Flexible Architecture for Transparency of a Bilateral Tele-Operation System implemented in Mobile Anthropomorphic Robots for the Oil and Gas Industry

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Abstract: The main problem of the exploration and production sector in the oil and gas industry worldwide, and especially in Ecuador, lies in the extreme environmental conditions inherent to each oilfield, which makes it difficult to perform daily tasks of maintenance or equipment verification. Due to these harsh environments, this industry has seen the need to implement bilateral tele-operation systems with a high degree of scalability that allows the interaction between equipment and trained personnel that could safely perform maintenance activities. In order to achieve this objective, it is necessary to select a standardized messaging protocol that meets the current needs of the Industrial Internet of Things (IIoT) and allows the efficient use of communication channels bandwidth. This paper presents the design of a bilateral tele-operation system that allows the operator to carry out maintenance or remote inspection activities in the Well-Pads located in Petroamazonas EP, Ecuador. For the development of this system, the MQTT protocol is selected over other IIoT protocols because of its high speed of response in real time as well as its low consumption of resources. In the local site a virtual reality environment developed in a 3D graphic engine is implemented. Through input devices an infinite transparency is obtained, besides transmitting the experience and skills of the operator to the slave through the senses of sight, hearing, and kinesthesis.

Keywords: Tele-operation, Oil & Gas industry, MQTT protocol, Virtual reality

1. INTRODUCTION

The world gas demand remains high and will remain so in the near future. However, this industry presents several problems such as access to reserves that are in extremely demanding environments. In this sense, since the exposure of human lives to this type of dynamic or unstructured environments is ineluctable (Nasirian and Khanesar, 2017), the gas and oil industry has chosen to use a contingency plan, which significantly reduces the inherent risk of its processes to its personnel (Burgner et al., 2011).

These challenges have led to the need to enhance the level of automation by introducing a combination of remote operations and tele-robotics, which has become the best option when it comes to the inspection, maintenance, and control of gas and oil extraction modules (Andaluz et al., 2016). Nowadays, many oil and gas companies are already managed remotely during normal operation, but there is still a need for highly qualified personnel to carry out specialized work, such as maintenance and repair during operation and scheduled shutdowns (Shukla and Karki, 2016a).

In the last decades, due to the increase of unconventional gas reserves, such as harsh deserts, deep-water, frozen arctic zones, and deep below ground level (Shukla and Karki, 2016b; McLean et al., 1994) that endanger human life, it has been necessary the intervention of professionals that, by means of the use of several levels of automation, have managed to reduce the inherent risks to this type of industries (Carlson and Murphy, 2005).

In the traditional industrial structure, each member of the value chain had inaccessible and unknown information for the rest of members. However, nowadays, knowledge and information systems can be integrated through collaborative networks thanks to the IIoT and Industry 4.0.

MQTT (Message Queue Telemetry Transport) was designed for simple devices with few resources, offering three qualities of service: i) fire-and-forget, ii) at least once and iii) exactly once. In addition, it is ideal for IIoT applications due to its low footprint. This type of protocols is considered as the core of future distributed automation systems offering a wide range of possibilities in the use of low cost hardware (García et al., 2015).

As described in previous paragraphs, this article proposes a teleoperated anthropomorphic manipulator system for dangerous activities in the gas and oil industry. The proposed bilateral system allows controlling the KUKA youBOT robot remotely through the integration of the Leap Motion device in the Unity 3D graphics engine, whose interface allows the operator by means of pre-established movements of his hand, to control both, locomotion and work movement of the slave robot. The communication has been implemented through the MQTT protocol, which, due to its low bandwidth requirements, consumes very little energy and allows a longer response time than the rest of the current web protocols.

This article is divided into 7 sections including the introduction. The state of the art is discussed in section 2. The approach of the developed study is explained in section 3, while the bilateral scheme of tele-operation is presented in section 4. In section 5, the development and programming of the virtual environment is described. The design of the local site of the human operator is discussed in section 6; and finally, the conclusions and future work are presented in section 7.

