Industrial robot control and operator training using virtual reality interfaces

Luis Pérez, Beatriz Menéndez, Eduardo Diez, Rubén Usamentiaga, and Daniel F. García

ABSTRACT

Nowadays, we are involved in the fourth industrial revolution, commonly referred to as "Industry 4.0," where cyber-physical systems and intelligent automation, including robotics, are the keys. Traditionally, the use of robots has been limited by safety and, in addition, some manufacturing tasks are too complex to be fully automated. Thus, human-robot collaborative applications, where robots are not isolated, are necessary in order to increase the productivity ensuring the safety of the operators with new perception systems for the robot and new interaction interfaces for the human. Moreover, virtual reality has been extended to industry in the last years, but most of its applications are not related to robots. In this context, this paper works on the synergies between virtual reality and robotics, and presents the use of commercial gaming technologies to create a totally immersive environment based on virtual reality. This environment includes an interface connected to the robot controller, where the necessary mathematical models have been implemented for the control of the virtual robot. The proposed system can be used for training, simulation, and what is more innovative, for robot controlling in an integrated, non-expensive and unique application. Results show that the immersive experience increments the efficiency of the training and simulation processes, and that it is cost-effective.

KEYWORDS

Robots, Virtual Reality, Human-Machine Interface, Virtual Manufacturing, Industry 4.0.

1 INTRODUCTION

The European Commission has set as objective for the Horizon 2020 Work Programme to achieve the leadership in industrial technologies. For this purpose, process automation and decreased accident rates are both important. Productivity and safety were limited by manual processes in the traditional industry; automatization and intelligent robots drive modern industry towards efficiency, resulting in a rapid increase in productivity, major material and energy savings, and safer working conditions. Industrial robots are designed to operate rapidly and repetitively [1]. Although some industries, such as the aerospace industry [2], the shipbuilding industry, or the construction industry, are reluctant to the use of robotics solutions, because they perceive their tasks and processes too complex to be fully automated, industrial robots have been identified as a key issue due to their importance for European economy [3]. Moreover, manufacturing industries are trying to improve their competitiveness introducing information and communication technologies.

The safety conditions limit the use of robots. Traditionally, they have been separated from operators. People protection is usually guaranteed by barriers or certified sensors, stopping the robot when the operator comes into the safety area. Nowadays, machine vision systems and other certified sensors are being used to avoid physical barriers and to make human-robot collaborative applications. These collaborative robots solve the complexity of the automation of certain operations in several industries, where human know-how and capacities are irreplaceable. Human-robot interfaces become the key issue for the interaction [4]. Because of safety reasons, it is necessary that the people, who are going to operate the robot or to work in a collaborative application, go through a learning and training process. The efficient and qualified control of robots and the safety around them in industrial environments are the core of the intelligent automation. Since many companies cannot afford to purchase a robot specifically for training purposes, simulators are considered a cost-effective solution for the acquisition of basic technical skills [5], and for workplace layout design [6].

At this point, virtual reality technologies for process simulation and interaction can provide an immersive experience in real situations without real risks. Virtual reality (VR) offers a way to simulate the reality. Originally, it was mainly used for entertainment purposes, but nowadays the evolution of the technologies, the appearance of multiple applications, and the reduction of costs have extended it to the manufacturing industry for a safer human-machine interaction. Testing and implementation of human-robot collaboration is dangerous due to the high-speed movements and massive forces generated by industrial robots [7]. Thus, this work presents how VR can be integrated as human-robot interface using commercial gaming technologies and real robotics control hardware and software. The paper proposes the architecture for a VR-controlled robot and an immersive interaction environment and interface. The operator can be trained in a virtual but totally immersive and interactive environment and, in addition, robot programs and trajectories can be tested, and the robot can be controlled, avoiding risks and improving safety in industrial facilities. The innovation of the proposed approach is that it combines training, simulation and control in a safe and non-expensive integrated application. Results show that the immersive experience increments the efficiency of the training and simulation processes, and that the solution is cost-effective and affordable for all type of companies.

The rest of the paper is organized as follows: Section 2 resumes the state of the art in VR applications for robotics, Section 3 describes the proposed solution and establishes the architecture of the system, Section 4 and Section 5 contain the description of the main components, Section 6 presents the results and the discussion, and finally the main conclusions are found in Section 7.

