Use Case Evaluation of a Cloud Robotics Teleoperation System

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***Abstract*— The paper describes a generic Cloud Robotics teleoperation system which allows to control in real-time a robot (connected with a 4G network) having its video stream as feedback. The proposed system relies on the Azure Cloud Platform and on recent web technologies. Particularly, we present an use case experiment in which an operator in Slovakia controls a robot situated in Italy in order to evaluate its real-time feasibility. We test the system to assess its performances providing the throughput value of the communication and the average delay between consecutive received packets on both robot and teleoperation side. Additionally, regarding the video streaming, we test several packet sizes to establish a suitable image quality. The results show how the chosen technology allows to have real-time performances in terms of video and velocity commands streaming.**

I. INTRODUCTION

Europe is facing unprecedented demographic changes due to the aging population and low birth rates [1]. From literature analysis, it is evident that ICT and Robotics solutions could support elderly people in mobility inside and outside the house and in daily activities, encouraging the social relationships and improving the feeling of safety delaying the physical and mental decline [2]. Nowadays, the advances on robotics field are spreading the mobile robots out in our daily lives. Compared to last years, the recent technology progress has made robotic applications also economically feasible [3]. In particular, service robotics have received large considerations especially from academia and industry in order to deal with the issues raising with the demographic changes [4]. Consequently, these solutions have to potentially enhance the independence and the quality of life of the users, and, at the same time, improve the health care system, reducing the overall costs [5]. A system with these requirements needs to be always available, accessible 24 hours and 7 days a week. Therefore, the integration with the Cloud technology is certainly a natural consequence [6].

The Cloud robotics paradigm has been recently defined as "*Any robot or automation system that relies on either data or code from a network to support its operation, i.e., where not all sensing, computation, and memory is integrated into a single standalone system*" [6]. Cloud technologies provide two main advantages in the field of robotics. Firstly, it can allow remote communication and the sharing of the knowledge, secondly it can offload heavy computational tasks. Nevertheless, many cloud robotic challenges are still to be addressed to meet the robot requirements in terms of bandwidth, latency, and internet coverage. For instance, the uncompressed video streaming of 2 cameras (640x480, 30fps, 8/24bit) is high bandwidth demanding and requires about 147 Mbit/s [7].

This paper presents a generic Cloud Robotics Teleoperation system in the context of AAL, allowing a caregiver to remotely monitor a patience from anywhere and constantly. The system relies on a teleoperation center that is able to control a domestic robot using the Azure Cloud platform [8]. A case study is presented, in which an operator located in Slovakia, controls the service robot situated in Italy, which is connected to a 4G network. We have chosen to use this mobile technology instead of a domestic WLAN, because we believe that it represents (together with the forthcoming 5G) the standard way of communication for mobile robots, due to its internet coverage and available bandwidth benefits. The goal of this paper is to analyse whether a Cloud infrastructure is a valid solution to serve as bridge between the robot and the robot operator.

II. RELATED WORKS

Over the last years, several research groups have focused their efforts on cloud robotic challenges [9][10]. One of the first examples of cloud robotics paradigm is the RoboEarth project [11] which utilizes the so-called Rapyuta cloud engine. It is an open-source platform mainly used to offload computational tasks. Nevertheless, the overall performances do not differ much from other solutions [12]. DAvinCi [13] is another cloud computing framework developed in 2010, but its focus is more on the computation side rather than in communication between robot and server. In [14] authors present a cloud robotic teleoperation system which provides assistance for impaired people in a museum. The users can teleoperate the robot to explore inaccessible museum's areas by means of a web users interface. However, they provide few details about the cloud infrastructure and the communication performances between cloud resource and the robot. Emarcora et al. [15] present a service, supported by open data, for emergency management in a smart city environment within a cloud robotics architecture. The user requests an emergency service using a smartphone application. The cloud platform chooses a robot in order to provide monitoring and support, but they do not provide any information regarding the latency and the quality of service proposed. In [16] authors present a cloud robotic system for healthcare providing localization based services to the users. However, they implement the system using a remote PC that acts as a cloud resource.

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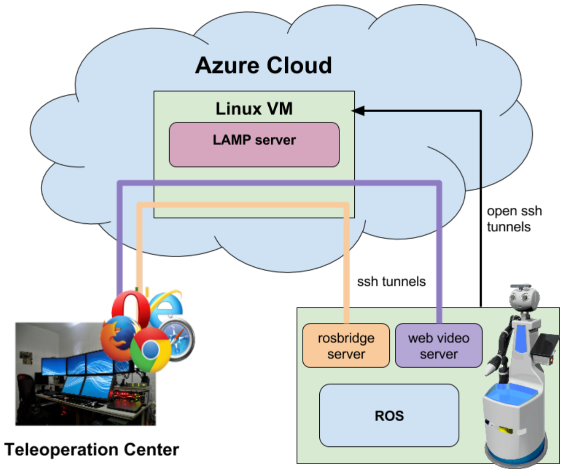

Fig. 1. Architecture of the system. The teleoperation center accesses the robot using the web browser through the Azure Cloud. The robot opens SSH tunnels on the virtual machine, avoiding the setup of a dedicated VPN.

