

THE EVOLUTION OF CLOUD ROBOTICS: A SURVEY

¹. Yalova University, Yalova, TURKEY

². University of Szeged, Faculty of Engineering, Robotics Laboratory, Szeged, HUNGARY

³. Óbuda University, Doctoral School of Safety and Security Sciences, Budapest, HUNGARY

Abstract: Cloud robotics is a rapidly evolving field that allows robots to offload computation-intensive and storage-intensive jobs into the cloud. Robots are limited in terms of computational capacity, memory and storage. Cloud provides unlimited computation power, memory, storage and especially collaboration opportunity. Cloud-enabled robots are divided into two categories as standalone and networked robots. This paper surveys cloud robotic platforms, standalone and networked robotic works such as grasping, simultaneous localization and mapping (SLAM), monitoring.

Keywords: cloud-enabled robots, cloud robotics, cloud technologies, standalone and networked robots, Software as a Service, Platform as a Service, Infrastructure as a Service

INTRODUCTION

Cloud Robotics (CR) is a term combination of cloud technologies and service robotics. The term “cloud-enabled robotics” was presented by James Kuffner for the first time at the IEEE RAS Int. Conference on Humanoid Robotics in 2010 [1]. Robots empowered with cloud technologies have been an important part of our daily lives. NIST [2] defines cloud computing as “a model for enabling ubiquitous, convenient, on-demand network 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 Robotics has rapidly gained momentum with initiatives by companies such as Google, Willow Garage and Gostai as well as more than a dozen active research projects around the world.

The paper is organized as follows:

- » Section 1: Introduction.
- » In Section 2 cloud computing technologies are presented.
- » In Section 3 the cloud robotics platforms are illustrated.
- » In Section 4 cloud-enabled robots are presented.
- » Conclusions are given in Section 5.

CLOUD COMPUTING TECHNOLOGIES

Cloud computing consist of three fundamental models as Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) as shown on Figure 1. (1).

SaaS applications are served over the internet, thus eliminating the need to install and run the application on the users system [3]. They are managed from a centralized location and accessed remotely by a web browser or a mobile client. Google Apps is the most widely used SaaS application suit. PaaS refers to a computing platform served by cloud infrastructure. PaaS offers developers to get a hold of all the systems and environments required for the life cycle of software, be it developing, testing, deploying and hosting of web applications. Some

examples are Amazon Web Services (AWS) [4] and Microsoft's Azure [5]. IaaS provides the required infrastructure as a service. The client need not purchase the required servers, data center or the network resources. The essence of IaaS model is a pay-as-you-go financial model. Amazon and Microsoft are also IaaS providers.

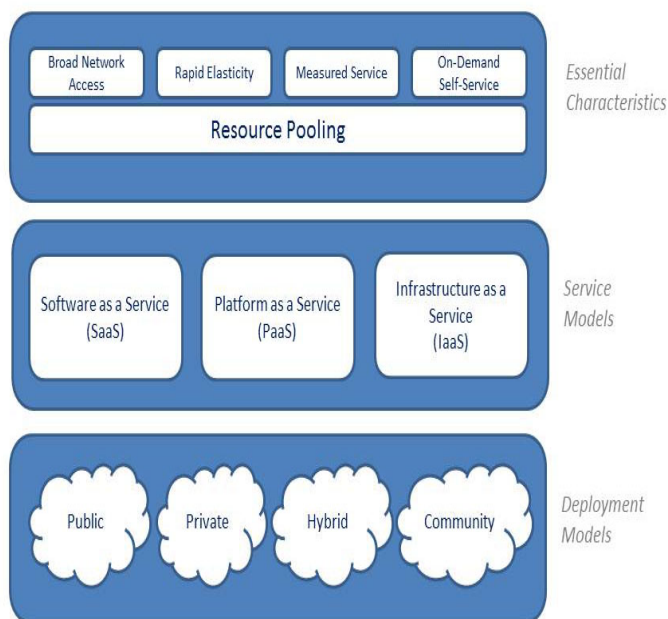


Figure 1. Cloud computing infrastructure

Robots make significant socioeconomic impacts to human lives [6], [7]. For example, robots can do repetitive or dangerous tasks, such as assembly, painting, packaging, and welding. However, robots are limited in terms of computational capacity, memory and storage. Also they have physical constraints such as size, shape, power supply, motion mode and working environment [8]. Robots are usually used for industrial purposes, they are not commonly used in daily life because of their cost. Cloud computing can be used to enhance robots' capabilities.

