On-line Training and Monitoring of Robot Tasks through Virtual Reality

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***Abstract*—Currently, the implementation of virtual, augmented and mixed realities-based solutions is one of the megatrends in the Industrial Automation domain. In this context, Virtual Reality (VR) permits the development of virtual environments that can be used for different purposes, such as designing, monitoring and/or training industrial machinery. Moreover, the access to such environments can be remote, facilitating the interaction of humans with cyber models of real-world systems without the need of being at the system facilities. This article presents a virtual environment that has been developed within VR technologies not only for training and monitoring robot tasks but also to be done at robot operation runtime within an on-line mode. In this manner, the user of the presented environment is able to train and monitor de tasks at the same time that the robot is operating. The research work is validated within the on-line training and monitoring tasks of an ABB IRB 14000 industrial robot.**

***Keywords*—Virtual reality; online training; WebGL; industrial robotics; cobot**

I. Introduction

The fourth industrial revolution (i.e., Industry 4.0) drives the industrial equipment manufacturers to include the advances from the Information and Computer Technology (ICT) field. These technologies and concepts have been enriching the final products that can be used at the factory shop floor [1], [2]. As an example, the Internet of Things (IoT) and the concept of highly-connected resources enforced the usage of the new communication protocols and standards [3], [4]. For instance, the feature of having an Open Platform Communications Unified Architecture (OPC UA) module to fulfill the high connectivity concept has been recently marketed as feature for several industrial controllers, robots, drives among other [5]. Similarly, the evolvement of visual technology in the Computer Science presents a valid example of adapting the new technologies in different fields. Moreover, the advances in the technologies for developing web interfaces motivated industrial equipment manufacturers to allow their devices to be configured and monitored through web browsers [6], [7]. Likewise, and with the advances on both hardware and software, the Virtual Reality (VR) and Augmented Reality (AR) are introduced to the industrial applications. This allows adaptable interfaces for the operators at the factory shop floor level. As an example, the ABB RobotStudio allows the usage of the VR set for teaching a virtual model, which facilitates the simulation and demonstration of robots' functionality [8].

The online programing tends to provide a simple and human-friendly approach for teaching the desired paths of robots. As a part of the human robot cooperation, the online robot programming can be achieved by 1) lead-through programming or 2) teaching by doing concept [9]. These approaches represent a cooperation of human and robot where the robot is programmed during the run mode and with limited needs for programming an application. In this manner, the robot is required to permit the flow of the information in order to be taught. This can be achieved by using the communication interfaces that the robot supports such as TCP/IP, MQTT and OPC UA protocols. With relation to the abovementioned technologies and applications, the objective of this research aims at applying the concept of teaching by doing approach in order to train and monitor an ABB collaborative robot (cobot) known as YuMi by using VR technology. As a hypothesis, it is expected to reach simpler and faster robot configuration since the operator can use a VR headset from the office to move around the factory and, in turn, to monitor the robot. It should be noted that this article presents first steps towards a ready-to-go prototype. Thus, some of the presented components might change in the future. Yet, the authors consider that the current status of the research work presents significant contributions to the state-of-the-art in the context of employing VR for online training and monitoring robot tasks.

Although robots have been implemented for a long time there is still a feeling of distrust when the operator has to work next to them until he/she catches confidence and, as a result of this state, the operator tends to make more mistakes. The introduction of new training methods for working with robots makes a difference, especially when working with cobots, in order to get the user comfortable while doing the training and then the task. The approach presented in this paper seeks to introduce a method that allows training industrial tasks that involve any type of robot and virtual reality device, regardless of the company to which it belongs.

The rest of the paper is structured as follows: Section II presents a literature review on the topics of Mixed Reality, which includes Augmented Reality and Virtual Reality, and online robots' programming. Section III presents the developed approach of this research work. Section IV addresses the use case that is planned to proof the concept of this research. Finally, Section V concludes the paper and provides the possible future work that can be conducted.

II. Related Work

A. *Mixed Reality for Industry*

A Mixed Reality (MR) environment is defined as the one in which real world and virtual world objects are presented together within a single display [10]. In addition, the concept of "virtuality continuum" defines all variations of MR as a combination of real and virtual environments in different proportions. This research considers four different variations of Mixed Reality:

1. Real Environment (RE) i.e., the natural world. The most realistic virtual worlds are based on recreations of elements from this environment.

