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Five Traits of Performance Enhancement using Cloud Robotics: A Survey

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Abstract

Recently, robots and automation systems have been at the front of research with the majority of systems still operating independently using onboard computation, memory manipulation and communication. With improvements in communication technology and the increasing availability of network, new approaches where robot and automation processing is performed remotely with access to large scale datasets, support a range of functions. Cloud Robotics supplements performance enhancement of robotics and autonomous systems by providing a global infrastructure in innovative ways. This paper summarizes recent research into five traits of Cloud Robotics for performance enhancement in robotics and autonomous systems: 1) Remote Brain, 2) Big Data and Shared Knowledge-base, 3) Collective Learning, 4) Intelligence and Behavior, and 5) Cloud architectures. Towards the end, in this survey, we present future directions for research in cloud robotics.

Keywords: Cloud Computing; Cloud Robotics; Big Data; Networked Robots; Autonomous Systems.

1. Introduction

With the recent popularity of “Cloud Computing”, there has been increasing interest in applying similar concepts to robotics and autonomous systems. Due to the limited capacities of on-board processing, storage and battery capacities, robotic devices are constrained to numerous limitations. Performing complex computations or storing large-scale knowledge bases can often be done more efficiently on dedicated server hardware, requiring less computing power, less memory and therefore less battery capacity on the robot itself. Applications of these concepts to robotics are commonly referred to as “Cloud Robotics”\textsuperscript{1}.

Recently there have been several contributions to cloud robotics in terms of offloading computations to large scale computing infrastructure, storing and sharing knowledge, coordination and

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collective learning among robots. Various platforms and frameworks have been developed with mainstream research done in the open source community.

With the availability of the world wide web, online web robotics became a realization. Some of the earliest work by K. Goldberg et al. focused on web based tele-operated robots controlled remotely via an Internet browser. Earlier work on networked robots using wireless sensor networks and swarm robotics was reported in. Kim et al developed a Real-time operating environment for networked control systems using the user datagram protocol (UDP). McKee in described the benefits of distributed processing in networked robotics and challenges in communication, synchronization and performance. Kuffner coined the term, "Cloud Robotics" in his paper on cloud enabled robotics published in 2010. He provided a wide vision where robots can harness the massively parallel computation resources and vast data storage available via the Internet.

Recently many works have been reported in the literature establishing the various benefits of using cloud computing in supplementing robotics and autonomous systems operations. Datasets for various images, maps etc. along with libraries and modules are being developed and made available on the Internet for research in cloud robotics. The cloud already houses programming constructs, libraries and frameworks that can help computers recognizing the types and classes of objects from images. Robots can determine the type of a certain object by recognizing its shape and how to grasp it. The Google autonomous driving project demonstrates the benefit of this approach. Maps and images for various locations are collected, indexed and updated by satellite, Street-view, and crowd-sourcing to facilitate accurate localization. This large dataset is then used by the self-driving car, which can resolve its whereabouts from its sensors. The European Union’s ‘RoboEarth’ project also provides a platform for a cloud-based system that would contain relevant information in a predetermined format that can be processed by autonomous robots.

This paper presents various approaches used in the literature for automation and performance enhancement by applying cloud computing and robotics, which we classify into five different but overlapping areas: 1) Remote Brain: Offloading computation to large scale computing resources, 2) Big Data and Shared Knowledge-base: Provide access to large scale data sets and remote libraries for navigation, programming, images, videos etc, 3) Collective Learning: Robots sharing maps, trajectories, control policies etc, 4) Intelligence and Behavior: Data mining into data sets and history of trajectories for improvement in intelligence and behavior of autonomous systems, and 5) Cloud architectures: frameworks and platforms recently developed for a host of applications. In this survey paper, we report recent works in the literature corresponding to the five traits mentioned above. Furthermore, insights into future research directions are presented towards the end.

2. Remote Brain: Offloading Computation

Robots are typically capable of processing information using multiple onboard processors. Certain types of robots such as mobile robots or Unmanned Aerial Vehicles (UAV) may have limited capacities of on-board processing due to their stringent requirements of dimensional size and limited payload. Such robots can harness remote processing by offloading heavy computation tasks to external computers. The Cloud permits running interactive, real-time simulation tasks in parallel including applications for video surveillance, image building using Point Cloud libraries (PCL), sensor information tracking, predicting and evaluating performance evaluation tasks etc.

