Leveraging the Cloud for Connected Service Robotics Applications

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***Abstract*—Cloud robotics is a new approach to robotics that exploits the internet as a resource for parallel computing and data sharing. Robots are no more considered as isolated devices but now they can add new functionalities, communicate with the environment and share knowledge base. Exploiting this new technology a robot can also take advantages by off-loading heavy computations to the cloud, thus reducing hardware costs, power consumption. The Joint Open Lab on Connected Robotic Applications laB (JOL CRAB) is a research laboratory created by Telecom Italia in collaboration with Politecnico di Torino. The aim is to investigate technologies and develop concepts where the focus is mainly placed on the relationship between robots and the cloud computing, addressing issues that arise from the use of robotic services in public/enterprise environments not only of technological, legal, economical, sociological or psychological kind, but also related to ergonomics, cognitive perception, and relational experience. The collaboration between university and the industry led to different field trials where issues and feasibility of new services were evaluated and a community of stakeholders was created in the territory. We present these field trials, the different issues that arise and how that can be solved.**

I. Introduction

Cloud robotics is an emerging field in robotics; by embracing typical internet-based technologies (e.g., cloud computing, cloud storage, web-services, etc.) it allows an artificial agent to take advantage of the network's resources, to share knowledge and to off-load intensive tasks (such as localization, mapping, grasping, multi-input mission planning, etc.) [1], [2]. This leads to a paradigm shift in which robots become simple agents, connected to a cloud computing platform [2]. Among the most notable works on cloud robotics, [3] presented a service-oriented architecture allowing distant groups of robots to share and exchange learned skills and improve cooperation with human agents. In [4] the requirements in typical daily supporting services have been examined through example scenarios that target senior citizens and the disabled, together with a discussion about the key research challenges offered by the cloud network-robotics approach. Similarly, in [5] the use of cloud robotics has been investigated for physical and virtual companions assisting people in their daily living (e.g., ubiquitous robots that are able to co-work alongside people). In [6] the authors present *Rapyuta*, an open source framework underlying *RoboEarth*, a Cloud Robotics infrastructure, which aims at creating a World-Wide-Web style database for storing knowledge generated by humans and robots in machine-readable format.

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The potential of a cloud infrastructure applied to robotics is particularly evident in applications that require high computational resources, quick access to vast remote knowledge bases and data repositories and that involve numerous robots - thus requiring high scalability and multi-agent management. At the same time, mobile robotics [7] is nowadays increasingly present in our daily life. This is mainly due to technology developments in the field of service robotics. Service robotics has already been widely applied in several fields, such as domestic and logistic robotics. This also pushes research in the field of *Human Robot Interaction* (HRI).

These new trends in robotics are attracting big companies interested in exploiting the market of service robotics. Telecom Italia S.p.A., the main telecommunication company in Italy, created a research lab in collaboration with Politecnico di Torino with the aim of exploring service robotics solutions and *Cloud Robotics*, to create new products and services for end users. The lab is know as Telecom Italia *Joint Open Lab Connected Robotics Application laB* (JOL CRAB).

Within the JOL CRAB, professors, researchers and students from Politecnico di Torino and employees of Telecom Italia collaborate in long terms projects in a multidisciplinary environments where various researchers from different fields (such as engineers, designers, lawyers, etc.) work on service robotics applications.

Aim of this paper is to present and describe different service robotic applications developed within the JOL CRAB. These applications rely on a common Cloud Robotics Platform developed within the JOL CRAB.

The rest of the paper is organized s follows: Section II presents a general description of the Cloud Robotics Platform; Sections III, IV and V present some projects carried on within the JOL CRAB (*Fly4SmartCity*, *Robot@CED* and *Virgil*), while Section VI presents a novel application for object recognition using Artificial Neural Networks for grasping. Finally, Section VII concludes the paper.