2. Augmented Reality (AR). On this environment, the non-real images are superposed on the user's view of the RE. These non-real images are computer generated objects that only the user can see.

3. Augmented Virtuality (AV). This can be defined as the inverse of the AR. In other words, the image of real objects is inserted into a virtual environment.

4. Virtual Reality (VR). This is a 3D computer generated environment that can seem real or fantastic. A VR simulation can be interacted by the human using sensory devices.

Some applications of the MR are industrial design [11], personal fabrication [12], stroke rehabilitation [13], learning [14] and teleconferencing [15]. Further, the concept of Collaborative Mixed Reality allows users to see each other and the real world at the same time as the virtual images [16].

B. Augmented Reality for Industry

An Augmented Reality system enhances the real world by adding virtual images to the user's view of the real world. As defined in [17], an AR system has 3 main properties: combines real and virtual objects in a real environment; runs interactively, and in real time; and registers real and virtual objects with each other.

According to [18], based on the way the virtual images are imposed on top of the real world, different types of AR can be classified as:

1. Marker-based Augmented Reality: uses a camera and a visual marker (e.g. QR code) to be sensed by the user.
2. Marker less Augmented Reality: uses a GPS to adapt the results to the user's location.
3. Projection-based Augmented Reality: an artificial light is projected onto real surfaces. A sensor detects the movements of the user who interacts with the light.
4. Superimposition-based Augmented Reality: substitutes some objects of the real world by an enhanced version.

The displays that allow seeing both real and virtual environments at the same time can be divided into three categories. Firstly, the head-worn which presents augmented information in front of the user's eyes. Then, the handheld, which provides the augmented information on a video displayed by a screen with an attached camera. Finally, the projective which presents the virtual information is projected directly on the physical objects to be augmented [17]. Some of the AR applications are education and training [19], surgery [20], robots [21] and directing a car driver [22].

C. Virtual Reality for Industry

Virtual Reality (VR) is a simulation of a non-real environment that can be interacted by the user within a realistic way using sensory devices. For a better comprehension of VR, five relevant concepts are introduced:

1. Virtual world (VW): The VW is a three-dimensional non-real environment that allows interaction between the users and with the environment.
2. Immersion: This can be defined as the perception of being present in a non-real world. Depending on the grade of immersion provided by the experience there are different types of VR systems:
   a. Non-immersive simulations: the user enters in a 3D environment through a window.
   b. Semi-immersive simulations: the user enters in the 3D environment through a large screen that stimulates both frontal and peripheral vision.
   c. Fully-immersive simulations: the user needs a head-mounted display and motion detection devices (e.g. joysticks, controllers, data gloves, body suits).
3. Total Immersion (TI): The TI is the extreme grade of immersion of fully-immersive simulation. In this situation the user loses awareness of being in an artificial environment. It happens when the experience feels so real that the user forgets to be in a virtual environment and acts as being in the real world. This state can be reached when the environment and the interaction with the user are completely based on the real world.
4. Sensory feedback (SF): VR experiences stimulate vision, hearing and touch senses. Stimulating these senses requires sensory feedback, which is achieved through input devices like Head Mounted Displays (HMD), gloves or hand controls.
5. Interactivity: Finally, the interactivity is critical for engaging the user with the virtual environment. If the virtual environment does not respond to the user's action in a natural manner and quick enough the human brain will lose the sense of immersion.

Some of the applications are collaborative e-learning [23], surgery [24], mining industry [25] and robots [26]. [27].

D. Mixed Reality Technologies for Industry

The VR uses four main technologies, according to [27]:

1. 3D computer graphics: the grade of immersion experienced by the user is conditioned by the grade of realistic graphics and the real-time interaction in the environment. For having a real-time interaction, it is needed to have an appropriate update rate. It is desirable to increase the rate of image updates to greater than 30 times per second. This rate conditions the quality and geometry complexity of the virtual world.

