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Architectures and Methodologies of Internet of Robotic Things Systems: A Systematic Review

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The Internet of Things is a highly versatile topic that nowadays encompasses not only objects but also robots. This paper focuses on analyzing the integration of devices from IoT environments and robotic devices based on integration methodologies or architectures. To fulfill this objective, a systematic literature review was conducted, yielding results on integration frameworks used in systems not only IoRT. Additionally, the advantages and disadvantages of integration methodologies are analyzed. This study highlights the importance of understanding how IoT and robotic devices are being integrated, as well as the benefits and challenges associated with these practices. Identifying the commonly used methodologies and architectures in this integration is crucial for improving the efficiency and effectiveness of IoRT systems, which can have a significant impact across a wide range of applications, from industry to everyday life.

Keywords: Internet of Robotic Things, methodologies, architectures, implementation.

1. Introduction

The Internet of Robotic Things (IoRT) represents a transformative paradigm that merges robotic systems with Internet of Things (IoT) technologies to create interconnected networks of robotic devices. This concept involves fusing sensor data from diverse sources, processing it using local and distributed intelligence, and utilizing it to manipulate objects in physical world.

The vision of IoRT is to enhance the functionality and efficiency of robotics systems by leveraging the capabilities of IoT Technologies, enabling advanced applications in fields such as intelligent manufacturing and Industry 4.0 realization.

In manufacturing sector and Industry 4.0, IoRT systems are employed for task like assembling, packing, welding, and quality control thereby enhancing automation, connectivity, and control processes (Vermesan et al., 2020; Romeo et al., 2020).

Moreover, IoRT has found applications in the establishment of smart cites networks where cognitive IoT architectures are utilized to analyze data from various smart city applications (Park et al., 2019) and in the healthcare sector, with projects concentrating on applications such us upper limb rehabilitation robot systems controlled remotely via IoT (Li & Zhong, 2020).

This uses of IoRT showcases its adaptability in enabling solutions for diverse environments thought the amalgamation of robotic and IoT Technologies.

The integration of various types of robots and sensors within the framework of the Internet of Robotic Things (IoRT) enhances the versatility and functionality of IoRT systems. By combining different robotic agents with a diverse array of sensors, IoRT systems can achieve a high degree of adaptability and efficiency across multiple applications.

The fusion of robotic agents and Internet of Things (IoT) technologies to form IoRT opens up new possibilities in industrial and research fields, spanning domains such as manufacturing, agriculture, health, surveillance, and education (Romeo et al, 2020). This integration allows for seamless coordination and communication between different types of robots and sensors, enabling IoRT systems to perform a wide range of tasks with precision and effectiveness.

It is observed that in integrating many different devices into the Internet of Robotic Things (IoRT), each project typically adapts its own frameworks due to the lack of a defined methodology or established architecture. Implementing a methodology or integration architecture is crucial to ensure interoperability between sensors and robots from different vendors, optimize operational efficiency, and facilitate scalability. One approach to integration in IoRT involves leveraging established quality management methodologies such as ISO 9001, ISO 31000, and Six Sigma. These methodologies focus on quality, environmental considerations, and occupational health and safety, providing a structured framework for integrating different components effectively (Blasco-Torregrosa et al, 2019).

Moreover, the development of open architectures for vertical integration based on cyber-physical systems and industry standards like IEC 61499 and OPC UA is crucial for enabling seamless communication and interoperability in IoRT systems (Garcia et al., 2018).

By leveraging established quality management methodologies, sensor fusion approaches, and open architectures for vertical integration, IoRT systems can achieve enhanced functionality, adaptability, and performance across a wide range of applications. However, the study of methodologies or integration architectures for IoT devices with robotics is scarcely explored.

This work proposes a rigorous systematic literature review of the methodologies and architectures implemented in the deployment of IoRT systems, with the aim of identifying the reference frameworks for the implementation and development of IoRT systems.

