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The New Approach to Comparative Analysis of Cloud Robotics Platforms And Its Security

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ABSTRACT:
In the 21st 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.
Hence, this research comprises of extensive study of the technical advancements in cloud robotics technologies, and extensive discussions on the practical applications of cloud robotics systems security since most cloud robotics systems are vulnerable to some cybersecurity threadsand most notably the denial of service as well as the Man In The Middle (MITM) attacks. Therefore, viable cybersecurity defense and mitigation strategies were recommended in order to enhance the safety of these platforms.
Keywords: *Automation, Cloud, Open Source, Service, Innovation, Business Models, Networking.*

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I. Introduction

1.1 Overview of Robotics and Cloud Computing

In the 21st century, recent progressions in the field of robotics and cloud computing technologies have resulted in the development and advancement of the cloud-robotics paradigm (Prasad, 2014). The impact of robots has continued to grow exponentially in different areas, not just the typical laboratories or manufacturing plants, as robotics services are presently used to support diverse human operations from gaming to education and health care delivery (Singh, 2016). However, for robotic systems to effectively function, it must have ubiquitous on-demand access to a shared pool of configurable network resources and cloud-data services (Nagarajan, et al., 2017). This has consequently led to the emergence of diverse cloud robotic platforms such as the AWS Robomaker, Google Cloud Robotics Platform, and the other Robot as a Service (RaaS) platforms having heterogeneous characteristics, network capabilities, and features (Spiteri, 2010). The National Institute of Standards and Technology (NIST) posits that out of all the existing digital technologies, the cloud presently has the most potential to enhance a broad range of robots and other automated systems (Masterson, et al., 2017).

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

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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, the field of networked robotics emerged mainly to address the issues associated with standalone hardware robotic systems by sharing perceived data and efficiently solving tasks in a coordinated manner (Aspragathos, et al., 2019). Nevertheless, networked robots and automation systems still encounter some of the same issues typically associated with single (standalone) hardware robot systems. The particular problem associated with networked robots mainly happens as a result of resource constraints, information sharing disruption, learning constraints, and communication limitations (Szewczyk, et al., 2015). Hence, minimizing the efficacy of these robots due to the limited computing and storage capacity thereby making it technically difficult to modify or enhance the resource configurations once a robot is in operation (RIRPA, 2019).

The information constraints of networked robots limit their possessing abilities for a vast variety of sensors connected within the network which can deter its performance gains in static environments that require real-time execution, sophisticated data analysis, and computational capabilities (Tianbiao, 2012).To address these challenges associated with networked robotic systems, researchers such as (Masterson, et al., 2017) have presently proposed the adoption of cloud-enabled robotics technology that uses the on-demand resources offered through ubiquitous cloud infrastructures.

Over the years, different cloud robotic platforms comprising of various underlying components such as the databases, proxy servers, and performance levels have emanated (Jatoth, et al., 2016). However, from a research point of view, the Open Source Robotics Foundation (OSRF, 2017) argues that most of the existing studies within this field mainly focuses on the technical aspects and architectures of cloud robotics. This implies that there have been limited literature, articles, or empirical studies that particularly focuses on the comparison of all the existing cloud robotic platforms. Also, the Robotics Interindustry Research and Production Association (RIRPA, 2019) explains that certain cloud robotics platforms are typically vulnerable to some distinct security flaws such as virtualization attacks, network-level attacks, and data-based seizures. Typically, every robotic service comprises of three central units namely the: Sensory Unit, Motion Unit, and the Control Unit (Barfoot, 2017). Also, at every given moment, numerous data signals pass through all these three units to ensure the effective operation of a robot, although these data can easily be intercepted and even compromised by malicious hackers for unethical purposes (Jensen, 2014).

Therefore, part of the main motivation for this research is fundamentally based on the need to comprehensively study some of the mainstream security strategies, as well as other forensic and cryptographic measures that would enhance the cybersecurity reliability and resilience of the major cloud-robotic platforms. This is because most cloud robotic technologies are prone to some of the major cybersecurity breaches such as Denial of Service attacks, Eavesdropping attacks, or Man in the Middle (MiTM) amongst other cybersecurity challenges (Kojima, et al., 2012). Thereby hindering the operational effectiveness and reliability of these robotic systems.

1.5 Aim and Objectives

Theaim 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 conduct a comparative assessment of the various cloud robotic platforms to ascertain their main characteristics and different areas of application in diverse sectors.

ii. To Perform Critical analysis of different arguments, and assertions from various reputable sources and industry professionals on the impact, benefits, network capabilities, and defects of cloud robotic platforms.

iii. To provide viable recommendations and proactive solutions to enhance the security of cloud robotics platforms so as to avoid cyber security attacks and breaches

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, theintegration of cloud computing capabilities with robots makes it possible to design multi-robot technologies havingincreased 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 ofcloud technologies in enhancing robotics functions, this research would describe the core concepts, functions, and developmentprocesses 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 issuesrelating 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.

II. 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:

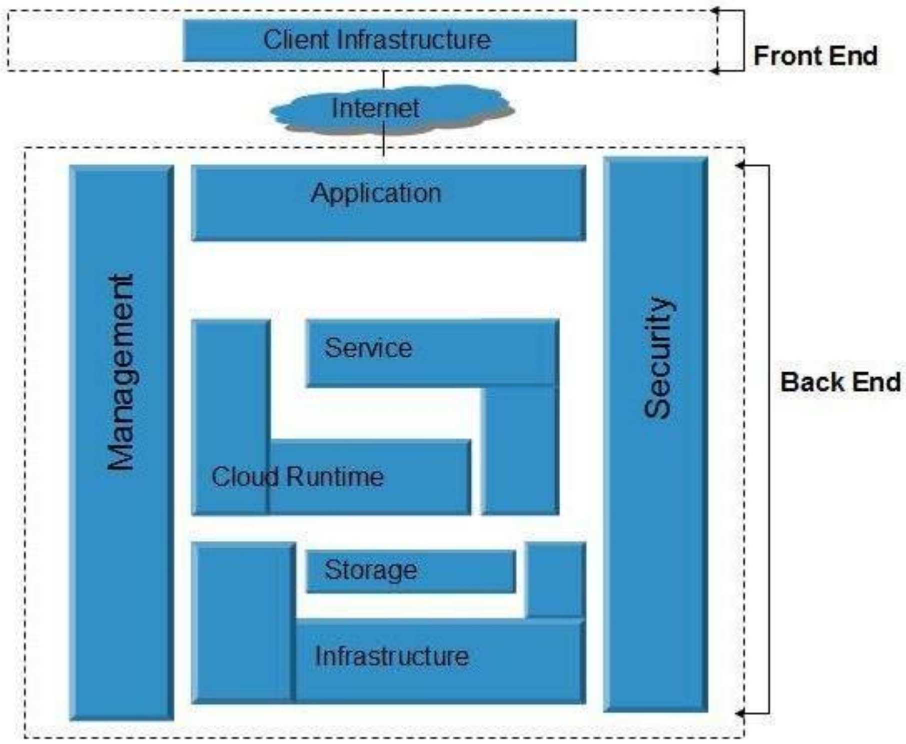


Figure 1 – Cloud Computing Architecture and Components (Kecskemeti, et al., 2016).

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:

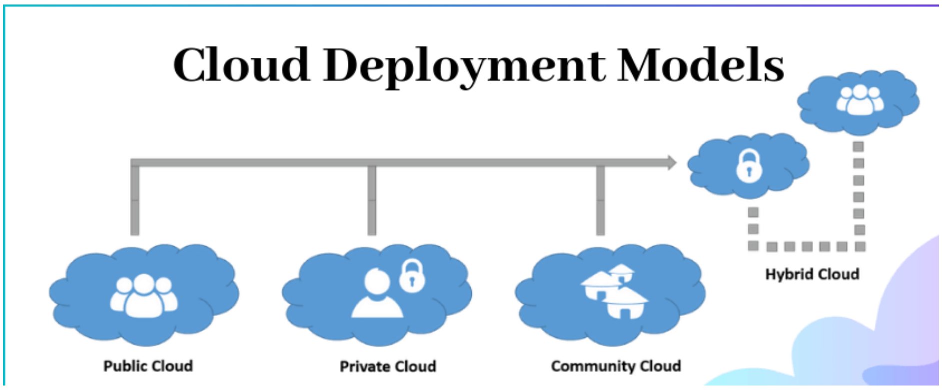


Figure 2 – Illustration of the major Cloud deployment models (Longo, et al., 2018)

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.