2. STATE OF THE ART

2.1 Tele-operation system

A tele-operation system allows the human operator to take his skills to a robot in order to perform tasks in dynamic environments. This type of remote operation is called bilateral when the forces and movements of both the master and slave mirror each other (Nasirian and Khanesar, 2017). The key parts of this system are: i) Local Site: where the worker operates a manipulator called master, the control action by the operator can be continuous or intermittent, which is based only on the supervision of the system; ii) Remote site where a "slave" works in the physical world according to the orders sent by the "master". iii) Interface: is the set of devices that allows a functional connection, and iv) Communication channel: is the means by which both the local site and the remote site are connected.

A useful software to develop virtual reality environments for tele-operation is Unity, which success is due to the fact that it allows any independent developer to access a 2D and 3D world of infinite possibilities when it comes to virtual reality. (Unity, 2017), it is the graphic engine in which a suitable environment is developed for the inspection of a pressure transmitter inside an oil refinery. One of the advantages offered by Unity is to make resources available to developers such as 3D models, projects and audios included in Unity Asset Server.

Additionally, the sensory device Leap Motion is part of the interface, allowing to send data and desired information to the slave robot. Leap Motion is an input peripheral, which can be defined as a sensor. When it is connected to a PC can virtually acquire the movement of the hands of a person, with the purpose of either interacting in a virtual environment with some type of interface or controlling a device or remote machine (Leap Motion, 2017).

2.2 Industrial mobile manipulator

Mobile robots as manipulators are key pieces of robotics. However, a mobile manipulator can be defined as a machine, which has several degrees of freedom and can be controlled automatically. These manipulators have a fixed or mobile place to perform their industrial tasks; which can be: repetitive, precision tasks or in turn perform activities that have a high risk of dangerousness for workers (Kelly, 2003).

For the development of the present investigation, the KUKA youBOT robot is proposed as the slave since it is intended for the development and understanding within the field of mobile manipulation. Furthermore, it has the necessary technology to be applied on the services field or on industrial robotics. It consists of three parts: i) omnidirectional platform; ii) robotic arm with five degrees of freedom, and iii) two-finger clamp (Kuka youBot Store, 2014).

2.3 MQTT protocol

It is a communication protocol which objective is to offer a light communication platform based on a publication/subscription model. The client publishes messages in an MQTT broker, which are subscribed by other clients. These messages are published in an address called topic (Fig. 1).

The visualization of the messages in this protocol are of JSON type, allowing a comfortable and clean reading. Its design principles make it ideal for emerging paradigms such as the Internet of Things (IoT), and therefore Smart Factories (Naik, 2017). MQTT is a very useful protocol for wireless systems which experience fluctuating levels of latency due to unstable connections. If the subscription connection is lost, the broker saves the message packet and forwards it to the subscriber when the connection is re-established. On the other hand, if the publication link becomes unstable, the broker can terminate the connection (Asaad et al., 2017). For the communication between the master (Leap Motion) and the slave (KUKA youBot robot) the MQTT protocol is proposed because within the 4.0 industry and the IoT, security is one of the most important aspects, besides the possibility of controlling objects remotely makes processes more efficient.

In the case of monitoring a gas or oil plant, confidential and extremely important data are exposed daily, making necessary the implementation of a secure communication

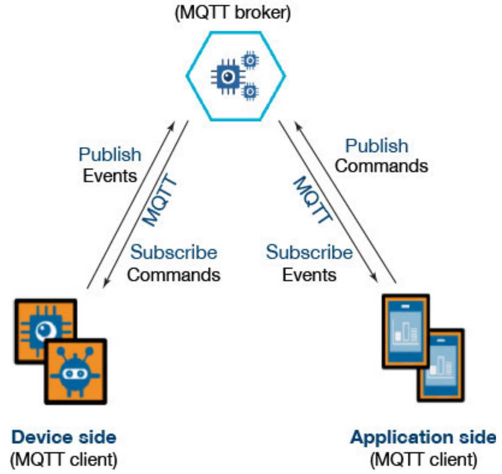

Fig. 1. MQTT Architecture

channel with excellent usability between devices (Bandyopadhyay and Bhattacharyya, 2013). This protocol provides three layers of security, which are: i) Network layer: the use of a physically secure network or a private virtual network (VPN) is essential for the assurance of communication between the broker and clients, ii) Transport Layer: to provide a secure communication channel without the possibility that information could be damaged or extracted, Transport Layer Security/Secure Sockets Layer (TLS / SSL) is used, and iii) Application layer: once the communication is encrypted at the transport layer, the MQTT protocol provides a client identifier and user/password credentials, which are used to authenticate devices in this layer.