2. Wide-angle stereoscopic displays: The fact of having two eyes provides the user of stereoscopic, or binocular, vision. Both eyes see the same environment, but from different view positions. The images got by both eyes are combined in the brain into a single view with larger amplitude. This is the way that images are introduced in the head-mounted display: two images of the same environment, but with different points of view, are introduced in the lens of the headset, relating each image to the corresponding eye. The brain combines them so that the user gets the maximum possible information from the environment. According to Kalawsky, the minimum features of a VR display system are greater than 110º for horizontal field of view, greater than 60º vertical field of view, and greater than 30º of stereo overlap [27].

3. Head tracking: All the objects designed in the virtual world and the user have a position and orientation respect to a global coordinate system. The virtual environment covers more than the user's field of view. Only by moving the orientation of the head, or even moving just the eyes independent of the head orientation, can the user access to the entire environment.

4. Hand and gesture tracking: the VR environment is the 3D space, so 6 degrees of freedom are needed in order to define the position and orientation of an element. This necessity is covered by the controllers.

The first three technologies are mandatory for simulating a VR experience, while the last one depends on the characteristics of the experience and the grade of interaction between the user and the virtual environment. The interactions between the components of a VR system are shown in Fig. 1.

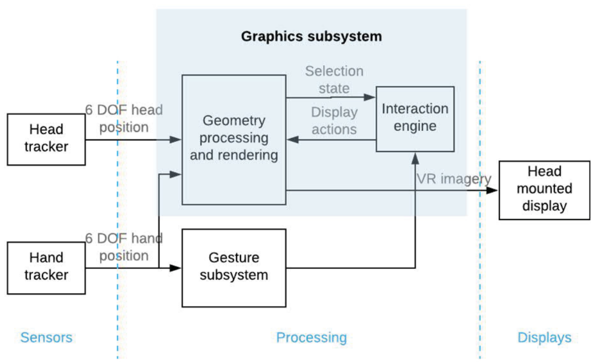

Fig. 1. VR System diagram [28].

E. *Online-Robot programming*

The configuration and calibration of the factory shop floor have been always a challenge in multi variant products production systems [29]. These variations require the production systems to adapt dynamically to such challenge [30], [31]. As a typical resource at various production systems, robots are considered as time demanding in terms of configuration and calibration [32]. In this manner, all robot manufacturers provide a control panel where the operator can configure and adjust the robot motion. In addition, and as a basic feature, robots can be programmed and configured using especially modified programming languages such as RAPID by ABB, KRL by KUKA and KAREL by FANUC. With these wide variations of robot programming languages, it is challenging for operators at the shop floor to master all programming languages for robots. In addition to that, each manufacturer uses different interface with different communication protocols, which in return increase the challenge for unified programming language for robotics. In attempt of solving this challenge, the University of Stanford has been developing the approach of open source operating systems for Robots known as Robot Operating System (ROS). It represents middleware for programming robots where developers from all around the world can contribute based on their experience in order to provide applications for the end user [33]. Nonetheless, ROS is still employing basic concepts of programming where a specially trained and skilled operators need to be expert in programming in order to develop the required applications [34].

The online robotic programming allows the robot to be programmed while it is on production mode. This requires the robot to be connected with a computer or a device that allows the robot to be trained according to task needs via a virtual model on run time [9]. The interaction can be achieved via human friendly interaction such as VR/AR [35], audio recognition [36], hand gestures [37] and graphical interfaces. With these approaches, the robot is expected to characterize the motion and then keep the parameters for future use. The advantage of online programming is that it reduces the dependency of having skilled robot operators at the shop floor [38]. The online programming can be achieved by several approaches. For instance, the lead-through robot programming is an approach for teaching the robot by physically grapping the end-effector of the robot and move it to the desired destination via a specific path [39]. This approach requires the robot to sense the force that is exerted by the operator hand by using force/torque sensor. According to this, the robot will follow the movement of the end effector by moving the final joint of the robot. As this approach simplifies the robot teaching process, it can be risky to move the robot physically while it is on the run mode. In other words, this requires overriding the safety chain of the robot [39].

III. The Approach

This section provides an approach for designing a training method for collaborative tasks with robots which is based on the approach presented in [44]. The method chosen is an interactive environment in virtual reality that reproduces the task involving users and robots. The application is opened on a browser so that it is possible to use the simulation in any computer which has VR equipment installed.