Cloud computing technologies provide numerous advantages that can be valuable for the composition and running robot services. For example, complex computations of computation intensive applications can be offloaded in the cloud like what is done for Apple’s voice recognition service “Siri”. Connecting the robots to semantic knowledge databases hosted in the cloud will allow a large number of heterogeneous robots to share common sense knowledge [9].

The concept of “robot-as-a-service” (RaaS) refers to robots that can be dynamically combined to give support to the execution of specific applications. RaaS has three aspects of the system: structure, interface, and behavior. There can be many kinds of robot cloud units or intelligent devices. For example, robot cops [10], restaurant robot waiters [11], robot pets [12], and patient care robots [13]. These robots are distributed in different locations and can be accessed through CR platforms.

CLOUD ROBOTICS PLATFORMS

Developing software solutions for robots is difficult, because of varying hardware and non-standardized APIs. Robotics researchers, have created a variety of frameworks to manage complexity and facilitate rapid prototyping of software for experiments, resulting in the many robotic software systems currently used in academia and industry [14].

Stanford University and Willow Garage developed a generalized open source operating system called Robot Operating System (ROS) for robots. ROS is not only an operating system; rather, it provides a structured communications layer above the host operating systems of a heterogeneous compute cluster [15].

Rapyuta is an open-source cloud robotics platform. It serves a platform-as-a-service (PaaS) framework for robots. Rapyuta architecture depends on LxC [16] containers. It provides an environment to access RoboEarth [17] Knowledge Repository. Massively parallel computation, allowing humans to monitor or intervene robots and serving as a global repository to store and share object models, environment maps, and actions recipes between various robotic platforms are some of specifications of Rapyuta. It is a competitor of Rosbridge [18] in terms of communication [19].

Survivable Cloud Multi-Robotics (SCMR) Framework is designed, implemented and evaluated for heterogeneous environments. One of the challenges for cloud robotics is the inherent problem of cloud disconnection. The SCMR framework provides the combination of a virtual Ad-hoc network formed by robot-to-robot communication and a physical cloud infrastructure formed by robot-to cloud communications. The design trade-off for SCMR is between the computation energy for the robot execution and the offloading energy for the cloud execution. The SCMR framework uses Web Sockets protocol for communication between the individual robots and the cloud server. In case of cloud disconnection a virtual ad hoc cloud is created between the individual robots and the robot leader and the individual robots communicate with one another through the gossip protocol [20].

Distributed Agents with Collective Intelligence (DAvinCi) is a software framework that provides the scalability and parallelism advantages of cloud computing for service robots in large environments [21]. It is implemented as a system around the Hadoop cluster with ROS as the messaging framework [22].

CLOUD-ENABLED ROBOTS

Robots have some constraints in terms of computational capacity, memory and storage. CR help them to overcome these challenges. Opportunity to use cloud allows cost effective robots to be produced. Robots can be classified as traditional robots and cloud-enabled robots. This paper focuses on cloud-enabled robots. A cloud technology not only empowers robots but also it allows them to network each other regardless of distance. Cloud-enabled robots are divided into two categories as standalone robots and networked robots. Classification of robots is shown in Figure 2.

