Robotics Evolution: from Remote Brain to Cloud

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Abstract

Robotic systems have been evolving since decades and touching almost all aspects of life, either for leisure or critical applications. Most of traditional robotic systems operate in well-defined environments utilizing pre-configured on-board processing units. However, modern and foreseen robotic applications ask for complex processing requirements that exceed the limits of on-board computing power. Cloud computing and the related technologies have high potential to overcome on-board hardware restrictions and can improve the performance efficiency. This research highlights the advancements in robotic systems with focus on cloud robotics as an emerging trend. There exists an extensive amount of effort to leverage the potentials of robotic systems and to handle arising shortcomings. Moreover, there are promising insights for future breed of intelligent, flexible, and autonomous robotic systems in the Internet of Things era.

1. Introduction

For more than five decades, robots have been successfully used to replace human in doing dangerous and tedious work in various domains, including hazard environments. A typical robot consists of sensors, control system, and actuators. Sensors are in charge of gathering information about an environment. The robot uses the collected information to manage its behavior and take appropriate action based on each situation. There are various types of sensors, for example light sensor, laser sensor, ultrasound transceiver, microphone, and camera. The robot control system, alternately robot brain [1], determines the behavior of the robot under various operating conditions. The brain is a program that receives continuous flow of inputs from the sensors, processes the inputs, and consequently sends appropriate action commands to the actuators. The actuators are mounted on the robot body and responsible for translating action commands into physical activities in the environment.

Embedding the robot's control program on its micro-controller is a common practice. Therefore, all necessary computations and data reside on the mother board of the robot itself. This configuration limits the capabilities of the robot with respect to computation power, memory, storage, and power consumption.

The research articles of M. Inaba [1–5] introduced the term "Remote-Brained Robots". The idea of Inaba suggests implementing a remote brain of the robot apart from its body. The possible characteristics and configurations of a remote brain are unlimited, such possibilities enable reconsidering more powerful robot brains. Other research area in remote brain can be found in [6]. Accordingly, wireless communication technologies play an essential role in data communication for the remote-brained robots.

This paper presents earlier applications of remote-brained robots, discussion on the advancements in robotic technology towards networked robot systems, and finally the rise of cloud robots. The presentation of the ideas is organized as follows: Section 2, presents research work on remote-brained robots and their utilization to solve challenging problems such as landmine detection. Networked robots challenges and applications will be presented in Section 3. The rise of cloud robots, their functions and main advantages will be discussed in Section 5. Future research directions and applications are presented in Section 6.

2. Remote-Brained Robots

Early research work on remote-brained robots in [2] illustrates the use of wireless communication network for the communication between a heavy brain and the body of a robot. The authors studied number of configurations to develop an ap-propriate control method. In which a video screen is able to present touch, force, and other visual data over the sensor image. They claimed that their approach en-abled building a massively powerful parallel computing base alongside the real time vision system. A robot with the brain separated from the body is presented in [3]. The brain resides in what they called "the mother environment" and the robot communicates with it using radio links.

An interesting research theme in [7] aims to conceptualize a platform for future brained-robots. The authors emphasized the idea of separating physically and logically the robot body and its "brain". Such separation makes it more encouraging and possible to utilize advanced and powerful processing techniques. Further-more, the authors conducted several experiments to perform different tasks using different types of robots that share the same remote intelligence platform. The experimented robots were motion enabled, vision-based and others. They concluded that a real-world application of the computer intelligence needs more investigation and research effort. Therefore, their platform allows students/researchers to experiment several algorithms and robots aiming to enrich the field with more applicable solutions and gap filling.

In [8] the authors developed and implemented a large-scale software platform for real time robotic systems. The platform consists of three layers that are the Mother, Brain, and Sensor-Motor. The authors proposed a mother of tools in charge of producing programs to control the brain. In addition, a method to develop variety of brain architectures with flexible multiprocessing network.

Remote-brained robots industry faces many challenges. One of the main challenges is the real-time integration of a large-scale brain and a lightweight humanoid body. The research project in [4] tried to prove that remote-brained robots would overcome main challenges of the industry.