The basic VR System [44] is composed by 5 main elements: the Task, the User, I/O Devices, VR Engine and Software & Databases. These components and the communication channels between them are represented in Fig. 2, adapted from [44].

Fig. 3 depicts a schema of the communication flow between the first three components (Task-User-I/O Devices). While the user is engaged in the task, he/she provides inputs and receives information to and from the Output Devices, such as the HMD.

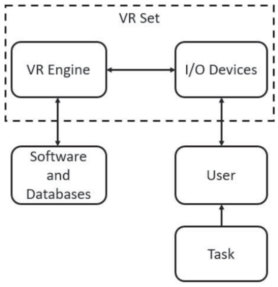

Fig. 2. Basic VR System.

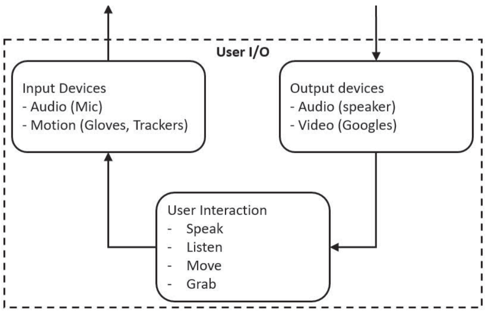

Fig. 3. User I/O communications.

This I/O flow is directly connected to the VR Engine which can be either a multiprocessor or a graphics accelerator. This component processes the input information and sends it to the Software & Databases block. After this process the VR Engine provides some information in the outputs as a response to the inputs received.

The task of interacting with the VR systems is performed in a fully-immersive simulation so it is needed a HMD and controllers for both hands. The user is connected to the PC by the aforementioned interaction devices while developing the task. Then, throughout the Internet, the PC is connected to a web with the corresponding server. In this web, it is possible to open a VR project and interact with it. The server generates a communication flow based on request-response between the user accessing the browser and the virtual environment. Finally, as the VR equipment is connected to the PC, the user can enter in the virtual world by wearing the VR-Headset and interact with it.

IV. THA USE CASE

This section presents an industrial implementation of the approach presented in section III intended for operators working with YuMi. This use case is structured in 4 subsections that describe the main steps of the process to create the VR simulation. The workflow of this process is presented in Fig. 4 :

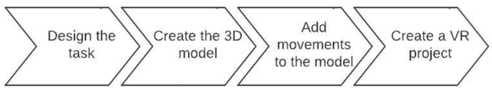

Fig. 4. Workflow of the process followed in the Use Case.

A. *Design of the task*

The use case consists on a VR simulation of an assembly task with YuMi, which is the ABB commercial cobot. As a cobot, it will be used in a process that requires a robot to work together with a human in a secure way. The task performed is the assembly of a box made of wood. Further, the scenario includes a table which contains all the parts for assembling the box, i.e., box sides, bolts and screws. Fig. 5 and Fig. 6 illustrate the elements involved in the task, corresponding to YuMi robot and the assembled box respectively.

Fig. 5. The YuMi robot from ABB used in the research work.

Fig. 6. The final product, i.e., assembled box, of the use case task

In the proposed scenario, YuMi's work is to pick up the different parts of the box and assembling them in a proper position for the user's activity. The human operator must link the parts that the robot is holding with bolts and screws. This is an iterative process that ends when the box is completed. As the goal of the training is getting the user used to working with the cobot, the simulation must be as similar as possible to the reality.

B. *Create the 3D model*

A 3D model of every component involved in the simulation is needed to be created. More specifically, there is a need to model the 6 sides of the box, the bolts and screws, and the YuMi robot. The elements of the box are built with a CAD application like SolidWorks, SolidEdge or FreeCAD. The latter is the one used in this experiment.

The CAD model of the YuMi is provided by its manufacturer, i.e., ABB. The model is provided as a group of STEP files that correspond to all the parts that compound the robot. Through the program FreeCAD, it is possible to import the STEP files of the robot and link one to each other in order to assembly the YuMi model.

C. *Adding movement to the model*

The program used for this task is Blender [45]. Blender is a 3D computer graphics software toolset that allows creating visual effects and interactive 3D applications, among other features. Blender accepts some different format files. For this research experiment, the models will be imported in COLLADA (.dae) format, as it is a compatible format to be exported from FreeCAD and to be imported in Blender.