II. General description of the Cloud Robotics Platform (CRP)

The proposed solutions are based on a Cloud Robotics Platform (CRP) [8], [9], a framework that makes use of the resources available on the cloud to develop a more powerful and centralized intelligence for robotics application. The main idea is to convert the robot to a simple low-cost agent, with low computational power, while most of the computation is done on remote servers. Moreover, the cloud robotics platform is also able to guarantee the robustness needed for long-term operativeness in real-world applications and to expose simple APIs to the final user. The mobile robots communicate with the CRP through a fast wireless internet connection, e.g., Long Term Evolution (LTE) cellular data network. The CRP has a central unit called Robot Clone Manager (RCM) which manages all the resources needed to control the robots and to give feedback to the user. Basically, RCM manages and processes information from the robot sensors and exposes a web based Graphical User Interface (GUI) to the user.

The Cloud Robotics Platform is based on the Robot Operating System (ROS) [10]. ROS is an open-source, meta-operating system for robot software development, providing a collection of packages, software building tools and an architecture for distributed inter-process and inter-machine communication. ROS building blocks are the so-called nodes, i.e., pieces of code implementing a specific functionality. Nodes interact with each other using request/reply and publish/subscribe communication models. The communication between nodes is based on the TCP network protocol. The first official release of ROS was originally developed by Stanford University and Willow Garage in 2011. From 2013 the project became propriety od Open Source Robotics Foundation (OSFR). ROS provides different tools such as hardware abstraction, drivers, libraries, visualization and communication tools, pack management and so on.

The aim is to become the standard for the development of mobile and industrial robotic applications compliant to different software and hardware platform. The whole set of libraries and tools is designed to be distributed, matching the principle of Cloud Robotics. ROS is open source and is supported by an active and fast-growing community.

A. Cloud Robotics platform Architecture

The proposed platform relies on the ROS framework in order to exploit the vast amount of already developed ROS nodes and service applications.

With reference to Figure 1, RCM generates a Service Container (SC) which hosts all ROS nodes needed to control the robot. These nodes perform the computation necessary to support the abstraction of hardware layer. We define 4 different types of ROS nodes:

- *Sensor Drivers (SD1, SD2)*: ROS nodes that abstract the information from the sensors (Laser scan and PT camera) and encapsulate them into ROS messages;
- *Robot Driver (RD)*: ROS node that abstracts status update from the robot and encapsulate them into ROS messages;
- *Application nodes (A1, A2, A3, A4)*: ROS nodes that process all the information coming from the sensors and the robot;
- *Bridge node*: ROS node that implements a Web-socket transport layer to connect the SC with the web application.

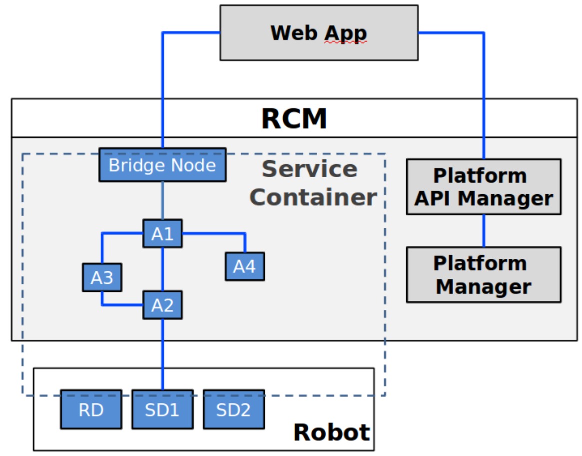


Fig. 1. Block diagram of the Cloud-based Robotics Platform

Basically, the web application knows nothing of the robot except the information that it publishes through ROS messages. As a meaning of fact, the platform creates a cloud abstraction of the physical robot, that we call the cloud-agent (or *robot clone*).

Exploiting this new technology a robot can take advantages by off-loading heavy computations to the cloud platform and consequently reducing power consumptions, costs of the hardware and the rate of software upgrades. Robots are not anymore considered as isolated devices but now they can add new functionalities for the accomplish a new or demanding task, communicate with the environment and sharing information connected to a network.

Our joint lab, JOL CRAB firmly believes in the importance of being up-to-date with the themes regarding data privacy and security gathered by robots, personal data, national laws regarding UAVs and more in order to apply robotic services as real services, out of the lab.