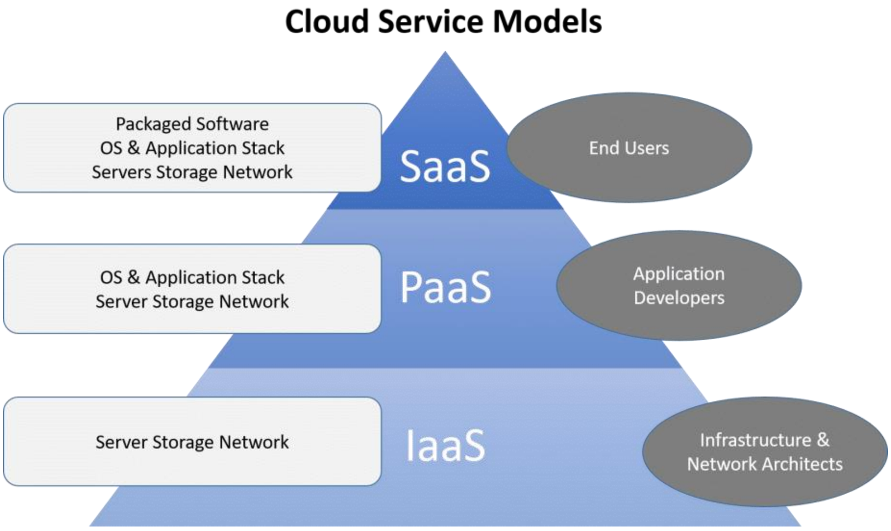


Figure 3 – Cloud service models and components. Source: (Dotson, 2019).

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:

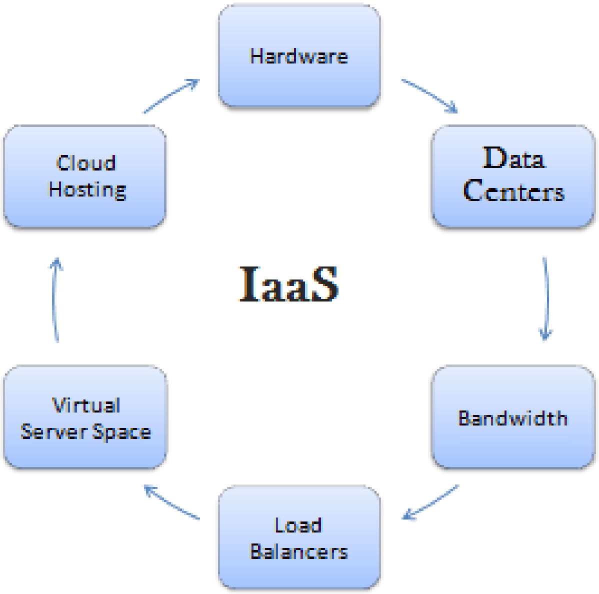


Figure 4 – Components of an Infrastructure as a Service (IaaS) cloud computing model (Pahl, 2017)

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.

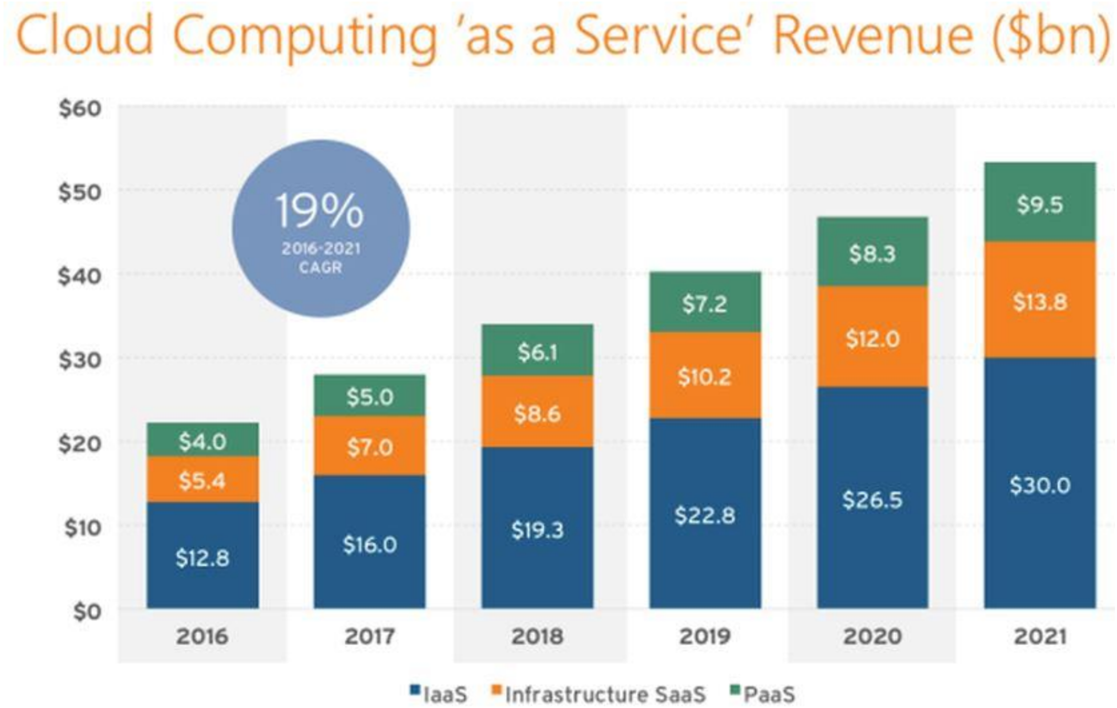


Figure 5 – Overview of cloud computing service model revenue and future projections (Doughlas, et al., 2020)

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:

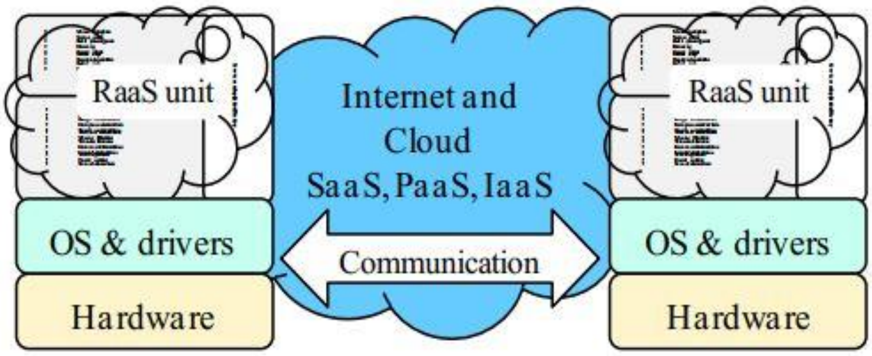


Figure 6 – RaaS in a Cloud Environment (Kazuya, et al., 2014)

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 7 – 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.

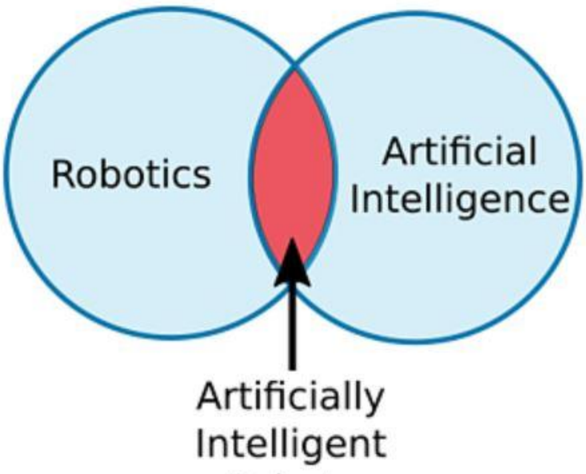


Figure 8 – Robotics and Artificial Intelligence (Kepple, 2015)

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).

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.

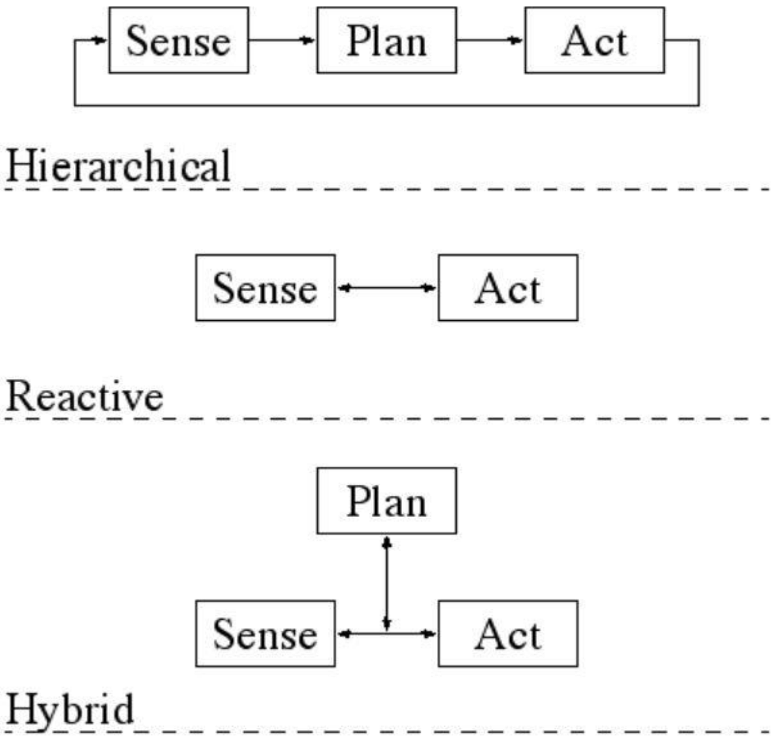
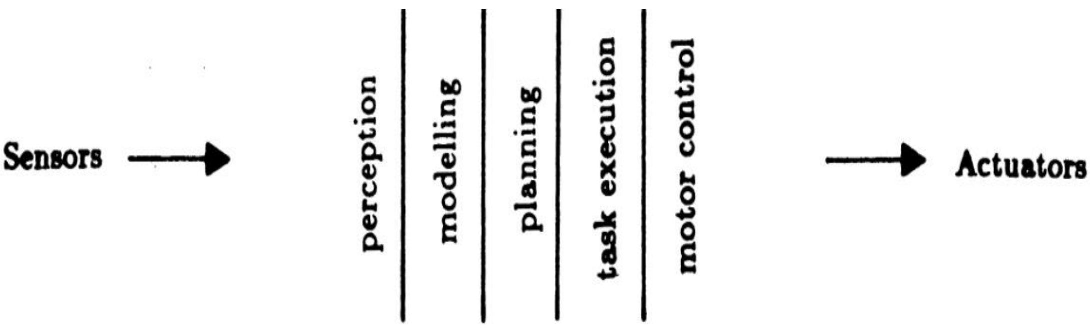