A real remote-brained robot that has human-machine interaction, vision systems, and manipulator was illustrated in [9]. The brain was separated from the robot's body. The brain was left on the mother environment, which has the brain's software. The brain and body are interacting via wireless communication links. Among several examples of remote-brained robots there are "Vision-Equipped Apelike Robot" [3], "Remote-brained LEGO robot" [10].

2.1. Vision-Equipped Apelike Robot

The Johou Systems Kougaku (JSK) Laboratory has been developing various types of robots since the early 90's [1, 3, 11, 12]. The main categories of JSK robots are wheeled, quadruped, and humanoid. Vision-Equipped Apelike Robot [3] is one of their various "remote-brained" robots. The main benefit from Apelike robot is to study the "vision-based behaviors" of locomotion. It enables the control of an equipped camera at any point of view, the mobility in unstructured environments, and the handling of objects using robot arms.

Apelike robot has a remote brain that makes it able to perform complex vision-based operations. A major physical characteristic of the robot is its light weight, which is possible because the processing system is not part of the physical robot. Figure 1 illustrates the main components of the Apelike robot system.

The system is composed of three main components:

(i)   The Remote Brain which is powered by Unix workstation on which the Euslisp language is used to model the behaviors of robot. The object-oriented modeling language made it possible to design various behaviors and interactions. Therefore, the remote brain is used to guide and control the balance, motion, and interactions with the physical robot.

(ii) The Brain-Body Interface which is equipped with a transputer for interpretation and communication. It consists of two sub-transputers: a) Vision receiver and interpreter, and b) Motion interpreter and transmitter. The inter-face is used to process a relatively adequate number of images for motion detection.

(iii) The Physical Robot Body weighs about 2.5 kilograms including power supply (*i.e.*, batteries). The body is equipped with two main radio-based communication components; the first one is the receiver of motion signals and the second is the transmitter of sensors data. The encoded communication between the robot and the brain enables it to perform kinetic motion behaviors.
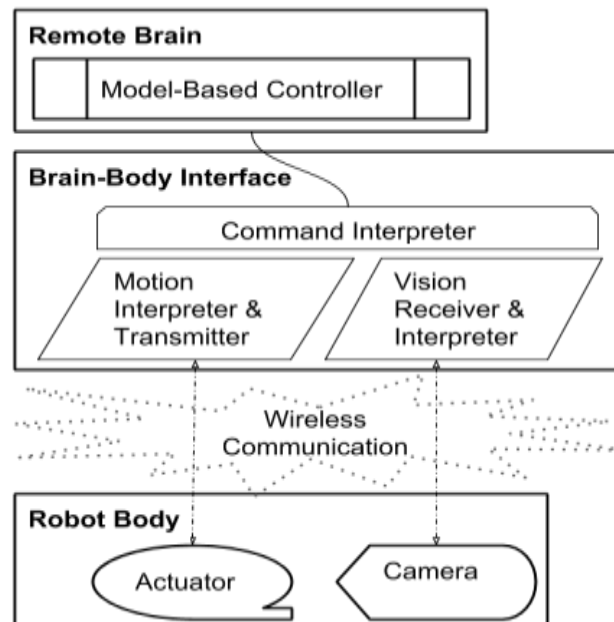

Figure 1. The System Architecture of an Apelike Robot System. (Adapted from [3])

The Apelike robot can perform three main tasks: a) Model-based motion calculations, b) Vision-based interaction, and c) Vision-based stairs climbing. This multi-limbed robot is able to respond to dynamic visual feedback and perform some human-like actions. Although the robot was able to mimic the human behaviors, it still needs improvements to learn from the performed actions and develop more skills.

2.2. Remote-brained LEGO robot

In [10], authors presented an innovative NXT mobile robot system that can simulate the landmine detection operation with some assumption. The proposed system relies on moving an NXT mobile robot to develop a map for the environment. The robot mission is to scan an environment based on a developed grid to detect ob-jects by using appropriate sensors attached to the mobile robot. The system was able to develop a map of the area under-study, showing the positions of located mines (i.e. objects). The early proposed remote-brained robot for object detection is presented in Figure 2.

