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Literature Survey and Review of Cloud Robotics Platforms

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ABSTRACT:

In today's fast-changing world, technology is revolutionizing the business landscape by digitalizing operational procedures. Organizations are presently compelled to constantly devise effective mechanisms to optimize business and production processes to optimize the value delivered to customers. However, traditional business functions can no longer remain competitive without productivity maximization and freeing capacity to tasks with innovative and creative nature. In this century, the concept of Robotics as a Service (RaaS) supports business activities by harnessing the means of automation in order to create enhanced value and reallocate capacity, so as to drive new business opportunities through cost reduction, increase in service quality, automation efficiency and error minimization. In return, efficient processes through robotics and automation systems enable people and organizations to focus on more motivating tasks that can utilize their core competencies, which creates greater prospects for new business innovations. That is why; this research study focuses on a literature survey and critical review on some of the mainstream cloud robotics platforms such as the AWS RoboMaker, Rapyupta, Rospeex, and the C2RO Core Cloud Robotics. The evolution and adoption of cloud robotics have remained fast-paced in this era simply because it eliminates the hardware constraints, or data transmission efficiency issues that typically affect the proficient operations of standalone or networked robots. Therefore, In addition an extensive secondary study by reviewing over one hundred (100) research papers, journals, and books in order to ascertain the peculiar characteristics, importance, and challenges of the major cloud robotics platforms. The findings from this reveals that the AWS RoboMaker, GostaiNet, and Rapyupta cloud robotics platforms are open-source which therefore makes them very easy to integrate different types of robots.

Keywords: *Automation, Cloud, Open Source, Service, Innovation, Business Models, Networking.*

1.0 Introduction

1.1 Overview of Robotics and Cloud Computing

Cloud robotics is an emerging field that combines cloud computing and robotics technologies, enabling robots to offload computation-intensive tasks to cloud infrastructure and share knowledge and resources across different platforms (Kehoe et al., 2015). This approach has the potential to overcome the limitations of traditional robotic systems in terms of processing power, memory, and scalability (Hu et al., 2012). With the rapid development of cloud computing, mobile networks, and artificial intelligence, cloud robotics has gained significant attention from researchers and industry alike. This research proposal aims to conduct a comprehensive literature review of existing cloud robotics platforms, their architectures, functionalities, and real-world applications.

The "Cloud" is a generic term that encapsulates a model for enabling ubiquitous on-demand network access to a shared pool of configurable resources (such as servers, network applications, and storage services). Domaine (2016) further asserts that the cloud has the potential to enable a new generation of robots and automation technologies using cloud computing, big data, wireless networking, statistical machine learning, and other shared resources to improve performance in a wide variety of tasks. Cloud robotics is therefore a distinct field in robotics that is fundamentally rooted in cloud storage and other internet infrastructures that are centered around a converged architecture so as to enable greater computational power, enhanced memory, and interconnectivity for robotics applications (Szewczyk, et al., 2015). The dynamic allocation of data and shared resource pools through ubiquitous cloud platforms aids in enhancing information passage, retrieval, and networking for robotic services (Kazuya, et al., 2014). This, therefore, implies that the major memory, sensing, and computation functions of a cloud robotic is not integrated into a centralized hardware system, but rather controlled through the cloud. The utilization of cloud-robotics further enables robots to share knowledge over a dedicated cloud space, thereby enhancing operational efficiency (Quesnel, 2014). The evolution in the field of cloud robotics has resulted in active research studies within this subject, spanning from the development of cloud robotics architectures to its varied applicability within different domains. In this regard, this project would involve an extensive review and critical analysis of the various cloud robotic platforms in order to examine the peculiar characteristics, importance, and applicability of these technologies.

1.2 Problem Statement

The field of robotics has witnessed substantial developments within the past decade thereby resulting in its increased adoption and application to several real-world problems including automated manufacturing, self-driving vehicles, socially assistive robots, and medical robots (Zhang, 2018). However, most traditional robots are limited by hardware constraints and other computational limitations. To address this challenge, this approach has the potential to overcome the limitations of traditional robotic systems in terms of processing power, memory, and scalability (Hu et al., 2012). With the rapid development of cloud computing, mobile networks, and artificial intelligence, cloud robotics has gained significant attention from researchers and industry alike. This research proposal aims to conduct a comprehensive literature review of existing cloud robotics platforms, their architectures, functionalities, and real-world applications.

1.3 Aim and Objectives

The aim of this research is to conduct a critical comparative assessment of the existing cloud-robotics platforms and their security. This would aid to ascertain the most proficient and secured cloud robotic platforms that can be adopted by business organizations within different sectors. Therefore, some of the main objectives of this research are as follows:

i. To provide a comprehensive overview of existing cloud robotics platforms, their architectures, and the underlying technologies.

ii. To identify and discuss the real-world applications and use cases of cloud robotics platforms in various domains, such as manufacturing, healthcare, and service robotics.

iii. To highlight the challenges and future research directions in the field of cloud robotics, including issues related to network infrastructure, data privacy, and system integration.

1.6 Study Significance

The evolution of autonomous technologies to facilitate industrial functions and other complex human endeavors has continued to grow within the past decades and has reached high levels of performance in terms of robustness, accuracy, and compatibility (Debauche, et al., 2019). However, when facing unknown conditions, most robotics cannot meet actual application needs due to network inadequacies and data shortfalls. With the prolific development of big data, cloud computing, and other emerging technologies, the integration of cloud computing capabilities with robots makes it possible to design multi-robot technologies having increased network efficiency, data-processing capacity, and high performance (Dang, et al., 2017). Research from Singh (2016) reveals that the intrinsic functionality of every robot alongside its information-sharing capability and computational power can be rapidly enhanced using cloud computing paradigms.

Hence, in a bid to explicitly examine the potential of cloud technologies in enhancing robotics functions, this research would describe the core concepts, functions, and development processes of cloud robotics including its underlying architecture of a cloud robotic system. The major differences between the existing cloud robotics platforms would be critically analyzed from the point of view of their respective open-source resources big data, cloud computing, robot cooperative learning, and network connectivity. Subsequently, the key challenges and issues relating to the existing cloud robotic systems would be outlined, and then possible solutions would be tendered. In addition to this problem, some robotic tasks are very computational complex and therefore cannot be tackled efficiently within robotic hardware (Jatoth, et al., 2017). These problems can be addressed with the use of cloud computing, which is a model that “enables ubiquitous, convenient, and efficient on-demand network access to a shared pool of configurable resources (including storage, servers, networks, and applications) that can be rapidly provisioned to release data with minimal service provider interaction or management effort” (Tianbiao, 2012).

1.7 Scope of the research

In the context of this research, it is important to recognize that there are various types of robots such as industrial robots, aquatic robots, cartesian robotics, and SCARA robots. However, the scope of this research would specifically focus on cloud robotics technology. This is aligned with the aims, objectives, and research questions for this study.

2.0 Literature Review

2.1 Contextual Background of this Study

The field of cloud robotics has experienced significant development within the past decades, thereby resulting in its increased application towards solving various real-world issues including automated manufacturing, self-driving vehicles, pharmaceutical processes, socially assistive robots, and medical operations (Hao, et al., 2017). However, it is essential to understand that previously, the robots used in these applications were mainly single robots with internal computational constraints (Selvaraj & Sundararajan, 2014). Therefore, in order to address this challenge, the concept of networked robotics using cloud technology emerged about two decades ago to specifically address issues that standalone robotic systems encounter as regards coordinated data sharing, transfer, and processing (Hunkins, 2018). The concept of cloud robotics has recently emerged as a progressive collaborative technology that intersects between service robotics and cloud computing and is enabled through the progress in communications technology, wireless networking, big data storage, and the Internet of Things (IoT) over the years (Harvey, et al., 2013). Cloud computing autonomously empowers robots by offering them speedy, reliable, and ubiquitous computational capabilities with higher data storage and remote processing functionalities. Also, it offers robots unilateral access to open-source, cooperative learning capability through the inculcation of knowledge sharing and transfers via crowdsourcing.

The significant impact of robotic services within different areas are exponentially growing, as it is not only limited to laboratory functions alone but further extends to support all spheres of human activities, thereby becoming an emerging research topic. Therefore, as a result, the recent progress and development within cloud robotics have led to intensive research and studies on the architecture and underlying components of various cloud robotic platforms. Hence, this study would extensively examine various aspects of this literature with the main reference to cloud computing and robotic technologies.

2.2 Basic overview of Cloud Computing

Cloud computing is simply described as a novel computing paradigm whereby a large pool of systems are interconnected to a public or private network to efficiently provide dynamically scalable infrastructure for either application, data storage, networking, or processing functions (Stephens, 2013). The advent of cloud computing technology has significantly aided in reducing the cost of application hosting, and computation, while enhancing the reliability of content storage, transfer, and delivery (Martino, et al., 2018). Basically, the International Data Corporation (IDC, 2019) research buttresses that the primary idea of cloud computing is fundamentally based on the principle of the “Reusability of IT resources, infrastructure, and capabilities”. Therefore, the main difference which cloud computing presents in comparison to the previous traditional concepts such as “Grid Computing”, is to broaden data storage and transmission horizons across organizational boundaries (Barfoot, 2017).

2.2.1 Cloud Computing Architecture

A cloud computing architecture basically refers to the underlying cloud components which are systematically coupled to proficiently offer digital data networking, and other on-demand computing services ranging from storage functionalities to processing power (Poisel, 2012). A cloud computing architecture is categorized into Front-end and Backend layers:

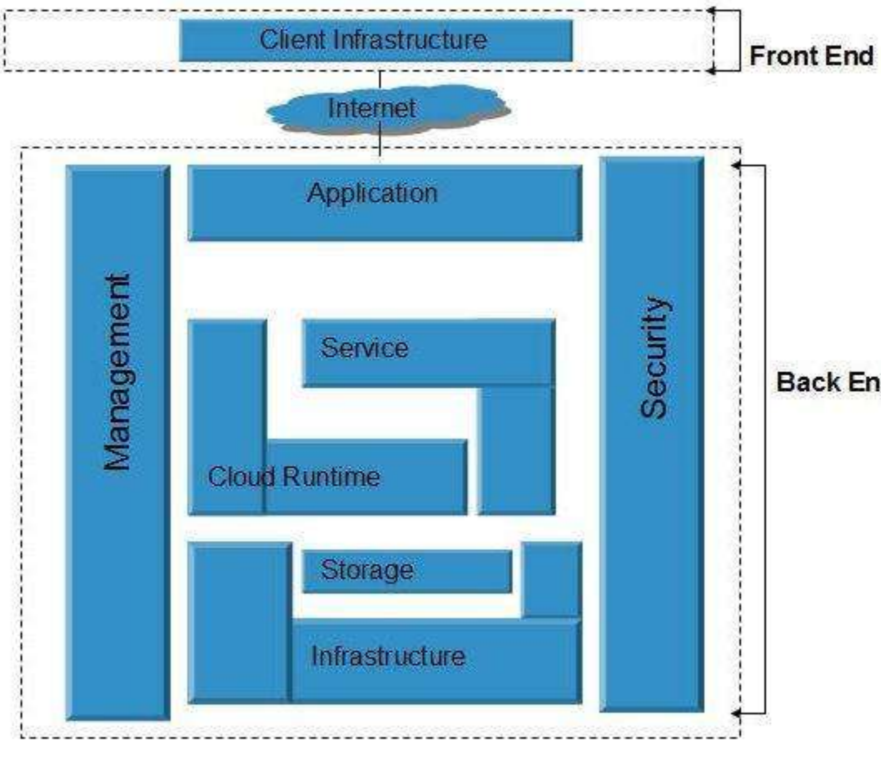


Figure 1 – Cloud Computing Architecture and Components (Kecskemeti, et al., 2016).