Cloud computing enables remote computation by enabling massively parallel computation on demand. Public domain cloud service providers such as Amazon Web Services, Elastic Compute Cloud, known as EC2, Google Compute Engine, and Microsoft Azure allow computing resources to be rented for various computing tasks. Researchers are increasingly utilizing these services for scientific and technical high performance computing (HPC) tasks. In, AbdelBaky et al. proposed the concept of HPC as a Service, aiming to transform traditional HPC resources into a more convenient and accessible service. The European Union, DreamCloud Project is a realization for enabling dynamic resource allocation in many core embedded and high performance systems. The project aims to enable HPC and cloud computing systems to balance workload and manage resources so that they can offer more meaningful guarantees in terms of performance and energy.

Various recently published works have utilized Cloud computing as a platform for offloading and processing compute tasks remotely. Agostinho et al. developed a cloud platform for robotics workflows using the Platform as Service approach. They concluded that the proposed platform provides strong advantages in performance without compromising security. The DAvinCi project reported in provides a platform for solving Fast SLAM as a paral-
lelization problem using Map/Reduce in the Cloud. This allows robots to explore the possibilities of creating a global map by allowing various robots to communicate and share localization data.

Researchers in\(^7\) have used Cloud computing for offloading computations for sample-based statistical motion planning. They showed that it can be used to explore many possible perturbations in object and environment pose, shape, and robot response to sensors and commands. Also, Wang et.al. in\(^7\) report using cloud for massive sampling over error distributions and Monte Carlo sampling of data. Rapyuta proposed by Hunziker et.al. in\(^7\) is the ROBOEARTH cloud engine that implements and allows computationally expensive algorithms to run in the cloud. B. Liu et.al. in\(^7\) present Cloud Enabled Robotics System (CERS) that allows robots to mesh together to form a local networked system. These robots can offload heavy computation tasks to the server side implementation of a cloud enabled software architecture. Researchers through experimental study tested the system for an application of Real-Time Video Tracking. Turnbull in\(^7\) develop a small scale cloud infrastructure to allow robots to offload computation tasks to the cloud.

Authors in\(^7\) present Jeeves, a distributed service framework for cloud based robot services. The key mechanism of the proposed framework is a robot assignment function, which discovers distributed robot resources and assign the requested tasks by end users to suitable robots. Jeeves integrate various devices including robots with Internet services and provides a platform for offloading and executing computations in the cloud. Jeeves system architecture is illustrated in Figure 3. In general cloud computing and robotics can correlate and mesh up to improve various limitations of robots by offloading the tasks for improved performance therefore realizing the notion of a remote brain.

3. Big Data and Shared Knowledge-base

The sheer scale of data that cannot be managed, transformed, moved or analyzed efficiently without using high performance computing resources, according to F. Alexander et. al. in\(^7\), is termed as Big Data. Examples of Big Data typically involve data that may not be structured using a relational database, including videos, images, maps, graphs, financial transactions, and real time network traffic.

Autonomous robots are typically equipped with multiple sensors, cameras etc. Data collected from these sensors is normally used for taking decisions on localization, movement, path determination etc for the robot. Sharing this data among multiple robots increases the volume to an extent that managing it would overwhelm limited capacities onboard a robot. To this end, knowledge bases for all collected may have to be created for processing large scale information in further research. Various research projects have yielded a large collection of datasets and knowledge bases that are available online. The Columbia Grasp dataset\(^7\) is a large dataset of pre-computed grasps on thousands of 3D models, that have been used in many research studies.

The Willow Garage Household Objects Database\(^7\) is another dataset that contains thousand of 3D models that can be used to evaluate various aspects of grasping. Google Goggles\(^7\), is a network-based image recognition service for mobile devices. It has also been used as a service for robotics research. Various datasets have been reported in the literature specific to research topics. Kim et.al. in\(^7\) generate a dataset for 3D point clouds. In this study they apply algorithms for matching 2D image features of images captured by a mobile robot, to 3D point cloud. Authors in\(^7\) propose a Multi-view point clouds registration method based on the 2D and 3D fusion information. Using cameras
and 3D laser radar, the mobile robot captures images, image features are matched to create 3D point clouds. Online datasets have also been used for machine learning, computer vision and augmented reality applications. Rodríguez-Silva et. al. in provide video surveillance and image analysis system using cloud that collects multimedia streams generated by surveillance cameras, optimizes their transmissions according to network condition and stores them in a cloud storage system in an efficient and secure way.