The proposed system consists of three components. They are:

(i)   A PC Server is a Pentium 4 computer with a 512 RAM and support Wi-Fi connection. The PC Server works as the robot brain for the whole system since it is responsible of both monitoring and control of the system.

(ii)   The LEGO NXT is the mobile robot which is used to execute the mission commands. The NXT robot will hold the N80 mobile phone and navigate in the minefield.

(iii)   N80 is a smart mobile phone device. N80 has an ARM-9 processor with clock rate of 220 MHz CPU, 18 MB RAM and Symbian OS v9.1[2]. N80 includes 3.0 Mega pixels camera and support for different types of wireless communication standards. They include (1) 3G network (384 kbps), (2) EDGE (286.8 kbps) (3) Bluetooth 2.0 and 4) WLAN 802.11b/g.
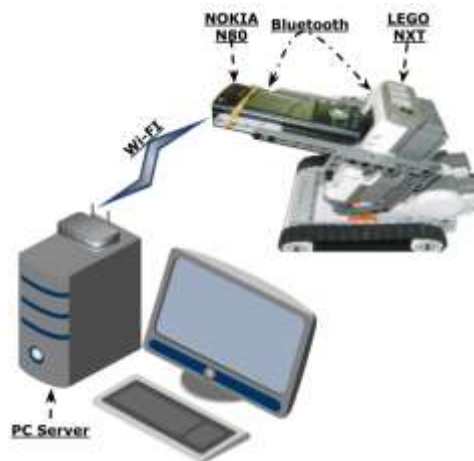

Figure 2. Remote-brained LEGO Robot Components (Adapted from [10])

The operation of the proposed system is presented in Figure 3. In the proposed system, the N80 mobile works as a sensor camera that captures images, frequently. These images are sent to a PC server (*i.e.*, the robot brain) such that a simple image

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[2] Symbian OS is a proprietary operating system, designed for mobile devices, with associated libraries, user interface frameworks and reference implementations of common tools, produced by Symbian Ltd. It is a descendant of Psion's EPOC and runs exclusively on ARM processors.

processing algorithm is executed to detect objects in an image, if any. The result of execution is a command sent back via wireless communication to the robot to navigate in the specified environment.

The general model of the Remote-brained LEGO Robot is shown in Figure 4. It can be seen that the brain is in charge of analyzing the environment based on the collected data, the choice of the optimal decision to be taken based on available information and finally send appropriate command to robot actuators to complete a mission.
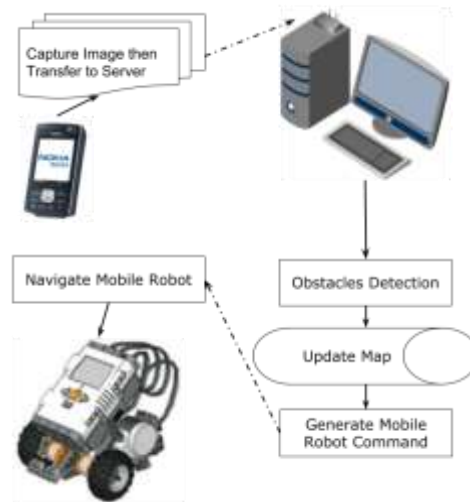

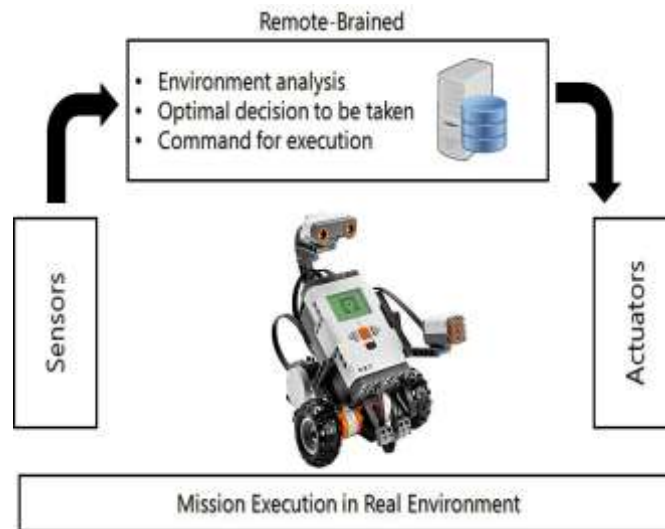**Figure 3. Remote-brained LEGO Robot Operations (Adapted from [10])**

