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Architectural foundations for the multi-agent Internet of Robotic Things: a literature review

Fundamentos arquitetônicos para a Internet das Coisas Robóticas multiagente: uma revisão da literatura

Fundamentos arquitectónicos para la Internet de las Cosas Robóticas multiagente: una revisión de la literatura

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Abstract:
The Internet of Robotic Things (IoRT) integrates robotics, Internet of Things (IoT), distributed computing, and intelligent systems to enable heterogeneous physical and virtual entities to perceive, communicate, collaborate, and act in dynamic environments. However, the heterogeneity and distribution of these entities introduce challenges related to interoperability, communication, context representation, and coordinated decision-making. This paper presents a literature review of the main concepts and technologies supporting multi-agent IoRT environments. The review discusses the evolution and architectural characteristics of IoRT, Edge–Fog–Cloud computing and next-generation communication networks, as well as the role of multi-agent systems in providing distributed and autonomous interactions among heterogeneous entities. Particular attention is given to context-aware computing and semantic representation as mechanisms for transforming heterogeneous sensor data into higher-level contextual information that can support reasoning and action. The study also examines architectural requirements for IoRT platforms and the role of local middleware and microservices in integrating devices, data, and distributed computational resources. The reviewed literature indicates that the combination of multi-agent systems, contextual information, semantic representation, and distributed computing provides a relevant foundation for developing flexible, scalable, interoperable, and adaptive IoRT environments.

Keywords:
Internet of Robotic Things; Multi-agent systems; Context-aware computing; Semantic representation; Distributed computing.

Resumo:
A Internet das Coisas Robóticas (IoRT) integra robótica, Internet das Coisas (IoT), computação distribuída e sistemas inteligentes para permitir que entidades físicas e virtuais heterogêneas percebam, comuniquem, colaborem e atuem em ambientes dinâmicos. No entanto, a heterogeneidade e distribuição dessas entidades introduz desafios relacionados à interoperabilidade, comunicação, representação do contexto e tomada de decisão coordenada. Este trabalho apresenta uma revisão bibliográfica dos principais conceitos e tecnologias que sustentam ambientes de IoRT multiagentes. A revisão discute a evolução e as características arquitetônicas da IoRT, da computação Edge-Fog-Cloud e das redes de comunicação de última geração, bem como o papel dos sistemas multiagentes no fornecimento de interações distribuídas e autônomas entre entidades heterogêneas. Uma atenção especial é dada à computação consciente do contexto e à representação semântica como mecanismos para transformar dados heterogêneos de sensores em informações contextuais de alto nível que possam suportar raciocínio e ação. O estudo também examina os requisitos arquitetônicos para plataformas IoRT e o papel de middleware local e microservices na integração de dispositivos, dados e recursos computacionais distribuídos. A literatura revisada indica que a combinação de sistemas multiagentes, informações contextuais, representação semântica e computação

distribuída fornece uma base relevante para o desenvolvimento de ambientes de IoRT flexíveis, escaláveis, interoperáveis e adaptativos.

Palavras-chave:
Internet das Coisas Robóticas; Sistemas multiagente; Computação sensível ao contexto; Representação semântica; Computação distribuída.

Resumen:
Internet de las cosas robóticas (IoRT) integra robótica, Internet de las cosas (IoT), computación distribuida y sistemas inteligentes para permitir que entidades físicas y virtuales heterogéneas puedan percibir, comunicar, colaborar y actuar en entornos dinámicos. Sin embargo, la heterogeneidad y distribución de estas entidades presentan desafíos relacionados con la interoperabilidad, la comunicación, la representación en el contexto y la adopción de decisiones coordinadas. Este documento presenta una revisión bibliográfica de los principales conceptos y tecnologías que apoyan entornos de IoRT múltiples. La revisión analiza la evolución y las características arquitectónicas de IoRT, Edge–Fog–Cloud computing y redes de comunicación de próxima generación, así como el papel de los sistemas multiagent en la prestación de interacciones distribuidas y autónomas entre las entidades heterogéneas. Se presta especial atención a la computación contextual y la representación semántica como mecanismos para transformar los datos de sensores heterogéneos en información contextual de alto nivel que pueda apoyar el razonamiento y la acción. El estudio también examina los requisitos arquitectónicos de las plataformas de IoRT y el papel de los intermediarios y microservicios locales en la integración de dispositivos, datos y recursos computacionales distribuidos. La literatura revisada indica que la combinación de sistemas multiagentes, información contextual, representación semántica y computación distribuida proporciona una base relevante para desarrollar entornos de IoRT flexibles, escalables, interoperables y adaptables.