Application of robotics in medical and healthcare industry is also gaining enormous attention. One such example is Yokoo et. al. work reported in where physical therapy robots collect patient information and log it into a medical cloud. This information serves as a knowledge-base for robots and medical practitioners in learning and improving the medical processes. RehabRobo-Onto is another work related to this area where rehabilitation robots data is made available on the cloud. The information in this repository is shared with online community for querying and processing of information. The European Union’s ROBOEARTH project develops a web-based knowledge base through which robots can share information they have obtained. ROBOEARTH projects main objective is to build a World Wide Web for Robots, a web-based Wikipedia-like platform for sharing knowledge about actions, objects, and environments between robots. Figure 2 illustrates the three layer architecture of the ROBOEARTH project.

4. Collective Learning

Cloud computing provides an excellent platform for networked robots to share data, process information and improve perception by various machine learning methods. A simple example of collective learning can be inspired from a disaster recovery scenario where various mobile robots are deployed to build a map of the location. Many robots communicating through a central cloud service, can post localization information that can be shared by other robots certainly enhancing map discovery. Furthermore, robots can also post control policies, sensor information of physical traits of an environment, trajectories, motion coordination, tracking data and updated localization data for collective learning. Another practical example of collective learning is the implementation of Kiva Automated Materials Handling Systems multiple mobile robots environment. The system uses hundreds of mobile platforms to move packages in warehouses using a local network to coordinate motion and update tracking data.

Kamei et al. introduce the Ubiquitous Networked Robot Platform (UNR-PF) as a framework for distributed task coordination and control. The UNR-PF deals with distributed task execution and supervision on multiple robots and sensorized devices at different locations. The UNR-PF abstracts away from the robots concrete hardware and offers a generic interface that can be used by application developers to create hardware-independent robotic services. A developer can request components that fulfill a given specification, and the UNR-PF will then assign suitable devices that can be controlled remotely.

The MyRobots project from RobotShop envisions a social network for robots, where users can connect, monitor and share robots. Robots can also share sensor information to learn about environments. As mentioned earlier, the datasets and knowledge-base created for ROBOEARTH project can also be used for collective learning. Turnbull in provide a small scale cloud infrastructure to facilitate information sharing among various networked robots. They test the cloud service infrastructure with minimal requirements resulting in successful implementation. Hu. et. al. in present an architecture for networked robots leveraging combination of ad-hoc cloud formed by machine-to-machine and machine-to-cloud communications. Authors propose the communication protocols that facilitate task offloading and information sharing in a ubiquitous cloud for robotic applications.

Chibani et. al. in and Sandygulova et.al. in describe a collective learning environment for ubiquitous robots. Sensors embedded in these robots can provide vast amounts of information that can be beneficial in further processing and collective learning. Pervasive technologies vastly used in healthcare environments such as service oriented sensor networks (SOSN) have been used to collect data through various sensors and RFID tags. These are incorporated in household objects that are monitored by central servers allowing them to communicate and share information. An example of this concept is the Gator House project for monitoring elderly patients.

5. Intelligence and Behavior

Data mining into data-sets and history of trajectories for data obtained by various sensors on the robot can lead to improvement in intelligence and behavior of autonomous systems. Recently A. Lim in highlighted the issue of robot
behavior in human-robot interaction. Three signs including spoken language synthesis, gesture and gaze play a key role in determining metrics and parameters for human-robot interaction. In a cloud robotics context, data available in various shared datasets and knowledge-bases can be mined for improvement in robot intelligence and human-robot interaction and behavior.

Quite a lot of work has been reported in behavior and human-robot interaction in the literature. Although cloud robotics is a relatively new paradigm for sharing information about human-robot interactions, nevertheless, it is gaining attention by researcher. Anzai in report using artificial neural networks (ANN) for analyzing huge amount of time series data collected by researchers. The effectiveness of these data mining techniques has been demonstrated using an available robotic dataset. Ho. Y. et al. present a system that collects human motions data to process data mining, and uses the result to detect human intention, and then provide services. The authors use cameras to determine human gestures and obtain human movements. The motion data are analyzed to process data mining and find the relation between motion and intention. The result of mining can be applied to provide information on the mobile device or to use for human-robot interaction. Authors in propose an intuitive tele-operation scheme by using human gesture in conjunction with multimodal human-robot interface. Their work showcases the effectiveness of the proposed scheme with experiments that were conducted to show how the operators can access the remotely placed robot in anytime and place.