Figure 9 – Primitive Paradigms of a Robotic Architecture (IFR, 2020)

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:

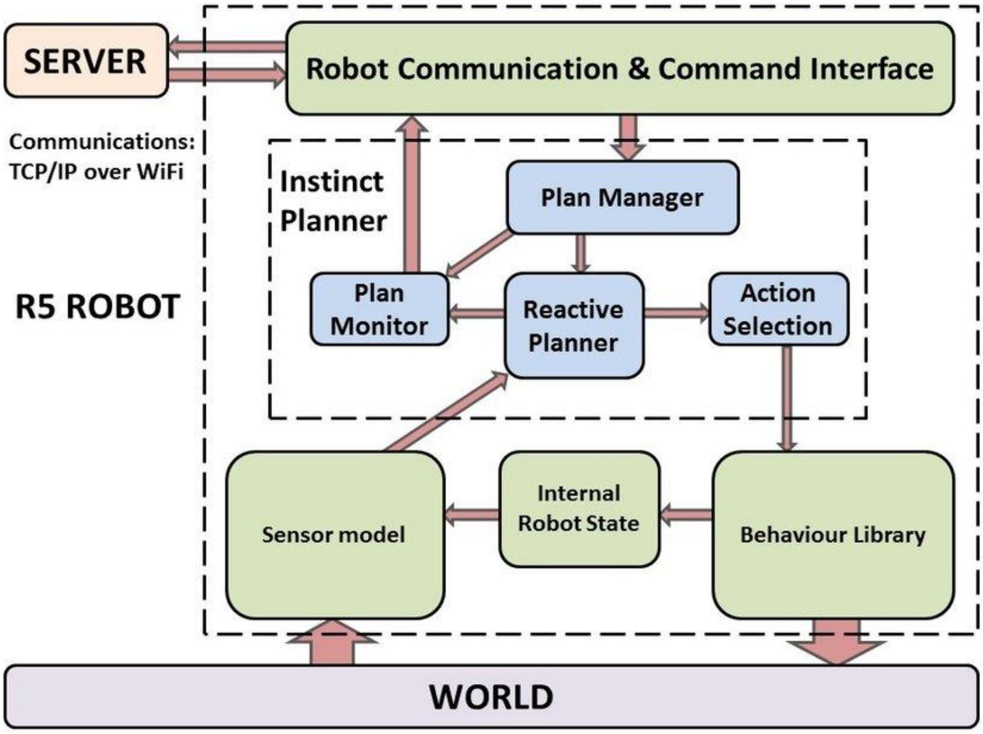


Figure 10 – Robotic System Architecture (Backman, et al., 2016)

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.

2.7 Overview of Cloud Robotics

There has been significant development in the field of robotics and automation due to its increased application in solving delicate real-world problems in areas such as automated manufacturing, healthcare, and medical robotics through the use of socially assistive robots (Borangiu, et al., 2013). In order to enhance the efficiency and functional range of robotic technologies, particularly within unstructured environments, the concept of networked robotics emerged almost two decades ago to address the challenges associated with standalone robot systems by sharing the perceived data with each other thereby solving tasks in a coordinated and cooperative manner (Blake, 2017). A networked robotic system simply refers to a group of robots connected through a wired or wireless communication network for efficient data protection and operational flow (Bouzary, 2020). Robotics Research Initiative (RRI, 2019) literature studies on “Future of Robotics” reveals that similar to the Standalone robots, networked robotics also experience inherent physical constraints because almost all its computations are performed onboard the robots which normally has limited computing capabilities and data constraints since information access are restricted to the collective storage of the network. In addition, networked robotics use the Machine-to-Machine (M2M) communications protocols, and this is illustrated below:

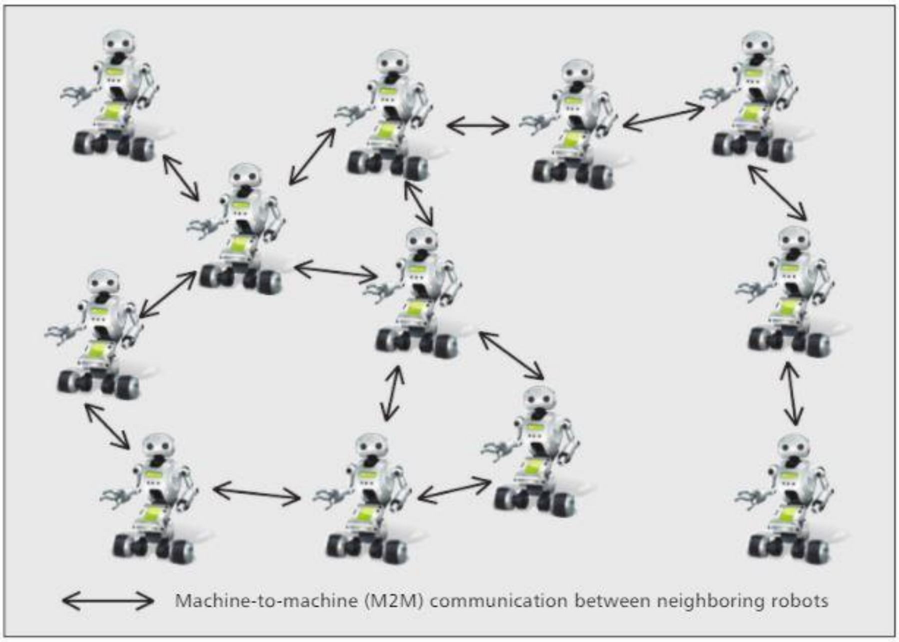


Figure 11 – M2M (Machine-to-Machine) communication paradigm for robots

Machine-to-machine (M2M) communications are characterized by proactive routing, and periodic exchange of messages,and ad-hoc routing. However,Siegwart et.al, (2020) studies reveal that proactive routing incurs high computation and memory load in the route discovery. The main challenge is that Ad-hoc routing protocols suffer from high latency, and these drawbacks might result in severe performance degradation (Quesnel, 2014). Therefore, with the rapid advancement in cloud computing technologies, most of these constraints can be overcome using the concept of cloud robotics, leading to more efficient, intelligent, and yet cheaper robotic operations through the utilization of elastic on-demand resources offered by an ubiquitous cloud infrastructure (Hao, et al., 2017).

2.7.1 Benefits of Cloud Robotics

Cloud robotics facilitates robots to autonomously unload computing and storage-related tasks into the cloud, and as such, the robots could then be built with smaller on-board computers (Hatzinakos, et al., 2013).The rapidly expanding collection of wireless networking capacities of the cloud have the potential to liberate robots and other automation systems from the limited memory, onboard computation by facilitating seamless data transfer and processing across applications and users (Givehchi, et al., 2017). For example, the Google self-driving car typifies this idea since it indexes images and maps obtained and updated through satellite and crowdsourcing from the Cloud so as to enable accurate localization. Another example is the Kiva warehouse pallet robot for logistics which communicates wirelessly through a centralized cloud server to coordinate routing and sharing of updates on detected changes within the environment (Wang, et al., 2020).The term “Cloud Robotics" which was coined in the year 2010 by James Kuffner presents several benefits and some of these benefits articulated in the IEEE (2017) research spectrum are as follow:

I. Cloud robotics tends to offer increased storage spaces and computational power to robots by facilitating access to on-demand parallel grid computing either for sensing, motion learning, and statistical analysis,learning (Aspragathos, et al., 2019).