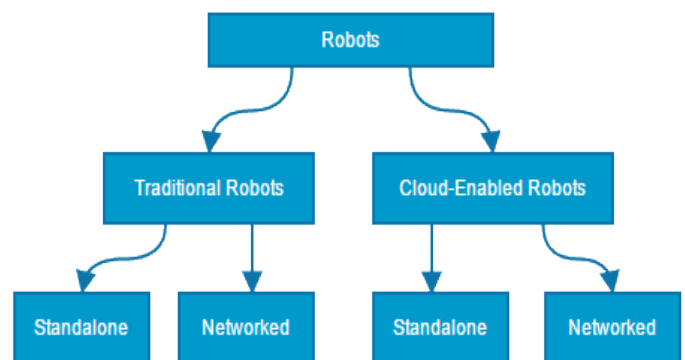


Figure 2. Classification of Robots

Standalone robots can benefit from cloud in terms of computation power, storage capacity and memory. However, networked robots can make networks, share their information through cloud and can perform collaborative works [23], [24], [25], [26]. CR infrastructure with standalone robots and networked robots is presented in Fig. 3.

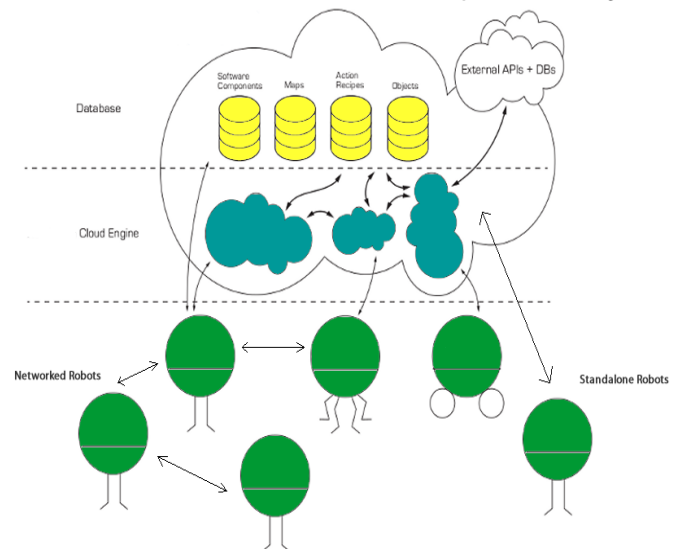


Figure 3. Standalone and Networked Robots

Robots can do a wide variety of works such as grasping, identifying objects, SLAM, monitoring, networking and some other actuating works. Robots can grasp formerly known objects easily. They can also grasp novel objects with the help of cloud. In [27], a study about

grasp planning in the presence of shape uncertainty and how cloud computing can facilitate parallel Monte Carlo sampling is presented. Kehoe et al focus on parallel-jaw push grasping for the class of parts that can be modeled as extruded 2-D polygons with statistical tolerancing. SLAM [28] refers to a technique for a robot or an autonomous vehicle to build a map of the environment without a priori knowledge, and to simultaneously localize itself in the unknown environment. SLAM is important in robotics and there are plenty of researches. It consists of statistical techniques such as Kalman filters, mapping and sensing. Riazuelo et al develop a cloud framework which name is Cloud framework for Cooperative Tracking and Mapping (C2TAM) [29]. This is a visual SLAM system based a distributed framework where the CPU-intensive map optimization and storage is allocated as a service in the Cloud, while a light camera runs on robots for tracking. The robots need only internet connection for tracking and cooperative relocation. C2TAM provides a database consisting maps can be built and stored, stored maps can be reused by other robots. A robot can fuse its map online with a map already in the database, and several robots can estimate individual maps and fuse them together if an overlap is detected. Virtual monitoring technology has been applied in more and more fields such as military, education, medical science, manufacturing engineering, and so forth. In order to realize resource sharing among all collaborating robots in a virtual monitoring system, cloud computing is proposed by combining professional computing equipment as a super virtual computing center. Zhang et al, proposed 3D virtual monitoring system based on CR. This system's architecture consist of communication language for agent communication, algorithm for cooperative working and conflict resolution. Prototype system is applied for the monitoring of fully mechanized coal-mining equipment [30]. Networking robots overcome the limitations of stand-alone robots by having robots, environment sensors, and humans communicate and cooperate through a network. Mateo et al, presented a work to decrease message overhead occurred because of communication. The proposed an information sharing model for group communication based on Brownian agent approach. In presented work they grouped robots in clusters with a cluster head to overcome message overhead [31]. Kamei et al, proposed prototype infrastructure of cloud networked robotics enables multi-location robotic services for life support [32]. Their study focuses on requirements in typical daily supporting services through example scenarios [33] that target senior citizens and the disabled.