Figure 4. The General Model of the Remote-brained LEGO Robot

3. Networked Robotics

In many applications such as search and rescue operation, a network of robots is al-ways needed. A networked robot's system is defined as: "a group of robotic devices that are connected via a wired and/or wireless communication network" [13]. Net-worked robots allow multiple robots to overcome the restrictions of stand-alone robot by allowing robot sensors, brain and actuators to communicate remotely. This concept allows the development of mission with multi-robots with different types to collaborate in mission accomplishment such as searching for an object in an environment. Robots among the network can share and distribute tasks. Networked

Robots allow the enhancement of interaction among robots, task integration, easy communication, and can enhance the overall robotics system security [14, 15].

Authors in [16] presented the basic idea of a Ubiquitous Networked Robot Platform (UNR-PF). UNR-PF is introduced as a framework to coordinate and control distributed missions. The UNR-PF separated the hardware from the brain and uses a suitable interface that allows an application developer to create hardware-independent robotic services. In this case, a developer can demand components to fulfill a given need, and the UNR-PF will allocate suitable resources that can be controlled remotely. This approach helps in the design of re-usable distributed applications that can be used in various robotics platforms. It was found that net-worked robot architectures can facilitate the development, deployment, management and adaptation of distributed robotic applications [17]. A Networked Robots of NXT mobile robots with Internet and Machine-to-Machine communication are illustrated in Figure 5.
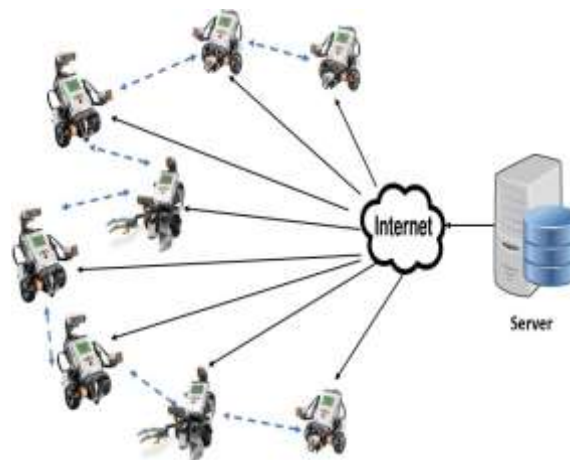

Figure 5. Networked Robotics of NXT Mobile Robots with Internet and Machine-to- Machine (M2M) Communication

3.1. Problems with Networked Robotics

There were many reported challenges of the networked robots that stimulate the urge to develop an action plan for the coordination of the multiple autonomous robot systems in terms of communication, control, and perception. For example, which one should have the highest priority to establish communication? What is the maximum allowable time slot for each member of the network? How can each member of the networked robots access information? All these questions could have different answers according to time and place in the work environment. The development of a networked robotic system is always limited by resources, information, and communication constraints.

A summary of the main challenges faces the development of networked robotics is presented in [13] as follows:

(i)   It is always the case that each robot member of the network has its own access to resources that include sensors, actuators and computing power (*i.e.*, brain). The networked robotics resources can be accessed by any member of the network. The problem is once a robot is built and deployed, it is always not easy to change or upgrade their body structures such as the robot size, shape or power supply.

(ii)   Networked robotics system is meant to develop a cooperative system that can accomplish a specific mission by using the available resources for each member of the network. Information fusion can be implemented in many ways

such as machine-to-machine (M2M) or machine-to-server communication (M2S). Therefore, the networked robotics is restricted by the information sensed by the robots and shared over the network or the server program. This limits the ability of the network to learn.