II. Cloud robotics platforms enable robots to easily offload computation-intensive tasks such as pattern matching, object recognition, computer vision, as well as speech synthesis and recognition to the cloud. These tasks are performed faster in real-time on the cloud, through the utilization of grid computing capabilities or massively parallel computation (Xun, 2012). Furthermore, in addition to the on-demand offloading of computational services, the cloud infrastructure which cloud robotics relies on tends to support elastic availability of various forms of computational resources.

III. Many robotics-based applications such as Simultaneous Localization And Mapping (SLAM) rapidly gives rise to significant sensor data which is mostly difficult to store since most robots possess limited onboard storage capacity (Bubak, et al., 2015).Therefore, cloud robotics technology tends to ensure that different forms of robots have adequate access to large and secure data storage offered within the cloud which can be used for immediate or futuristic purposes. This, therefore, enables robots’ unequivocal access to big data technologies such as global mapping for navigation and localization.

IV. Cloud robotics platforms facilitate collective robot learning through the enhancements of trajectories sharing, and policies control outcomes.In this case, the cooperative learning between geographically distributed robots facilitated by cloud robotics platforms further aids information sharing towards solving complicated tasks (Aspragathos, et al., 2019). In addition, most of the mainstream cloud robotics platforms further enable robots to readily access any form of human knowledge mostly through cloud crowdsourcing utilizing models. This, therefore, implies that with the introduction of cloud robotics, robots are no longer self-constrained systems typically limited by their onboard capabilities (Asharaf, 2018).

2.7.2 Cloud Robotics System Architectures

A Cloud robotics technology is broadly classified into two categories, which includes the: Cloud Robotics Architecture and Cloud Robotics Applications (Spiteri, 2010).The Cloud robotics architecture in itself consists of two components which are the cloud infrastructure and its bottom facility (see Figure 11 – M2M (Machine-to-Machine) communication paradigm for robots).A cloud infrastructure typically comprises of different high-performance servers including proxy servers and databases which supports high-speed computation and processing alongside a massive storage capability (Chen, et al., 2019). On the other hand, the bottom facility of a cloud computing architecture typically includes several types of robots which mostly range from varied unmanned aerial robots and other integral automated machineries.The diagram below graphically illustrates the high-level architecture of a cloud robotics system along with some of the applications.

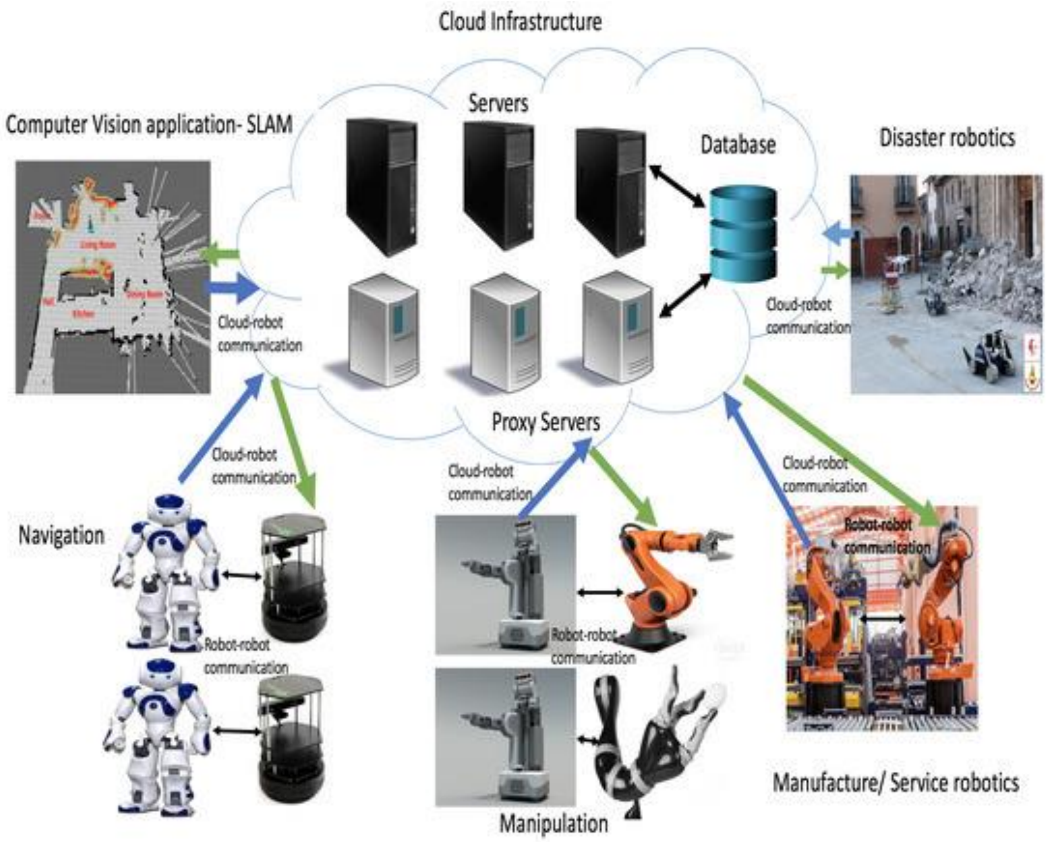


Figure 12 – High-level Overview of Cloud robotics architecture

In terms of the intrinsic communication mechanism, the cloud robotic architecture majorly leverages on the combination of both the machine-to-machine(M2M) communications among participating robots, as well as an infrastructure cloud-enabled by machine-to-cloud (M2C) communications (Bing, 2016).Cloud robotics uses an ubiquitous and elastic computing model, in which all resources are dynamically allocated from a shared pool within the ubiquitous cloud, so as to support task or resource offloading and information sharing in a robotic system(Prasad, 2014). The communication and information transfer architecture of a cloud robot are organized into two complementary tiers:

1. A machine-to-machine (M2M) level and
2. A machine-to-cloud (M2C) level.

This is represented in the diagram below:

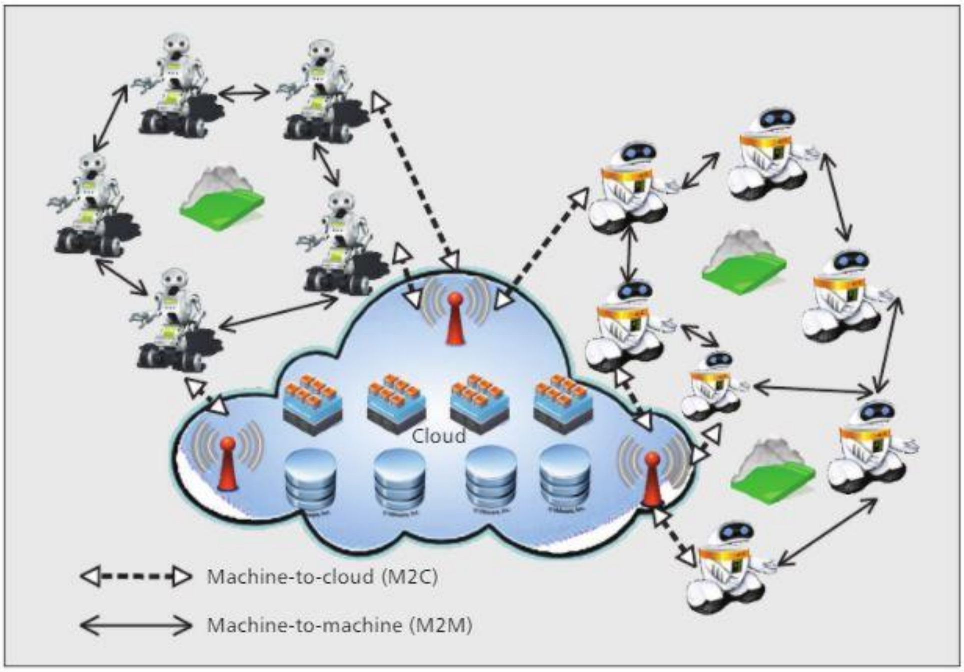


Figure 13 – Communication architecture of a cloud robot

It is essential to note that on the **M2M** (Machine-to-Machine) level, robots autonomously communicate through wireless links so as to form a collaborative computing fabric (Anirban, 2010). There are multi-dimensional benefits of forming a collaborative computing fabric as shown in the above diagram.

1. Firstly, the computing capabilities from individual robots are cohesively pooled together so as to form specific virtual ad-hoc cloud infrastructures.
2. Second, within any collaborative computing units, data is interchanged to efficiently facilitate collaborative decision making in various robot-related applications.
3. Thirdly, it enables robots that are not within close communication proximity or data transmission range of a cloud access point to speedily access stored data within the cloud infrastructure.

Alternatively, on the M2C level, the infrastructure cloud would tend to supply a pool of storage resources and shared computation which could be strategically leveraged and allocated elastically for real-time demand. Moreover, the large storage volume provided by the centralized cloud significantly helps in unifying a large volume of data regarding its environment, which can then be within a logical format that is usable by robots. Secondly, it could also provide an extensive library of behavioral insights that are related to situational complexities, and task requirements thereby making it feasible to continuously improve robotics operations.