III. FLY4SMARTCITY

The goal of Fly4SmartCity[1] [9] is to provide a service for emergency management in smart city environments using small Unmanned Aerial Vehicles (UAV). For validating the service we imagined a test case as follows: a citizen is in a dangerous situation and requests the emergency service; using a smartphone application he/she sends back to the cloud platform his/her GPS coordinates and an unique identification number. the cloud platform is able to find the most suitable UAV for the mission and sends it to the citizen in order to provide monitoring and support. A police officer can access the service in real-time to monitor the actual position of the UAV, its telemetry, and to visualize on the web interface the video stream coming from the UAVs camera.

Fly4SmartCity supports various missions requests, including monitoring, emergency-management, delivery and user-defined flight plans. The main idea is to aggregate different

[1] http://jol.telecomitalia.com/jolcrab/principali-progetti/fly4smartcity-3/info

Fig. 2. Fly4SmartCity

open data and other online sources of information in order to provide different path planning strategies for unmanned aerial vehicles. The cloud robotics platform retrieves information available on internet about obstacles and mobile connectivity by aggregating several Open Data providers, as well as additional geo-referenced data (some of these data belong to private companies and are usually subject to restrictive license and limited access, hence they cannot be defined ”open” in a strict sense, however they are typically publicly available under some constraints). Given the current position of the UAV and a goal, a bounding box is created which includes these two points, plus a suitable padding in all directions, and gathers open data and other geo-referenced data. Given a planning strategy, the optimal path is computed using D*-Lite [11].

The system was tested during a final live demonstration. A commercial quadrotor equipped with a MicroPilot’s MP2128[g] autopilot was used . The live demonstration was performed in Aero Club Torino’s airport in Turin, Italy, and was authorized by *ENAC*, the Italian civil flight authority. The UAV was connected both to a ground station via a standard Radio Frequency (RF) 5.8Ghz radio link and to the cloud robotics platform via a 4G LTE link. The flight was performed at line-of-sight and a pilot was ready to take control of the UAV in case of trouble, as required by the current Italian legislation. In addition to that, the flight zone was segregated. In the first test, a user requests the emergency service using a mobile phone. The authorized user authorizes the flight using the GUI. The UAV reaches the user and performs a circle around him and sends back video streaming and telemetry. A screenshot of the GUI during the experiment is shown in Figure 2. In the second case, the authorized user selects a set of waypoints using the GUI, by clicking on the map. Then, the user authorizes the mission and the UAV performs the mission and sends the video streaming and its telemetry to the GUI. Videos of the experiment are available online[2].

[2]http://tinyurl.com/l5lbry4, http://tinyurl.com/qd2whr5

IV. ROBOT@CED

This work[3] [12], [8] concerns the introduction of autonomous mobile robots in Data Centers with the goal of reducing energy consumption by optimizing the use of Computer Room Air Conditioning (CRAC) systems through the detection of hot spots (i.e. areas of higher temperature at the inlet side of computer equipment). Data center monitoring has been a critical subject of both research and engineering in recent years. The presented robotic system consists of a mobile robot equipped with a laser range sensor and an IMU, able to autonomously navigate in a data center room for accurate monitoring of servers external temperature. The system is fully based on the Robot Operating System (ROS). The robot is able to autonomously create a map of a previously unknown room, localize therein and execute a list of measurements at different locations, which are provided by the user via a web Graphical User Interface (GUI). The application is based on the cloud robotics infrastructure.

During the prototyping, we encountered several issues regarding navigation: racks containing servers are usually covered by metal grids that introduce noise in laser readings, due to hardware interpolation and to the fact that laser beams sometimes pass through the grid holes. Moreover, new racks are constantly added or removed, so that the application has to deal with intrinsically dynamic environments.

The system has been tested in a Telecom Italia S.p.A. data center in order to prove the effectiveness of the various components of the navigation system, in two different data center rooms of average dimensions during normal daily operations, in presence of workers and small changes in the environment.

The first trials in the Telecom Italia S.p.A. datacenter lead to the foundation of a startup company called *Hotblack Robotics Srls*, with the aim of bringing the proposed solution to the market. *Hotblack Robotics Srls* is also participating to the TIM #Wcap Accelerator, that is a Telecom Italia’s open innovation program which selects, finances and accelerates digital startups.

