Cloud Robotics for Industry 4.0 - A Literature Review

Nancy Velásquez Villagrán[1(✉)], Patricia Pesado[1], and Elsa Estevez[2,3]

[1] Facultad de Informática, Universidad Nacional de La Plata (UNLP), La Plata, Argentina
ngvelasquezv@gmail.com, ppesado@lidi.info.unlp.edu.ar

[2] Departamento de Ciencias e Ingeniería de la Computación, Universidad Nacional del Sur (UNS), Bahía Blanca, Argentina
ece@cs.uns.edu.ar

[3] Instituto de Ciencias e Ingeniería de la Computación, UNS-CONICET, Bahía Blanca, Argentina

Abstract. Robots in the industry have been used for decades, much before the so-called Fourth Industrial Revolution. They have been incorporated into industrial processes in various ways, for example, with mechanic arms, in assembly processes, welding, and painting, among others. Industrial robots are located in restricted access sites and their space is delimited by means of physical barriers and security measures. In recent years, Industry 4.0 proposes the use robots, able to collaborate with persons, known as collaborative robots or "cobots". Cobots are characterized by cooperating with human work, sharing the same workspace, and able to respond to simple human-machine interactions. In addition, given the benefits of applying cloud computing in Industry 4.0, research has been conducted in applying such technologies to robots. The approach is known as "cloud robotics" and appears as an emerging topic. The objective of this work is to carry out a systematic literature review of cloud robotics for Industry 4.0, in an attempt to present the state of the art in this field and identify opportunities for future research. From the analysis of the results, we observe an emerging interest in this area, and we identify main technologies applied, research themes, and application areas, as well as a special interest on security and safety aspects.

Keywords: Industry 4.0 · Industrial Internet of Things (IIoT) · Internet of Robotics Things (IoRT) · Cloud robotics · Big data · Machine learning · Mobile robots←

1 Introduction

Industry 4.0 was announced by the German Government in 2011. It is also called the Fourth Industrial Revolution and is characterized for promoting the transformation of the traditional way of producing towards digitization, providing flexibility to productive value chains [1]. In such context, the concepts of smart factory and smart product emerge. In a smart factory, people and machines communicate naturally to produce

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more customized products [2]. Kumar et al. explain that Industry 4.0 integrates various technologies, especially Information Technology and robotics, in the automation and control of manufacturing systems [3]. However, several authors agree that the technologies associated with Industry 4.0 are Internet of Things (IoT), Cloud Computing, Big Data Analytics, Blockchain, Cybersecurity, Augmented Reality, Automation and Industrial Robots, Additive Manufacturing, Simulation and Modeling, Cyber-Physical Systems, Semantic Technologies [4], real-time communication, advanced computing, and Information Technology (IT) in manufacturing systems [3].

Together, automation and industrial robotics are growing and multiple benefits are recognized, such as: lower defect rate, higher quality and reliability, less waste, and better use of factory space. Robots have been used in industry and their use has increased annually [5]. Industrial robots are installed in restricted spaces and their tasks are pre-programmed for specific tasks. For changes, each robot must be reprogrammed and they are limited to their own computing capacity.

Robots play an important role in Industry 4.0, and robotics will allow manufacturers to attain customized mass production. In particular, second generation industrial robots are used in Industry 4.0. They are called "collaborative robots or cobots", and present a number of advantages over their predecessors, including being more productive and flexible [6]. Cobots allow tasks between workers and machines to complement each other, they share the same workspace and can be used in different activities, such as: mobile robots for transport automation in the automotive industry, service robots for logistics in production processes [7], exoskeletons to replace the physical work of people, handling heavy loads, and automate repetitive tasks, among others [8].

Currently, the so-called "cloud robotics" enable robots to connect to the cloud to obtain computing, storage and communication capacity. Robots connected to the cloud are less expensive and more versatile than cobots. They can be programmed by accessing the cloud, communicate with other robots and share knowledge. Additionally, this robots benefit from the cloud computing infrastructure existing for Industry 4.0.

In recent years, researchers have become increasingly interested in cloud robotics. This claim is based on the increasing number of scientific publications. However, a paper on the state of the art of cloud robotics for Industry 4.0 could not be identified. Only Aissam presents a specific study on "Cloud Robotics and Industry 4.0" [10]. Some studies argue that a barrier to the implementation of Industry 4.0 is the need of a high investment [9], and thus, cloud robotics could be an approach to lower the costs. Despite these initial observations, additional studies are needed to understand the development and current trends of cloud robotics for Industry 4.0.