(iii)   Transferring information or decision making via a network involves the use of routing protocols. Routing protocols are responsible for sharing the information among the network members in a fast, efficient and reliable way. One of the known M2M communication protocols is the proactive routing. This protocol is usually used for routing messages across the network [18]. Some of its disadvantages are: the need for high computation and memory resources to discover the best route over the network.

4. Cloud Computing

Cloud computing or on-demand computing is a paradigm of Internet computing systems such that computing, memory and information are shared among set of devices belonging to a network. Cloud computing is considered as one of the most recent evolution in computing paradigms. The definition of cloud computing provided by the US National Institute of Standards and Technology (NIST) has gained significant attraction within the IT industry. According to this definition (see [NIST]):

> *Cloud computing is a model for enabling convenient, on-demand net- work access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.*

Cloud computing offers a wide range of elasticity and self-serving computing resources according to the system requirements [19]. It also aids in reducing infrastructure costs for many projects. Cloud computing establish a broad range of applications in variety of fields such as manufacturing, automation and control applications [20].

5. Cloud Robotics

The integration between cloud computing and robotics is found to be an upgrade to networked robotics. James J. Kuffner a Professor at Carnegie Mellon working at Google in 2010 was the first to coin the expression "Cloud Robotics" and described a number of potential benefits [21]. This concept allows the robot to become lighter, cheaper, and smarter. According to J. Kuffner, "robots that have access to a cloud could offload CPU-heavy jobs to remote servers, relying on smaller and less power-hungry onboard computers. Even more promising, the robots could turn to cloud-based services to expand their capabilities." Later on, Steve Cousins introduced the concept of "No robot is an island".

The analysis of the scholarly articles, including patents, on GoogleScholar illustrates the emergence of four specific terms. Figure 6 illustrates the density of four specific search terms over several Years. Equation 1 is used to calculate the Term Density (TD) in a specific Year (y). Where Mentions is the total number of search results for a specific term in the current Year (y), and the (total) number of search results over all Years.
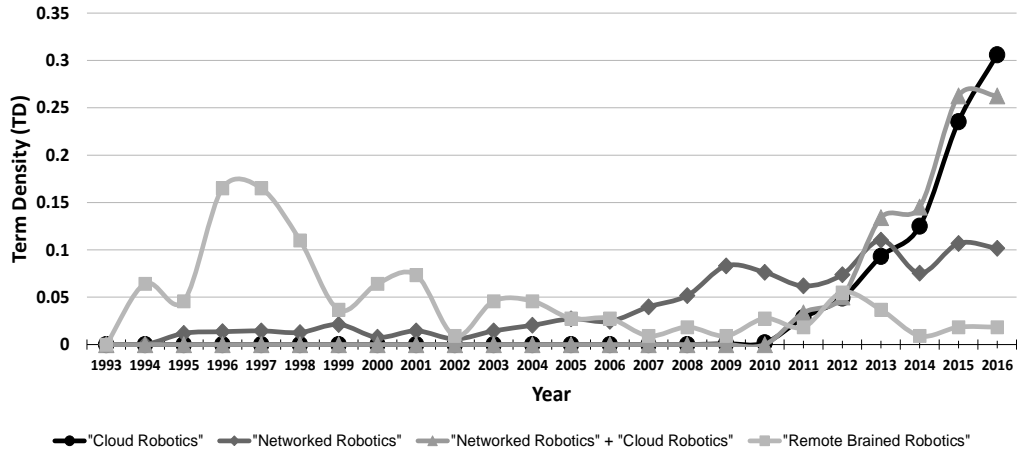
Figure 6 Timeline of Terms Density based on GoogleScholar

$$TD_y = \frac{Mentions_y}{Mentions_{total}} \times 100\%$$

(1)

The search results count of the four terms "Cloud Robotic", "Networked Robotic", "Networked Robotics" + "Cloud Robotics", and "Remote Brained Robotics" till 23 August 2017 are 1160, 1180, 179, and 109 respectively. The numbers are based on the search query using GoogleScholar system which is prone to some errors. However, the results give clear indication about the emergence time of each search term and its level of attention among researchers over the Years. The existence of close relationship between cloud and networked robotics is supported by the analysis results.