The client infrastructure, otherwise known as the front-end layer of a cloud computing technology, majorly comprises of the various interfaces and underlying components that are required to gain access to a cloud computing platform (Furht & Escalante, 2010). Therefore, the main aspects of cloud computing front-end include the web-browsers or other user interfaces through which a cloud service can be accessed. Thereafter, the Back-end layer of a cloud computing technology fundamentally comprises of centralized resources such as virtual machines, data storage, security mechanism, and deployment servers which are required to provide various cloud services to the clients, be it individuals or organizations (Linthicum, 2017). The main responsibility of a cloud computing backend is to provide built-in traffic control, security mechanisms, and protocols (Pethuru, et al., 2014). This is illustrated in ***Figure 1*** cloud computing architecture diagram. Besides, the back-end server of a cloud computing technology employs specific transmission protocols known as Middleware, which helps all interconnected devices effectively relay information (Quesnel, 2014). Then, the internet connects both the front-end architecture and the back-end architecture of a cloud computing platform, thereby providing cost-effective, flexible, reliable, and on-demand digital resource availability for users.

2.3 Cloud Computing Deployment Models

Cloud computing is unarguably the future of computing, as it facilities the outsourcing of basic computing services and infrastructures and makes them remotely accessible to users through the internet (Wieder, 2011). The cloud deployment models basically involve the precise configurations of environment parameters including the accessibility and ownership of the deployed cloud infrastructures and storage sizes. The four main cloud deployment models are shown below:

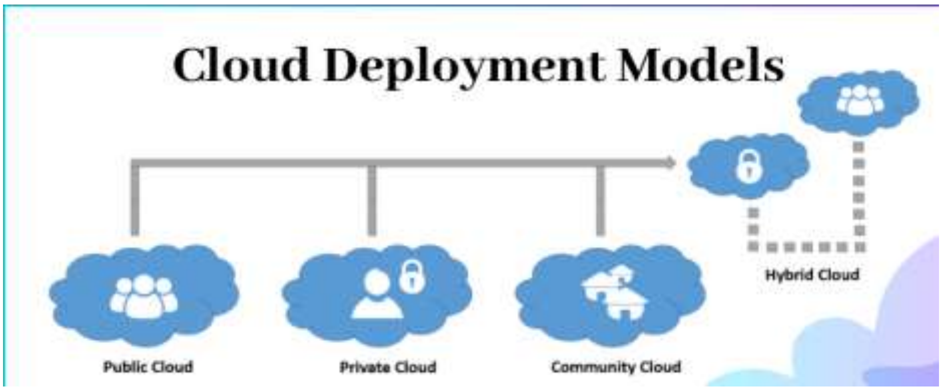


Figure 2 – Illustration of the major Cloud deployment models (Longo, et al., 2018)

As seen in the diagram above, the four main cloud deployment models include Public Cloud, Private Cloud, Community, and Hybrid Cloud. Each of them would be explained in detail below:

2.3.1 Public Cloud

Public cloud is simply described as a deployment model of cloud computing whereby versatile and flexible IT-empowered capacities and functionalities are provided to clients as a service utilizing Internet advances (Huang, 2018). It is by and large offered on a compensation for each utilization model, whereby customers are billed on a Pay-As-You-Go model. Although, Bruneo (2018) highlights that in a public cloud computing deployment model, the customers do not have any form of control over the underlying cloud infrastructure, and other back-end server capabilities. While this can make economies of scale and cost efficiency advantages, this often results in privacy and security risk which mostly occurs due to the vulnerabilities which result from sharing resources publicly. Although Azad (2012) still maintains that the public cloud deployment model still has enormous benefits some of which include the ease of scalability and lack of management or maintenance of the cloud infrastructure which enhances cost savings and convenience for most businesses especially startups.

2.3.2 Private Cloud

Technically, both private and public cloud deployment models do have homogeneous (similar) designs, however unlike the public cloud deployment model, a private cloud is primarily owned by a single user (mostly an organization), and its services are usually not offered to the general public (Yangsheng, et al., 2015). This, therefore, enhances the security and privacy of this cloud model, because the main data architectures of a private cloud mainly reside within a firewall, thereby giving the owner more control of all configurations (Aspragathos, et al., 2019). Hence, making it ideal for handling confidential data particularly for corporate organizations. Also, the private cloud offers increased customization options as well as scalability prospects, although the main drawback revolves around the high cost. Moulianitis (2019) argues that the deployment of a private cloud is typically difficult due to the associated setup and maintenance costs. Furthermore, unlike the public cloud deployment model, (Barfoot, 2017) explains that private clouds are typically is too scalable. Nevertheless, despite some of these drawbacks, organizations using the private cloud deployment model benefit from guaranteed resource availability, regulatory compliance, and stronger security protocols.

2.3.3 Community Cloud

This is a new cloud computing deployment model that is gradually gaining traction in the IT sector. The community cloud deployment model involves a group of organizations having similar privacy, security, and performance requirements combine to share a single cloud resource and infrastructure. Hence, all the user of a community cloud tends to share the usage and maintenance costs amongst themselves, therefore making it cost-efficient in most cases (Tomer, 2015). The purpose of this cloud deployment model is to systematically enable multiple clients to work on joint projects and applications that belong to the community, where it is essential to have a centralized cloud infrastructure (Loof, 2013). The community cloud deployment model offers the benefits of flexibility, reliability, and security for the users since a tightly knit community of users set the configuration capability of the cloud systems.

2.3.4 Hybrid Cloud

Hybrid cloud is a distinct cloud computing deployment model that combines a mix of the private cloud, public cloud, and hybrid cloud services with orchestration between all the platforms (Waschke, 2015). Hybrid cloud models fundamentally provide businesses greater flexibility and increased data deployment options by simply enabling workloads to move between private and public clouds as computing needs and costs change (Klaffenbach, et al., 2018).

2.4 Cloud Computing Service Models

Basically, cloud computing is offered in three (3) different service models that distinctively satisfies a unique set of business requirements. These three service models include Software as a Service, (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS) model.

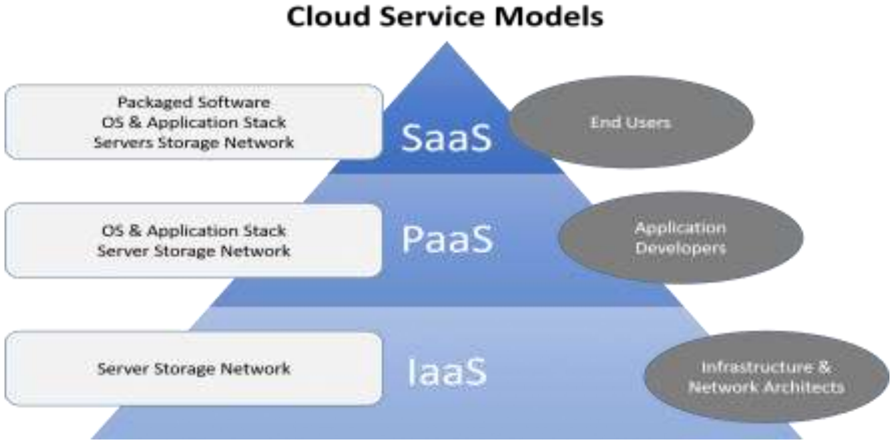


Figure 3 – Cloud service models and components. Source: (Dotson, 2019).

2.4.1 Software as a Service [SaaS]:

The Software as a Service (SaaS) is a cloud computing distribution model in which a third-party vendor hosts the application and makes them readily available to clients (customers) over the internet for easy accessibility, which is why this model is commonly referred to as software on demand (Zhang, 2018). Basically, in the Software as a Service (SaaS) model, the cloud service provider clients with network-based access to a single copy of an application or cloud service (Rajkumar, et al., 2013). Hence, the application source code and underlying scripts are usually the same for all clients, and whenever new functionalities and features are rolled out, they can be accessible to all clients depending on the Service Level Agreements (SLA).

In a Software as a Service (SaaS) cloud computing distribution model, the application or cloud service is predominantly hosted centrally on a cloud server by the cloud service provider or third-party cloud computing vendor (Chun, 2016). They are then distributed to customers through the internet. Part of the main benefit of this cloud service model is that it eliminates the expenses involved in acquiring, and maintaining hardware infrastructures since all the cloud services are offered via the internet (Dotson, 2019). Furthermore, Smith (2011) added that out of all three cloud computing service models, the Software as a Service (SaaS) offers the highest vertical scalability as it gives clients the option to access fewer or more data storage, processing, or other cloud-based services on-demand. Popular examples of SaaS include Salesforce, Basecamp, Google Docs, and Microsoft Office 365 (Blake, 2017).

2.4.2 Platform as a Service [PaaS]:

The Platform as a Service (PaaS) cloud computing cloud service model majorly provides a programming platform for developers by creating a digital avenue that facilitates independent creation, testing, and management of applications virtually (Xiangjun, 2012). Hence, this model fundamentally benefits clients that are in need of application development, which implies that a developer can seamlessly code an application and deploy it directly into a PaaS cloud computing model. These PaaS which might be Windows Azure, Google Apps Engine (GAE), or a host of other systems provides a stable runtime environment and deployment tools so that developers of either robotics or other digital systems can effectively focus on innovation and development without worrying about the infrastructure (Smith, 2011). Although, Baker (2018) argues that the main disadvantage of this cloud computing service model is that developers can be locked-in with a particular vendor.

2.4.3 Infrastructure as a Service [IaaS]

The Infrastructure as a Service (IaaS) was formerly known as Hardware as a Service (HaaS) model. This cloud computing service model provides clients with basic computing capabilities and storage infrastructures such as the hardware, cloud hosting, bandwidth, storage server, operating system, and network providing virtual services (Jia, et al., 2014). Part of the distinct feature of this cloud service model is that it offers a user the option to dynamically select their preferred computing, data storage, or additional cloud configuration (Chen, 2016). In this case, the user of an IaaS cloud computing model is billed based on the computing power utilized. Common examples of IaaS include Tera or the AWS (Amazon Web Service). Some of the main features of this cloud service model are shown below:

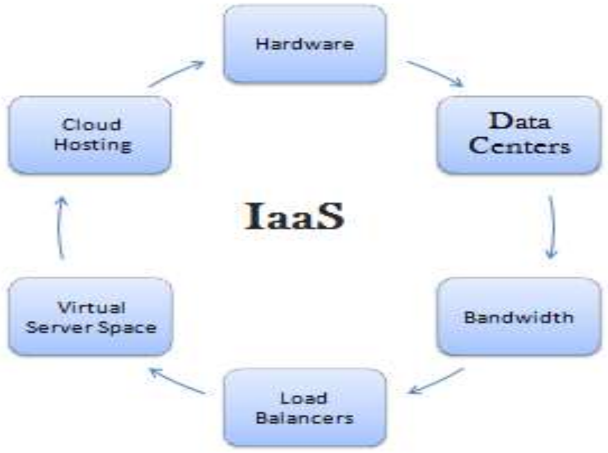


Figure 4 – Components of an Infrastructure as a Service (IaaS) cloud computing model (Pahl, 2017)

Cloudflare Research Network (CRN) explains that the Infrastructure as a Service (IaaS) remains one of the highly sought cloud service models mainly because it enables the users (mostly corporate organizations) to acquire and utilize infrastructures from a cloud provider who is then responsible for its management and maintenance (Ranjan & Sankha, 2010). The diagram below illustrates the global cumulative revenue of the different cloud computing service models (from 2016), and its projected growth rate till the year 2021.