3. CASE STUDY

Within the oil production field, companies are usually geographically distributed in several regions of a country. Therefore, remote access to the process is of great importance in order to monitor the entire process or make decisions that may affect different production locations. In fact, oil production companies are usually composed of multiple blocks of oil production, called Well-Pad, which refer to a surface that contains oil wells, horizontally drilled to reduce environmental impact. The additional benefit of a drilling rig is that operators can drill multiple wells in a shorter time than with just one well per location.

The case study focuses on Petroamazonas EP, an Ecuadorian public company dedicated to the exploration and production of hydrocarbons. It is located in the eastern side of Ecuador. The thick vegetation, the protected areas, as well as the diversity of animals in danger of extinction, make this area an almost inaccessible place to carry out the scheduled maintenance of equipment.

Due to the infeasibility to implement the system in all the blocks, the design has been simplified to the set of well-pads of a specific Block. In our case Block 18 has been selected. In this Block there are currently 4 well-pads and each of them clusters approximately 28 to 30 oil wells. Each oil well has a bottom sensor that collects pressure, temperature, and vibration measurements. Specifically, the crude oil is extracted from the bottom of the wells by electro-submersible pumping or hydraulic pumping and once on the surface this crude is collected in a central pipe called production manifold. It is here, in the manifold, where the crude is collected from all the wells that constitute a well-pad. Each well-pad has storage tanks and three-phase oil separators used for production tests. The crude extraction process ends when the crude oil is sent by means of pumping to the Central Production Facility (CPF), located several kilometers away from the Well-pads. The CPF is made up of several equipment, one of the most important is the Crude Separator, which is a pressure vessel used to three-phase separate the crude. In this equipment, oil, formation water, and gas are obtained separately.

The purpose of the case study is to use a KUKA youBOT mobile anthropomorphic manipulator in each wellpad to perform inspection, verification and testing of pipelines, transmitters and equipment located in remote wellpads. For this case, a human operator located in the CPF represents the control center. This worker uses the Leap Motion device to detect movement commands, both position and speed of the robotic arm and omnidirectional platform. The underlying philosophy behind this robotic system remotely managed, is that robots are integrated into the oilfield and are considered as resources in the control system. These robots participate as physical tools and as "eyes, ears, and hands" of the operator in a dangerous process environment. Within the control system, the operator, who is too remote from the well, interacts with the robot through a human-robot interface (HRI), thanks to which the different tasks that the robotic system can perfectly complete are defined and initiated. The control system, by means of both speed and position sensors, presents a feedback of the states of the KUKA youBOT robot to the operator. Also, it returns the actual audio of the plant that is being inspected (Fig. 2).

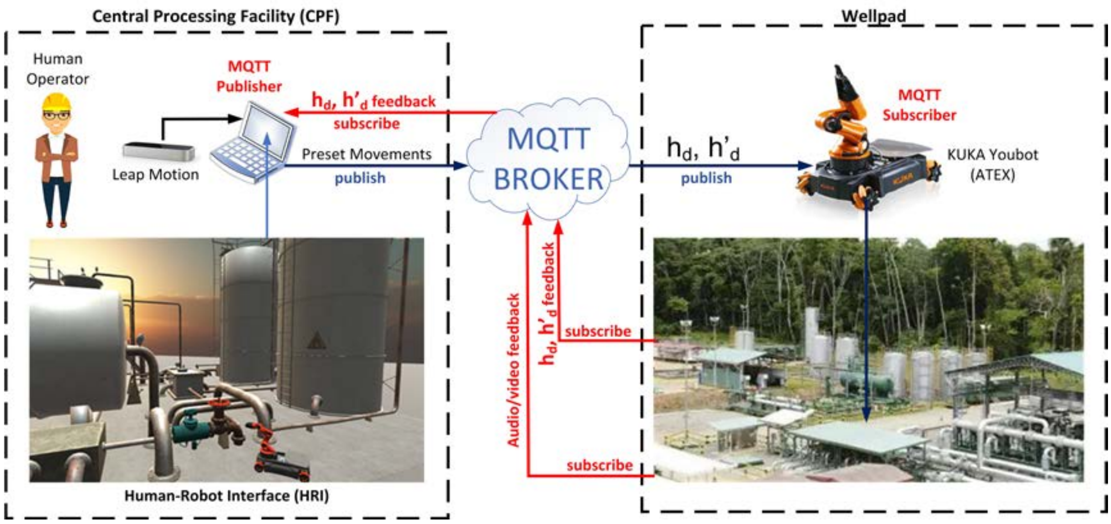

Fig. 2. Bilateral tele-operation system architecture.