This review allows for the identification and consolidation of existing best practices and standards, improving interoperability among heterogeneous components and optimizing development and deployment processes. Additionally, it contributes to enhancing the security and reliability of systems, facilitates regulatory compliance, and promotes innovation by revealing areas of opportunity and gaps in current knowledge. Furthermore, this work adds to the existing body of knowledge, serving as a valuable resource for both researchers and professionals in the IoRT field, providing a solid documentary foundation for future research and development.

2. Background

To effectively deploy robotic systems, various methodologies and architectures are utilized to ensure seamless integration and operation. One key approach is the utilization of cloud robotics, which leverages cloud infrastructure to provide significant benefits to robots and automation systems (Kehoe et al.2015). This methodology enables the deployment of robotic systems with enhanced capabilities and scalability through cloud resources.

Another essential methodology involves the deployment of component-based robot software using a reference architecture that supports both initial deployment and re-deployment at runtime to accommodate changing requirements and conditions (Hochgeschwender et al., 2018). This approach ensures flexibility and adaptability in deploying robotic systems, allowing for efficient management of software components.

Moreover, the adoption of service-oriented architectures (SOA) in designing robotic systems enhances maintainability and reusability, providing a structured process for developing quality architectures for robotic systems (Oliveira et al., 2014). By focusing on architectural styles that prioritize quality and reusability, robotic systems can be designed and deployed with improved efficiency and effectiveness.

Additionally, the implementation of cognitive architectures for service robots, such as MERLIN, enhances the autonomy and intelligence of robotic systems, enabling advanced functionalities and interactions in various applications (González-Santamarta et al., 2020). These architectures support behavior generation and human-robot interaction, contributing to the development of sophisticated robotic systems.

In the other hand the integration of IoT based on layers is essential for structuring and organizing the components of an IoT architecture. A common approach is to adopt a layered architecture that includes different levels of abstraction and functionality. For example, a four-layer architecture is often utilized, consisting of the sensing layer, network layer, service layer, and application layer (Meziane & Ouerdi, 2022). This layered model aids in organizing the various components of an IoT system, from physical sensors to application interfaces, ensuring efficient communication and data flow across different layers.

Regarding Industrial Internet adoption, the Industrial Internet Reference Architecture (IIRA) is a significant reference model that has been pivotal in promoting the adoption of Industrial Internet of Things (IIoT) globally (Yli-Ojanperä et al., 2019).

The integration of IoT infrastructure with enterprise systems blurs the line between business IT systems and the physical world, leading to changes in the design, deployment, and utilization of services (Spieß et al., 2009).

A Meta-model of the Internet of Things system is created based on microservices, utilizing Devops tools like Docker, Ansible, and Kubernetes .

The emergence of IoT has transformed the application of new technologies in daily life, with the development of a software architecture for the Industrial Internet of Things (Ungurean & Gaitan, 2020).

To implement an Internet of Robotic Things (IoRT) system one approach adopted is a layered architecture that encompasses different levels of abstraction and functionality, such as the sensing layer, network layer, service layer, and application layer. This layered model aids in organizing the components of an IoRT system, from physical sensors to application interfaces, facilitating efficient communication and data flow across various layers (Dai & Lee, 2020).

The Industrial Internet Reference Architecture (IIRA) serves as a valuable reference for the adoption and deployment of Industrial Internet solutions, providing a standardized framework for designing and implementing IIoT systems. This reference architecture offers guidelines for organizations seeking to implement IoRT systems, ensuring interoperability, scalability, and security in industrial settings.

3. Background

Following the methodology proposed by B. Kitchenham, a Systematic Literature Review (SLR) was conducted. An SLR refers to the process by which a researcher verifies and documents the current state of knowledge on a specific topic. The systematic literature review analyzes and determines relevant information to coherently answer research questions within an area of interest. This SLR includes the following steps: (1) Propose a review protocol and define the research questions (Section 3), (2) Conduct the review by identifying and evaluating primary studies (Section 3), (3) Extract the results (Section 4), and (4) Discuss and analyze the results of the systematic literature review (Section 4).