Blender permits the animation of the model by adding the movements that the robot will perform during the simulation. It is important to have in mind when creating the animations that they must be close to the real robot's movements.

D. Creating a VR project

The goal of the last task shown in the workflow of Fig. 4 is creating a project that can be accessed on the browser. The project is created in A-Frame [46], which is a web framework of open code designed for creating 3D and WebVR experiences rendered with WebGL. The A-Frame project is written in HTML code.

The models that have to be imported in the simulation need an appropriate format for working in A-Frame. This most convenient format is glTF (GL Transmission Format) that is used for 3D scenes and models using the JSON standard, which is capable of supporting animations. There are some available GLTF converters online that make possible to export the file with the animations as a .glb extension. The converters developed by blackthread.io [47] or modelconverter.com [48] are some of the available options online. The file imported to the converter requires a compatible format for the converter and for blender exporter, and must support animations. For the described use case, the chosen format is FBX.

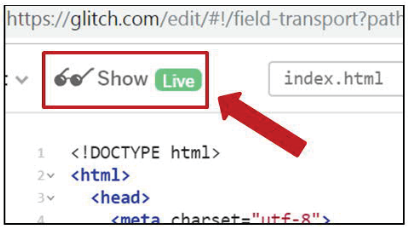

Fig. 7. Show-Live button on the interface

On the other hand, the A-Frame project is opened from Glitch, which is web that allows creating a site from the browser. Glitch generates the server needed for the communication between the user accessing the browser and the virtual environment. Once the code is finished, by clicking on the option Show-Live that is on the top side of the page as Fig. 7 shows a new tab opens with the project's VR environment.

The interfaces of an A-Frame's example project in the VR environment are shown in the Fig. 8. In the left side, it is shown the VR tab. By clicking on the icon below or by wearing the VR Headset, the screen changes and shows two images. These images correspond to the ones seen by each of the eyes when wearing a Head-Mounted Display.

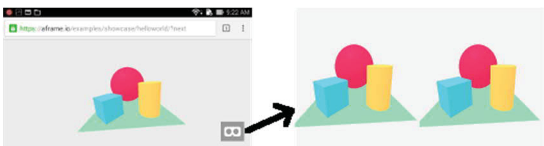

Fig. 8. Inerfaces of an A-Frame's example project

The VR equipment is the Oculus Rift. It consists of a Head-Mounted Display, with integrated audio for taking VR immersion deeper, and a pair of controllers for the hand movements. Summing up, for opening the VR application the user has to follow four main steps, illustrated in Fig. 9.

1. Access a computer with a VR equipment installed
2. Open the A-Frame project in Glitch
3. Click "Show-Live" option to open the virtual environment
4. Wear on the Headset

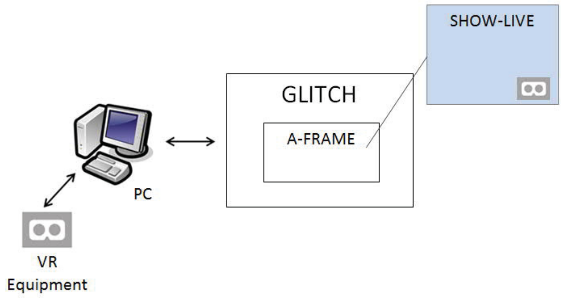

Fig. 9. Communications diagram of the Use Case.

V. CONCLUSION

Users who work in an industrial scenario do not necessarily have a previous formation related to robots. This lack of experience working with robots can generate unease when facing collaborative tasks with them. The main goal of this research work is to create a safe environment for users to train working with robots, as it still takes time for operators to feel totally confident when performing this kind of tasks. This method is an easy way for users to enter the application from any computer. The virtual environment is simple and intuitive. By changing the code, it is possible to create different scenarios for training other tasks with different robots.

Once the simulator was finished, various participants with no experience working with robots tested the application and then they were interviewed in order to evaluate their acceptance to the VR training and to working with cobots. Each participant was tested individually. By analyzing these experimental results it was found that all the participants were feeling comfortable and focused on the task while performing the simulation and after the performance they were feeling more confident when facing the real robot. A more detailed evaluation has to be done in future work, by using a large number of participants and performing different tasks in the virtual training.

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