2 Virtual Reality for Robotics

Virtual reality is a high-end human-computer interface allowing user interaction with simulated environments in real time and through multiple sensorial channels [8]. Tridimensional vision is the main communication with the simulation, but also sounds, touch, or even smell and taste [9]. The user believes to be inside a reality that does not exist in truth, but he or she acts like in the real world [10]. The virtual world is generated by a computer and allows an immersive interaction in real time. The quality of the 3D reconstruction, the latencies between actions and feedback, and the realistic behavior of the elements, among others, are the factors which cause this immersive perception. Engaging proprioception is what causes a person to feel present in a virtual environment [11].

First VR applications appear almost sixty years ago, when Heiling, who is considered the father of VR by several authors, created the *Sensorama Machine* [12] and the *Telesphere Mask* [13]. Since the beginning of the XXI century, VR has expanded through the Internet especially for the reconstruction of real scenarios and for videogames. Recently, VR has been extended to industry thanks to its multiple applications [14], [15].

The benefits of VR technology have been recognized by scientists and engineers, with applications in architectural modeling, manufacturing plant layout, training in servicing equipment, medicine, etc. To a large extent, robotics and VR research communities have been working independently. In 1999, Burdea pointed out in [16] that the synergies between robotics and the at-that-time emergent VR would grow in the future years. Nowadays, the integration of the two technologies is possible and very beneficial, similarly to the convergence of machine vision and robotics for guidance and inspection tasks [17]. VR can be used for robot programming, simulation, and teleoperation, serving as a flexible operator interface modality to the remote system. This includes task visualization for action planning, motion preview and prediction, operator training, enable visual perception of non-visible events, etc.

One of the main limitations of robots is that they are not easy to program. The kinematic for one position and orientation of the tool is not unique due to the different axis which form the robot [18]. The same point can be reached with several combinations, which allows great accessibility and flexibility, but complicates the programming. Moreover, robotic languages are dependent on each manipulator. The complexity of programming remains one of the major hurdles preventing automation using industrial robots [19]. Simplifying robot programming has become a priority in the current context where inexperienced users might be required to program robot tasks. Programming by demonstration can reduce the complexity incurred in programming some robot tasks. It has spanned across general research areas such as human-robot interaction, machine learning, machine vision, and motor control [20]. Teaching a robot with on-line programming methods is time-consuming, and requires trial and error procedures. Furthermore, it requires the use of the entire work cell, including the robot. Traditional computer graphics for simulation and off-line programming of robots, such as [21], offer the potential to overcome these limitations, but on a computer screen, and without immersive environment. VR enables controlling a robot in a virtual environment, giving the programmer an immersive experience where any angle, any singularity, etc., which could not be visible in the real scenario, can be simulated and checked. Performing the demonstration in a virtual environment may decrease the time and fatigue required for demonstration and improve overall safety by preventing execution of incorrectly learned tasks [22]. Recent works, such as [23], show that this is really feasible.

Teleoperation systems map objects from the user's space and the robot's space. Looking directly at the robot at a certain distance or helped by one or several cameras displayed on a screen, the user operates the control with a keyboard, a mouse, a joystick, or even by hand tracking and gestures recognition [24]. This is the traditional teleoperation, where there is no immersive experience. VR can provide this immersive feeling of the robot in its environment using commercial systems and reducing costs as shown in [25] for pick and place, assembly, and manufacturing tasks. In addition to this, when the robot working scenario is too dangerous for humans because of radiation, explosions, contamination, or other risks, immersive training and teleoperation become both a challenge [26]. Immersive telepresence is difficult as it demands incredibly high standards for realism to produce the effect on the human senses and brain [27]. Decreasing transmission time of visual feedback for a VR-operated robot is crucial [28].

Head mounted devices (HMD) might cause sickness during the use, especially in intensive applications, as they stimulate the vestibular and vision sensory systems [29]. It is necessary to avoid health-related problems to the users, eliminating latencies, distortions, blurry images, etc. Alternatively to VR, augmented reality (AR) overlays computer graphics onto the real worldview. It is also used for facilitating intuitive robot programming in the literature [30], reducing sickness and allowing to see the real world directly.