V. MUSEUM ROBOT

Improvement of cultural heritage fruition is a recurrent theme that has been addressed with the application of the most diverse technologies. The exemplary case represented by virtual tours, which offer the opportunity of a remote visiting experience to the user, enabling a wide range of new design opportunities. Nevertheless, the limits of these solutions drove to a deep reflection on the effectiveness of a totally virtual experience. For this reason, the use of service robotics in museums is becoming increasingly common. Robots, indeed, represent a bridge between the virtual and the physical world, due to their composite nature. However, the observation of international case studies of museum robotics shows that, until now, many of the proposed solutions were not actually meeting

[3]http://jol.telecomitalia.com/jolcrab/category/robotced

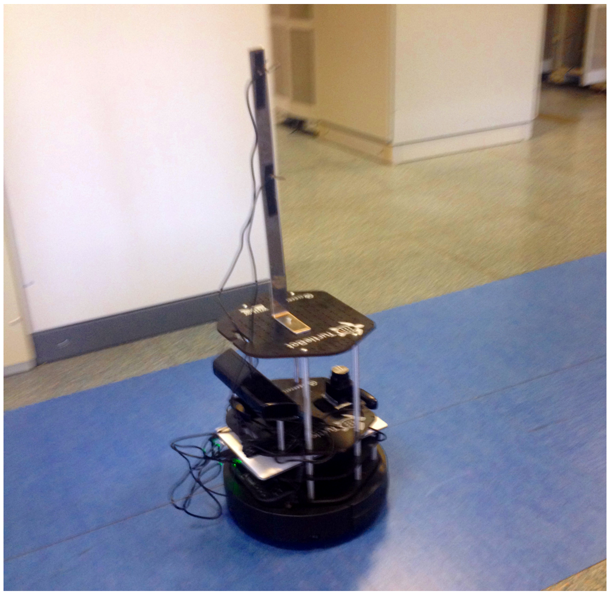


Fig. 3. Robot@CED platform

Fig. 4. The first prototype of Virgil

the location and stakeholders requirements, which usually vary based on the context.

Starting from this consideration, a new robotic museum experience has been designed[4] [13], [14] with the aim to increase museum attractiveness, to offer a more involving experience to the visitors and enhance museum guides activity. The proposed solution was developed paying particular attention to the ethical aspects and is meant to represent a shifting in the robotic design process. The applications of new robotic solutions, indeed, are usually based on the opportunities offered by the technology, whereas this project was developed using a human centered design approach, which focuses on people instead of technology.

The *Virgil project* was aimed at the study and development of a set of algorithms and services, enabling autonomous navigation of a mobile robot in museums to promote cultural heritage, in particular the network of Savoys royal residences. The service proposal consists of an extension of the tour through a real-time virtual tour, made possible by placing the robot in otherwise inaccessible areas. The remote control of the robot is entrusted, mainly, to the museum guide but also to the visitors to experience a cultural game. For this purpose, the team has designed a mobile robotic platform (depicted in 4) which is a four-wheel drive for indoor structured environments, specifically designed for purpose reasons. This robot implements a fully ROS compatible platform suitable for a wide range of activities. Its mechanical structure is designed in a pyramid shape with a rectangular base of 50 x 55 cm, a height of 120 cm and a weight of 10 kg approx. Wheels are operated by two electric motors and a set of gears and belts. Each motor provides traction to each side in a separate way. Robot autonomy is up to 8 hours; power is provided by a 12V Li-Fe battery and the robot is equipped with both proprioceptive and exteroceptive sensors to estimate its own motion. Its maximum speed is of 1 m/s and it can move in teleoperation mode or in autonomous navigation mode through the assisted guidance of an user connected remotely via a web server application. It mounts several on-board sensors, including wheel encoders, a Hokuyo UTM-30LX laser range finder and a DCS-5222L pan/tilt camera that sends a streaming video displayed to users on a special screen or on personal devices.