The aim of this article is to identify and analyze the state of the art on cloud robotics for Industry. 4.0. For this, we conducted a systematic literature review (SLR) to identify opportunities and gaps in the field, as well as to determine areas of interest for future work. Among the main contributions of this study, the IoT, IoRT, CPS, mobile cloud, as well as artificial intelligence, machine learning and neural networks were identified as the technologies applied in this field, and clearly, security aspects came up as a critical aspect as well as a priority to explore in more depth.

The rest of this paper is structured as follows, Sect. 2 presents the research methodology. In Sect. 3, we introduce the literature review; while in Sect. 4, we explain the results obtained. Finally, in Sect. 5 we discuss conclusions and outline possible research lines for future work.

2 Research Methodology

Our aim was to conduct an exploratory research to assess the state of the art of cloud robotics for Industry 4.0. We followed the approach suggested by Kitchenham [9], to identify, analyze and interpret the relevant studies. Thus, the research methodology applied comprises three phases, as shown in Fig. 1.

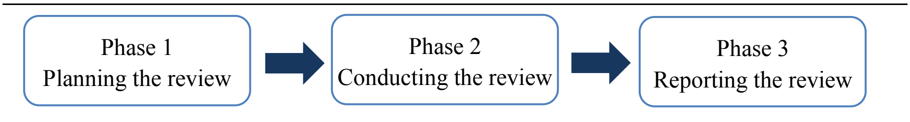

Fig. 1. Research Methodology

In phase 1, the goal was to establish a review protocol for searching and selecting papers. In phase 2, the purpose was to identify and choose the relevant studies, extract and synthesize the information. In phase 3, the results obtained are presented. To guide the research work, we formulate two research questions: Q1) What are the main technologies associated with cloud robotics for Industry 4.0 that are being investigated?; and Q2) Which are the areas of interest for researchers?

According to the research questions, we define the following keywords for conducting the searches: “cloud robotics” AND “industry 4.0”. Considering that “Industry 4.0” is a “collective term” [10], we rely on the study conducted by Muhuri et al. in 2019, publishing an extensive bibliometric study of the state of the art of Industry 4.0 [11] and identified the most popular keywords for Industry 4.0. These words, enumerated in Table 1 were taken as alternative search terms. The table also shows the libraries used for the searches, i.e. Scopus and Web of Science (WoS). Both libraries were selected because they contain recognized journal publications and proceedings of academic conferences, and are well recognized in the fields of Engineering and Computer Science.

Based on the above, we used the keywords previously mentioned combined with all alternative terms, as follows - “cloud robotics” AND “industry 4.0” OR ≪alternative term≫. In addition, we define the following criteria for selecting publications.

Inclusion criteria: Articles written in English, full papers, peer reviewed, containing the keywords in their titles, abstracts or keywords.

Exclusion criteria: Non-academic papers, without references, or just presentations.

The search in Scopus found 44 papers, and the one conducted in WOS, 33. For selecting relevant and non-duplicate papers, we apply the PRISMA methodology [12] with its four phases: identification, screening, eligibility and inclusion. In total, 41 papers were selected.

Table 1. Alternative terms used for the literature review

Main terms	Alternative terms in Scopus	Alternative terms in WoS
Cloud Robotics	cloud robotics	cloud robotics
Industry 4.0	industry 4.0	industry 4.0
	industrie 4.0	industrie 4.0
	smart factory	smart factory
	smart manufacturing	smart manufacturing
	industrial internet	digital factory
	intelligent manufacturing	

To have a broader picture of the relevance of cloud robotics in Industry 4.0, we conducted searches using only the keywords "cloud robotics" in both libraries. We obtained 364 publications in Scopus, and 89 in WoS. Thus, from 453 publications in cloud robotics, 41 refer more specifically to Industry 4.0 and are of interest to this study. The systematic review of the literature was carried out with the first 41 papers.

3 Literature Review

After analyzing the literature, it was possible to find different types of studies about cloud robotics for Industry 4.0. Some of them claim that cloud robotics is an emerging and evolving field of robotics. The kind of robots applied in this field appear from the union of cloud computing and service robotics, they are characterized by obtaining the computing power, memory and storage space of the cloud, as well as, they connect to each other through the cloud to exchange information between them [13]. The use of cloud computing with the robots allows to save energy, physical space and data storage. It facilitates the utilization of big data and artificial intelligence [14].