2.5 Robotics and Automation As A Service (RAaaS)

Although many are presently familiar with the concept of Big Data as a Service (BDaaS), Software as a Service (SaaS) as well as the other subscription-based service models. Similarly, the Robots and Automation as a Service (RAaaS) integrates all the benefits of Robotic Process Automation (RPA) by simply leasing robotic devices and accessing a cloud-based subscription service rather than only purchasing the equipment outright (Domaine, 2016). This, therefore, eliminates the long-standing issues associated with the ownership structure, expensive handling process, and maintenance of robots and other automation systems. Furthermore, Huang (2018) studies explain that a complete Robot-as-a-Service (RaaS) solution goes beyond the leasing of the robotic hardware. But this service further goes to offer users continuous value while charging users based on their needs and usage requirements. This continuous value creation generally emanates from the tactical combination of a cloud service, an Integral Operating System (OS), and an available fleet of robots' hardware that can be readily deployed as-needed (Linthicum, 2017). This is illustrated below:

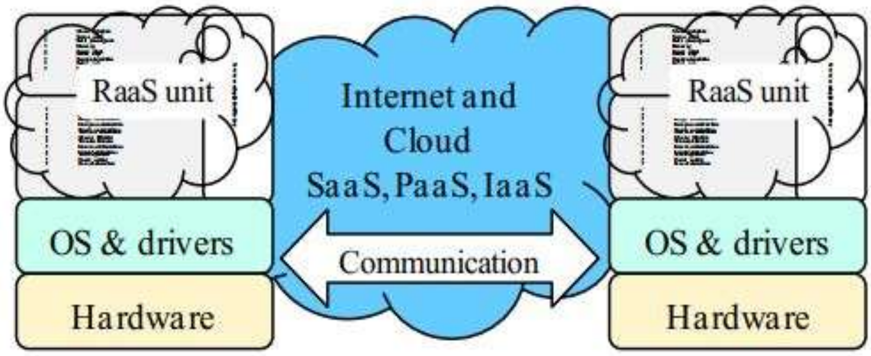


Figure 5 – RaaS in a Cloud Environment (Kazuya, et al., 2014)

Therefore, using the Robot-as-a-Service (RaaS) model, clients requiring various robotic services are not mandated to make upfront investments or payments in order to purchase the robots and maintain them as assets thereby incurring maintenance costs and depreciate over time (Pahl, 2017). As an alternative, it is more efficient to purchase robotic services from RaaS companies such as Fetch Robotics which provides an autonomous mobile robot service that clients can deploy within hours with a unified cloud platform. Other examples include industrial robotics service firms such as Kuka, and most commonly the Google Cloud Robotics Core (GCRC) which is an open-source platform that fundamentally provides the requisite infrastructures and supporting services for building and maintaining different robotic services or solutions mainly for business process automation (Jatoth, et al., 2017).

Similarly, the AWS (Amazon Web Service) RoboMaker is another RaaS solution provider that makes it easy to efficiently build, test, and deploy intelligent robotics services at scale (IEEE, 2019). Hence, customers are billed on a recurring basis based on their usage or other metrics, therefore avoiding the typical risk from asset deterioration and obsolescence. This is why Sarma and Krishna (2019) posit that the biggest benefit of a RaaS is that individuals or corporate organizations readily access various cloud-based subscriptions, thereby resulting in a shift from their Capital Expenditures (CAPEX) to operational expenditure. Therefore, enabling the re-allocation of freed-up capital to other projects that would enhance business effectiveness. The concept of RaaS continues to gain popularity across all sectors of the economy, as IEEE (2019) estimates that the installed base for robots as a service will exponentially increase from around 4,442 units in 2016 to a whopping 1.3 million in 2026, generating $34 billion in revenue. This is due to the increased adoption and application of RaaS in different fields or sectors as shown below:

Figure 6 – Robotics-as-a-Service (RaaS) Overview (Poisel, 2012)

A deeper insight into the concept of Robotics and Artificial Intelligence (AI) is explained below.

2.6 Robotics and Artificial Intelligence

Robotics is generally described as an interdisciplinary area of research that interfaces engineering and computer science, and this field fundamentally involves the design, construction, use, and management of robots which are intelligently programmed machines that can efficiently replicate human actions. Similarly, Kepple (2015) defines a robot as an intelligent and urbane system programmed to perform complex operations with minimal human interventions. To put things in perspective, it is essential to consider that robotics is a branch of Artificial Intelligence (AI), which is the distinct branch of computer science that involves the systematic development of computer programs to perform discrete functions that previously could only be undertaken by humans (Brady, 2015). Therefore, AI algorithms mainly tackle aspects such as problem-solving, perception, cognitive learning, and logical reasoning. Waschke (2015) explains that the major research studies in the field of Artificial Intelligence (AI) primarily focuses on the development of proficient algorithms that could be leveraged to adapt and perform smart decisions or tasks, with minimal human interventions. In this modern age, there are various applications of artificial intelligence and some of the most common examples can be the case of the utilization of AI Algorithms in Google Searches, GPS route finders, Amazon, and other eCommerce product recommendation options (Singh, 2016).

Part of the main reasons there is a blurry line regarding the differences between artificial intelligence and robotics is because robots are fundamentally controlled by Artificial Intelligence (AI) algorithms. In essence, the Center for Cybernetics Research (CCR, 2016) emphasizes that AI is the brain that controls the central functions of any robotic platform.

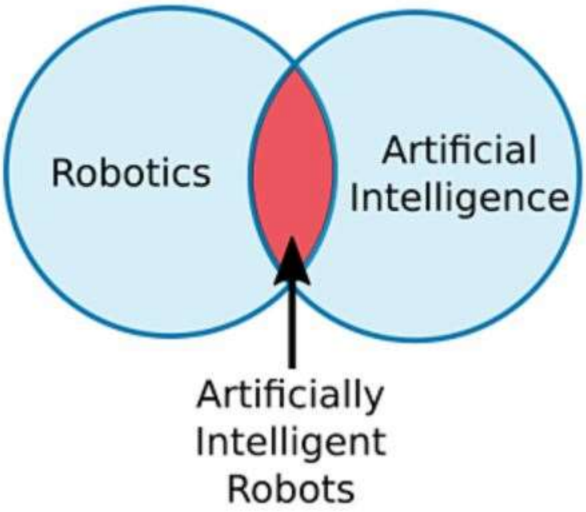


Figure 7 – Robotics and Artificial Intelligence (Kepple, 2015)

As the scope of technology continues to evolve, it is eminent to establish that there has also been significant progress in the field of robotics. The International Federation of Robotics (IFR) study reveals that as of the first quarter of 2020, there were over twelve (12) million robotic units worldwide (IFR, 2020). Yet, IFR (2020) projects that there would be a 15% global increase in the number of robotics units globally. This is mainly because almost all sectors have gradually integrated various forms of robotic systems into their operations in order to efficiently supplement human actions. For example, the automotive sector presently utilizes over 30% of the total units of robots globally (Aspragathos, et al., 2019).

Hengzhang (2012) literature study reveals that there are various types of robots, which are programmed for different types of functions and tasks from healthcare delivery to automobile assembly, and logistics services amongst other operations. Generally, some of the major types of robotic systems include:

I. **Pre-Programmed Robots**: Pre-programmed robots are usually utilized in a controlled environment for static, repetitive, or monotonous tasks that have already been programmed (Quesnel, 2014). An example of a pre-programmed robot would be a mechanical arm on an automotive assembly line which only serves one function such as to insert a certain part into the engine or weld a door and its main duty is to perform that longer task in a fast more efficiently than a normal human (Takacs, 1988).

II. **Humanoid Robots**: A humanoid robot is one with its body shape built to resemble that of a human body (Xun, 2012). In this vein, Saha and Dasgupta (2018) posit that humanoid robots are usually designed for functional purposes, such as interacting with human environments/tools or for experimental purposes. In addition, similar to the service robots, humanoid robots also provide value by automating tasks in a manner that would enhance efficiency, cost savings, and productivity.

III. **Autonomous Robots**: An autonomous robot, otherwise referred to as an Autobot or auto-robot is a robot that performs tasks, behaviors, or functions with a high degree of autonomy and self-sufficiency devoid of any external influence (Villaronga, et al., 2019). Examples of these forms of robots range from the conventional Roomba vacuum cleaner to autonomous helicopters.

IV. **Teleoperated Robots**: These are remotely controlled robots that possess some sort of Artificial Intelligence (AI) capabilities, but customarily receives their command from a human operator and then execute based on the instructions obtained (Arunajyothi, 2018). For this reason, Weider (2011) argues that most teleoperated robots are task-oriented having a limited range of functionalities.

V. **Augmented Robots**: Augmenting robots just as the name suggests, mainly enhances the existing capabilities that a person already possesses or rather replaces the capabilities that a person has lost (Sorrentino, et al., 2020). For instance, within the medical field, some orthopedic robotic legs or arms enable incapacitated patients to do incredible things to augment their disabilities (Blake, 2017). Common examples of augmenting robots include the Deka arm and prehistoric limb (Dotson, 2019).

Cloud robotics platforms have been proposed and developed by various research groups and companies. Some notable examples include:

1. **Rapyuta (Mohanarajah et al., 2015):** A cloud-based platform that provides a middleware layer for managing and coordinating heterogeneous robotic systems, enabling resource sharing and task offloading.

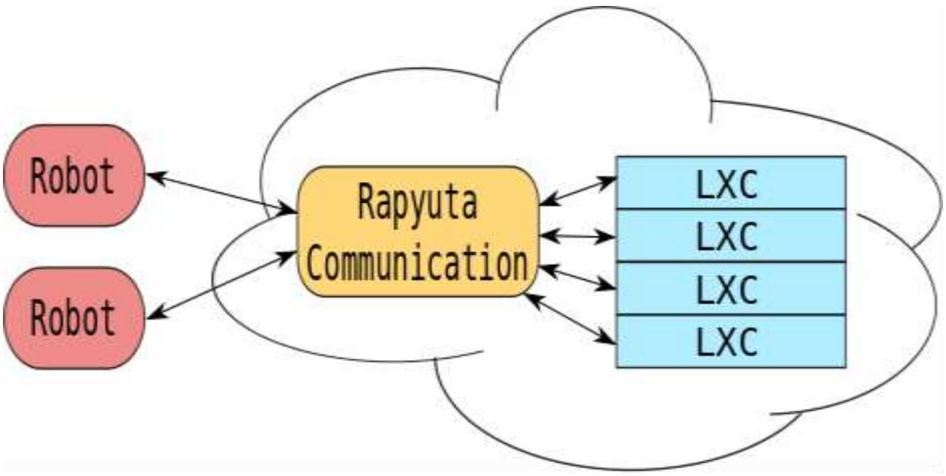


Figure 8 – Rayputa cloud robotics communication protocols

2. **RoboEarth (Waibel et al., 2011):** A web-based platform that allows robots to share knowledge and experiences, facilitating collaborative learning and task execution.