3 System Architecture

In general, a robot is composed of the mechanical structure, the electronics, the motors, the controller, and the human-machine interface (HMI), which is usually a console. The proposed work replaces this console with a VR system directly connected with the robot controller to act as HMI.

The proposed solution is planned to virtually visualize the trajectories generated by the real robot controller with two main functionalities. The purpose of the first one is to visualize in real time the trajectories generated by the real robot controller. The user selects the desired position and the controller commands the virtual robot. This functionality attempts to reproduce movements for beforehand error detection and accidents prediction.

The purpose of the second functionality is to reproduce the controller trajectories which were previously executed by the robot and stored in the database. The user selects the desired trajectory, indicating date and time, and the virtual robot reproduces it. It is aimed to repeat movements for afterwards error detection and analysis.

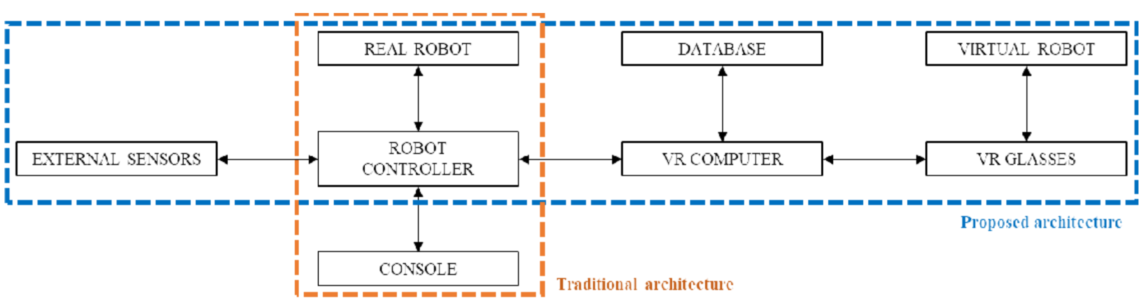

Fig. 1. System architecture, where the console is replaced by the VR system.

The system is composed of elements presented in Fig. 1, with two robots, the real one and the virtual one. Both are controlled by the same controller, which is connected with the VR computer and with the database server. VR glasses are connected to the VR computer. External sensors connected to the robot controller are necessary to provide additional information and feedback about safety issues, pose and accuracy, etc. if the real robot is commanded using the VR system.

A robotic manipulator is a mechanical structure with motorized joins which is able to move at different speeds in a limited area. It includes a controller, which sends the movement instructions to the motors, and ensures that movements are efficient and safe. The controller implements the mathematical models that govern the movements of the robot, and the position and the orientation of its end-effector. These models are the kinematics and the dynamics [31]. As the virtual robot has to move like the real robot, it is necessary to correctly implement these models.

In addition to these standard components, the new system includes a database, and the VR system, which includes a computer and the glasses. The database is used to store the movements executed by the robot in order to be virtually reproduced later to help the operator and for future automatization purposes.

People need to feel a satisfying sense of presence and a totally immersive experience for the success of a VR application. For this purpose, as previously mentioned, there are three main key factors: the latencies between actions and feedback, the quality of the 3D reconstruction, and the realistic behavior of the elements. In order to avoid latencies managing large volumes of data and allowing real time interaction, the VR system requires a powerful dedicated computer [32], [33]. Recent researches use computer graphics and algorithms to improve the rendering process, such as reducing the number of polygons. Moreover, data must be read from and written to the database according to high speed application requirements. For the implementation of the robot controller, a real time operating system is required and it must allow the incorporation of external modules, such as input/output and communication cards, the interaction through different bus formats, code programming and execution, and simultaneous enabling of motion programs.

4 THE ROBOT CONTROLLER

The robot controller is the core for handling the mechanical structure. It processes the movement instructions, commands the motors, and controls the movements of the whole structure. For these proposes, it implements the mathematical models and can include some external sensors to improve positioning and safety.

4.1. Kinematics

The control of a real robot or a virtual one is carried out through the mathematical models called kinematics. They govern the position, the speed, and the acceleration during a movement. In order to obtain the solution, two partial problems must be solved: direct kinematics, and inverse kinematics (Fig. 2).

