**: 2513-2530.

[29] Razzaq, Abdul. (2020) "A systematic review on software architectures for iot systems and future direction to the adoption of microservices architecture." *SN Computer Science* **1** (6): 1-30.

[30] Laigner, Rodrigo, Yongluan Zhou, Marcos Antonio Vaz Salles, Yijian Liu, and Marcos Kalinowski. (2021) "Data management in microservices: State of the practice, challenges, and research directions." *arXiv preprint arXiv 2103.00170*.