3. **Robotics Operating System (ROS) (Quigley et al., 2009**): A widely-used open-source framework for developing robotic applications, with extensions and tools for cloud integration.

4. **DavinCi (Kehoe et al., 2013):** A cloud-based system that provides a virtualized environment for robotic applications, enabling efficient resource allocation and scalability.

5. **Cloud Robotics Platform (CRP) (Kamei et al., 2018):** A platform that integrates cloud computing, robotics, and Internet of Things (IoT) technologies, enabling distributed data processing and resource sharing.

2.6.1 Architecture of a robot

Having previously explored the architecture and models of cloud computing, this literature review further explores the architecture of a typical robotic system, and the specific technicalities that distinguish a sophisticated software system from a normal software program. Bouzary and Chen (2020) studies explain that the heart of scheming a robotic system architecture is fundamentally based on the demands of cleverly responding to the demands of the environment in a timely manner which therefore necessitates a close relationship between the computational requirements for initiating an appropriate response to a given challenge or task. The International Federation of Robotics (IFR, 2020) describes the typical architecture of a robot in terms of the relationships between three main primitives i.e. (Sensing, Planning, and Acting) and in terms of how sensory data is being processed and propagated around the system. The graphic below simply illustrates the relationships between the primitives of a robotic system in terms of the three dominant paradigms.

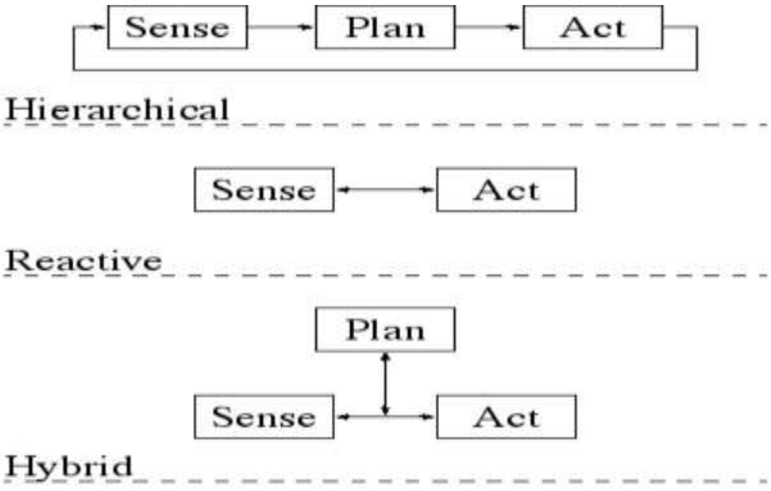
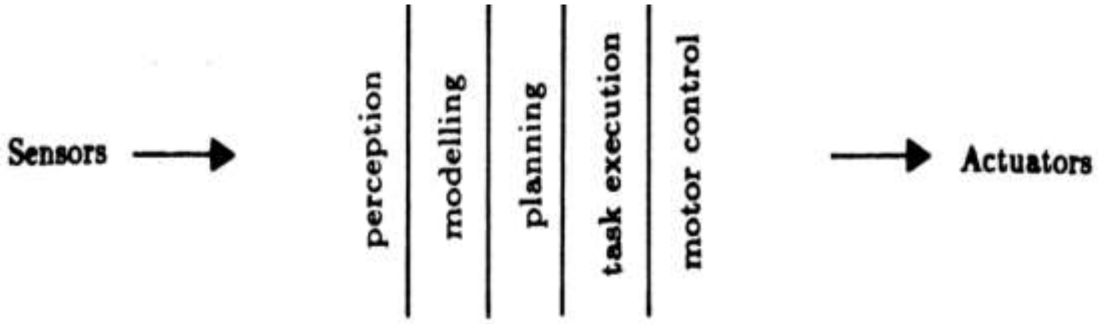


Figure 9 – Primitive Paradigms of a Robotic Architecture (IFR, 2020)

The hierarchical paradigm is the dominant paradigm in AI robotics as the central emphasis is on coordinating a robotic system to adequately sense signals, plan rightly, and give the corresponding action. The British Automation and Robot Association (Bara, 2018) studies reveal that all robots and automation systems have special sensors activated to aid perception, modeling, planning, task execution of autonomous functions, and the motor control whose outputs are reflected through the Actuators as shown below.



Based on the data shown above, and also, the further insights gained from Anirbar (2010) studies reveal that any information or surrounding data from typically in the form of sensor data must filter through numerous intermediate stages of interpretation before it finally becomes available for response by a robotic system. In some robotic applications, every module is distinctively implemented on a separate processor with data propagated from inputs to outputs using a parallel or serial communication paradigm (Camarinha, 2016). In summary, Brady (2015) studies elucidate a three-tier classification of a robotic architecture comprising of a Server (Robotic Communication and Command Interface), the Instinct Planner which comprises of the (Plan monitor, manager, and action selection planner of a robot and lastly the Sensor model. These are all illustrated below:

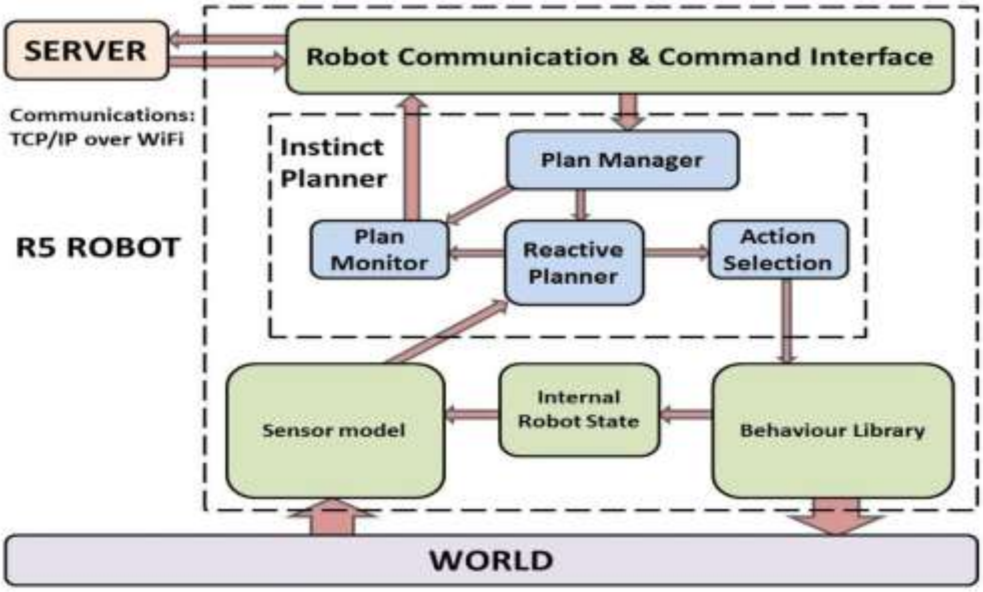


Figure 10 – Robotic System Architecture (Backman, et al., 2016)

Having comprehensively analyzed the concept of the cloud computing paradigm, as well as robotics technologies, it is therefore significant to present a detailed overview of cloud robotics in this present realm.

3.0 Methodology

The literature review will be conducted by systematically searching relevant academic databases, such as IEEE Xplore, ACM Digital Library, ScienceDirect, and Google Scholar. The search will be performed using a combination of keywords related to cloud robotics, cloud computing, and robotics platforms. The collected literature will be carefully analyzed, and relevant information will be extracted and synthesized to address the research objectives.

In summary, as a literature survey of the different cloud robotic systems, the secondary research method would be used since the main data source for the analysis and findings in existing journals, books, and research studies that have been conducted on the different cloud robotic technologies. In addition, all necessary ethical measures are fully considered and implemented as as well the study was conducted within three phases namely, planning, conducting, and reporting. In the planning phase, the necessity for conducting the analysis and the review framework was specified. As part of the review framework, a preconceived plan was formulated that discusses research issues as well as how to undertake the systematic review. The second phase involved the identification of existing research, choice of primary studies according to inclusion and exclusion criteria, quality assessment of the study, the extraction and monitoring of data to finish the synthesis of results. Finally, the third phase consisted of reporting the documents and all the data obtained during the review. These phases are further explained as follows:

3.1 Phase 1 – Planning

The planning phase consists of finding the appropriate research questions to identify the topic for research. For this study, four research questions were derived from gaps identified in the literature as examined in the earlier section, and these are provided in Table 1. The below four questions form a basis for the development of a research strategy for the extraction of literature, which is further discussed in the sections to follow. The first research question (RQ1) for this systematic review seeks to determine the key components of cloud robotic systems. In this process, a dig in the literature comprising the selection of peer-reviewed online bibliographic database is conducted to search for key components that tracking, where the reference lists of all the retrieved text papers are scanned thoroughly so as to decide the relevance of the research. For the purposes of this study, the following international online bibliographic databases were used during the period of November to December 2019; (a) IEEE Xplore, (b) ACM Digital Library, (c) ScienceDirect, (d) Springer, (e) Scopus, (f) Wiley Online Library and (g) Taylor & Francis. The searches were limited to peer-reviewed publications, written in English language, and released between 2009 and 2019, including all research conducted over the last decade. The main keywords used for the searches were "Cloud Robotic System" and "Robot Cloud" together with the following search string ("components of cloud robotic system" OR "elements of robot cloud" OR "Cloud Robotic platform components") AND ("implementation of cloud robotic system" OR "development of cloud robotic architecture") AND ("evaluation of cloud robotic architecture" OR "evaluation metrics for cloud robotic system"). The Boolean OR was used in the search string to connect the key terms with related terms whereas the Boolean AND operator combined the terms. The concepts of inclusion criteria (IC) and exclusion criteria (EC) are other essential aspects of the systematic review planning as it sets the boundaries for the review. All the inclusion and exclusion criteria of this study are specified in Table 2. The final step in the planning phase involved study selection and assessment. An initial selection including the screening of titles, keywords and abstract of possible primary studies was performed in this phase. The inclusion and exclusion criteria were then applied to select relevant articles for extensive reading. Subsequently, a second selection was conducted, where the selected research articles were read thoroughly, and associated research were analysed to enhance the depth of study. Finally, to complete the planning phase, all data obtained were extracted based on the research questions addressed in this study before synthesising the results.

3.2 Phase 2 – Conduction

Conduction is the second phase in regard to the study selection where data are extracted from online databases and are analysed. The activities conducted as part of this phase are described as follows:

3.2.1 First selection

The first step is to obtain a list of primary studies from all the selected online bibliographic databases using the defined search strings. The search protocol that was conducted in all the selected online databases is illustrated in Table 3. Since the primary search criteria were based on the title and abstract, this led to a large number of unrelated studies that were eventually improved with a secondary search.