Figure 7 illustrates an NXT Cloud Robot mobile system. The system consists of set of NXT robots that can connect to the cloud that act as a robot brain. Mean- while, they can also communicate with each other. This allows the robots inside the system to get advantages of the accessibility to the cloud and the possible access to all robot's sensors inside the cloud.
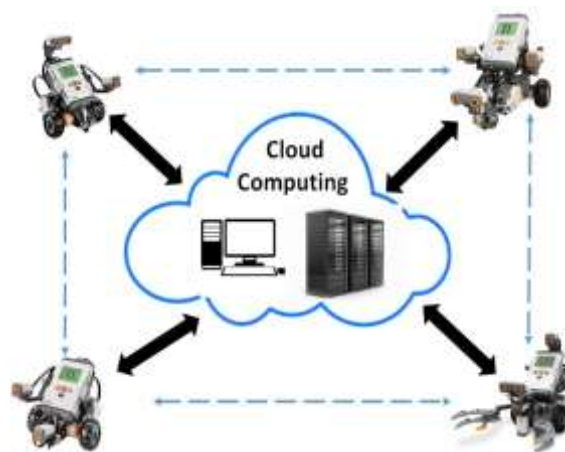

Figure 7 NXT Cloud Robot Mobile System

Cloud computing was introduced as a solution to many constrained problems for networked robotics. These problems include limited computing power, un-availability of adequate storage space, and lack of communication and routing protocols. Networked robotics was considered as an evolutionary step on the way to cloud

robotics [13]. A survey of research on cloud robotics and automation is presented in [22].

There are several up to date research efforts in the sake of formulating robust futuristic cloud-based robotic applications. Researchers are tackling various areas for an unlimited number of objectives to improve existing systems or to overcome critical limitations.

5.1. Applications of Cloud Robotics

At the beginning, robots were designed and planned to be utilized as industrial robots with simple, repetitive and limited tasks [13, 23]. However, with the advancements of cloud robotic technologies, the robots are becoming lighter and smarter [24]. Due to this progress, in the last decade, there has been an expansion in the applications of the cloud robotics. These applications cover a wide spectrum of applications and services in different domains including smart cities, transportation, health care and rehabilitation, housekeeping, environment monitoring, and entertainment [13, 22].

In cloud-based robotics, robot units enjoy some powerful advantages like the accessibility to big data and shared knowledge, and the ability to transfer computation-intensive tasks to the high computing resources in the cloud [25]. These advantages enabled cloud robots to be deployed more efficiently in classical robotic ap-plications such as simultaneous localization and mapping (SLAM) [26], grasping, and navigation [13]. In SLAM applications the robot localizes itself in unknown environment based on building maps for the environment. SLAM techniques are computationally and data intensive algorithms which makes could robots have a great advantage in such applications. An example of these techniques is Fast-SLAM which can be implemented in parallel processing in cloud frameworks [27]. Grasping is another common task in the field of robotics. This task can be computationally expensive and requires accessing huge amount of data when the targeted object is unknown. Moreover, deploying cloud robots for this task enables the robots to benefit from the shared training and learning experience. An example of this type of tasks can be found in [28] where a cloud robotics system was proposed for identifying and grasping common household objects based on Google Object Recognition Engine.

Different cloud robotics have been designed and deployed to support some ser-vices as a part of a specific application at different complexity levels. In this con-text, the term "robot-as-a-service" (RaaS) was coined to describe such robot units [29].

A worth mentioning example comes from Carnegie Mellon University and the Intel Pittsburgh Laboratory where a special service robot was designed, developed and named as Home Exploring Robotic Butler (HERB) where its main job is to care for the elderly and the disabled people [23]. Such a service required an access to a vast amount of shared knowledge and experience collected from different robot units in order to cover and deal with a wide range of possible scenarios and interactions.

In general, cloud robot units could play different assigned roles as assistive technology in schools, houses and offices [23].