2.8 Different Application of Cloud Robotics

The real-time application of Cloud robotics applications can be classified into the following subcategories:

1. Perception and computer vision applications, navigation,
2. Social and medical applications,
3. Manufacturing or service robotics,

2.8.1 A Perception and Computer Vision Application

Over the past years, there have been numerous works that were specifically centered on examining the utilization of cloud-based solutions for the enhancement of different aspects of perception, computer vision, and object recognition in robotic systems.(Risius, 2017)proposed a Cloud Object Recognition Engine (CORE) which couldperform classification of 3D point cloud data, train on large-scale datasets, and consequently perform efficient data transfer within a robotic network. The Cloud Object Recognition Engine (CORE) was evaluated during point cloud transmission through the use of Transmission Control Protocol (TCP), User Datagram Protocol (UDP), and other Websocket protocols (Arzberger, 2016). In this case, a User Datagram Protocol (UDP) usually provides extremely fast round-trip times although it is less reliable in comparison to Transmission Control Protocol (TCP) and Websocket (Backman, et al., 2016). Thereby, resulting in the enhancement of a robot vision through the use of Cloud Robotics Visual Platform (CRVP) which significantly aids in various forms of perception and computer vision application.

Some of the fundamental benefits of the Cloud Robotics Visual Platform (CRVP) system further entails the use of parallel computation models to facilitate a drastic reduction in the time- cycle involved in image sensing and recognition (Fragopoulou, et al., 2018). In addition, the adoption and utilization of a Service-oriented architecture (SOA) at its core, coupled with the outright adoption of real-time sensing protocols as well as the H264 encoding algorithm helps to enhance the video transmission capabilities of robotics systems. The impact of cloud robotics in facilitating image recognition, computer vision, and perception is illustrated in the diagram below:

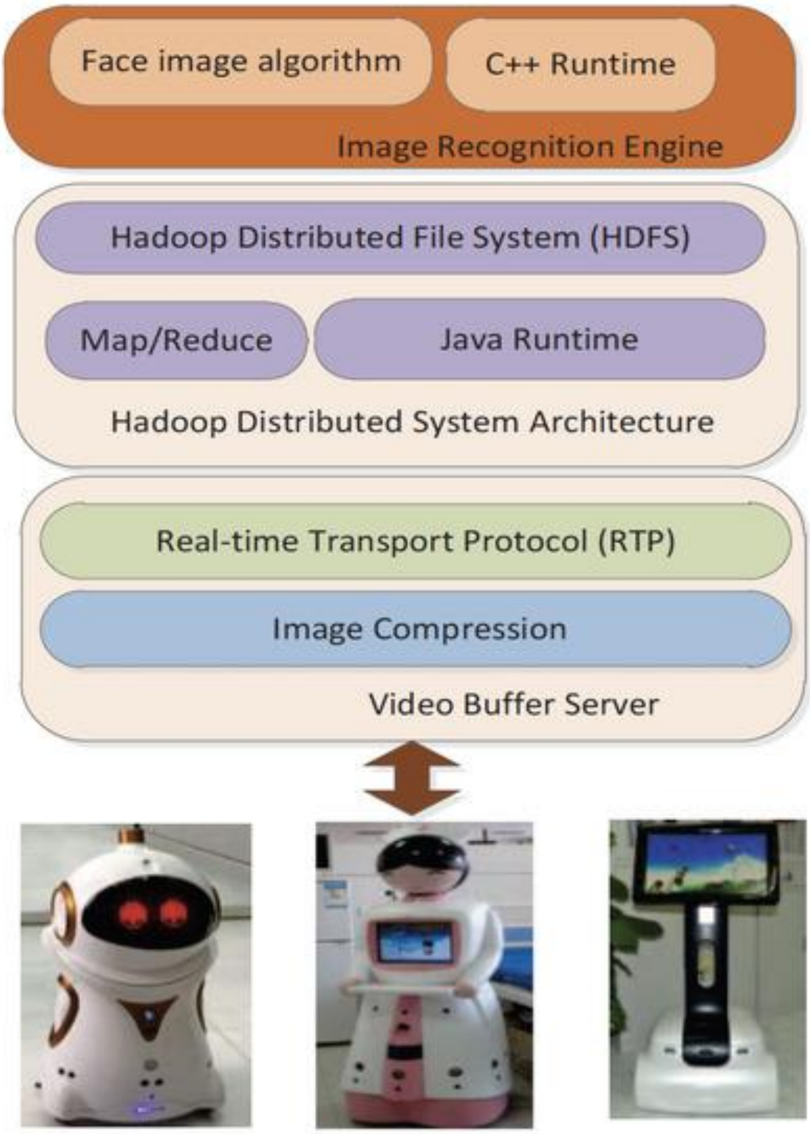


Figure 14 – Computer vision and image recognition process patterns of cloud robotics

(Linthicum, 2017) explains that various cloud robotics platforms such as Rapyupta, C2RO Cloud robotics, and Rospeex all provide a sustainable system that facilitates life-long training data and perception parameters refinements by using MongoDB (a schema-less database technology).The system practically ensures that every robot which is attached to it can seamlessly learn new data and can also share these datasets with other robots through the use of an available cloud model (Magoulès, 2019).Similarly, (Dang, et al., 2017) studies reveal the GostaiNet cloud robotics system serves as an interlink between different big data and cloud-based resources for accessing distributed computing resources so as to effectively execute classic computer vision tasks such as face detection and recognition. The performance efficiency of cloud robotics system is usually assessed through the evaluation of different performance metrics such as False Acceptance Rate (FAR), and False Rejection Rate (FRR) which respectively measures the likelihood of false image recognition through the use of cloud-based biometric security system (Hatzinakos, et al., 2013). Also, the primary role of a Multi-sensor data retrieval (MSDR) embedded in cloud robotic platforms is explicitly designed to achieve asynchronous access to the cloud for efficient data retrieval (Wang, et al., 2020). This is part of the reasons why scholars such as (Poirier & Reiter, 2016) proposed an inclusive framework for data fusion in cloud robotics so as to offer desirable features such as elasticity and scalability.

2.8.2 Manufacturing and Service Robotics

The advent of cloud robotics platforms has ushered in a new era of smart manufacturing in various where autonomous robots are equipped with cloud resources that are deployed to enhance practical industrial functions such as production, automated packing, and warehouse management (Jatoth, et al., 2016).Most manufacturing organization solely relies on the implementation of advanced navigation strategies within industrial environments for the management of a fleet of autonomous robots operating in a warehouse or factory environment(Debauche, et al., 2019). The implemented system through which cloud robotics platforms provides autonomous support includes a global planner, which decides the destination for each robot (Szewczyk, et al., 2015).The industrial application of these systems is primarily aimed at enabling an industrial robot to perform surface blending to aid diverse forms of manufacturing operations either within production plants or warehouses (Arzberger, 2016).

Besides, scholars such as (Risius, 2017) also proposed a Cognitive industrial entity (CIE) also known as Context-Aware Cloud Robotics (CACR) which basically integrates the benefits of cloud computing, big data analytics, and industrial Internet of Things (IoT) together with cloud robotics so as to aid enhancements in industrial functions (Zhenyu, 2017). The Context-Aware Cloud Robotics (CACR) is characterized by effective load balancing mechanisms that significantly enhance manufacturing processes and intelligent production in smart factories (Groover, 2019).This tends to solve most of the mainstream challenges that have been associated with smart manufacturing

III. Methodology

The methodology chapter for this project explicitly highlighted the different research methods, design strategies, data collection methods, and approaches that would be used in this study. Importantly, for every research method that would be adopted for this study, a critical analysis of the benefits and limitations were conducted, after which adequate justifications would be given to support the selection of the research methods. 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.

3.1 Procedures

The comparative analysis of cloud robotic platforms is a vital research study whose output could be used within various sectors and regions. This, therefore, emphasizes the need for adequate research methods to be adopted in order to ensure the validity, credibility, and reliability of all research findings. To give an overview of this study, it is essential to recognize that the primary problem which this project intends to tackle is that: information constraints of networked robots limit their processing abilities for a vast variety of sensors connected within the network which can deter performance gains in static environments that require real-time execution, sophisticated data analysis and computational capabilities (Tianbiao, 2012). Thereby emphasizing the need to address these challenges by conducting a comparative analysis of various cloud-enabled robotics platform. In addition, the research question for this project basically aims to find =:

1. The main differential factors that distinguish the major cloud-robotic platforms?
2. What are some of the predominant network security challenges associated with cloud robotics, and how can it be handled efficiently?

Therefore, the most essential consideration in this research methodology includes

- Ascertaining the most suitable method or technique to tackle the research problem and also answer all research questions.
- Comparing the alternative methods and then justifying the choice of the method selected in terms of its accuracy and efficacy.

Based on the title specification for this project, the research is mainly a literature survey involving a comparative analysis of the different cloud robotics systems and their respective impacts. In view of this, the diagram below specifically illustrates a concise methodical flowchart for this study.