Palabras clave:
Internet de las Cosas Robóticas; Sistemas multiagente; Computación sensible al contexto; Representación semántica; Computación distribuida.

1. Introduction

The Internet of Robotic Things (IoRT) is an emerging technological paradigm. IoRT brings together robotics, the Internet of Things (IoT) and cloud computing. IoRT is an ecosystem of intelligent devices capable of monitoring events, collecting and analyzing data from different sources, exchanging information, utilizing local and distributed intelligence to determine an optimal sequence of actions, and acting or sensing the physical environment while moving physically in the location [1], [2]. As new devices and activities are integrated, these relationships must adapt to ensure efficient data management and interoperability. In the integration of multiple entities in an IoRT solution, interoperability is a crucial aspect, essential for creating inter-domain services that support the dynamic movement of physical devices and the exchange, storage, and processing of information between them [3]. Another important factor in supporting interoperability is context.

Context-aware computing is essential for meeting the personalized needs of the environment [4]. Perception in IoRT depends on context, which characterizes situations of entities, including location, status, time, and identity [3], [1]. The application of multi-agent systems (MAS) in such environments is promising due to the diversity of devices and interactions involved. The implementation of MAS involves strategically organized agents that perceive the environment and act based on defined objectives [5], [6]. Connectivity seeks a synergy between collaboration, communication, and cognition in complex vertical systems that bring together technologies from various domains [7], [8]. Concepts derived from 5G and 6G guide current telecommunications research. This establishes an IoRT communication framework in three domains: Edge, Fog, and Cloud. The Edge processes data closer to devices, while the Fog handles more robust data processing below the Cloud [9].

2. Internet of Robotic Things

The subject matter is notably multidisciplinary, requiring the integration of diverse knowledge to develop an effective solution. As noted by [10], the high heterogeneity of the components of these systems requires expertise in several areas. Furthermore, [3] highlights that, with the advancement of technologies, new concepts emerge, reflecting both the evolution of applications and the constant need for innovation. This scenario requires a well-structured theoretical basis and a phased development, providing a solid and coherent organization for the project. Technological transformations have driven the creation of intelligent services, which are essential for social and scientific advances, aiming to improve quality of life with personalized digital solutions [11]. In the 1990s, networked robotics emerged to integrate robots into a network, expanding their functionalities.

Over time, its limitations led to the development of cloud robotics, allowing sensors, processing, and memory to be distributed, without the need for them to be in a single system [2]. However, challenges remain in interoperability, heterogeneity, latency, security, robot management, infrastructure, QoS, and standardization, characteristics that are the focus of work in IoT. Advances in IoT have enabled the emergence of cyber-physical systems (CPS), in which robots, software, and sensors cooperate to achieve common goals [10]. IoRT emerges in this context, expanding what IoT already achieved, with smart, mobile and autonomous devices, interacting in different sectors [3]. This IoRT scenario allows modern robots to share large volumes of data and knowledge, mutually improving skills and overcoming limitations of traditional robotics [11].