Identification of the needs to carry out the Systematic Review

Two research questions were defined to address the objectives stated in the introduction. Accordingly, the following questions were formulated:

Research Question 1 (RQ1): What are the most used methodologies and architectures in the implementation of IoRT systems?

Based on the systematic literature review, the most used methodologies and architectures for designing or implementing an IoRT system can be identified. Additionally, the importance of studying these architectures and methodologies will be highlighted.

Research Question 2 (RQ2): What are the advantages and disadvantages of the most used methodologies and architectures in the implementation of IoRT systems?

This second question would allow for a more comprehensive and critical evaluation of the identified methodologies and architectures, providing deeper insights into their effectiveness and applicability in different contexts.

PICO Review protocol.

The B. Kitchenham model was implemented alongside the PICO (Population, Intervention, Comparison, and Outcome) protocol, which has been validated and recognized for conducting systematic literature reviews. This choice is based on the reliability of the protocol, ensuring an effective methodological approach to the study.

- Population: This includes relevant publications on the most commonly used methodologies and architectures in the deployment of IoRT systems.
- Intervention: This involves examining research studies that focus on the various methodologies and architectures frequently employed in IoRT systems.
- Comparison: This entails recognizing and relating the methodologies and architectures applied in IoRT systems and how these were adapted to different use cases and environments.
- Outcome: This identifies the most frequently used methodologies and architectures in the deployment of IoRT systems and assesses their adaptability and effectiveness.

Research and string generation

By selecting keywords that represent the research topic, it was possible to obtain relevant and comprehensive results from studies that delve into the application of methodologies in IoRT. Additionally, the inclusion of synonyms for the keywords enhances the precision and effectiveness of the search string construction, as demonstrated in Table 1.

Table 1. Keywords and synonyms used

Keyword	**Synonyms**
Internet of Robotic Things	IoRT
methodologies	methods, techniques
architectures	frameworks
implementation	Deployment, application

The research string "Internet of Robotic Things" OR IoRT captures the primary focus on IoRT systems. The terms "methodologies" OR "methods" OR "techniques" cover different aspects related to the methodologies used. "Architectures" OR "designs" OR "frameworks" encompass various terms related to system architectures. The inclusion of "deployment" OR " implementation " OR "application" ensures that the focus remains on the practical deployment of these systems.

Revisión

In reference to the criteria for selecting information sources, the method used by Dyba et al. and Petersen et al. was considered. Key criteria included free access to the information from the publications found using the search string and the time period of the publications. The selected scientific databases are 1) ACM Digital Library, 2) IEEE Digital Library, 3)ScienceDirect, 4) Scopus, and 5) Springer Link. The search string described in next section was utilized across these scientific databases.

Inclusion Criteria:

Open Access Studies: Only studies that allow free access to their content were included.

Consistency of the Study: Only studies relevant to the field of IoRT were included. Specifically, studies mentioning methodologies, schemes, strategies, best practices, and techniques related to the review of IoRT methodologies and architectures.

Content of the Study: The main content of the studies was validated to ensure they addressed research questions RQ1 and RQ2. This evaluation involved reviewing the title, abstract, and keywords of the corresponding studies.

Full Text Studies: All selected studies from the digital libraries were examined for completeness, considering only those that provided comprehensive information on IoRT methodologies and architectures.

Studies Within the Period: Studies were reviewed to ensure they were published within the specified period from 2019 to 2024, maintaining the relevance and currency of information for this SLR on IoRT methodologies and architectures.

Accurate Digital Libraries: The level of confidence, quality, and quantity of the studies published in the five digital libraries mentioned were assessed.

Exclusion Criteria:

Studies Influenced by a Single Point of View: Studies that presented a particular opinion without addressing applied methodologies or architectures for IoRT were rejected.