During the development of this work, several tests have been made with the robot in a real scenario, the Royal Castle of Racconigi. Platform response and network latency during remote teleoperation were evaluated. In all the experiments, commands from the web GUI reached the robot in less than 100ms while the video stream latency from the robot camera never exceeded 0.5 s. Some tests in a real session with visitors were performed by the museum guide who controls the robot in teleoperation with the support of a developed GUI. The set of visitors was of about 40 people, aged between 16 and 25. After the experience, a number of feedbacks about the movements of the robot and the quality of the video have been collected from visitors. The results indicated that one third of the visitors had a perception of a constant and precise movement, 45% indicated that the movement was cautious while the rest had a perception of an imprecise movement. With respect to the quality of the video, about 95% gave a positive feedback.

VI. Object recognition using Artificial Neural Networks for grasping

Object manipulation is a growing area of interest in robotics research. For example, interaction with common household objects is a crucial task for human-robot collaboration. We investigated for 3D object recognition with application to the scenario of an anthropomorphic arm interacting with objects in

[4]http://jol.telecomitalia.com/jolcrab/category/robot-museale

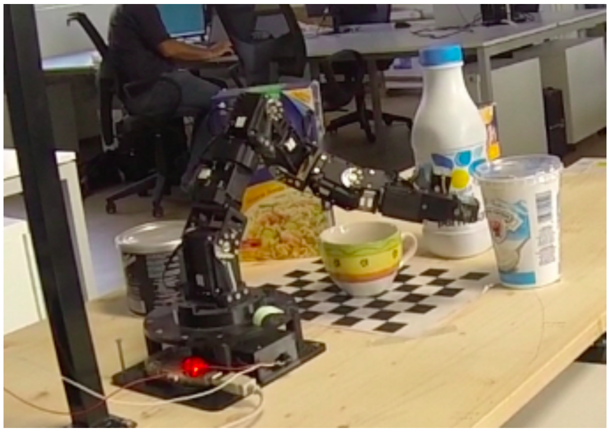


Fig. 5. The pick and place application (real experiment)

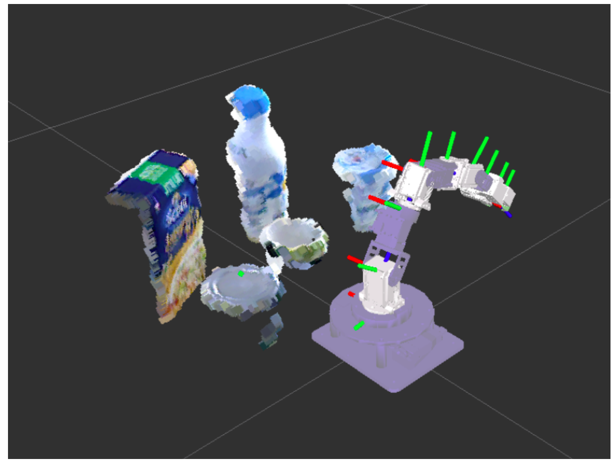


Fig. 6. The pick and place application (simulated view)

the environment. In this context, we developed an application in which a robotic arm is able to detect, classify and interact with any objects placed on a table.

The proposed approach uses Multi-layer Perceptron Artificial Neural Networks (MLP-ANN) [15] and is based on combining 2D and 3D feature descriptors to improve classification accuracy and to limit over-fitting. 2D and 3D features are extracted using a low-cost RGB-D camera. In the scenario, a robotic arm has to grab or pick and place objects on a tabletop-like surface. The RGB-D camera stream is sent remotely to the cloud platform where preprocessing and the classification algorithms are executed.

First, 3D point clouds are extracted from the RGB-D camera, then object of interest are extracted from the main plane using the PCL library [16]. The main plane is estimated and removed using *RANdom SAmple Consensus* (RANSAC) [17]. Then the objects are detected using euclidean clustering on the 3D points. 3D points of each object are projected onto the image plane and 3D and 2D descriptors are computed in parallel. *Viewpoint Feature Histograms* (VFH) [18] and *Speeded-Up Robust Features* (SURF) feature descriptors [19] are used for 3D and 2D respectively. Descriptor lengths are normalized using a Bag of Words algorithm. An ANN is then trained using the computed histograms on a training dataset divided in object classes, and give the probability of presence of one object class as output.