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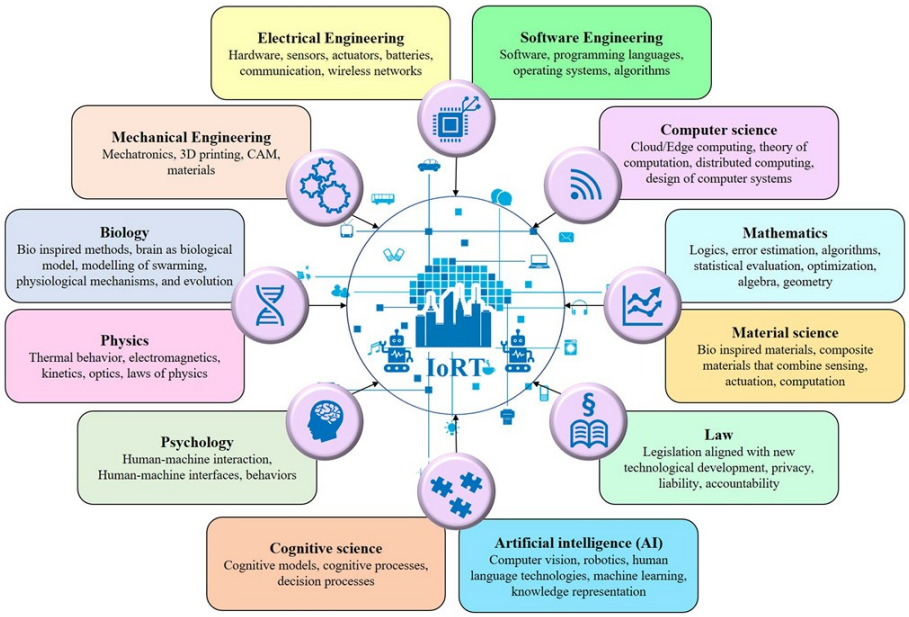


Figure 1. IoRT - interdisciplinary field. Source: [3].

The advancement of artificial intelligence has enabled robotic things to operate with learning algorithms and cognitive decision-making, in addition to the integration of IoRT with various scientific fields, as illustrated in Figure 1 [3]. IoRT systems are becoming essential in sectors such as industry, healthcare, and education, as well as influencing areas such as entertainment and tourism [11]. The expansion of IoT to IoRT involves the virtualization of cloud computing and the flexible design of robots, with technological convergence being central, bringing both challenges and opportunities [12], [3]. Cooperation and reliability between robotic devices are fundamental for their efficient operation. IoRT requires a multidimensional architectural approach to manage its diverse tasks, with features such as sensing, actuation, control, and cognition [2]. IoRT capabilities include sensing, locating, thinking, connecting, collaborating, learning, and acting [3].

The IoRT architecture can be modeled in different ways, such as the 4-tier architecture proposed by [13], which includes physical elements, networks and infrastructure, applications and services, and business processes. In its modeling, [1] highlights aspects such as acting as a service, perception combined with knowledge modeling, and distributed cognition. The main functions of IoRT include Robotic Interaction Services (RoIS) and Human-Robot Interaction (HRI) [1]. The interaction between robotic and social devices is enhanced by the interaction network between them, creating new innovative solutions [14]. The massive presence of IoRT devices brings challenges of updating and maintenance, and the use of Digital Twins has proven useful to enhance devices in virtual environments, as described by [15], [11]. The Digital Twin

connects physical modules to their virtual versions, requiring a robust network structure for its operation [16].

IoRT is expected to provide more intelligent, collaborative, heterogeneous, efficient, self-adaptive, context-aware, and even cheaper robotic networks. Based on the evolution presented, the IoRT features add to the relationship between robotics, the internet of things, and cloud computing. This allows dividing the work into three areas [3]:

The first is about robotics, which is applied in the edge (local network) and defines requisites as motion, interaction, and manipulation.

The second area is about the internet of things and defines all connections between the local devices beyond the semantic reasoning over data.

The third area is cloud computing. It defines remote services, enabling virtualization of resources, elasticity, and multi-tenancy. In IoRT, robots cooperate in multi-robot systems, which integrate several agents operating in the same environment. The devices used can be classified as cyber-physical systems (CPS). This type of application is characterized by integrating local devices (physical) with the internet (cyber). CPS help to improve with IoT work. Modern robotic technologies are merged with cloud computing and networks, integrating CPSs and IoT protocols to develop new technologies. Smart devices can monitor events, merge sensor data from multiple sources, and use local and distributed intelligence to determine the best course of action. The exponential growth in the semiconductor domain has resulted in an expansion of standards for the use of sensor-based processor systems. These systems enabled with advanced communication technologies (Bluetooth, Wi- Fi, 4G, 5G, etc.) converge on IoT technology.