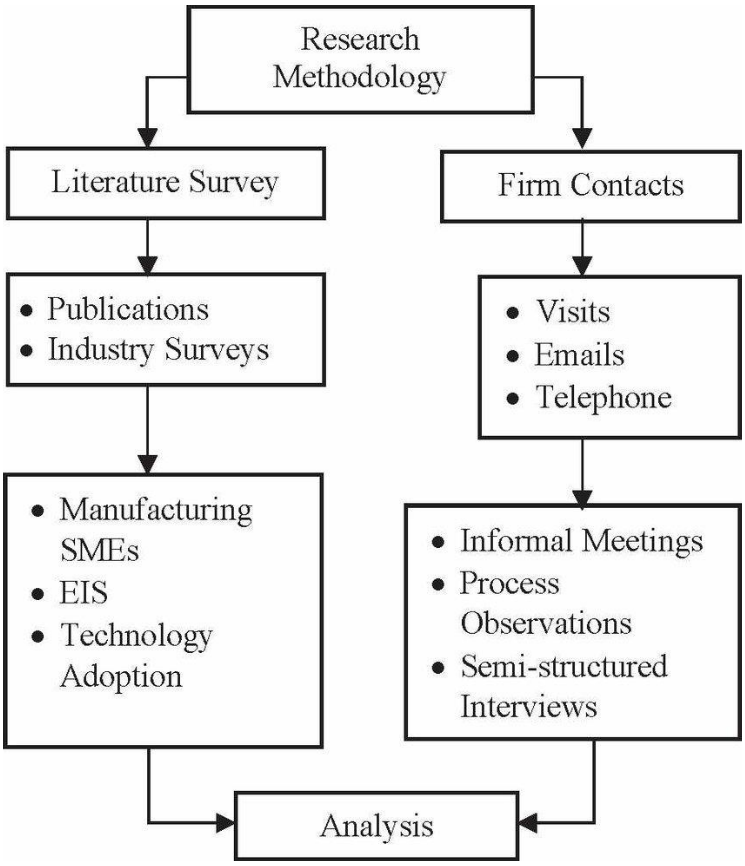


Figure 15 – Methodology Flowchart (Jaatun, et al., 2019)

The above flowchart basically illustrates that a systematic approach would be followed to ensure the collection of accurate data from diverse sources including publications, and industry surveys in a bid to find a logical and credible solution to the research problem of this project. This implies that methodical research procedures are an integral part of the process that sets the objective. In addition, relevant ethics and code of conduct would be fundamentally considered while making observations or drawing conclusions.

3.2 Analysis

This part of the study involves a comprehensive analysis of the different cloud robotic platforms based using diverse secondary data sources that would be outlined. The findings obtained would be critically analyzed, and other counter-arguments would be further scrutinized so as to enhance the objectivity and credibility of the research findings. Basically, the main objective of this analysis is to comprehensively examine different credible data sources in order to find reliable answers to the main research questions of this study which mainly centers around knowing the main differential factor that distinguishes the major cloud-robotic platforms. Furthermore, an analysis of the predominant network security challenges associated with cloud robotics would also be performed. Therefore, the analysis chapter for this project would utilize over one hundred (100) scholarly articles on cloud robotics, so as to first gain an individual insight of the mainstream cloud robotic platforms, before performing a comparative analysis.

3.2.1 Individual Analysis of Cloud Robotics Platforms

In terms of the analytical methodology process for this study, a vast pool of cloud robotic technologies were initially searched on scholarly platforms such as Middlesex University Summon Portal, the popular Google Scholar platform, Academia, and JSTOR. Saha (2018) emphasizes that there are eight (8) major cloud robotic platforms which include: Rapyuta, AWS RoboMaker, Cobalt Robotics, REALabs, C2RO Cloud Robotics, Fetch Robotics, Google Cloud Robotics Core, and Rospeex. Based on the analysis of (Furht & Escalante, 2010) studies, the major selection criteria used to select the major cloud robotic platforms include universal acceptance, operationality, and compatibility with other platforms, underlying models, and architectures.

3.2.1.1 Rapyuta

Rapyuta is an open-source cloud robotic technology that essentially serves as a Platform-as-a-Service (PaaS) framework for robots and other intelligent systems. An analysis of the Rapyuta cloud robotics based on a study conducted by (Mohanarajah, et al., 2015) has proven to be an effective cloud robotic platform that facilitates massive parallel computation thereby serving as a global repository to store object models. Allowing humans to monitor robots and also provides a platform to access RoboEarth environment maps, knowledge repository. and action recipes between various robotic platforms (Huang, 2018). Further analysis of this cloud robotic platform reveals that it is also a competitor of Rosbridge particularly as it regards communication and information transfer protocols. Rapyuta architecture depends on LxC (Linux Communication) containers as illustrated below.

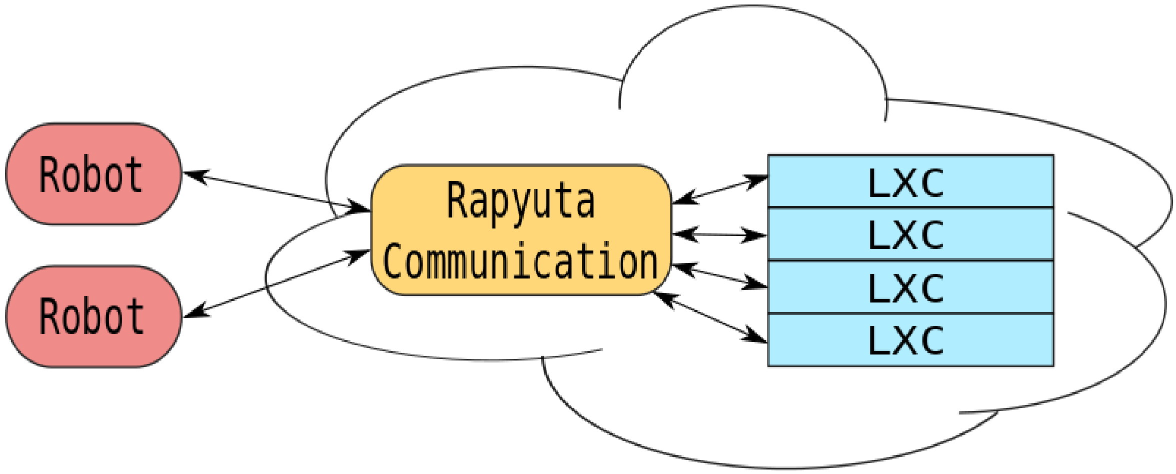


Figure 16 – Rayputa cloud robotics communication protocols

A thorough evaluation of the RoboEarth Cloud Engine which is the foundational basis of Rapyuta reveals that it is not just an open-source cloud robotics platform, but it is also based on an elastic computing model that comprises a distributed environment in which robots are deeply integrated, while enables seamless transfer of most of their services to other robots.In terms of the operational impact, Fosch and Millard (2019) analysis revealed that the Rapyuta cloud robotics platform significantly eliminates complexity, expenditures, and communication gaps that affect effective interfacing, real-time pattern recognition so that more time is available to do other tasks. Importantly, it significant to note that through the seamless access to the RobotEarth integrated environment,Rapyuta cloud robotics functionality permits robots to save and transfer data, offload computation and then collaborate in order to achieve a common task.Moreover, (Saha, 2018) research studies on cloud robotics indicate that through the Rapyupta platform, different range of capabilities including disk quota, expansive memory limits configuration, and extensive I/O limits amongst others.Furthermore, (Quesnel, 2014) analysis of Rapyupta cloud robotics further indicates that it also enables the outsourcing of over 3000 standard Robot Operating System (ROS) packages and is also extensible to other robotic middleware.Moreover, recent experimental studies using this platform by (Treiblmaier, 2019) show that the pre-installation of Amazon Machine Image (AMI) which could also launch within Rapyuta permits the robots to authenticate themselves in a typical cloud-based environment and launch the process.