Some of the studies describe the open source operating system for robots called Robot Operative Systems (ROS) [13], [15], OpenRAVE architecture [16] and the architecture of the global network for robots RoboEarth [17]. Santhosh et al. present a cloud robot used in industrial and manufacturing environments, it works on a ROS platform [18]. Chibani et al. present an overview of the cloud robotics concept and projects [19]. Yan et al. analyze the cloud robotics from different viewpoints, such as cloud computing, big data, applications, and the current problems and challenges [20]. Chaâri presents the potential use of cloud computing to promote cyber physical application [21]. Toquica et al. propose an open source program for the teleoperation of an industrial robot with the socket communication method [22]. Tang et al. underpin the evolution from robots to cloud robotics and presents a system architecture of cloud robotics [15]. Kehoe et al. present a survey of research on the benefits of cloud computing for robots and include a website with updated information [23]. Ronzhin et al. propose a conceptual model of a cyber physical environment for relationship among mobile robots, embedded devices, mobile client devices, stationary service equipment and cloud computing [24]. Shah proposes an energy efficient resource management system for mobile cyber physical system applications as a solution to limited battery power, high latency, and dynamic network environment [25]. Dinh et al. present a survey of Mobile cloud computing, including the definition and applications [26]. Russo el at are developing a cloud robotics architecture for deafblind people [27]. Hong et al. analyze the multi-hop cooperative communication model in robot swarms [28] and Liu, J et al. design a robot cloud platform called cloud robotics intelligent cloud platform [29].

Other studies describe the potential of the interaction of cloud computing with robotics for industry applications and explain how the improvement in the performance of robots facilitates their adoption in Industry 4.0, for example in: SLAM, grasping and navigation [30]. Hussnain et al. propose the adoption of cloud robotics in factories to improve the control and supervision of processes, he presents a scale system to carry out intelligent material handling and to support the process of handling basic products in the factory [31]. The author also analyzes the use of cloud robotics in the manufacture of personalized products, by updating the programming of the robots at runtime, without reprogramming [32]. Rahman et al. propose the optimization of the maintenance application in an oil factory. The results indicate superior performance with minimal resource consumption for industrial applications [33]. Krishna et al. present a project of a robotic cloud for supervision and security to be used in the industry. For example, it can be used to detect gas leaks. It works with ROS platform and Raspberry Pi controller, the data obtained from the robot is stored in the cloud [18].

Wan et al. introduce Context-Aware Cloud Robotics (CACR) for materials handling using the cloud for decision-making, location and mapping. CACR is aligned with industrial production requirements in the context of Industry 4.0 [34]. Lihui Wang, presents a study of a cyber physical system that connects to the cloud for remote monitoring and control of a physical robot, and for remote assembly. He argues that cloud robotics allow better energy efficiency [35].

Duran and Pobil, propose a model of a robotic system that correlates the morphology and the internal parameters of the model, uses neural networks and presents a case study. The results of this research can be used in self-configuring robots and cloud robotics for Industry 4.0 [36]. Anton et al. present a solution for accessing and controlling a manufacturing system for cloud computing research, development and training purposes, including system architecture, deployment scenarios, limitations and testing of system performance [37]. Cardarelli et al. present a cloud robotics architecture for groups of Automated Guided Vehicles (AGVs) that are used in industrial logistics processes [38].

From the point of view of mobility and autonomous vehicles, Mello et al. present a case study of cloud robotics to implement the autonomous navigation service in real time, for unmanned autonomous land vehicles. From the cloud he analyzes the download of the computing tasks on navigation. In addition, it integrates several test benches through FUTEBOL, which allows the experimentation with Industry 4.0 applications [39]. De Mello et al. also present a pilot experiment of a cloud-connected mobility assisted device, which interacts with users. For this author, robotic devices that employ small degrees of cloud computing are lighter and less expensive [40]. Okumus and Kocamaz, propose a cloud-based communication and navigation method for multiple guided autonomous vehicles, using the ROS operating system and presents the results carried out on flat surfaces obtained in the laboratory [41]. Dharmasena et al. propose an automated system to control the optimum growth of plants of a greenhouse. A cloud robotic platform controls lighting and water supply. This platform contains a robotic agent, multiple sensors, and a cloud platform using MYSQL to store all the climate data and robotic communication network [42]. Portaluri et al. propose an open testbed for Cloud robotics (Open Cloro) [43] and Do Nascimento et al. present the evolution of a software platform for experimentation of mobile robotics [44].