IoT is incredibly pervasive, which makes integration with cloud computing important due to the amount of data that can be generated and the requirement to use virtual resources and storage capacity. Thus, it is possible to obtain several uses with the data generated by the IoT and develop several intelligent applications for users. By optimizing network services, the IoT-Cloud relationship enables an advanced services model, for a multi-robot system, that can be rapidly provisioned and launched with minimal management effort. This lessens the connectivity issues of heterogeneous user-centric devices as it allows for easy inter-action with service providers. The IoT is made up of physical objects such as sensors, software, electronics, and a network connection that allows data to be collected and referenced. Among its characteristics and general requirements, heterogeneity and scalability stand out, given the imposition that it is a complex and dynamic system.

In Cloud Computing, there are two very important concepts: scalability and virtualization. It is characterized as a type of computing that is based on the internet and provides data sharing and processing capabilities for computers and other devices on demand.

3. Remote connection and beyond-5G scenario

The evolution of IoRT involves autonomous robots collaborating in smart networks, performing functions such as sensing, manipulation and communication, requiring robust and interoperable networks capable of supporting heterogeneous devices with different levels of intelligence [3]. IoRT operates in the Edge, Fog and Cloud communication regions, with Edge processing data closer to the devices, while Fog processes more robust data below the cloud [9], [17]. Fog computing extends the capabilities of the cloud to the edge, enabling IoRT applications to handle large data sets [3]. 5G expands connectivity and distributed resource capacity, enabling end-to-end vertical systems, as highlighted by [17], [7], and [18]. 5G is organized into three main scenarios: eMBB (enhanced Mobile Broadband), mMTC (massive Machine Type Communications), and URLLC (Ultra Reliable Low Latency Communications), each with different capacity and latency focuses [19], [20].

6G research aims to achieve extremely high data speeds and instantaneous transfer, as well as enhance cognition and collaboration through artificial intelligence [8]. 6G networks will be edge-based to support emerging applications and will require autonomous adaptation [16]. IoRT also faces connectivity challenges in distributed deployment models, requiring the development of new orchestration methods to distribute the energy load and reduce power requirements [3]. Osmotic computing, as described by [21], emerged to serve distributed environments, enabling the automatic deployment of interconnected microservices at the edge and in the cloud, which facilitates the scalability of technological solutions [22].

4. Multi-agent systems

When addressing multi-agent systems, [23] defines the concept of multi-agents by the acronym PAGE, where P = Perceptions, A = Actions, G = Goals and E = Environment. An entity, whether human or artificial, immersed in a physical or virtual environment, is characterized by the ability to perceive the environment, interact with it, set goals and make decisions to achieve them. [24] complement, stating that multi-agent systems are composed of autonomous agents that interact with each other and with the environment to solve problems in a distributed manner. Each agent can perceive, decide and act, promoting a decentralized

structure that facilitates flexibility, scalability and resilience. When integrating multiple entities into an IoRT solution, interoperability is an essential aspect, as mentioned by [3]. They highlight that interoperability is crucial to create interdomain services that support the dynamic movement of physical devices and the exchange, storage, and processing of information between them.

Overcoming interoperability challenges is essential for the success of IoRT solutions, also favoring the development of federated interoperability structures between platforms. [25] propose a runtime verification approach to increase security and reliability in multi-agent systems, especially in contexts with complex interactions between other agents and humans. Among the main challenges is interoperability. They note that traditional verification is hampered by the number of possible states and interactions, requiring a lightweight and efficient approach to monitor in real time. In a case study on hospital bed allocation, the approach demonstrated the ability to monitor messages and ensure that agents follow strict communication protocols. Finally, [5] define a multi-agent model for Ambient Assisted Living (AAL), based on an M2M communication infrastructure that facilitates the integration of robots and human agents.

This model uses the concept of "indistinguishability", allowing the automatic selection of agents with equivalent minimum capabilities, depending on the task or objective. They identify six roles of agents in AAL systems: Context Agent (obtains information), Assistive Agent (supports other agents), True Agent (receives assistance), Agent with Leadership Capabilities (gives instructions), Source Agent (initiates the process) and Destination Agent (ends the process). Thus, the heterogeneity of multi-agent systems requires the definition of communication standards and understanding of the capabilities of agents, whether physical or virtual, to promote effective interoperability. Furthermore, as previously discussed, a robust organization of the local physical network is crucial to ensure efficient data transmission in environments with a high density of connected devices.