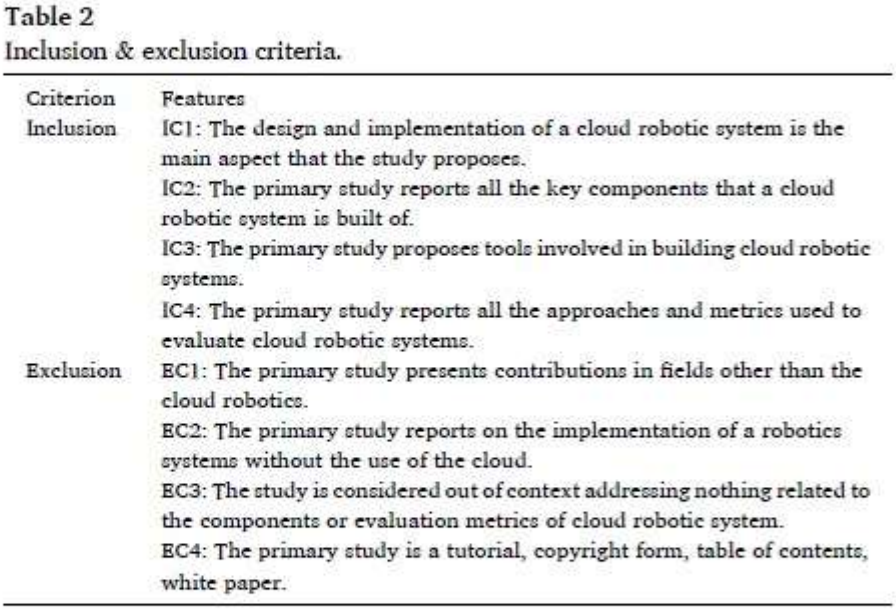
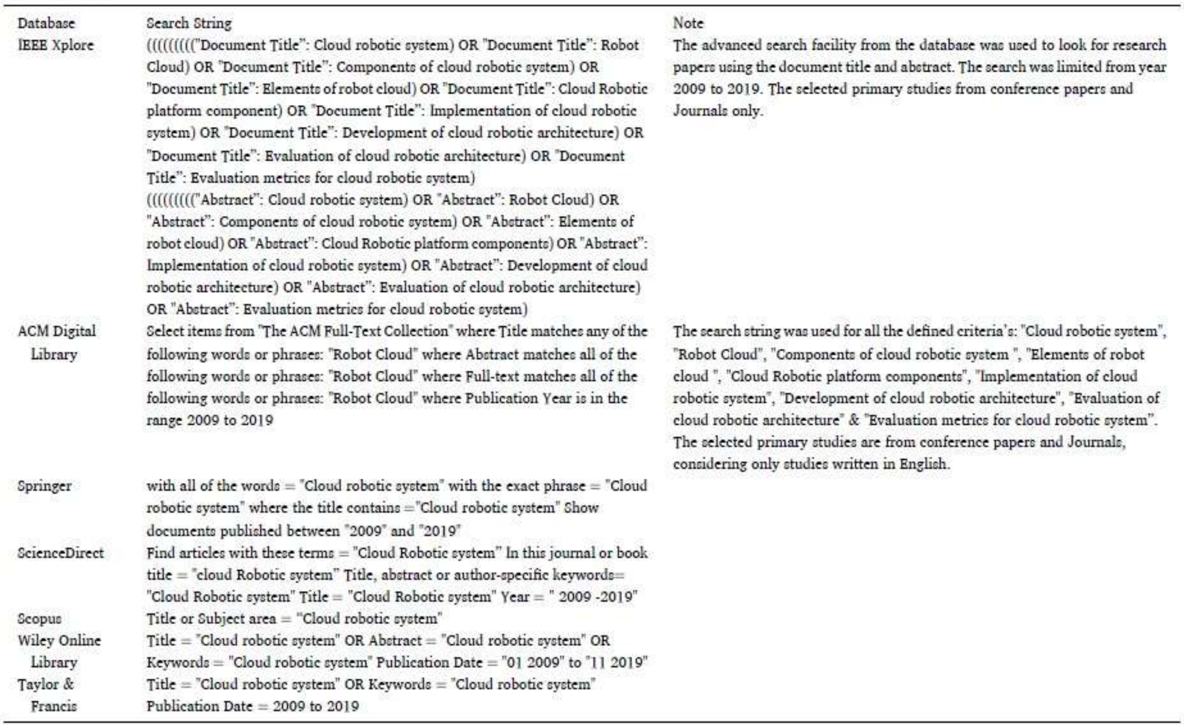


Table 2
Inclusion & exclusion criteria.

Criterion	Features
Inclusion	IC1: The design and implementation of a cloud robotic system is the main aspect that the study proposes.
	IC2: The primary study reports all the key components that a cloud robotic system is built of.
	IC3: The primary study proposes tools involved in building cloud robotic systems.
	IC4: The primary study reports all the approaches and metrics used to evaluate cloud robotic systems.
Exclusion	EC1: The primary study presents contributions in fields other than the cloud robotics.
	EC2: The primary study reports on the implementation of a robotics systems without the use of the cloud.
	EC3: The study is considered out of context addressing nothing related to the components or evaluation metrics of cloud robotic system.
	EC4: The primary study is a tutorial, copyright form, table of contents, white paper.

Table 3
Search protocol.



Database	Search String	Note
IEEE Xplore	((((((((("Document Title”: Cloud robotic system) OR "Document Title”: Robot Cloud) OR "Document Title”: Components of cloud robotic system) OR "Document Title”: Elements of robot cloud) OR "Document Title”: Cloud Robotic platform component) OR "Document Title”: Implementation of cloud robotic system) OR "Document Title”: Development of cloud robotic architecture) OR "Document Title”: Evaluation of cloud robotic architecture) OR "Document Title”: Evaluation metrics for cloud robotic system) ((((((((("Abstract”: Cloud robotic system) OR "Abstract”: Robot Cloud) OR "Abstract”: Components of cloud robotic system) OR "Abstract”: Elements of robot cloud) OR "Abstract”: Cloud Robotic platform components) OR "Abstract”: Implementation of cloud robotic system) OR "Abstract”: Development of cloud robotic architecture) OR "Abstract”: Evaluation of cloud robotic architecture) OR "Abstract”: Evaluation metrics for cloud robotic system)	The advanced search facility from the database was used to look for research papers using the document title and abstract. The search was limited from year 2009 to 2019. The selected primary studies from conference papers and Journals only.
ACM Digital Library	Select items from "The ACM Full-Text Collection" where Title matches any of the following words or phrases: "Robot Cloud" where Abstract matches all of the following words or phrases: "Robot Cloud" where Full-text matches all of the following words or phrases: "Robot Cloud" where Publication Year is in the range 2009 to 2019	The search string was used for all the defined criteria's: "Cloud robotic system", "Robot Cloud", "Components of cloud robotic system ", "Elements of robot cloud ", "Cloud Robotic platform components", "Implementation of cloud robotic system", "Development of cloud robotic architecture", "Evaluation of cloud robotic architecture" & "Evaluation metrics for cloud robotic system”. The selected primary studies are from conference papers and Journals, considering only studies written in English.
Springer	with all of the words = "Cloud robotic system" with the exact phrase = "Cloud robotic system" where the title contains ="Cloud robotic system" Show documents published between "2009" and "2019"	
ScienceDirect	Find articles with these terms = "Cloud Robotic system” In this journal or book title = "cloud Robotic system” Title, abstract or author-specific keywords= "Cloud Robotic system" Title = "Cloud Robotic system" Year = " 2009 -2019"	
Scopus	Title or Subject area = “Cloud robotic system"	
Wiley Online Library	Title = "Cloud robotic system" OR Abstract = "Cloud robotic system" OR Keywords = "Cloud robotic system" Publication Date = "01 2009" to "11 2019"	
Taylor & Francis	Title = "Cloud robotic system" OR Keywords = "Cloud robotic system" Publication Date = 2009 to 2019	

3.2.2 Primary and secondary searches

During the primary search, only titles and abstracts related to the inclusion criteria were analysed. Following this process, a total of 1482 studies were obtained. After filtering, it was observed that 155 document titles from IEEE Xplore database were replicates in the conducted search and after subtracting these, the total number of peer-reviewed literature as primary source resulted to 1327 from years 2014 to 2024 (inclusive) as displayed in Table 4. As it can be seen in the same table, approximately 91% of the articles were excluded because of Exclusion Criteria 1 (EC1), as the articles did not relate precisely to the field of cloud robotics but rather to the cloud or robotics. Again, many articles were excluded due to EC3 which relates to out of context addressing. Nevertheless, during the primary search, it was impossible to exclude articles based on the abstract and title alone because of the specificities of the criteria. Since each inclusion criterion was applied to the same pool of articles, duplicate items were obtained in the total result leading to 121 papers. Thus, to obtain a concise list of articles, a comparison check for duplication was conducted followed by the reading of the introduction and conclusion of the remaining articles to know exactly which papers to select or discard. After analysing and evaluating all 121 research papers, 44 articles were chosen based on their relevance to the study topic, which is "Cloud Robotics", its applicability to any suggested use case scenario, and any associated proposed cloud robotics frameworks or architectures. Table 5 illustrates the selection of the 44 research papers according to database. The selected 44 articles are presented in Table 6, where the column “type” indicates if an article was published as a conference paper (CP) or journal article (JA) since for this study, only these two types of articles were utilised. The column “Criteria” indicates the type of criteria addressed despite all the articles contain Inclusion Criteria 1 (IC1) which relate to the design and implementation of a cloud robotic system since it is the main aspect investigated in this paper. Finally, the column “Sources” shows the sources where the article was obtained using abbreviations such as IEEE Xplore (IE), ACM Digital Library (ACM), Springer (SP), ScienceDirect (SD), Scopus (SC), Wiley Online Library (WL) and Taylor & Francis (TF).

3.3 Phase 3 – Reporting

The final phase of the adopted systematic review framework involved deriving the analytical results towards answering the research questions. The results obtained are based on the extraction of data conducted from the selection process and the analysis of the selected papers. An overview of these papers is provided in Table 7, followed by a discussion of all the acquired answers for the research questions within the next section.

Multiple use case scenarios, frameworks, and architectures are available on cloud robotics, as presented in the 44 articles collected via the selection process and listed in Table 7. However, despite the availability of the 44 reviewed publications, none of the research publications explored the same element of cloud robotics. For example, publications (S4, S6, S10, S18, S26, S28, S34, S35, S38, S39, S43, S44) have discussed and proposed cloud robotic systems in different use case scenarios related to the industrial manufacturing field, thus facilitating the production and delivery of goods. Through the list of publications from Table 7, it was also observed that proposition of cloud robotic system was available in the healthcare sector (S7, S24, S30, S40), education sector (S21, S32), networking field (S1, S11, S15) and biometric field (S5, S9). With so many cloud robotic systems available in various fields to solve a variety of challenges, it is tough to come up with a common framework that may be used to construct a novel cloud robotic system. Thus, it becomes necessary to identify a skeleton structure for a cloud robotic system with key components that can be applied in most of the fields. The next section will deal with the analysis and discussion of results obtained from Table 7.

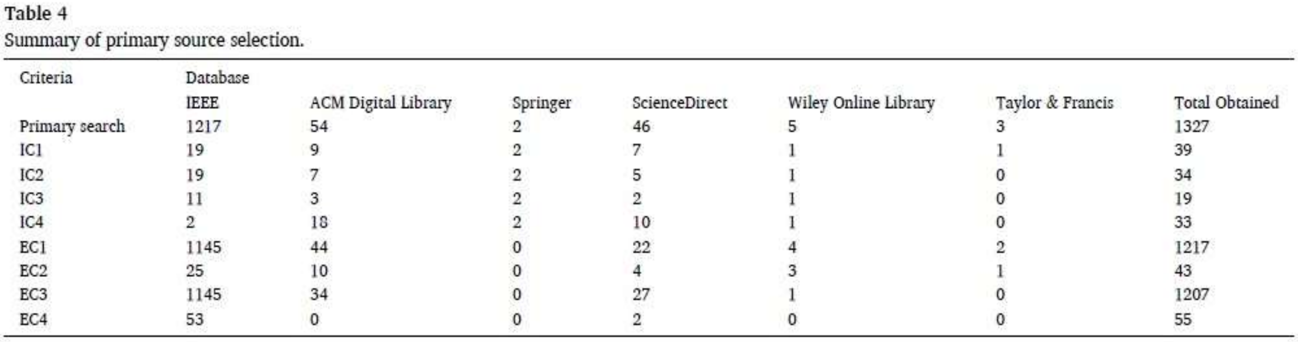


Table 4

Summary of primary source selection.