Studies Not Related to the Topic: Studies that did not pertain to any of the research questions RQ1 and RQ2 were excluded.

Studies Addressing IoRT in Other Contexts: Studies that did not specifically focus on methodologies, architectures, guidelines, strategies, best practices, or techniques related to IoRT were excluded.

Ambiguous Studies: Studies lacking clarity, sufficient detail, or relevance to IoRT methodologies and architectures were rejected.

Studies Published Before 2019: To ensure relevance and up-to-date information, studies published before 2019 were omitted, considering the rapid advancements in IoRT.

Studies from Non-Traditional Publishers: Studies from unreliable or non-traditional sources were discarded.

Duplicate Studies: To avoid redundancy, duplicate studies from the selected digital libraries were eliminated.

Selection of Primary Studies

To determine the primary studies for the research, a three-phase exclusion process was implemented. In the first phase, the number of studies retrieved using the search string from each of the scientific databases was recorded, yielding a total of 277 studies. The results are presented in Table 2.

Table 2. Selected studies by source

Source	Initial studies (First activity)	Relevant studies (Second activity)	Primary studies Task 1(Third activity)	Primary studies Task 2(Third activity)
ACM Digital Library (ACM)	27	15	7	3
IEEE Digital Library (IEEE)	11	7	4	2
Springer Link (SP)	113	64	10	8
Science Direct (SD)	66	48	11	5
Scopus (SC)	60	49	19	1
Total	**277**	**183**	**51**	**19**

During the second phase, inclusion and exclusion criteria were implemented through a brief review of the title, abstract, and keywords of each publication. This process yielded acceptance of 183 studies. Subsequently, in the third phase, a comprehensive review of each study was conducted to ascertain the presence of relevant information and alignment with the research topic. Upon completion of the primary study selection phases, 19 studies were deemed suitable for inclusion, serving as the foundational basis for this research article.

4. Results, analysis and interpretation.

At the conclusion of the systematic literature review, the findings were analyzed in relation to the research questions. The studies were categorized based on their relevance to the two primary objectives of the research: (a) identifying the most commonly used methodologies and architectures in the deployment of IoRT systems, and (b) To assess the advantages and disadvantages associated with the most commonly used methodologies and architectures in the deployment of IoRT systems.

Discussion of the results of RQ1

In the implementation of Internet of Robotic Things (IoRT) systems, various methodologies and architectures are commonly utilized to enhance functionality and efficiency. One prevalent approach involves the integration of Fog Computing (FC) networks to support IoRT tracing, as presented by Alamer (Malarczyk, 2023). This method leverages Secure Anonymous Tracing (SAT) in a fog-assisted manner, enabling the seamless tracking of IoRT devices within a network system. Additionally, the utilization of SCADA/HMI hardware and software is highlighted for tasks such as data debugging, configuration updates, and process visualization in IoRT systems (Malarczyk, 2023). These methodologies contribute to the robustness and adaptability of IoRT implementations by enhancing monitoring and control capabilities.

Furthermore, the convergence of Industry 5.0 applications with digital twins and Human-Robot Collaboration (HRC) is emphasized as a transformative pathway in IoRT architecture, as discussed by (Coronado, 2024). This integration facilitates the development of innovative scenarios beyond traditional robotics, fostering advancements in Industry 5.0 domains. Moreover, the incorporation of continual planning frameworks that integrate IoT device capabilities into IoRT systems is proposed by (Harman et al., 2019). This hierarchical approach enhances state estimation, task planning, and execution within dynamic smart environments, showcasing a structured methodology for optimizing IoRT operations.

In the realm of data exchange and connectivity for IoRT systems, recent developments in network connectivity and data exchange techniques play a pivotal role in enabling real-time information updates, cloud storage, and secure communication protocols, as highlighted by (Koul et al., 2022). These advancements underscore the significance of seamless data flow and secure communication channels in IoRT architectures to ensure operational reliability and data integrity. Additionally, the critical analysis and future directions of the Internet of Robotic Things for independent living are explored by (Sandhu, 2024), shedding light on the potential applications and implications of IoRT systems in enhancing autonomous living scenarios.