CONCLUSION

This paper presents cloud computing, cloud robotics and cloud interaction of robots. It surveys cloud platforms and cloud-enabled robotics studies. Standalone robots can benefit cloud technologies and networked robots can perform collaborative works. Networked cloud-enabled robots can share computation resources, information and data with each other and can access new knowledge and skills not learned by themselves. This is a new paradigm in robotics that we

believe leads to exciting future developments. Future works can focus on reliable connection, data offloading methods and ubiquitous networking among robots and cloud services.

REFERENCES

- [1] J. Kuffner: *Cloud-Enabled Robots*, Proceedings of the IEEE Internationale Conference on Humanoid Robots, Nashville, TN, 2010.
- [2] P. Mell and T. Grance: *The Nist Definition of Cloud Computing*. NIST Special Publication [Online]. Available: <http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf>, Sept., 2011.
- [3] Mathur, P.; Nishchal, N.: *Cloud computing: New challenge to the entire computer industry*, Parallel Distributed and Grid Computing (PDGC), 2010 1st International Conference, pp. 223-228, 28-30 Oct. 2010.
- [4] Amazon Web Services [Online]. Available: <http://aws.amazon.com>
- [5] Rimal, B.P., Eunmi Choi, Lumb, I.: *A Taxonomy and Survey of Cloud Computing Systems*, INC, IMS and IDC, 2009. NCM '09, 5th International Joint Conference, pp.44-51, 25-27 Aug. 2009.
- [6] B. Siciliano and O. Khatib, Eds.: *Springer Handbook of Robotics*, Springer, 2008.
- [7] J.S. Jordán, T. Haidegger, L. Kovács, I. Felde and I. Rudas: *The Rising Prospects of Cloud Robotic Applications*, Proceedings of the ICC 2013, IEEE 9th International Conference on Computational Cybernetics, Tihany, Hungary, pp. 327-332, July 8-10, 2013.
- [8] Guoqiang Hu, Wee Peng Tay, Yonggang Wen: *Cloud robotics: architecture, challenges and applications*, Network, IEEE, vol.26, no.3, pp.21,28, May-June 2012.
- [9] A. Chibani, Y. Amirat, S. Mohammed, E. Matson, N Hagita, M. Barreto: *Ubiquitous robotics: Recent challenges and future trends*. Robotics and Autonomous Systems, 2013.
- [10] Wired Blog, *Robot Cops to Patrol Korean Streets* [Online]. Available: http://www.wired.com/gadgetlab/2006/01/robot_cops_to_p/
- [11] *Robot Waiters* [Online]. Available: <http://www.technovelgy.com/ct/Science-Fiction-News.asp?NewsNum=771/>
- [12] *Robot Pets* [Online]. Available: <http://en.wikipedia.org/wiki/AIBO>
- [13] *Robot to be added at Hoag Hospital Irvine* [Online]. Available: <http://www.intouchhealth.com/>
- [14] Kramer, J.; Scheutz, M., "Development environments for autonomous mobile robots: A survey," *Autonomous Robots*, vol. 22, no. 2, pp. 101-132, 2007.
- [15] K. Wyobek, E. Berger, H. V. der Loos, and K. Salisbury, "Towards a personal robotics development platform: Rationale and design of an intrinsically safe personal robot," in *Proceedings of the IEEE Intl. Conf. on Robotics and Automation (ICRA)*, 2008.
- [16] *LxC Userspace tools for the Linux kernel containers* [Online]. Available: <https://linuxcontainers.org>
- [17] *RoboEart Cloud Computing Platform* [Online]. Available: <http://roboearth.org>
- [18] *Robot Web Tools Open-Source Modules and Tools for Building Web-Based Robot Apps* [Online]. Available: <http://robotwebtools.org>