Criteria	Database						
	IEEE	ACM Digital Library	Springer	ScienceDirect	Wiley Online Library	Taylor & Francis	Total Obtained
Primary search	1217	54	2	46	5	3	1327
IC1	19	9	2	7	1	1	39
IC2	19	7	2	5	1	0	34
IC3	11	3	2	2	1	0	19
IC4	2	18	2	10	1	0	33
EC1	1145	44	0	22	4	2	1217
EC2	25	10	0	4	3	1	43
EC3	1145	34	0	27	1	0	1207
EC4	53	0	0	2	0	0	55

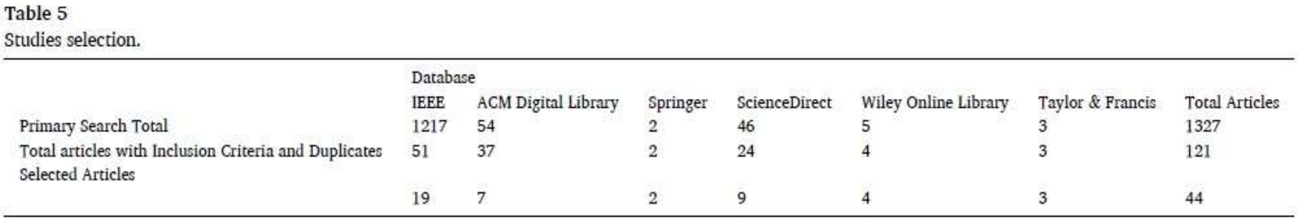


Table 5

Studies selection.

	Database						
	IEEE	ACM Digital Library	Springer	ScienceDirect	Wiley Online Library	Taylor & Francis	Total Articles
Primary Search Total	1217	54	2	46	5	3	1327
Total articles with Inclusion Criteria and Duplicates	51	37	2	24	4	3	121
Selected Articles	19	7	2	9	4	3	44

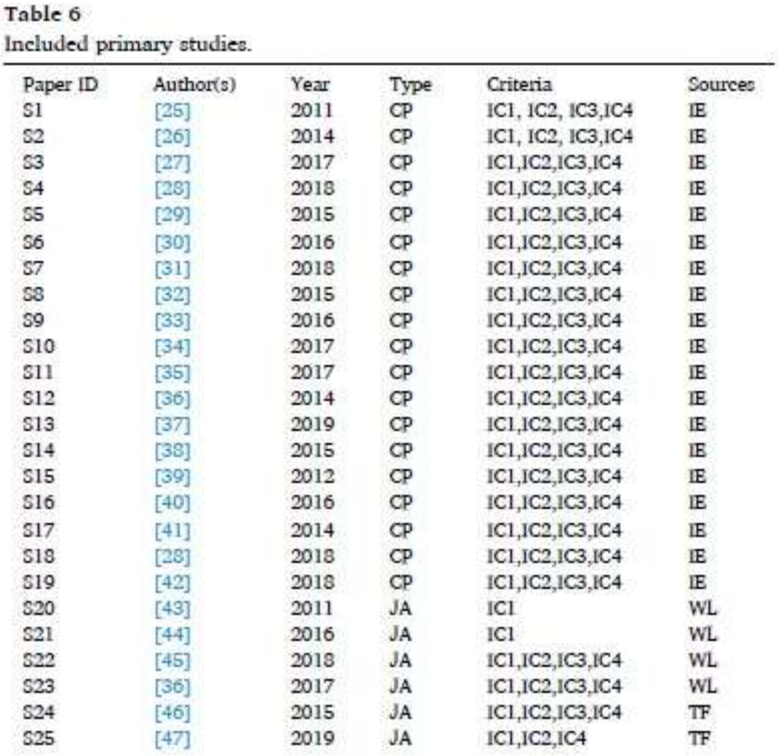
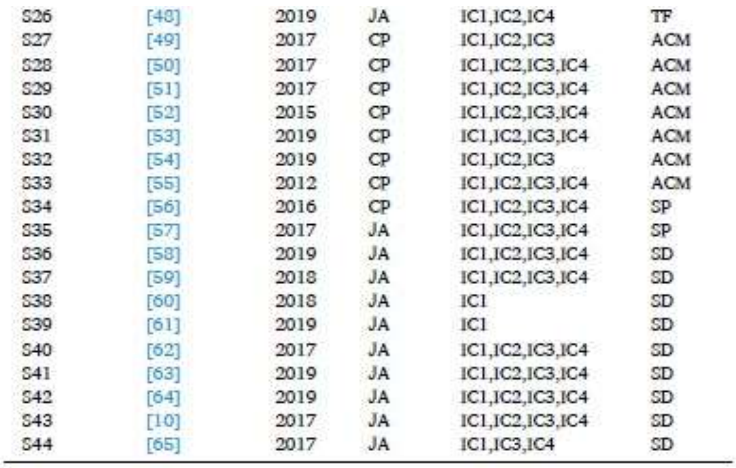


Table 6

Included primary studies.

Paper ID	Author(s)	Year	Type	Criteria	Sources
S1	[25]	2011	CP	IC1, IC2, IC3,IC4	IE
S2	[26]	2014	CP	IC1, IC2, IC3,IC4	IE
S3	[27]	2017	CP	IC1,IC2,IC3,IC4	IE
S4	[28]	2018	CP	IC1,IC2,IC3,IC4	IE
S5	[29]	2015	CP	IC1,IC2,IC3,IC4	IE
S6	[30]	2016	CP	IC1,IC2,IC3,IC4	IE
S7	[31]	2018	CP	IC1,IC2,IC3,IC4	IE
S8	[32]	2015	CP	IC1,IC2,IC3,IC4	IE
S9	[33]	2016	CP	IC1,IC2,IC3,IC4	IE
S10	[34]	2017	CP	IC1,IC2,IC3,IC4	IE
S11	[35]	2017	CP	IC1,IC2,IC3,IC4	IE
S12	[36]	2014	CP	IC1,IC2,IC3,IC4	IE
S13	[37]	2019	CP	IC1,IC2,IC3,IC4	IE
S14	[38]	2015	CP	IC1,IC2,IC3,IC4	IE
S15	[39]	2012	CP	IC1,IC2,IC3,IC4	IE
S16	[40]	2016	CP	IC1,IC2,IC3,IC4	IE
S17	[41]	2014	CP	IC1,IC2,IC3,IC4	IE
S18	[28]	2018	CP	IC1,IC2,IC3,IC4	IE
S19	[42]	2018	CP	IC1,IC2,IC3,IC4	IE
S20	[43]	2011	JA	IC1	WL
S21	[44]	2016	JA	IC1	WL
S22	[45]	2018	JA	IC1,IC2,IC3,IC4	WL
S23	[36]	2017	JA	IC1,IC2,IC3,IC4	WL
S24	[46]	2015	JA	IC1,IC2,IC3,IC4	TF
S25	[47]	2019	JA	IC1,IC2,IC4	TF



S26	[48]	2019	JA	IC1,IC2,IC4	TF
S27	[49]	2017	CP	IC1,IC2,IC3	ACM
S28	[50]	2017	CP	IC1,IC2,IC3,IC4	ACM
S29	[51]	2017	CP	IC1,IC2,IC3,IC4	ACM
S30	[52]	2015	CP	IC1,IC2,IC3,IC4	ACM
S31	[53]	2019	CP	IC1,IC2,IC3,IC4	ACM
S32	[54]	2019	CP	IC1,IC2,IC3	ACM
S33	[55]	2012	CP	IC1,IC2,IC3,IC4	ACM
S34	[56]	2016	CP	IC1,IC2,IC3,IC4	SP
S35	[57]	2017	JA	IC1,IC2,IC3,IC4	SP
S36	[58]	2019	JA	IC1,IC2,IC3,IC4	SD
S37	[59]	2018	JA	IC1,IC2,IC3,IC4	SD
S38	[60]	2018	JA	IC1	SD
S39	[61]	2019	JA	IC1	SD
S40	[62]	2017	JA	IC1,IC2,IC3,IC4	SD
S41	[63]	2019	JA	IC1,IC2,IC3,IC4	SD
S42	[64]	2019	JA	IC1,IC2,IC3,IC4	SD
S43	[10]	2017	JA	IC1,IC2,IC3,IC4	SD
S44	[65]	2017	JA	IC1,IC3,IC4	SD

4. Results and discussions

The selected publications listed in Table 7 were examined using the technique described in the preceding section to address research questions RQ1 through RQ4. The findings from the 44 papers are discussed as follows:

4.1 The key components of cloud robotic systems

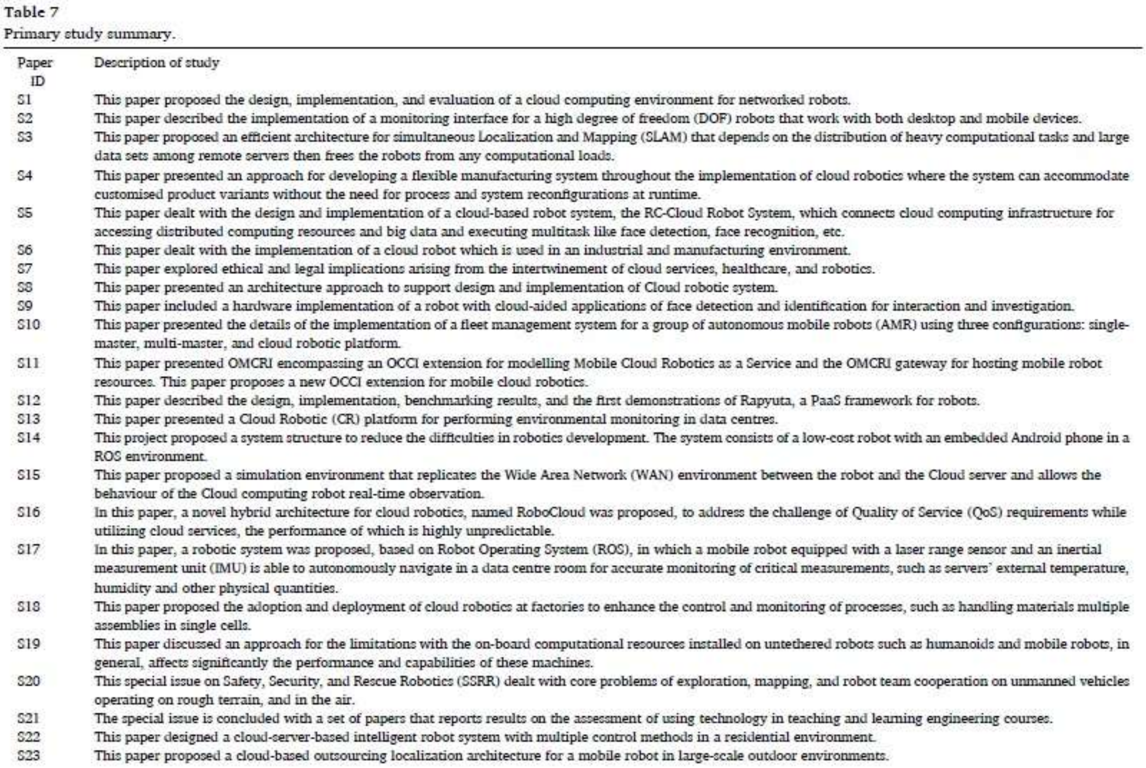
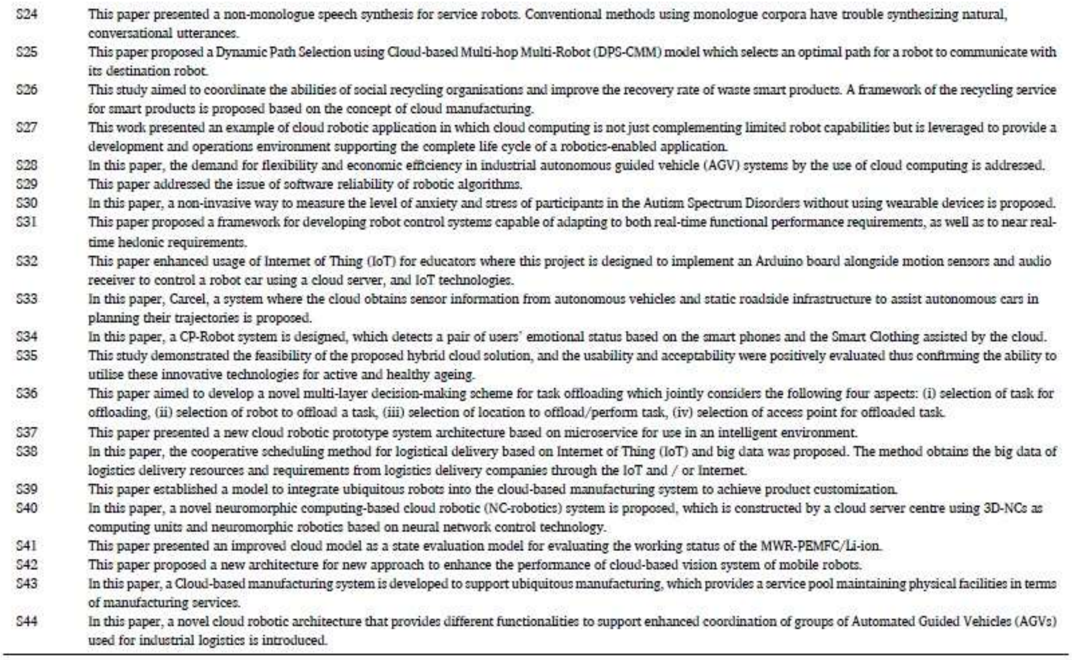


Table 7
Primary study summary.

Paper ID	Description of study
S1	This paper proposed the design, implementation, and evaluation of a cloud computing environment for networked robots.
S2	This paper described the implementation of a monitoring interface for a high degree of freedom (DOF) robots that work with both desktop and mobile devices.
S3	This paper proposed an efficient architecture for simultaneous Localization and Mapping (SLAM) that depends on the distribution of heavy computational tasks and large data sets among remote servers then frees the robots from any computational loads.
S4	This paper presented an approach for developing a flexible manufacturing system throughout the implementation of cloud robotics where the system can accommodate customised product variants without the need for process and system reconfigurations at runtime.
S5	This paper dealt with the design and implementation of a cloud-based robot system, the RC-Cloud Robot System, which connects cloud computing infrastructure for accessing distributed computing resources and big data and executing multitask like face detection, face recognition, etc.
S6	This paper dealt with the implementation of a cloud robot which is used in an industrial and manufacturing environment.
S7	This paper explored ethical and legal implications arising from the intertwinement of cloud services, healthcare, and robotics.
S8	This paper presented an architecture approach to support design and implementation of Cloud robotic system.
S9	This paper included a hardware implementation of a robot with cloud-aided applications of face detection and identification for interaction and investigation.
S10	This paper presented the details of the implementation of a fleet management system for a group of autonomous mobile robots (AMR) using three configurations: single-master, multi-master, and cloud robotic platform.
S11	This paper presented OMCRI encompassing an OCCI extension for modelling Mobile Cloud Robotics as a Service and the OMCRI gateway for hosting mobile robot resources. This paper proposes a new OCCI extension for mobile cloud robotics.
S12	This paper described the design, implementation, benchmarking results, and the first demonstrations of Rapyuta, a PaaS framework for robots.
S13	This paper presented a Cloud Robotic (CR) platform for performing environmental monitoring in data centres.
S14	This project proposed a system structure to reduce the difficulties in robotics development. The system consists of a low-cost robot with an embedded Android phone in a ROS environment.
S15	This paper proposed a simulation environment that replicates the Wide Area Network (WAN) environment between the robot and the Cloud server and allows the behaviour of the Cloud computing robot real-time observation.
S16	In this paper, a novel hybrid architecture for cloud robotics, named RoboCloud was proposed, to address the challenge of Quality of Service (QoS) requirements while utilizing cloud services, the performance of which is highly unpredictable.
S17	In this paper, a robotic system was proposed, based on Robot Operating System (ROS), in which a mobile robot equipped with a laser range sensor and an inertial measurement unit (IMU) is able to autonomously navigate in a data centre room for accurate monitoring of critical measurements, such as servers' external temperature, humidity and other physical quantities.
S18	This paper proposed the adoption and deployment of cloud robotics at factories to enhance the control and monitoring of processes, such as handling materials multiple assemblies in single cells.
S19	This paper discussed an approach for the limitations with the on-board computational resources installed on untethered robots such as humanoids and mobile robots, in general, affects significantly the performance and capabilities of these machines.
S20	This special issue on Safety, Security, and Rescue Robotics (SSRR) dealt with core problems of exploration, mapping, and robot team cooperation on unmanned vehicles operating on rough terrain, and in the air.
S21	The special issue is concluded with a set of papers that reports results on the assessment of using technology in teaching and learning engineering courses.
S22	This paper designed a cloud-server-based intelligent robot system with multiple control methods in a residential environment.
S23	This paper proposed a cloud-based outsourcing localization architecture for a mobile robot in large-scale outdoor environments.



S24	This paper presented a non-monologue speech synthesis for service robots. Conventional methods using monologue corpora have trouble synthesizing natural, conversational utterances.
S25	This paper proposed a Dynamic Path Selection using Cloud-based Multi-hop Multi-Robot (DPS-CMM) model which selects an optimal path for a robot to communicate with its destination robot.
S26	This study aimed to coordinate the abilities of social recycling organisations and improve the recovery rate of waste smart products. A framework of the recycling service for smart products is proposed based on the concept of cloud manufacturing.
S27	This work presented an example of cloud robotic application in which cloud computing is not just complementing limited robot capabilities but is leveraged to provide a development and operations environment supporting the complete life cycle of a robotics-enabled application.
S28	In this paper, the demand for flexibility and economic efficiency in industrial autonomous guided vehicle (AGV) systems by the use of cloud computing is addressed.
S29	This paper addressed the issue of software reliability of robotic algorithms.
S30	In this paper, a non-invasive way to measure the level of anxiety and stress of participants in the Autism Spectrum Disorders without using wearable devices is proposed.
S31	This paper proposed a framework for developing robot control systems capable of adapting to both real-time functional performance requirements, as well as to near real-time hedonic requirements.
S32	This paper enhanced usage of Internet of Thing (IoT) for educators where this project is designed to implement an Arduino board alongside motion sensors and audio receiver to control a robot car using a cloud server, and IoT technologies.
S33	In this paper, Carcel, a system where the cloud obtains sensor information from autonomous vehicles and static roadside infrastructure to assist autonomous cars in planning their trajectories is proposed.
S34	In this paper, a CP-Robot system is designed, which detects a pair of users' emotional status based on the smart phones and the Smart Clothing assisted by the cloud.
S35	This study demonstrated the feasibility of the proposed hybrid cloud solution, and the usability and acceptability were positively evaluated thus confirming the ability to utilise these innovative technologies for active and healthy ageing.
S36	This paper aimed to develop a novel multi-layer decision-making scheme for task offloading which jointly considers the following four aspects: (i) selection of task for offloading, (ii) selection of robot to offload a task, (iii) selection of location to offload/perform task, (iv) selection of access point for offloaded task.
S37	This paper presented a new cloud robotic prototype system architecture based on microservice for use in an intelligent environment.
S38	In this paper, the cooperative scheduling method for logistical delivery based on Internet of Thing (IoT) and big data was proposed. The method obtains the big data of logistics delivery resources and requirements from logistics delivery companies through the IoT and / or Internet.
S39	This paper established a model to integrate ubiquitous robots into the cloud-based manufacturing system to achieve product customization.
S40	In this paper, a novel neuromorphic computing-based cloud robotic (NC-robotics) system is proposed, which is constructed by a cloud server centre using 3D-NCs as computing units and neuromorphic robotics based on neural network control technology.
S41	This paper presented an improved cloud model as a state evaluation model for evaluating the working status of the MWR-PEMFC/Li-ion.
S42	This paper proposed a new architecture for new approach to enhance the performance of cloud-based vision system of mobile robots.
S43	In this paper, a Cloud-based manufacturing system is developed to support ubiquitous manufacturing, which provides a service pool maintaining physical facilities in terms of manufacturing services.
S44	In this paper, a novel cloud robotic architecture that provides different functionalities to support enhanced coordination of groups of Automated Guided Vehicles (AGVs) used for industrial logistics is introduced.

RQ1 seeks to determine the key components that form cloud robotic systems. From existing literature, a list of utilised components referred to within each paper was retrieved to devise a generic architecture for cloud robotic systems. When analysing the selected papers, it was observed that various components were mentioned in each reviewed paper as different scenarios were involved. Among these components, some remained distinct and can be deemed as the key components of cloud robotic systems. These key components are listed in Table 8, which also summarises the cumulative number of primary studies covering each component. Within the same table, the column "key component" presents the list of commonly used building blocks retrieved from the selected articles reviewed and "paper" refers to the studies covering each of the identified components. Statistical information is also provided in the form of the total number of papers that refer to a particular component, in addition to the utilisation frequency of the key components in all the 44 selected primary studies. From Table 8, it can be observed that the usage frequency of cloud infrastructure and robots are 61.4% and 59.1% respectively as these are two important components for the implementation of a cloud robotic system. It was noticed that from the 44 selected publications, the I/O devices component consisting of sensors and actuators used in collaboration with the robot has an average usage frequency of 25% together with networking & communications component and data processing & control component. With a 25% usage frequency, it is understood these three key components are compulsory in the overall functioning and operation of cloud robotic systems. With a few cloud robotic frameworks and architectures from the reviewed publication opting for SOA & servers, web components, API & third party tools and libraries, and virtual simulation or network emulator, it can be deduced that these components can be considered in exceptional use case scenarios or be optional if not required. From existing literature, it is observed that building a cloud robotic system requires a defined set of connecting components to be fully operational. The set of connecting components provides flow in the main feature of cloud robotic system which is composed of sensors and actuators and can also be used in a physical form or as a simulator. Utilising robots in this system enables the automatic data collection from physical and challenging environments. Since the data captured by the robots cannot be accessed and read directly by humans, the data are transferred to a data control and processing unit, the second component of the cloud robotic system, which is connected to the robots. The data control and processing unit simplifies the analysis, verification, and validation of data collected from the robots and allows users to read the data in a more understandable format. Once the data is obtained from robots, read, and analysed through the desired output devices, the networking and communication component is used to transfer the data from the data control and processing unit to the chosen cloud infrastructure which is the fourth key component of a cloud robotic system. The networking and communication component acts as a bridge between the user interface and the cloud. Data transferred to the cloud are stored safely for further use as the robot does not have inbuilt large data storage capacity. To retrieve and view the stored data from the cloud, the same networking & communication component is used to transfer the data in a particular desired output using a particular user interface component of a cloud robotic system. It was also noted that developers or researchers can view the transferred data from the robot via the data control and processing unit on any particular desired output devices since some cloud services are equipped with web dashboards. Based on the above-mentioned flow of communication and components discussed, a generic architecture for cloud robotic systems is designed and built, as illustrated in Fig. 1.