AWS RoboMaker

AWS RoboMaker is a distinct cloud robotic service developed by Amazon that makes it easy to create other robotics applications at scale (Pethuru, et al., 2014). An analysis of this technology by (Vijaykumar, 2019) specifies that theAWS RoboMaker primarily extends the Robot Operating System (ROS) framework which therefore enables cloud connectivity to the Amazon Web Service (AWS) to take advantage of cognitive monitoring, machine learning, and analytics services. Thereby enabling a robot to autonomously perform several functions such as sensing, navigation, comprehension, and communication simultaneously. Jaatun (2019) study of this cloud robotic platform further reveals that the AWS RoboMaker provides a distinct and functional robotics application development environment as well as a robot simulation service that speeds application testing. In addition, Singh (2016) analysis of this platform reveals that the AWS RoboMaker is the most complete cloud solution for robotic developers to securely simulate, test, and then deploy robotic applications at scale mainly through a fleet management service that can be deployed to efficiently manage applications remotely. Tomer (2015) further expatiates that the AWS RoboMaker cloud roboticsprovides a scalable fully managed infrastructure for multi-robot simulation. In addition, Xun (2012) evaluation of this cloud robotic platform indicates that the AWS RoboMaker infrastructure provides a robust Integrated Development Environment (IDE), ROS extensions, and seamless integration with various AWS to provide world-class robotic solutions.Traditionally, it has been extremely complex and difficult to build robotic services due to fragmented

tooling for development, and fleet management, and this challenge has created numerous inefficiencies that the AWS RoboMaker tends to solve(Spiteri, 2010).
The analysis of (Chen, et al., 2019) studies brings up a cogent argument that the AWS Cloud robotics is inherently distinct in the sense that while it offers traditional cloud robotics services such as high storage spaces and computational power to facilitate activities like pattern matching, speech sensing, and object recognition. It also simultaneously provides in-built services to support and also simplify the development, test, and deployment of intelligent robotic programs at scale.

C2RO Cloud Robotics

The C2RO Cloud Robotics, which was developed in 2016 in Montreal, is a cloud-based software robotics platform specifically designed for the global service robotics market (Magoulès, 2019). An extensive analysis of this technology by Bing (2016) indicates that theC2RO cloud robotics platform connects robots mainly through the use of patent-pending systems which then augments the capabilities of robots through an integrated communication transmission protocol that is not just fast but also secure.In addition, this cloud robotic technology does act as an information processing robot-agnostic software-as-a-service (SaaS) platform that functions in a real-time manner to deliverrobots an integrated Artificial Intelligence (AI) solution in a fast, secure, and inexpensive manner. To give further insight on this platform, (Camarinha, 2016) analysis of the C2RO cloud robotics reveals that it was specifically developed to address the mainstream industrial automation demand comprising of issues like the lack of robots' connectivity which consequently result in the inability to monitor real-time problem. This is mainly due to the limitation of onboard sensing, data flow, and computing power within robots (Quesnel, 2014). Therefore, in order to address this challenge, the C2RO cloud robotics platforms tend to upgrade both the data storage and processing power of robots or other intelligent systems through a hybrid solution whereby multiple robots can share knowledge instantly in a speedy manner.

GostaiNet

GostaiNet is another cloud robotics platform that was developed by a French robotic enterprise known as Gostai, and this system has gained significant acceptance mainly because it enables robots to perform core functions such as data transmission, face detection, sensing, speech recognition, and other intelligent operations (Treiblmaier, 2019).The unified control of robots from all locations provided through a web service being hosted by Gostai on the GostaiNet robotics cloud(Martino, et al., 2018). A review of the GostaiNet cloud robotics based on empirical studies conducted by Bekaroo and Dawarka (2017) indicates that the GostaiNet architecture provides the opportunity to autonomouslydecentralize artificial intelligence incentives so as to produce economic robotic systems with autonomous capabilities and competent performance. Other complementary innovations such as the Jazz robots were implemented on Gostai'sopen-source Robot Operating System (ROS) whilealso using some graphical programming tools for robotics systems coupled with the premium GostaiNet cloud computing infrastructure to ease core data and other computational functionalities.

Rospeex

Rospeex is a cloud robotic technology developed by the National Institute of Information and Communications Technology (NICT) that is distinctively designed to facilitate multilingual dialogues with robots for the Robot Operating System (ROS). The Rospeex cloud robotic platform is equipped with a straightforward interface for speech recognition and synthesis in various languages and is free for use by roboticists without any requirement for authentication. Blake (2016) studies reveal that in order to effectively build and utilize conversational robots, roboticists do require to have an in-depth knowledge of spoken dialogue systems mainly through the use of in-built services such as voice search that can share robotics-specific speech corpora obtained as server logs. Moreover, in-depth analysis of the Rospeex cloud robotics reveals that it does come with a bundle including Rospeex cloud services, a dedicated browser user interface, as well as the Rospeex modules comprising of voice activity detection, speech synthesis, and noise reduction. In terms of the intrinsic aspects, theGraphical User Interface (GUI) of the rospeex platform is developed in HTML5 and can also operate on various other platforms such as Windows, Linux, and Android smart devices. Also, this cloud robotic platform can easily be adopted by both developers and end-users likewise. Yin (2016) emphasizes that this cloud robotic platform does not only benefit robot users, but also adds immense value to the developers as well due to its vast array of functionalities ranging from high-quality multilingual speech recognition and synthesis engines.

3.3 Comparative analysis of Robotics

Part of the fundamental objectives of this project is to conduct a comparative analysis of the different cloud robotics platforms. Basically, the five mainstream cloud robotics platforms that were individually analyzed based on secondary research data include the (AWS RoboMaker, Rapyupta, C2RO Cloud Robotics, GostaiNet, and Rospeex. Having evaluated the features, prospects, and potentials of each of these platforms individually, it is essential to have a detailed comparative overview of them. Hence, the main criteria made for the comparative analysis of these different cloud robotics platforms include:

1. **Underlying Architecture/Model**: Evaluating the underlying models, nodes, frameworks, architectures, and composite infrastructures that constitute these platforms.
2. **Security**: This involves a comparative analysis of the level of security, authentication layer, and overall safety protocols of the different cloud robotics platforms.
3. **Compatibility with other Platforms**: This involves an analysis of the level of compatibility of each of these cloud robotics platforms with other cloud systems, communication protocols, and transmission infrastructures. Further comparative analysis on whether the cloud platforms are open source or restricted.

Table 1 – Cloud robotics technologies (Bekaroo & Dawarka, 2020)

Cloud Robotics Platform	Underlying Model / Architecture	Open Source	Security	Compatibility to Platform
AWS RoboMaker	Amazon Web Service / Robot Operating System	Yes	Combines the security architecture of the Amazon Web Service (AWS) and Robotics Operating System (ROS) to provide a multi-layer cryptography safety	Highly Compatible
Rapyupta	Elastic Computing Model	Yes	Provides an extremely secure and customizable computing ecosystem within the cloud in order to offload heavy (mass) computation.	Highly Compatible
C2RO Cloud Robotic	Hybrid Cloud Robotics Model	No	Virtual barriers are tactically positioned for Secure Socket Layer (SSL) and Transport Layer Security (TLS) so as to enhance data access control. Thereby minimizing eavesdropping and Man In The Middle (MITM) attacks.	Moderately Compatible
GostaiNet	GostaiNet Cloud Computing Architecture	Yes	The Image analysis within the GostaiNet cloud robotics system enables movement detection specifically for robots thereby making it easier to detect network intrusion and other cyber risks.	Moderately Compatible
Rospeex	Node Structure Model	No	A dedicated ROS Node is implemented specifically for network safety and security purposes as its main focus are the safety of Voice Activity Detection	Moderately Compatible

4.1 Findings from the comparative analysis

A comparative analysis of the five major cloud-robotic platforms indicates that most of them are open-source apart from the Rospeex and C2RO cloud robotics. While the other platforms are typically open-source, which then tends to evolve continually as developers and other users can continue to either add or update features. This has significantly helped in promoting the adoption of such cloud robotics solutions amongst developers, thereby increasing the amount of support from the community.Coupled with the fact that most of the Open source cloud robotics platforms such as GostaiNet, Rapyupta, and AWS RoboMaker provide a more user-friendly interface and up-to-date documentation where user can easily offload robotic data to the cloud service. Similarly, based on the analysis conducted, most of the cloud robotics platforms enable some form of compatibility and sharing to other robots through the cloud environment, although the AWS RoboMaker and Rapyupta have more integration functionalities and interfaces.

However, Asharaf (2018) argues that whenever sharing data to robots built in a different platform, a major problem experienced involves the precise format for the representation and exchange of these data from the cloud robotics platforms to the robots themselves. For example,despite the fact that sensor data have minimal compatible formats, the trajectory-related data on the other hand has no standardized format. This is why the Rapyuta, AWS RoboMaker, and ROS were identified to be highly compatible with other platforms as earlier highlighted in comparison with the GostaiNet, Rospeex, or even the C2RO cloud robotics. To give a deeper insight and perspective to this finding, it is essential to note that in *(Table 1 – Cloud robotics technologies)* the compatibility with other platform analysis was mainly discussed in terms of cross-platform integral capabilities which enables a cloud robotics service to be used by a large number of other platforms.

Furthermore, as shown in ***(Table 1 – Cloud robotics technologies)*** different cloud robotic platformshave varying underlying models or architectures utilized, whereas also having variations regarding focus on the platforms in terms of functionalities and features. This essentially provides the benefit of developing service-oriented, asynchronous and concurrent applications with a myriad of programming languages, including **C++** and Visual Basic language.Also, the Robotic Operating System (ROS) which constitutes the underlying architecture of most cloud robotic platforms ensures a clean programmingstandard that enables multiple threads in the application to publish messages only.ROS further provides spectacular modularity that aid in the management of robot applications.