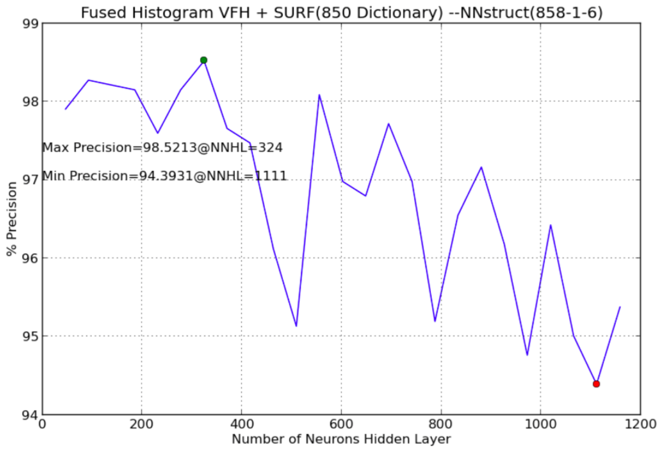
Two integration methods are investigated: in the first method 2D and 3D descriptors are concatenated into a single histogram for training a single ANN. In the second method, two ANNs are trained, one with 3D descriptors and the other with 2D descriptors. The outputs of the two ANNs are given as inputs to a new ANN which will provides the final classification. The third ANN is trained on the same training set as the first two. The method bears some similarity to a Deep Neural Network approach.

In Figure 7 we show the recognition precision of the two approaches, while varying the number of neurons in the hidden layer. 6 object classes are used for training. In the first method the number of neurons in the hidden layer plays a primary role in the recognition rate. The precision steadily decreases with oscillations, at the increasing of the numbers of neurons. The maximum precision has value of 98.52% In the second method the accuracy is already high with just few neurons in the hidden layer; in fact an accuracy of 91.31% is reached with only 3 neurons. Despite this, the accuracy achieves his steady state after only eight neurons. From there on, incrementing the number of neurons only yields oscillations around the steady state. The maximum precision is 98.39%

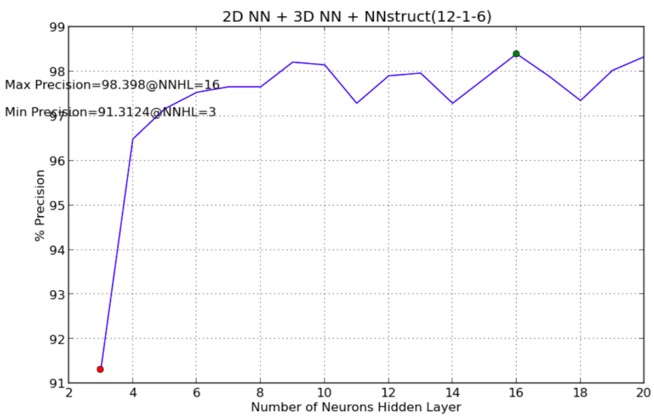
The results show that we are able to achieve high classification accuracy with both methods. We also show the results of a real application using a 7-DOF Robotic Arm, in combination with an RGBD-camera. Figure 5 depicts the setup of the proposed system, while Figure 6 shows the same setup simulated using the ROS *MoveIt!* framework for mobile manipulation, with the dominant plane singled out, the segmented objects and the kinematic chain of the 7 Degree of Freedom (DoF) robotic arm used in the experiment (Cyton Gamma 300).

VII. Conclusion

In this paper we report the results of the ongoing collaboration between the Telecom Italia Joint Open Lab (JOL CRAB) and Politecnico di Torino on service robotic applications. The underlying paradigm is that of cloud robotics, which exploits the internet as a resource for parallel computing and data sharing. We show how the integration of an industrial-grade cloud robotics platform, high-bandwidth/low-latency mobile networks and the integration of state-of-the-art autonomous navigation algorithms coming from the academia makes the design of real-world robotics applications feasible. Future work will need be devoted also to data security. When working with both private and confidential user's data and the cloud, security issues have to be tackled using secure algorithms and industrial LTE networks.



(a)



(b)

Fig. 7. Results for two classification methods. (a) Width Concatenated descriptors (b) With training of a third NN

VIII. Acknowledgments

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