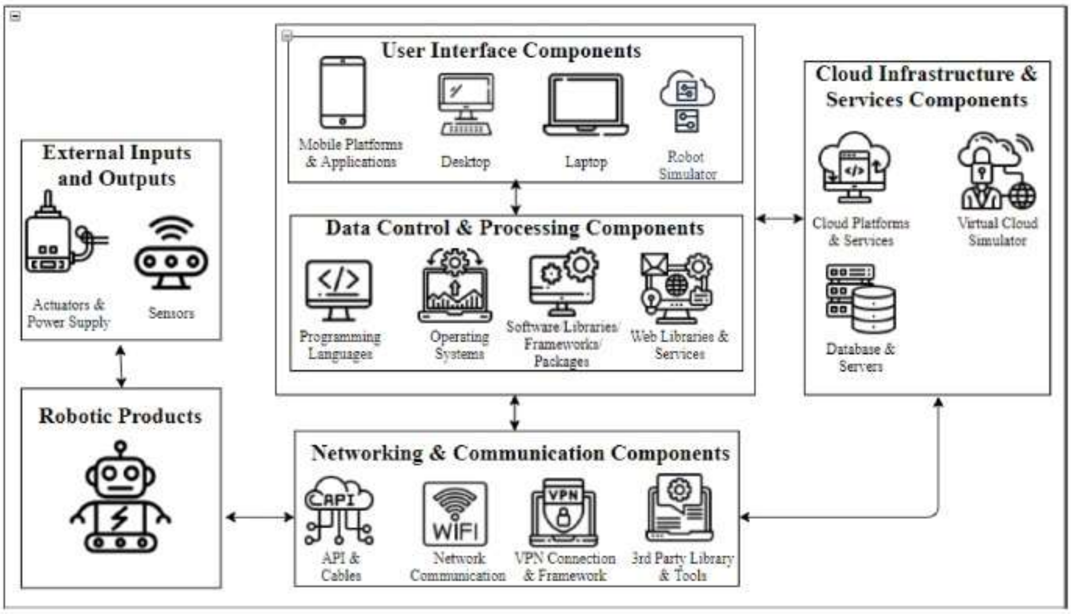


Fig. 1. Generic architecture of cloud robotic system.

Within the architecture proposed in Fig. 1, different components and sub-components of a cloud robotic system are present, and these are outlined as follows:

• Robotic Products: It is equipped with a plethora of sensors and actuators to collect real-time data in the different physical environments for the cloud robotic system to process. There are different types of built-in robotic products readily available in the market or can also be customised depending on the scenario and functionality. In a robot, the sensor acts as the input device for data collection and actuator is used as an output component to showcase a particular reaction from the input.

• External Inputs and Outputs: It consists of external sensors and actuators that are connected to the robot in case the latter does not possess an inbuilt one. The sub-components are as follows

- *Sensor*: It includes different types of sensors such as temperature, humidity, pressure, and proximity among others to collect data for processing by the cloud robotic system.
- *Actuator & Power Supply*: It comprises of devices such as temperature control valve or robotic arm so that data can be manipulated in the physical environment and sent for processing by the cloud robotic system. Power supply is used to provide energy to the actuators and robot to operate.
- **Data Control & Processing Components**: It acts as a processing component in the cloud robotic system where it processes the data obtained from the robot's integrated sensors and actuators or external sensors and actuators. This component comprises of several sub-components such as operating system, software development tools, programming languages and web libraries & services which can be used to process the data received from the robot.
- **Network and Communication Components**: This component deals with the network and communication protocol between the input components that sit between the robot and the cloud infrastructure. It acts as a medium of communication between the robot and the cloud that is once the robot's data is processed, it is then transferred to the cloud though use of network. The sub-components are as follows:

- 3rd Party Tools & Libraries: They act as a bridge between the cloud, the robot, and the Internet of Things (IoT) devices to allow a flow of communication.
- Network Communication: It provides network facility to the data processing component to send the processed data to the cloud service. The data sent to the cloud can be viewed onto cloud's dashboard over the output devices.
- VPN Connection & Framework: It allows data to be transmitted to the internet through the Virtual Private Network (VPN) while ensuring the security of transmitted data.
- API Gateway and Cables: Application Programming Interface (API) sits between a collection of backend services and the client where it accepts API calls, form the required services needed to accomplish the request and submit the appropriate result. Within the architecture, most of the components are interlinked using cables to communicate through analog or digital signals to each other.

• **Cloud Infrastructure & Services Components**: The cloud services enable the robot to store its data for future use and for analytic purposes. When constructing a cloud robotic system, the process of integrating cloud services into the robot begins by connecting the robot to the internet then with the data and processing component, namely with the programming component, which specifies all of the codes required to link the robot to the cloud. Once the link is established between the robot and the cloud, data communication can be established between each other. The data stored on the cloud can also help in predicting future trends of the use-case.

- Cloud Platforms & Services: It consists of four core cloud services:

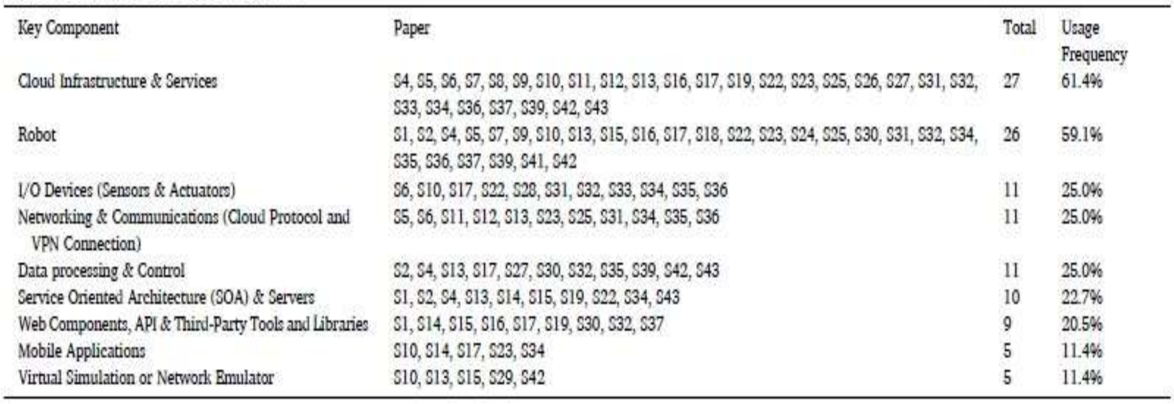
▪ In a cloud computing system, the Infrastructure as a Service (IaaS) hosts virtualized computing resources via the network and provides data storage, high-speed computation, and other tasks.

  - Software as a Service (SaaS) allows clients to access cloud-based applications from a variety of end-client devices through a web program.
  - Platform as a Service (PaaS) is a cloud computing model that includes a database system and software management, with the purpose of allowing developers to consume IaaS resources and publish their applications to a virtualized cloud platform
  - Anything as a Service (XaaS) refers to any function given to clients through the cloud rather than relying on in-house technology

- Database & Servers: They are required when using specific programming languages when implementing a cloud robotic system. They provide storage service to other components in the system over a network and the data can also be transmitted to a cloud service.

Table 8

Key components of cloud robotic system.



Key Component	Paper	Total	Usage Frequency
Cloud Infrastructure & Services	S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S16, S17, S19, S22, S23, S25, S26, S27, S31, S32, S33, S34, S36, S37, S39, S42, S43	27	61.4%
Robot	S1, S2, S4, S5, S7, S9, S10, S13, S15, S16, S17, S18, S22, S23, S24, S25, S30, S31, S32, S34, S35, S36, S37, S39, S41, S42	26	59.1%
I/O Devices (Sensors & Actuators)	S6, S10, S17, S22, S28, S31, S32, S33, S34, S35, S36	11	25.0%
Networking & Communications (Cloud Protocol and VPN Connection)	S5, S6, S11, S12, S13, S23, S25, S31, S34, S35, S36	11	25.0%
Data processing & Control	S2, S4, S13, S17, S27, S30, S32, S35, S39, S42, S43	11	25.0%
Service Oriented Architecture (SOA) & Servers	S1, S2, S4, S13, S14, S15, S19, S22, S34, S43	10	22.7%
Web Components, API & Third-Party Tools and Libraries	S1, S14, S15, S16, S17, S19, S30, S32, S37	9	20.5%
Mobile Applications	S10, S14, S17, S23, S34	5	11.4%
Virtual Simulation or Network Emulator	S10, S13, S15, S29, S42	5	11.4%

5.1 Conclusions

Cloud robotics is an emerging field that enables the connectivity of robots to gain access to several cloud services on the fly. This research study reveals that cloud robotics was initially borne by merging robotics with cloud technologies so as to aid efficient data transmission, and operational efficiency. The robot intelligence is centrally not in the robot itself but is rather remotely executed on the data storage server or cloud. Thereby making the robot act as a thin client. Several frameworks have already been developed with immense growth within the field of cloud robotics so as to aid in the enhancement of storage and offloading of computation through the cloud which is the further step in robotic evolution

Therefore, this research involved a comparative analysis of the various cloud robotics platform, and the mainstream cloud robotics systems analyzed includes the: AWS RoboMaker, Rapyupta, GostaiNet, and the Rospees cloud robotics.

To this end, this research study revealed that the entire cloud robotics technology ecosystem is still in its infancy (emerging) stages. Despite the present significant of these cloud robotics platforms in enhancing network connectivity and constant data flow between interconnected robots, the future potentials of cloud robotics cannot be overemphasized, and its practical adoption would result in significant disruptions in all sectors and field. The findings from this research study vividly indicate that most of the cloud platforms are open-source, thereby inheriting some benefits as well as the drawbacks involved with being an open-source cloud robotic system. Moreover, cloud robotic system and the approaches used to evaluate such systems are presented following a systematic review of the literature. For achieving the purpose of this paper, a precise list of all articles related to cloud robotic system selected from six online peer-reviewed bibliographic databases was explored and out of 1327 peer-reviewed papers initially identified from years 2009 to 2019 (inclusive), 44 were selected based on defined inclusion and exclusion criteria. In the systematic review conducted, four research questions were answered while also targeting four contributions to literature. The first research question attempted to determine the key components of cloud robotic systems and in this process, a generic architecture for such type of systems was proposed that could be utilised by builders of such systems as reference. As the second contribution to literature, the tools involved in building the cloud robotic systems were compiled and analysed from literature, consequently, it was found that there was no agreed consensus on the tools used in the build-up of such systems. This lack of consensus could be a key reason for various reported problems in the implementation of cloud robotic systems including integration issues and management of big data.

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