- [19] Mohanarajah, G.; Hunziker, D.; D'Andrea, R.; Waibel, M., "Rapyuta: A Cloud Robotics Platform," *Automation Science and Engineering, IEEE Transactions on*, vol. 99, pp. 1-13.
- [20] Osunmakinde, I.; Ramharuk, V., "Development of a Survivable Cloud Multi-robot Framework for Heterogeneous Environments," *International Journal Advanced Robotic Systems*, vol. 11, pp. 164, 2014.
- [21] A Rodić, K Addi, "Mathematical Modeling of Human Affective Behavior Aimed to Design Robot EI-Controller", *Book: New Trends in Medical and Service Robots, Springer International Publishing*, : (1, 1), pp. 141-162, 2014.
- [22] Arumugam, R.; Enti, V.R.; Liu Bingbing; Wu Xiaojun; Baskaran, K.; Foong Foo Kong; Kumar, A.S.; Kang Dee Meng; Goh Wai Kit, "DAvinCi: A cloud computing framework for service robots," *Robotics and Automation (ICRA), 2010 IEEE International Conference*, pp. 3084-3089, 3-7 May 2010.
- [23] Gyula Mester, "Intelligent Mobil Robot Control in Unknown Environments", *Intelligent Engineering Systems and Computational Cybernetics, Part I Intelligent Robotics*, pp. 15-26, ISBN 978-1-4020-8677-9, Library of Congress: 2008934137, DOI 10.1007/978-1-4020-8678-6_2, Springer, 2009
- [24] Gyula Mester, "Obstacle Avoidance of Mobile Robots in Unknown Environments," *Proceedings of the 5th International Symposium on Intelligent Systems and Informatics, SISY2007*, pp. 123-127, ISBN 978-1-4244-1442-0, DOI 10.1109/SISY.2007.4342637, Subotica, Serbia, August 24-25, 2007.
- [25] Gyula Mester: „Adaptive Force and Position Control of Rigid Link Flexible- Joint Scara Robots". *Proceedings of the 20th Annual Conference of the IEEE Industrial Electronics Society IECON'94, Vol. 3*, pp. 1639-1644, DOI: 10.1109/IECON.1994.398059, Bologna, Italy, September 1994.
- [26] R. Zoltán, *Új kommunikációs technológiák a védelmi szektorban: New Communication Technologies in the Defense Sector, Bánki Közlemények*, (1) pp. 1-11 2013.
- [27] Guoqiang Hu; Wee Peng Tay; Yonggang Wen: *Cloud robotics: architecture, challenges and applications, Network, IEEE* , vol.26, no.3, pp.21,28, May-June 2012.
- [28] H. Durrant-Whyte and T. Bailey: *Simultaneous Localization and Mapping: Part I, IEEE Robotics & Automation Mag.* , Vol. 13, pp. 99–110, 2006,
- [29] A. Chibani, Y. Amirat, S. Mohammed, E. Matson, N Hagita, M. Barreto: *Ubiquitous robotics: Recent challenges and future trends. Robotics and Autonomous Systems*, 2013.
- [30] Zhang, L.; Wang, Z.; Liu, X.: *Development of a Collaborative 3D Virtual Monitoring System through Integration of Cloud Computing and Multiagent Technology, Advances in Mechanical Engineering*, Vol. 2014.
- [31] Mateo, R. M. A.: *Scalable Adaptive Group Communication for Collaboration Framework of Cloud-enabled Robots, Procedia Computer Science*, Vol. 22, pp. 1239-1248.
- [32] Kamei, K.; Nishio, S.; Hagita, N.; Sato, M.: *Cloud networked robotics, Network, IEEE* , Vol.26, No.3, pp.28,34, May-June 2012.
- [33] Gyula Mester: *Sensor Based Control of Autonomous Wheeled Mobile Robots, The Ipsi BgD Transactions on Internet Research, TIR, Volume 6, Number 2*, pp. 29-34, ISSN 1820-4503, 2010.



ACTA Technica CORVINIENSIS
BULLETIN OF ENGINEERING

ISSN:2067-3809

copyright ©

University POLITEHNICA Timisoara, Faculty of Engineering Hunedoara,
5, Revolutiei, 331128, Hunedoara, ROMANIA

<http://acta.fih.upt.ro>