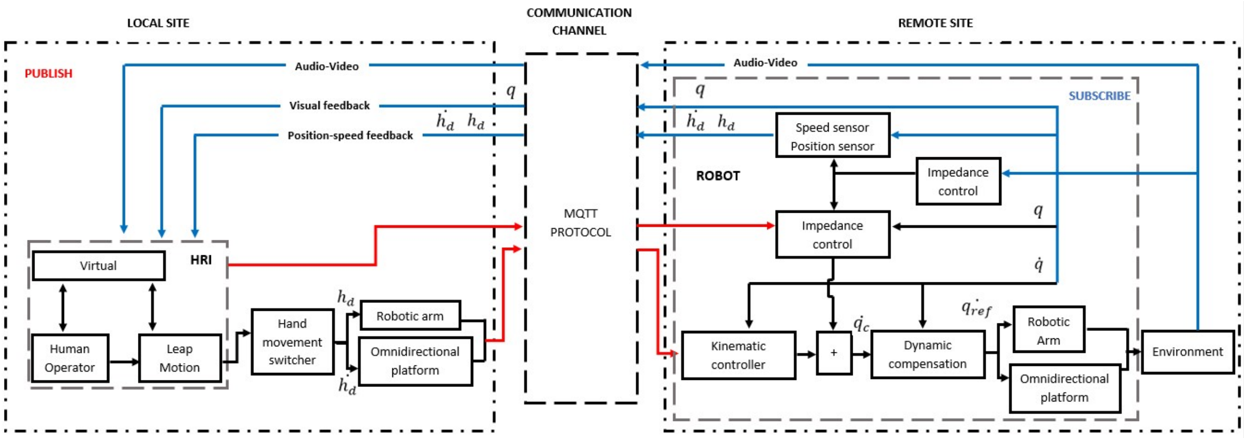

Fig. 3. Tele-operation system block diagram.

4. CONTROL SCHEME

The purpose of this section is to present the kinematics of the mobile manipulator robot. The instantaneous kinematic model of a robotic arm is expressed as the speed of its clamp as a function of the derivative of both the robotic arm, as well as the location of the platform, see (1).

$$\dot{h}_{(t)} = J_{(q)} v_{(t)} \tag{1}$$

J(q) represents the Jacobian matrix, which defines the linear mapping between v(t) and the clamp velocity. V(t) refers to the mobile manipulator velocity. The Jacobian of the robot represents a tool that serves to characterize the manipulator robot, find singular configurations, analyze redundancies, determine the inverse differential kinematics, as well as describe the relationship between the applied force and the pairs or torques resulting from the end-effector. The Jacobian matrix is, in general, a function of the configuration q. In addition, the configurations in which J(q) is of deficient rank are called singular kinematic configurations.

The position and orientation of the omnidirectional platform as well as the orientation of the robotic arm are represented by the robot kinematics. The Leap Motion device sends to the slave the desired speed for the manipulation mode as shown in (2), or the desired position for the locomotion mode as is depicted in (3). Once the desired information has been sent to the KUKA youBot robot, it will proceed to perform the entrusted task, respecting the speed, orientation, and position previously assigned by the master.

$$\dot{h}_d = \begin{bmatrix} \dot{h}_l & \dot{h}_m & \dot{h}_n \end{bmatrix}^T \tag{2}$$

$$h_d = \begin{bmatrix} h_l & h_m & h_n \end{bmatrix}^T \tag{3}$$

On the other hand, the proposed tele-operation system is presented in (Fig. 3). At the remote site, once the operator has sent the locomotion and manipulation orders, an impedance control is carried out through a dynamic compensation, i.e., by means of the developed virtual environment it is intended to reduce to the maximum the error existing between the slave force and the precision of its work movement.