Another observation is that the overall performance of cloud robotics systems significantly varies based on the number and types of nodes integrated into the system.Rapyuta cloud robotics platform is fundamentally based on the elastic computing model which tends to provide a usable interface so as to facilitate quick robotic data offloading while simultaneously giving access to a repository of shared knowledge amongst robots (Aspragathos, et al., 2019).Furthermore, an important forensic and security aspect is imparted to every robot within the cloud platform so as to give bidirectional data transmission to the robots (Sorrentino, et al., 2020). In addition, the comparative analysis of the mainstream cloud robotic indicates that Rospeex is fundamentally based on the node structure model which is completely dedicated to the speech capabilities of robots through the utilization of a browser user interface. Its modules are fundamentally related to speech synthesis, voice activity, and noise reduction together with cloud services. Although, the main distinction is that Rospeex has its inbuilt cloud service, which could be easily integrated into other services. In summary, the AWS Robomaker and Rapyuta are the most proficient mainstream cloud robotics platforms due to their high platform interdepence, interconnectivity, efficiency, and security value.

5.2 Recommendations

Based on the comparative analysis of the cloud robotics platforms indicated in the previous chapter, numerous issues and vulnerabilities were associated with all the four mainstream cloud robotic platforms were discovered. Therefore, the table below itemizes some of the mainstream recommendations in line with the insights gained from each of the cloud robotics platforms analyzed.

Table 2 – Recommendations on the cloud robotics issues and vulnerabilities

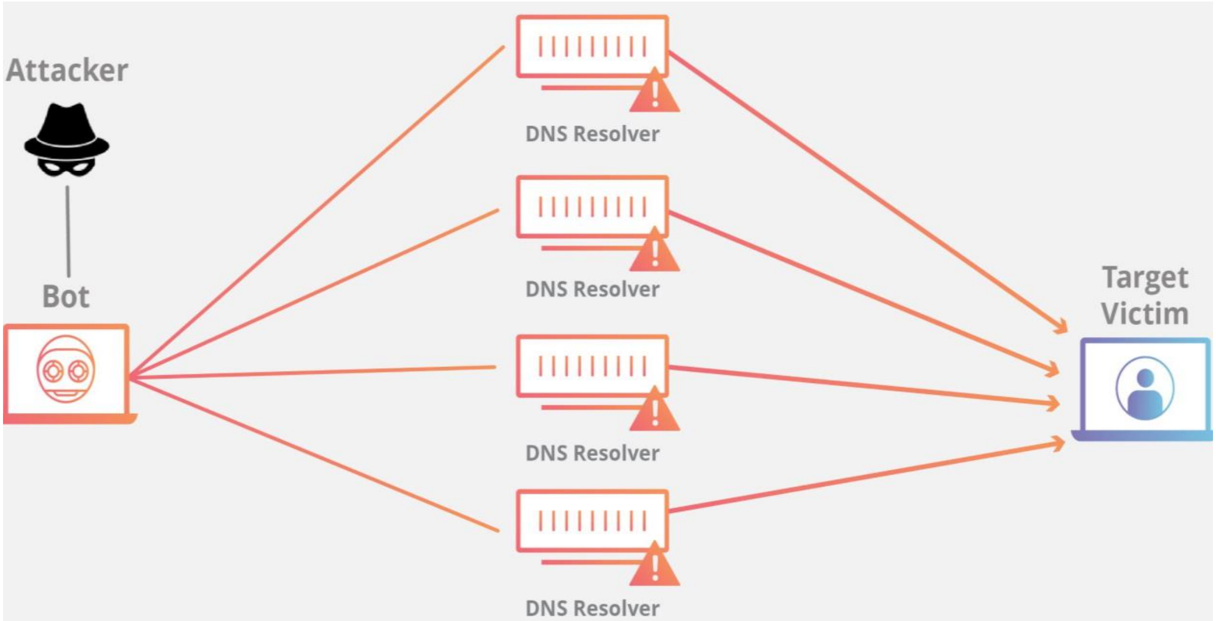
Cloud Robotic Platform	Reported Issue	Recommendations
AWS RoboMaker	Minimial issues discovered expect for the premium costs, and need for additional support services to ease integration effectiveness.	Providing up-to-data documentation to enable easy integration by other open-source robotics platforms.
Rapyuta	High computational latency and vulnerability to cyberattacks due to its open-source patches bypass.	The integration of colocation data centers can be integrated so as to minimize the high computational latency. Thereby ensuring exceptional network coverage and signal transmission with robots or other intelligent systems attached to it.
C2RO Cloud Robotic	A very large computation power is needed when integrating this cloud robotic system with robots. This is due to some of its components such as the Simulteneous, Localization and Mapping (SLAM) modules.	An AI (Artificial Intelligence) module can be implemented in order to increase the computational power of the robot attached to this cloud robotic platform. This would make it more autonomous and decentralized for decision making.
Rospeex	Poor integration with other systems and long processing time for speech recognition and signaling.	Segmentation of the Rospeex modules to specific segments that would specifically track speech and image recognition. This would aid in minimizing processing time and tranmision speed between cloud robotics platform and associated robots.
GostaiNet	Similar to the issues associated with other open-source cloud robotic platforms, GostaiNet comprises is significantly vulnerable to authentication and authorization issues and access protocol loopholes that present enormous security issues.	Implementation of Two-Factor authentication mechanisms in order to minimize authorized access. In addition, the

4.3 Analysis of the Cloud Robotics Security Gaps

Based on the insights gained from the comparative analysis of the cloud robotics platforms, it is essential to also note that most of the open-source cloud robotics platforms are massively vulnerable to insecure authorization, authentication, and communication issues. The predominant cybersecurity breach faced by most of the cloud robotic platform includes the Distributed Denial of Service Attack.

4.3.1 Distributed Denial of Service (DOS) Attack

A Distributed Denial-Of-Service (DDoS) attack can be described as a malicious attempt initiated by an attacker to technically disrupt the normal traffic of a targeted server, cloud service, or network flow(Prasad, 2014). This typically happens by overwhelming the target network, server, or its surrounding infrastructure with an enormous flood of traffic through the use ofnumerous compromised and malicious computer systems as sources of attack traffic to disrupt a network or cloud server, thereby limiting the operations of a cloud robotic services due to the unexpected traffic jam preventing regular network operation and data transmission on a network.



The most obvious indicator of a distributed denial-of-service attack on a cloud robotic platform is that the underlying cloud server suddenly becomes very slow or in certain cases completely unavailable due to a significant spike in traffic, thereby resulting in significant performance issues (Xiangjun, 2012). Therefore, one of the recommendations to overcome these cybersecurity issues is to integrate traffic analytics tools can help to spot a DDoS attack.

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 cannotbe 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, other cloud robotics platforms such as Rospeex and the Rapyuta cloud robotics were discovered to be highly compatible with other cloud-robotic platforms through the tactical enabling integration of features and network effects as well.In addition, different cloud robotics platforms were found to have varying underlying models and architectures whereas also having dissimilarity in terms of performance features and abilities. This implies that depending on the architecture or framework which would be utilized in a way that every platform will perform and will then blend accordinglyto give efficient support to different types of robots and intelligent systems.

In addition, the various cybersecurity challenges bothering most of the cloud robotics platforms were also examined, and practical recommendations were given on ways to minimize all forms of unathorized access, denial of service attacks, man in the middle attack as well as password hijack amongst others. The need for multi-factor authentication, particularly for open-source cloud robotic platforms such as the AWS RoboMaker, and Rapyuta were further buttressed in this study, in addition to other proven cryptography and foreinsic measures as well.

5.2 Study Significance and Contributions

The field of robotics in general have been in existence for years past, although within the last decades, it has garnered significant momentum, mostly due to its massive contributions towards automating human tasks efficiently. In this regards, the use of cloud robotic platforms to enhance the data processing, computation and network capabilities of robots aids in enhancing the numerous challenges of robots. The particular problem associated with networked robots mainly happens as a result of resource constraints, information sharing disruption, learning constraints, and communication limitations. These issues minimize the efficacy of these robots due to the limited computing and storage capacity thereby making it technically difficult to modify or enhance the resource configurations once a robot is in operation. However, this study which involves the comparative analysis of cloud robotics systems is significant because it highlights the most effective robotic platforms that could be used to overcome the existing challenges associated with robots. In addition, the significant cyber breaches and risks of these cloud robotics systems were analyzed and practical recommendations were provided on ways to enhance these breaches.

6.3 Research Limitations and Further Works

In the course of this research study, certain limitations were encountered which is important to explicitly discuss these limits and their impact on this research study. Firstly, the main limitation of this study is the inability to physically access the different cloud robotics studies. Therefore, as a result of this limitation, all findings and discoveries from this research were based on the insights gained from existing studies which is why this study is completely a secondary-based research project. In terms of further work, more theoretical and empirical studies would be conducted on practical means that can be adopted in order to minimize the high cybersecurity risk associated with cloud robotic technology.

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