In addition, other studies refer to the Internet of Robotic Things (IoRT) and Industry.4.0. For instance, the research published by Nayyar et al. conduct a survey and review the IoRT architecture and technologies required for developing IoRT systems [45], Simoens et al. conduct a survey on the Internet of Robotic Things (IoRT) for the analysis of new disruptive services and technological challenges created by the fusion of IoT and robotics [46]. Harman et al. propose a framework, which aims to improve a robot´s ability to act in dynamic environments with IoT devices [47]. Horton et al. developed security best practices and a framework with an open source, for use in a secure cloud robotics infrastructure [48]. Finally, authors such as: Hussnain et al. [32], Rogue [49], Chen [50], Wang, X et al. [51] present the study of various applications and Fosch Villaronga and Millard assessed the key legal and regulatory topics about the cloud robotics [52].

In the set of publications analyzed, there was none presenting a systematic review of the literature on cloud robotics for Industry 4.0, which is why we claim that this work offers a vision of the state of the art in this field.

4 Results

The first publication on cloud robotics referring to Industry 4.0 appeared in 2015, while, 2018 and 2019 are the years with the highest number of publications. We exclude papers published on 2020, since it is ongoing and not all publications are available yet. Figure 2 shows the number of publication through the years. Results confirm the availability of studies about cloud robotics for Industry 4.0; and although scarce, the number of publications is increasing in recent years, and proves that it is an emerging topic.

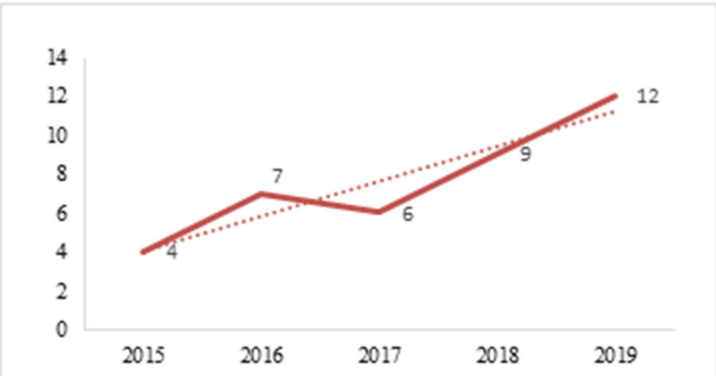

Fig. 2. Number of publications per year

The analysis of the selected publications highlights the technologies applied in the field, including big data, Internet of Things, Internet of Robotic Things, cyber-physical systems, mobile cloud, as well as artificial intelligence (AI), machine learning, neural networks and even open source technologies. The identified technologies are shown in Table 2.

Table 2. Technologies and studies in cloud robotics for Industry 4.0

Technology	References
Big Data	Kehoe et al. [23], Nayyar et al. [45], Tang et al. [15], Wan et al. [34], Duran and Pobil [36], Chaâri et al. [21], Aissam [13]
Internet of Things	Nayyar et al. [45], Dharmasena et al. [42], Portaluri et al. [43], Simoens et al. [46], Tang et al. [15], Wan et al. [34], Chaâri [21], Harman et al. [47]
Internet of Robotic Things	Nayyar et al. [45], Simoens et al. [46], Harman et al. [47]
Cyber Physical Systems	Nayyar et al. [45], Simoens et al. [46], Wan et al. [34], De Mello et al. [40], Hussnain et al. [31], Okumus and Kocamaz [41], Wang [35], Ronzhin et al. [24], Chaâri et al. [21]
Mobile Cloud	Shah [25], Dinh et al. [26]
Artificial Intelligence	Nayyar et al. [45], Aissam et al. [13]
Machine Learning	Nayyar et al. [45], Dharmasena et al. [42], Wan et al. [34], Duran and Pobil [36], Aissam et al. [13]
Neural Network	Nayyar et al. [45], Duran and Pobil [36]
Open Source	Kehoe et al. [23], Portaluri et al. [43], Tang et al. [15], Wan et al. [30], Okumus [41], Yan et al. [20], Aissam et al. [13], Toquica et al. [22]

Through our analysis, we identified major research themes of cloud robotics for Industry 4.0. As summarized in Table 3, they include autonomous robots, ambient intelligence, Automatic Guided Vehicle (AGV), Context Aware Cloud Robotics, mobile robots, localization and mapping, service robots and robot swarms. In addition, some of the application areas, e.g. industrial processes, manufacturing systems, agriculture and oil, gas industries (see Table 4).