5. VIRTUAL ENVIRONMENT

Virtual reality applied to the simulation of robotic systems in the industry, has gained great interest in recent years, introducing new expectations for the use of these virtualized

Fig. (a). Programmed oil Well-Pad

Fig. (b). Programmed KUKA youBOT.

Fig. 4. Virtual Environment

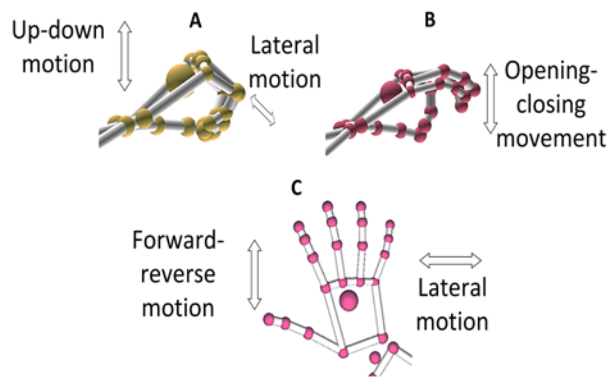

Fig. 5. Slave control movements. A) Up-down and lateral motion for the robotic arm. B) Opening-closing movement for the two-finger grip. C) Forward-reverse motion for the omnidirectional platform.

environments. The coupling of simulators to current technology, the low cost of training operational personnel and the wide field of research that they possess are just some examples of the motivations to implement this technology in the current industry.

For the development of the virtual environment, the Unity 3D graphic engine is used, here we define the workspace where environments modeled by collision regions are manipulated in a real environment. (Fig. 4a) and (Fig. 4b) present the oil well-pad and the slave robot designed in Unity 3D respectively.

Additionally, the KUKA youBot robot has been programmed so that, depending on the inspection requirement within the proposed well-pad, it would move following a pattern of previously specified hand movements, i.e., according to the hand movement of the operator captured by the Leap Motion device, the slave will have a forward, backward and lateral movement of the omnidirectional platform, an up-down and lateral motion for the robotic arm, and an opening-closing movement of the two-finger clamp (Fig. 5).

In addition, for a better transparency of the system, an audio output has been implemented, this will allow the operator to be aware of the sounds that the real environment produces, as well as to listen to the noise produced by the slave robot engine. With this precedent it can be known if the KUKA youBOT robot is moving according to the speed previously established or if there is any type of mechanical failure.

6. TRANSPARENCY OF THE LOCAL SITE

A tele-operation system seeks to keep the operator as close as possible to the task that is being done remotely. However, one of its main objectives is to preserve the integrity of operators and not expose them to dangerous environments. Ideally, this type of system must be completely transparent so that the operator has a direct interaction with the task that the slave is performing (Slawiski and Mut, 2008). The KUKA youBot robot needs a high degree of precision in its use, that is why a visual feedback is necessary for viewing the working positions of the slave, i.e., the transparency is

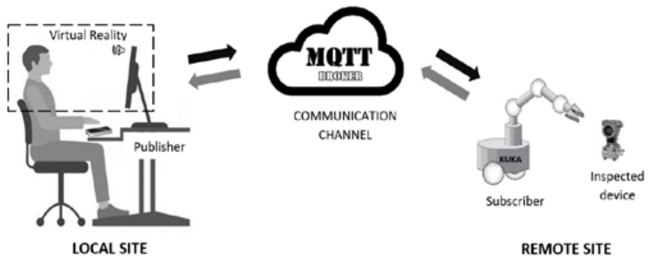

Fig. 6. System transparency diagram.

measured based on the level of control that the remote system offers to the operator.

For this reason, the virtual environment developed in Unity 3D shows the operator the remote site in which the task entrusted to the slave is being carried out, as well as allowing him to listen to the real audio of the proposed environment (Fig. 6).

In this paper three ways in which the human operator can transmit his skills to the slave robot are presented: i) Sense of sight, through which the operator can monitor the movements of the slave robot, observing in a virtual environment the exact recreation of the real working environment, ii) Kinesthesia, is the ability to feel the positions and movements of the muscles and joints of the human body. This ability allows to coordinate the necessary movements to control the slave robot, as well as to manipulate the elements to be inspected within the proposed environment. This sense is developed and applied through the use of the Leap Motion device, and iii) Sense of hearing, allows the operator to be alert of what happens in the real environment, it also allows him to perceive any change of sound frequency which lay outside the normal modus operandi of the system, admitting to take preventive and corrective actions in situ.