5. Context-aware computing

In the proposal presented by [5], one of the functions attributed to agents is context. In agreement, [3] highlights that the concept of context in IoRT is fundamental, involving information that characterizes the situation of entities, such as location, status, time and identity. As discussed by [1], perception in IoRT depends directly on context. According to [4], context-aware computing has evolved rapidly due to advances in low-cost sensors, computing devices,

and wireless communication networks. This evolution has transformed context-aware computing into an applicable approach, enabling the creation of high-level services in smart environments, which enable multimodal interactions and personalized assistance with ontology-based activity recognition. The ability to recognize activities is essential for context-aware environments, as it provides the necessary information for the intelligent behavior of these environments, and is supported by specific context modeling.

[26] propose a semantic approach for IoRT, integrating heterogeneous sensor data into high-level symbolic representations. This approach enables first-order logic-based reasoning and abstracts low-level data into knowledge structures that represent the context. Figure 2 summarizes the proposal. The architecture of a semantic IoRT platform involves a Sensor and Actuator Platform that abstracts access to sensors and actuators. The Symbolic Reasoning layer interprets context entities based on data collected by sensors and, from the domain knowledge represented in ontologies and rules, generates relevant actions. These actions are then decoded to generate real commands for the actuators, allowing an informed and contextualized response from the system.

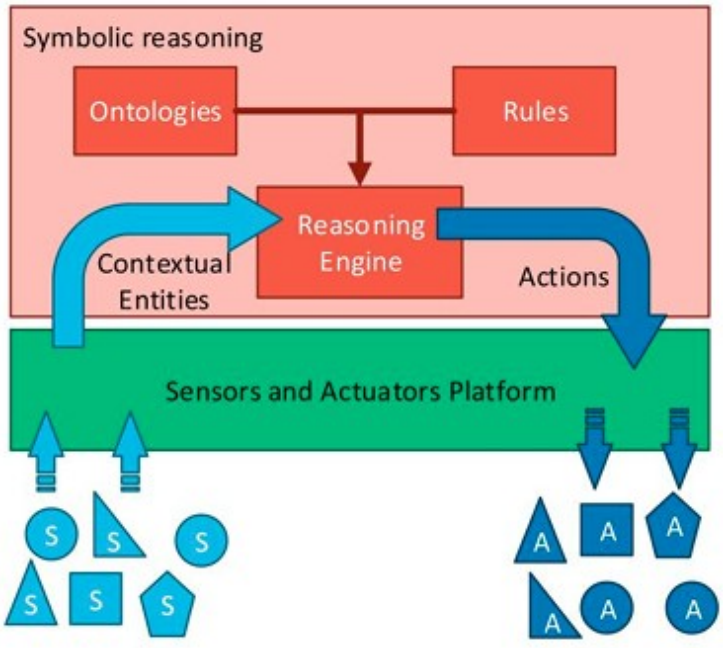


Figure 2. Semantic IoRT architecture. Source: [26].

6. The IoRT platform

The design of an IoRT platform, according to [3], must offer flexibility, scalability, usability, interoperability and different levels of intelligence. The essential elements for the platform include: physical devices and resources, virtualization, data management, semantic

representation, security, networking, open interfaces, data analysis, machine learning, standardized development tools, and the flow of information between the layers of the architecture. In the solution proposed by [22], the need for a local middleware stands out, which functions as an intermediate abstraction layer, connecting different layers. The middleware facilitates data acquisition and processing through high-level APIs. The authors note that middleware developed for the cloud do not handle edge computing well, which justifies the implementation of local solutions. They also claim that the use of microservices offers scalability, accelerates development, and reduces the time to implement innovations.

Finally, [27] argue that a cognitive architecture can be a control system inspired by human and animal cognition, functioning both as a theoretical model and as a reusable computational framework. These architectures have been widely applied in areas such as robotics, games, human-machine interaction, and natural language processing. In addition, the authors discuss the Dual Process Theory, which suggests the existence of two cognitive systems: System 1, which is fast and automatic, and System 2, which is deliberative and conscious, with limited capacity and can inhibit the automatic responses of System 1.

7. Conclusions

Overall, IoRT is poised to drive innovation in autonomous and intelligent environments by providing scalable, flexible, and adaptable solutions. Its potential to transform industries and improve quality of life underscores the importance of continued research and development in this multidisciplinary domain.

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