The implementation of IoRT systems encompasses a diverse range of methodologies and architectures that aim to enhance functionality, security, and connectivity. By leveraging fog-assisted tracing, continual planning frameworks, digital twin integration, and advanced data exchange techniques, IoRT systems can achieve heightened efficiency, adaptability, and autonomy. These approaches pave the way for the seamless integration of robotic devices into interconnected networks, fostering innovation in Industry 5.0 applications and smart environments.

Discussion of the results of RQ2

The implementation of Internet of Robotic Things (IoRT) systems involves various methodologies and architectures that offer distinct advantages and disadvantages. One prevalent methodology involves the integration of Fog Computing (FC) networks, which can enhance IoRT tracing capabilities. This approach provides the advantage of enabling seamless tracking of IoRT devices within a network system. However, a potential disadvantage of this methodology could be the increased complexity in managing and securing the distributed fog nodes, as highlighted in the context of robotics cyber security vulnerabilities and countermeasures (Yaacoub et al., 2021). Ensuring the security of fog nodes becomes crucial to prevent potential cyber-attacks on IoRT systems.

Another commonly used methodology in IoRT systems is the utilization of SCADA/HMI hardware and software for tasks such as data debugging and process visualization. This methodology offers the advantage of facilitating quick data gathering and visualization for maintenance workers. However, a potential disadvantage could be the susceptibility to cyber threats due to the interconnected nature of SCADA systems, as discussed in the context of robotics cyber security vulnerabilities (Yaacoub et al., 2021). Implementing robust cyber security measures becomes essential to mitigate such risks in IoRT architectures.

Moreover, the convergence of Industry 5.0 applications with digital twins and Human-Robot Collaboration (HRC) presents a transformative pathway in IoRT architecture. This integration offers the advantage of fostering innovative scenarios and advancements in Industry 5.0 domains. Nevertheless, a potential disadvantage could arise from the complexity of integrating diverse technologies and frameworks, as highlighted in the context of harmonizing ROS with NEP+ for human-centered development (Coronado, 2024). Overcoming interoperability challenges and ensuring seamless integration become critical considerations in leveraging such methodologies for IoRT systems.

In the realm of data exchange techniques for IoRT systems, advancements in network connectivity and communication protocols play a crucial role in enabling real-time information updates and secure data exchange. This methodology offers the advantage of ensuring operational reliability and data integrity in IoRT architectures. However, a potential disadvantage could stem from the increased network traffic and communication overhead, which may impact system latency and efficiency. Balancing the trade-offs between data exchange efficiency and system performance becomes essential in optimizing IoRT implementations.

5. Conclusions

The convergence of Industry 5.0 applications with digital twins and Human-Robot Collaboration (HRC) architectures offers innovative possibilities for advancing IoRT systems. By bridging frameworks like NEP+ and ROS, IoRT implementations can benefit from enhanced communication performance and collaborative capabilities. Despite the advantages of integrating diverse technologies, interoperability challenges and the complexity of harmonizing different platforms pose significant hurdles. Addressing these challenges through meticulous planning and strategic integration strategies is crucial to unlocking the full potential of Industry 5.0 applications in IoRT systems.

The integration of Fog Computing (FC) networks and Secure Anonymous Tracing (SAT) methodologies in IoRT systems presents a promising pathway for enhancing device tracking and network efficiency. Leveraging fog-assisted tracing can significantly improve the monitoring and control capabilities of IoRT devices within interconnected systems. However, the complexity of managing distributed fog nodes and ensuring their security remains a critical challenge that needs to be addressed to prevent potential cyber threats. Policy reforms and standardization efforts are essential to harmonize these methodologies and drive the IoRT agenda forward, especially with the impending era of the Internet of Everything.

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