Table 3. Research themes of cloud robotics for Industry 4.0

Research themes	References
Autonomous robots/systems	Dharmasena et al. [42], Nayyar et al. [45], Simoens et al. [46], Diankov and Kuffner [16], Aissam et al. [13]
Ambient intelligence	Chibani et al. [19], Harman et al. [47]

(*continued*)

Table 3. (*continued*)

Research themes	References
Automatic guided vehicle	Okumus and Kocamaz [41], Cardarelli et al. [38]
Context-Aware Cloud Robotics	Wan et al. [34]
Mobile robots	Nayyar et al. [45], Simoens et al. [46], Ronzhin et al. [24], Harman et al. [47], Mello et al. [39], Yan et al. [20], Rahman et al. [33], Aissam et al. [13], Toquica et al. [22], Do Nascimento et al. [44]
Localization and mapping	Yan et al. [20], Wan et al. [34]
Service robots	Liu et al. [29], Russo et al. [27], Chaâri et al. [21], Fosch-Villaronga and Millard [52]
Robot swarms	Hong et al. [28]

Table 4. Application areas of cloud robotics for Industry 4.0

Application Areas	References
Industrial processes	Hussnain et al. [31], Okumus et al. [41], Cardarelli et al. [38], Yan et al. [20], Chaâri et al. [21], Anton et al. [37], Rahman et al. [33], Krishna et al. [18], Fosch-Villaronga and Millard [52], Aissam et al. [13], Toquica et al. [22]
Manufacturing systems/applications	Anton et al. [37], Krishna et al. [18], Aissam et al. [13], Toquica et al. [22]
Oil factories	Rahman et al. [33]
Gas industry	Krishna et al. [18]
Agriculture	Dharmasena et al. [42], Simoens et al. [46]

Finally, we identified that a major aspect investigated in the field refers to safety and security. Table 5 identifies the papers addressing such topics.

Table 5. Publications analyzing safety and security aspects

Aspect	References
Safety	Nayyar et al. [45], De Mello et al. [40], Chibani et al. [19], Cardarelli et al. [38], Mello et al. [39], Chaâri et al. [21], Anton et al. [37], Fosch Villaronga and Millard [52], Wang et al. [51]
Security	Nayyar et al. [45], Kehoe et al. [23], Wan et al. [34], Tang et al. [15], Wan et al. [34], Wang et al. [51], Chibani et al. [19], Do Nascimento et al. [44], Yan et al. [20], Chaâri et al. [21], Dinh et al. [26], Toquica et al. [22], Anton et al. [37], Krishna et al. [18], Fosch Villaronga and Millard [52], Aissam et al. [13], Horton et al. [48], Liu et al. [29], Mello et al. [39]

5 Discussion, Conclusions and Future Work

In this paper, we presented a systematic literature review aiming at analyzing the state of the art of cloud robotics for Industry 4.0. Cloud computing and robots are enabling technologies for Industry 4.0 [53], and their combination, cloud robotics, leverages their potential by taking computing, storage and communication resources from the cloud. Such feature avoids the obsolescence of robots.

Results show that the first publication appeared in 2015 and since then, the number of publications is slowly increasing, hinting that is an emerging field. Through the assessment of the state of the art, we were able to identify major technologies applied in the field, including Internet of Things, Big Data, Cyber Physical Systems [21], Internet of Robotics Things, mobile cloud, as well as artificial intelligence, machine learning and neural networks [45]. There are even authors who are working with open source technologies. We also classified main themes being investigated in relation to cloud robotics for Industry 4.0 including: autonomous robots/systems, ambient intelligence, automatic guided vehicles, mobile robots, localization and mapping, service robots and robot swarms. Similarly, we identified some application areas of cloud robotics for Industry 4.0, including industrial processes, manufacturing systems, agriculture, oil factories and gas industry.

As shown by the work of many authors, two areas of interest refer to security and safety. Even more, considering that connecting to a cyberspace requires greater protection [54], cloud robotics, for its nature based in the cloud, is vulnerable to threats of cloud computing, e.g. a hacker attacks could interrupt the provided services and damage to customers or industrial information stored in the cloud and more risky, the attacks could change the orders that the robots execute

In general, the available publications show that there is interest of the scientific community in broadening the application of cloud robotics for Industry 4.0. In this line, future work can be considered in the Internet of Robotic Things and security aspects. Another important research line to explore is the use of cloud robotics for Industry 4.0 to support production processes in the digital factory.

Finally, a line yet not fully explored is the use of cloud robotics in SMEs [55] and security [20]. Cloud robotics could help more industries to implement Industry 4.0 at lower costs compared to currently existing robots. SMEs are characterized by contributing to the local economy and being job generators. They generally react more quickly to changes in market demand, have a greater diversity of products and are closer to customers. Thus, robots contributing to SMEs should be versatile, inexpensive, learn from experience, and relate their work to human workers. With this lens and in this line, we plan to continue our future work.

The limitation of this study is that the literature revised on cloud robotics for Industry 4.0 comprises scientific publications available in Scopus and WoS databases. Thus, we do not claim that the review was complete.

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