Fig. 2. DoRo, the domestic robot used for the teleoperation use-case.

This paper describes a robotic teleoperation system based on the Azure Cloud platform with the aim to demonstrate the real-time feasibility of the selected technologies to deploy a general robotic framework. An use-case, in which a robot is teleoperated from Slovakia to Italy, is evaluated in terms of packets per seconds and bandwidth.

III. SYSTEM

The system implements a Cloud-based robotic teleoperation center that allows an operator to control a mobile platform having as feedback both the video camera streaming and the commands it is executing. Hence, one of the first prerequisites is the real-time performance. In addition, since it is based on the Cloud, another desirable feature is the interoperability between heterogeneous devices and robots. This means that different kinds of robots and also devices (e.g. computer, tablet, smartphone) have to be able to easily access the Cloud resources. Therefore, the use of standardized communication mechanism is crucial. Concerning robotics, the Robot Operating System (ROS) [17] is currently the *de facto* standard middleware. Introduced in 2009, both the use of ROS and its community is growing exponentially [18]. For this reason, the implemented system makes use of a ROS-based robot. Regarding the network communication, our choice is driven by the use of modern web-oriented technology in order to gain as much interoperability as possible. One of the most promising tools in this area is the Robot Web Tools (RWT) [19], which aims to converge ROS and web protocols, using the WebSocket and the JSON data structure, which is a lightweight and language-independent data interchange format. The WebSocket is a protocol built over HTTP that provides a full-duplex communication channels over a single TCP connection. It facilitates the real-time data transfer from and to the server. Nowadays, all the modern browsers support this protocol, therefore they are the ideal platform for the development of the user front-end.

The architecture of the system is depicted in Fig. 1 and it is composed of 3 main components: the Cloud Platform, the Graphical User Interface (GUI), and the robot.

The Cloud Resource is a Linux virtual machine running on the Microsoft Azure Cloud. It executes a LAMP server (Linux Apache MySQL PHP) which implements a web service model. In other words, this server contains a database to store information and web pages that make use of the aforementioned RWT JavaScript libraries. The current implementation uses the Azure virtual machine basic size, which means a low power machine with 1 core and 0.75 Gb RAM.

The user GUI, running on the LAMP server, is implemented as a web page showing both the video streaming from the robot camera and the velocity command it is executing. In this case, the user moves the robot by means of computer keyboard but, of course, other types of interfaces can be implemented. The adoption of web protocols allows to have a teleoperation center running on a wide range of devices. It uses a set of JavaScript libraries providing a convenient abstraction to the core ROS functionality.

The robot used during the use-case experiment is the DoRo domestic platform (see Fig. 2) developed during the FP7 European project Robot-Era [20]. It is based on the SCITOS G5 mobile platform (from Metralabs [21]). It mounts a front and rear laser scanner to safely navigate the environment and has cameras for video streaming. Although DoRo is able to autonomously move, it implements also a “safe teleoperation mode”. It means that when it receives velocity commands it checks the presence of obstacles by means of the laser scanners. If an obstacle is too close, it prevents the collision, allowing only the safe commands. On the software side, two packages provide the interface with the Cloud service. The first one is the *rosbridge server* which provides a JSON API to ROS functionality for non-ROS programs implementing the server side of the WebSocket protocol. The second is the *web_video server* encoding the raw video packets into a series of JPEG images, which are embedded in the HTML format for the HTTP network streaming.

In the aforementioned system, each of the three components operates on a different network. While the Cloud virtual machine has a public IP address, both the teleoperation center and the robot are not directly accessible. A common solution is to setup a virtual private network (VPN), which extends a private network across the public network. However, setting a VPN is not a straightforward operation and all the devices and robots that want to access the system must setup it. To overcome this issue, in our implementation, we opted for the "ssh tunneling", which allows to forwards a TCP connection only. In details, in order to make the *rosbridge server* and *web_video server* accessible, the robot executes a "reverse ssh tunneling" on the Azure virtual machine. In this way, the robot just connects to the Cloud, but without becoming part of its network.

IV. USE CASE

To evaluate the real-time feasibility of the proposed system we setup an use case experiment in which an operator located at the TUKE University in Košice (Slovakia) controls the DoRo robot, situated in the DomoCasa Lab in Peccioli (Italy), which is the Italian site for the EU Echord++ project [22]. The Azure virtual machine is located in North Europe. As already said, the system allows to have a video stream from the robot camera and to send velocity commands to move the robot. Hence, we setup two different tests for each case.

