Review of research in the area of Cloud Robotics

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Abstract. Due to the recent growth in *cloud computing*, many robot designers around the world began to link their robots to the cloud, hence *cloud robotics* when connected, robots could tap into its software, storage, computational, and social benefits of the cloud. Generic tasks such as navigation, mapping, sensor data processing, and hardware abstraction, could be performed using software obtained from the cloud. The main target of cloud robotics is to relieve robots of most of the heavy computational burdens, allowing it to focus on its primary tasks. This paper reviews the latest in research in cloud robotics. This is an emerging field; the term *cloud robotics* was defined only in 2011, and indeed all the research reviewed here was published in 2012 or later. The paper concludes with real life applications of cloud robotics in many robotics fields; social robots, mobile robots, group robotics, rehabilitation and medical robots, as well as *human robot interaction*.

Introduction

In *cloud computing*, service providers maintain computer servers that host products and services in remote locations to end-users. End-users simply log on to these servers, through the internet or other forms of networks, and use these products and services over the network, rather than hosting the servers themselves. This is very cost effective to the end-users as they save on IT costs and maintenance [1].

There are many models of cloud services; *software as a service* (SaaS) provides software capabilities and support to the end-users, such as email, virtual desk-tops, games, etc.; *Infrastructure as a service* (IaaS) provides even a deeper level of services, such as virtual machines, storage and network capabilities [1]; *Backend as a service* (BaaS) provides web and mobile app developers with a way to link their applications to the cloud while also providing features such as user management, push notifications, and integration with various social networks, and services [2,3].

Cloud Robotics

The theory of *cloud robotics* is to allow robots to benefit from the powerful resources of the cloud, and ease a huge amount of the burden of the robots themselves. Instead of doing everything individually (mapping, localization, data processing from sensors, etc.), robots could benefit from the computational capabilities, storage, communications resources, development tools, and sharing capabilities that are available at the cloud [4,5].

Cloud robotics allows robots to take advantage of the rapid increase in data transfer rates to offload tasks without hard real time requirements. This is of particular interest for mobile robots, where on-board computation entails additional power requirements which may reduce operating duration and constrain robot mobility as well as increase costs [4, 5].

Overview of research in the area of Cloud Robotics

Interest and research in cloud robotics closely followed the development and the readiness of cloud computing. Figure 1 shows research volume on cloud computing and Cloud Robotics since 2004.

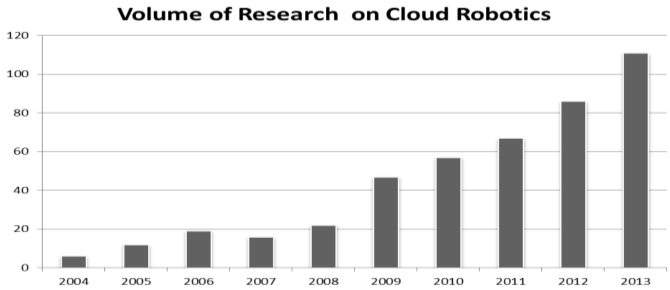

Figure 1. Publication volume on Cloud Robotics since 2004 [6].

As it can be seen from the figure, research exploded after 2009, which was a very important event in cloud computing as it marked the introduction of *Google Cloud*, the first free cloud service.
Around the same time, other important events occurred; the *Android* operating system was introduced in 2007, its development platform was launched soon after (2008), allowing anyone with the right knowledge to contribute.

In 2007, the *Robot Operating System*, or ROS, began as a student project in *Stanford Artificial Intelligence* labs; in 2010 ROS 1.0 was released for public use. After that, other providers launched their own versions of cloud services and products.

As it can be seen from Figure 2, research on cloud robotics is divided into 4 major areas; *Introductory Research* and big picture, *Proposed Architectures* to implement cloud robotics, *Tackling Challenges* that face implementation of cloud robotics, and finally real life *Applications* of cloud robotics in action.

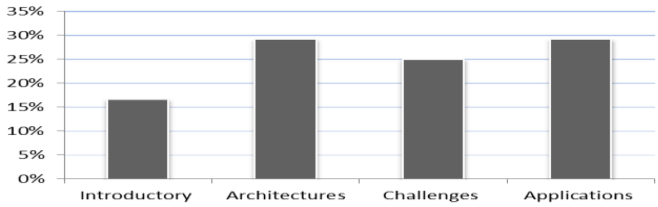

Figure 2. Breakdown of research in *cloud robotics* [7]

This paper reviews research published in each of these areas, identifies any sub-groups (if they exist) based on the topic of interest, and outlines important findings and breakthroughs in each. All in the attempt to identify in which direction research in cloud robotics is heading.