One of the great challenges in this type of systems is to achieve a fast response in real time that allows perfect monitoring and transparency. Due to this, the MQTT protocol has been chosen for transmitting the data related to the kinematics of the robot, i.e., the position and orientation of the omnidirectional platform, as well as the orientation of the robotic arm. MQTT is an open, simple, lightweight and easy to implement protocol, which responds to the needs of Industry 4.0, such as being fast, using network bandwidth efficiently and consequently having a better response time than the rest of the current web protocols. In addition, this protocol uses TCP/IP to connect to the broker, thereby integrating a connection-oriented protocol that provides error correction and guarantees that the message is received by the subscriber in the order in which it was sent.

Fig. 7 represents the publish-subscriber communication through the MQTT protocol, in this research the KUKA youBOT robot is considered as the slave and the gesture control device Leap Motion as the master.

The data corresponding to the kinematics of the mobile manipulator are transmitted from the sensory device Leap Motion to the slave through the MQTT protocol. This is done in JSON format once the structure is standardized. Since this protocol allows full duplex communication between the

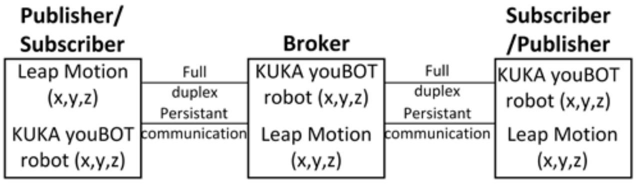

Fig. 7. Local site block diagram

publisher and subscriber, the states of the KUKA youBOT robot can be obtained. This aims to a more efficient control of the system. Furthermore, the MQTT protocol has an exceptional real-time response, and remains open until there is an explicit order from the human operator.

7. CONCLUSIONS AND FUTURE WORK

This research has presented the development of a bilateral tele-operation system for the non-structured environments of Petroamazonas EP, an Ecuadorian public company dedicated to the exploration and production of hydrocarbons.

It has been proven how the use of this type of systems at an industrial level can be considered an alternative to perform tasks of inspection and verification of equipment located at great distances, where the traditional inspection of unstructured environments, carried out by human personnel, becomes risky and inaccessible. In this work, the MQTT protocol has been implemented as a means of communication between the Leap Motion device and the KUKA youBOT robot.

Furthermore, it has been demonstrated that the speed of response in real time of this protocol makes it ideal for the communication of remote systems in dynamic environments, adapting to the paradigm of the Industrial Internet of Things (IIoT) and Industry 4.0.

In Fig. 9 shows the throughput of the MQTT protocol, establishing its efficiency, speed, and capacity to support thousands of concurrent connections of several devices. On the contrary Fig. 10, shows the throughput of the HTTPS protocol, denoting poor performance and communication. This has been used as a point of comparison within the developed system. It can be seen that the decision to choose MQTT as a means of communication for this type of systems has been accurate, since its data transfer rate is higher than any other IIoT protocol.

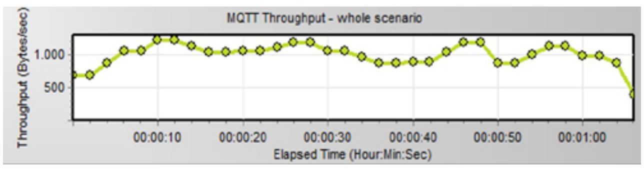

Fig. 8. MQTT throughput.

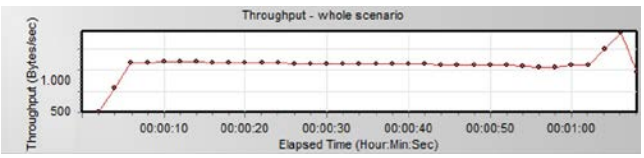

Fig. 9. MQTT throughput.

For future research, it is proposed to implement augmented reality in the tele-operation system interface in order to improve transparency in the local site. In addition, multiple sensing modalities will be implemented so that the operator can handle more reliable information and have a greater control of the slave to be manipulated.

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