5.2. Algorithms for Cloud Robotics

There are research efforts towards developing algorithms for autonomous exploration of virtually unknown environments [30]; such algorithms have the potential of being applied in real life robotic applications. Authors in [31] presented a data fusion system for optimizing the coordinated motion of industrial Automated Guided Vehicles (AGVs). They illustrated the contribution of two main algorithms in achieving better performance, namely "Geometric Level" and "Decision" data fusion algorithms. Geometric level algorithm enables autonomous global navigation and

local path planning. On the other hand, decision algorithm is a "Global Live View" implementation at high level. Both algorithms enable processing sensors input to classify the obstacles in the environment. The authors show 93.2% overall classification rate in 15ms processing time of 60Hz "Global Live View". They claim that data fusion technologies and advanced sensing allow AGVs to overcome obstacles without the need for human intervention.

A survey [22] covers an idea of the cloud as enabler for collective robot learning, crowd sourcing, open-source and open-access. The survey states that up to date, many robots still rely on their on-board computer, while there is a great opportunity in relocating the processing algorithms over computing clouds. In [32] the authors presented algorithms and an implementation of cloud-based system with the aim to leverage the cloud-based robot systems flexibility, reusability and extensibility. Others [13] proposed and illustrated various algorithms to support and improve the overall idea of cloud-based robot brain, including parallel processing approaches.

5.3. Challenges of Cloud Robotics

The authors in [33] discussed the key technical challenges of cloud robotics.

- First is the computation challenge that needs a common computation frame-work, optimizing the allocation and management of virtual resources, and bargaining between cloud and networked computation decisions.

- Second is the communication challenge which is prone to failure or delay in message passing, in addition to selecting the best topology of communication networks.

- Finally, the authors pointed to security and trust challenges regarding the cloud provider. Trust either when the robot tried to connect to the cloud or when executing a task over the cloud. Furthermore, storing data over the cloud might be with high risk, especially when the data is highly confidential or sensitive.

The quality of cloud services and network latency are expected to vary, there-fore it is challenging to guarantee highly stable performance. The performance variability is critical for time sensitive applications that seek real-time responses [22, 34]. Due to tasks complexity in cloud-based robotic applications, it is challenging to select the best resource allocation and task scheduling approach. Apparently, communicating various structures of data from various sensors and devices creates a challenging interaction between the robots and the clouds. In terms of reliability analysis, there are no simple methods to assess the cloud-based robot system [34]. In [32] the authors suggested the need to tackle the challenges of reducing the running cost, improving the collaboration of robots to solve more complex tasks, and enhancing the adaptability of the robots in various domains.

6. Future Research

With the acceleration and advancement of cloud robotics and their applications, challenges become more sophisticated and complex. Challenges can fall into main streams like security, fault tolerance, scalability of the infrastructure, integration of affection and intelligence, quality of service provided by robot units, trust and the influence on interpersonal relationships.

Developing new algorithms for fault tolerance control, load balancing and for handling the varying in network latency are really open challenges in robots future research directions [35]. Moreover, scalable cloud infrastructures and data scaling techniques are needed where the first is important to scale the infra upon the size of

the robots and the latter to scale the size of big data captured by robots to get better performance results.

On the other hand, ensuring effective privacy and security of data procedures is important since data that are captured by robots (cloud data) need to be secure by not allowing unauthorized party from accessing it or controlling the robot using it [35]. In some critical cases, there is a need to contact a human to assist rather than a robot (available on-demand), where this approach must be balanced with the cost associated with it. Algorithms will be developed to decide when best to contact a human or when to proceed with the robot's control [22]. Optimistic researchers expect and demand developing robotic systems that fulfill real-time requirements [22, 34], and thorough analysis toward assuring the reliability and conformance to standards to achieve better performance [34].

In summary, cloud robotics is a result of radical advancements in the technology. In terms of computing, cloud services offer virtually unlimited scalability options. And in terms of communication technology, the wide spread of high-speed wireless networks. However, as any generic cloud-based service, security, privacy, communication cost, reliability, and many others are still with high level of concern. It is essential to assess the feasibility of cloud robotics in terms available technical capabilities, financial resources and running cost, and user acceptance. The idea of cloud robotics seems to be conceptually ideal in the meantime, but the concerns and open issues ask for investigating more in assurance mechanisms.

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