Collective Modelling of terrain by mobile robots has also gained attention. Data collected from various mobile robots is made available to a central server where it can be further processed using various methods for improved robot behavior and intelligence. Work presented in develop Gaussian process (GP) model that is applied to the problems of modeling and data fusion in the context of large-scale terrain modeling. The proposed model naturally provides a multi-resolution representation of space, incorporates and handles uncertainties aptly, and copes with incompleteness of sensory information. These attributes are considered essential to support most field robotics applications, including autonomous mining. Thompson et. al. also tackle efficient fusion and distributed estimation techniques for large scale terrain. Authors in use data mining techniques for classification of humanoid soccer robots using machine learning. Data was gathered to generate a meaningful multi-class dataset for improving soccer robots. Gopalapillai et. al. report using artificial neural networks (ANN) for analyzing huge amount of time series data collected by sensors mounted on a robot navigating in a simulated environment. The Artificial Neural Network system employing back propagation learning algorithm classified different scenarios encountered by the robot using the data collected by sensors.

6. Cloud Architectures

Cloud provides scalable resources for sharing information between humans, systems and robots. Recently many works have provided middle-wares, frameworks and platforms for Cloud robotics. Nakagawa et. al. developed a distributed service framework that realizes the coordination of various devices, robots, and service functions based on RSNP (Robot Service Network Protocol), a protocol specification for robot services. Kato et. al. propose the Research Cloud (RSi-Cloud), which enables integration of robot services with Internet services and mash-up of robot services. RSi-Cloud also utilizes RSNP. Another application of RSNP can
be found in where Narita et. al. address the reliability and security issues in communication. Researchers in address Next Generation Cloud Computing and propose Architecture for cloud robot networks that allow sharing of information among various mobile robots. Riazuelo et al. demonstrate a cloud framework for cooperative tracking and mapping (C2TAM); computer intensive bundle adjustment for simultaneous localization and mapping (SLAM) performed in the Cloud.

Software as a Service (SaaS) has been gaining attraction. With SaaS, the code does not need to be provided, nor even the algorithms used. Instead, an interface to the software is provided for other users, allowing them to utilize the algorithm. This model has been successfully used by Amazon and Google. Chen et al., define the paradigm Robot as a Service (RaaS), proposing a cloud framework for interacting with robots in the area of service oriented computing. In , the authors exploited the Service Oriented Architecture (SOA) technology to design and implement a prototype of the Robot as a Service (RaaS) cloud computing model. The design complies with the common service standards, development platforms, and execution infrastructure, following the Web 2.0 principles and participation. In , the authors made extensions to the Robot Operating System (ROS) middleware, called rosjs, which is a JavaScript library for ROS that exposes the robot functionalities as web services, and rosbridge, which is a light weight protocol that exposes robot sensor data and controllers, through web sockets accessible anywhere over the Internet, and provides security mechanisms and runtime tools for remotely manipulating the robots. In , Koubaa proposed RoboWeb, a SOAP-based service-oriented architecture that virtualizes robotic hardware and software resources and exposes them as services through the Web, contributing to the evolving concept of cloud robotics. RoboWeb consists in the integration of different Web services technologies with the (ROS) middleware to allow for different levels of abstraction (multi-layer architecture), ensuring more modularity and flexibility of the deployment.

7. Further Directions

Networked robotics has been there for a long time. The ubiquitous nature of the Cloud is enabling new research into remote human operation. Real-time communication between mobile robots deployed in an open environment could be challenging. Although research in communication technologies is rapidly advancing the boundaries of wireless connectivity, it remains to be seen how this will affect networked and cloud robotics. Mining into large datasets captured by robots sensors would provide an insight into improving robots interactions. In fact Big Data analytics of robotics data could open a new pathway for improving human-robot interaction. Furthermore, online datasets would grow giving a chance for research communities to build new algorithms in order to enhance the Knowledge of automation systems. Robot as a Service (RaaS) paradigm defined in could see wider acceptance and use. Researchers may also use Service Oriented Architectures to provide algorithms, routines and compute resources as services for remote execution.

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References