Introductory research and big picture

All the research reviewed here was published in 2012 or later. Hence, many researchers and institutions took it upon themselves to set the standards and define the terms properly.

Jordan et al. understood the importance of cloud robotics, so in their work they provided a structured, systematic overview of the numerous definitions, concepts and technologies linked to cloud robotics and the relevant cloud technologies. They also presented a roadmap for the near future, describing development trends and emerging application areas [8].

Rudas (2012) and Lorencik and Sincak (2013) summarized the basic ideas and terminologies of cloud computing. Secondly, they discussed the future of cloud robotics and its applications, with special emphases on robots as a service in cloud computing. Finally, they introduced some of the many recently launched cloud robotics projects, including the European project; *RoboEarth* [9, 10].

Proposed Cloud Robotics architectures

The main idea of cloud robotics is to link robots to the cloud. However, there are many ways to actually implement that. The following are some examples.

Tenorth et al. attempted to modularize robotic tasks and control decisions so that human operators of cloud applications with different areas of expertise could adapt to the respective parts of the knowledge independently. They proposed to modularize applications by factoring out environment and robot-specific knowledge components and representing them explicitly in a formal knowledge base that is shared between the robots and service applications [11].

Turnbull et al. developed a small scale cloud infrastructure utilizing a single virtual machine operating with the boundaries of a hypervisor's resource pool. A robot with minimal hardware was constructed to work within the control of the cloud. They also planned to test more advance robotics concepts, such as Null-Spaced-base behavior control and advanced neural network control. They were able to demonstrate the ability to implement control on a global scale utilizing the cloud [12].

Speers et al. examined the use of lightweight tablet computers as a generic interface to autonomous systems. They demonstrated how ROS-enabled computers could be controlled using *Android* tablets using standard software toolkits. Tools have been developed for the automatic conversion between ROS messages and the corresponding user interface elements on the tablet. Interface elements have been developed to assist in developing systems for different robot sensors and platforms. Finally, they demonstrated their system for unmanned underwater, surface, flying and rolling ground contact vehicles [13].

Challenges faced when implementing Cloud Robotics

Connecting the robots to the cloud poses many challenges; the connection must stable and reliable, bandwidth allocation must be managed, data from multiple robots must be processed in real time, and the effect of loss of connectivity to the cloud must be understood and planned for.

Guoqiang et al. proposed a cloud robotic architecture that leverages the combination of machine-to-machine communication among participating robots, and machine-to-cloud [14].

Using their proposed architecture, they were able to extend the computation and information sharing capabilities of networked robots. Also, they demonstrated how resources were dynamically allocated to support task offloading and information sharing for the participating robots [14].

Multi-robot systems utilizing the cloud present even bigger challenges, such as bandwidth allocation, real time multi-sensor data retrieval and synchronization, as well as others [15].

Lujia and Meng proposed and implemented a game-theoretic problem formulation and linear pricing scheme of bandwidth allocation [15]. They also presented a priority scheduling and buffer management scheme for near real time multi-sensor data retrieval. Their experiments showed the proposed framework performed better than typical cloud robotics scenarios [15].

Applications of Cloud Robotics

Many researchers utilized the cloud for their projects; applications of cloud robotics include social robotics, robots assisting the elderly, rehabilitation robots, mobile robots, *human robot interaction* (HRI), and others.

Dugmus et al. demonstrated the use of cloud robotics through their own rehabilitation robotics ontology system, called *RehabRoboOnto*. It is a *RehabRoboQuery* software system to facilitate access to this ontology, which was made available on the cloud, utilizing *Amazon* web services [16].

Summary

We are witnessing the birth and rise of a new research field. The marriage of Robotics and Cloud Computing resulted in new and exciting possibilities. Researchers from around the world are working on making robots more efficient, less cumbersome, and less costly by tapping in to the powers of the cloud.

This field is so new that researchers are still defining the terms and outlining the terminologies. They are also proposing new architectures to achieve cloud robotics, tackling and solving challenges coming out of it, and finally achieving great and amazing results.

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[6] The graph was developed by the author. This was done by looking up the term "cloud robotics" in the IEEE database for each year from 1990 till 2013.

[7] The graph was developed by the author. This was done by looking up the term "Cloud robotics" in the IEEE database, and reviewing the relevant research. By counting the number publications in each area and relating them to the total number of publications, percentages (and the graph) could be developed.

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