A. Methodology

Firstly, a suitable image quality for the streaming has to be established. In fact, it is possible to reduce the latency of the data packets, compressing the images to lower the bandwidth required by the system. For this purpose, the video quality rate is tuned ranging from 90% to 50%, i.e. reducing the packet size. Then, the throughput relative to the different packet sizes is evaluated in terms of packets per second (pps) and Kbit/sec. The average delay between consecutive received packets is also measured. (see Sect. IV-B.1)

Secondly, the communication of velocity commands was evaluated; these are sent using the WebSocket protocol and, in addition, sent back by robot when executed. In order to use WebSocket, the protocol needs to upgrade the HTTP connection at the beginning by means of the handshake procedure . Furthermore, multiple data packets (i.e. multiple commands) can be encoded in a single WebSocket packet. The communication is evaluated providing the average delay between consecutive received packets on both robot and teleoperation side, considering also the throughput (see Sect. IV-B.2).

During the tests, the average 4G network speed of the robot has been 8 Mbit/s in download and 3.4 Mbit/s in upload. At the teleoperation center, the network speed was much higher, around 30 Mbit/s download and 60 Mbit/s upload.

B. Experimental results

During the use case test, the operator was able to control the robot without experiencing any significative delays. In the remainder, we analyze the results considering both video streaming and velocity commands.

TABLE I

COMPARISON BETWEEN PACKET SIZE, PPS AND THROUGHPUT.

Size (Quality%)	avg. pps	avg. Kbit/sec
60.0 kB (90%)	7.2	9
30.5 kB (80%)	8.9	11
23.5 kB (70%)	11.5	14
19.3 kB (60%)	11.6	14
18.5 kB (50%)	11.7	14

1) Video Streaming: Several image parameters can be tuned for the video streaming. We decided to keep the original resolution size of the robot camera (640x480 pixels) since lower values can decrease the user experience. Then, we have conducted some tests about the encoding quality of the images comparing packets per seconds (pps) and the throughput rate. We have set the image quality at 90%, 80%, 70%, 60%, and 50% with respect to the original source. The results of these tests are reported in Tab. I. A reduction of the quality below 70% does not further improve the pps rate. The average packet size is around 23.5 KB with a rate of 11.5 pps and a throughput value of 14 Kbit/sec on average (the robot publishes the video at 15 Hz locally). Considering the differences between consecutive received packets, we obtain a mean value $\mu = 0.086$ and a standard deviation $\sigma = 0.042$ seconds. The biggest delay is 0.540 seconds.

2) Velocity Commands: The average packet size of the velocity messages sent to the robot is about 236 bytes. The average packets per seconds are 65.4 pps, with a throughput of 124 Kbit/sec. The frame rate on the teleoperation and on the robot side is the same (65.4 Hz), meaning that no data have been lost during the communication. In fact, the total number of the messages sent from the teleoperation center and received by the robot is the same ($\sim$120000). The mean of the delays between consecutive packets is $\mu = 0.015$ ($\sigma = 0.036$) seconds, with a maximum value of 0.463, which is the largest delay for one single packet in our tests.

If we consider the velocity commands received by the teleoperation center, we have that the packet size ranges from 210 bytes to a maximum of 1514, i.e. the protocol encodes up to 9 velocity data in one WebSocket message. The average packets per second are 44.3 pps with a throughput of 100 Kbit/sec. The mean of the difference between consecutive received packets is $\mu = 0.022$ ($\sigma = 0.010$) seconds and the largest delay is equal to 0.232 seconds.

V. DISCUSSION AND CONCLUSION

In this paper, we present a Cloud-based teleoperation system for ROS-enabled robots. The architecture relies on recent web technology (WebSocket) and on the Azure Cloud Platform. The robot, located in Italy and connected on a 4G network, has been controlled from the TUKE University in Slovakia. The operator, using a web browser, was able to move the robot in a domestic environment having the video streaming from the robot camera without experiencing any significative delay. We have monitored our system to evaluate the real-time capability offered by the technology we have chosen. The results show that the used 4G connection is sufficient enough to receive velocity commands and send video streaming data (with a 70% of the original image quality) to allow a real-time control of the robot over the Cloud.

The successful use of the 4G network underlines that the developed system can be used also for the outdoor mobile platforms. In addition, the use of web technology allows using this teleoperation solution on any modern device, such as tablet and smartphone, providing wider possibility for human-robot interaction. Furthermore, it can be easily extended to no ROS robots, providing a suitable interface with the web protocols. Even if the 4G network is not guaranteed for all the territory, the performed tests represent a realistic scenario since, for example, the main 4g Italian provider cover up to 73% of population [23]

Future works will address the use of this system to exchange bigger data, like point clouds or 3D-maps, to implement additional cloud robotics applications. Nevertheless, more data over the cloud requires higher bandwidth and lower latency. However, the forthcoming 5G infrastructure, defined as ubiquitous ultra-broadband network, will lead a revolution in ICT fields. "Anything as a Service" will be the key-words for 5G [24]. The 5G is expecting to transform the connection of the Digital Society into a "low-latency nervous system" meeting the requirements of the most demanding robotics applications [25]. Recent forecast provided by Massachusetts Institute of Technology (MIT) claims that "5G is expected to provide Internet connections at least 40 times faster and with at least four times more coverage worldwide than the current standard, known as 4G LTE "[26].

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