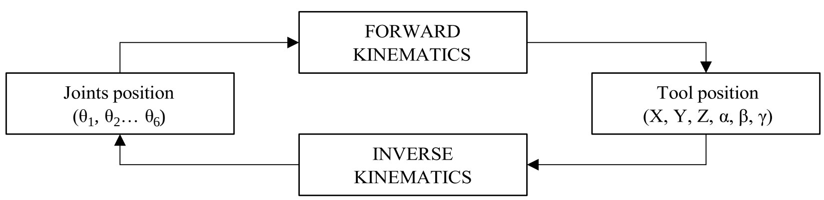

Fig. 2. Kinematics.

The direct kinematics allows to obtain the position and the orientation of the end-effector from the rotation angles of each joint. The inverse kinematics allows to obtain the join rotations from a given position and orientation.

Direct and inverse kinematics allow the position static control by the allocation of the end-effector in a certain point. However, the position and the orientation of the end-effector are not the unique variables to be considered. Velocities must be taken into account, coordinating the instant velocity of the end-effector (linear and angular) and the velocities of the joints (angular).

4.2. Dynamics

The forces that cause the movement of the robot are studied through the mathematical models called dynamics. They analyze the centers of gravity and the inertia tensors, which represent the relations between the movement, the forces, and the torques. Similarly to the kinematics, there are two approaches to solve the problem: direct dynamics, and inverse dynamics (Fig. 3).

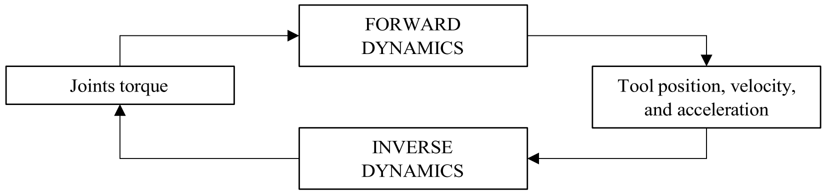

Fig. 3. Dynamics.

The direct dynamics allows to obtain the acceleration resulting of the application of an external torque in the joins. The inverse dynamics allows to obtain the necessary torques to be applied in the joins from a given trajectory, velocity, and acceleration.

4.3. External Sensors

Apart from the previously mentioned mathematical models, the robot controller can be fed with additional information provided by external sensors to improve positioning and safety.

Industrial robots are able to move to a position repeatedly with a small error of 0.1 mm or even less in some cases, although their absolute accuracy can be several millimeters due to tolerances, eccentricities, elasticities, play, wear-out, load, temperature, and insufficient knowledge of model parameters for the transformation from poses into robot axis angles [34]. Conventional robots are not capable of achieving the accuracy requirements of, for example, the aerospace industry [35]. To overcome this accuracy deficiency, a laser tracker (LT) system can be used to detect the spatial position of the tool tip and to correct the robot motion. In addition to this, this LT can provide feedback to the VR system to monitor the exact position and orientation of the real robot as an external and independent sensor. This information combined with other data, such as visual feedback provided by a camera, can be used to avoid risks, estimate possible collisions, and guarantee the safety in teleoperated robots, as the operator cannot directly see the real environment, and accidents can occur.

5 The Virtual Reality Environment

Consciousness of the immediate environment necessarily depends on the data picked up by human’s sensory systems. The sensory inputs are combined and processed according to the previously existing model of the world. VR replaces real sense perceptions by computer-generated ones describing a 3D scene and animations of objects within the scene, including changes caused by the intervention of the user. The user needs to feel a totally immersive and authentic experience in the VR application. This is achieved by a realistic behavior of the elements, avoiding the latencies between actions and feedback, and creating a high quality 3D reconstruction to transmit to the user the sense of presence, i.e., the illusion of being there and the sensation that events are really happening, although he or she know~~n~~s for sure that it is not actually truth.

Latencies are avoided with the previously mentioned requirements for the VR computer, for the database engine, and for the control hardware. To ensure the quality of the 3D reconstruction, it is necessary to accurately scan and model the environment including walls, objects, tools, machines, panels, pipelines, lamps, boxes, etc. Textures, colors, and lighting effects should be also considered to replicate the real scenario and to create the immersive effect.

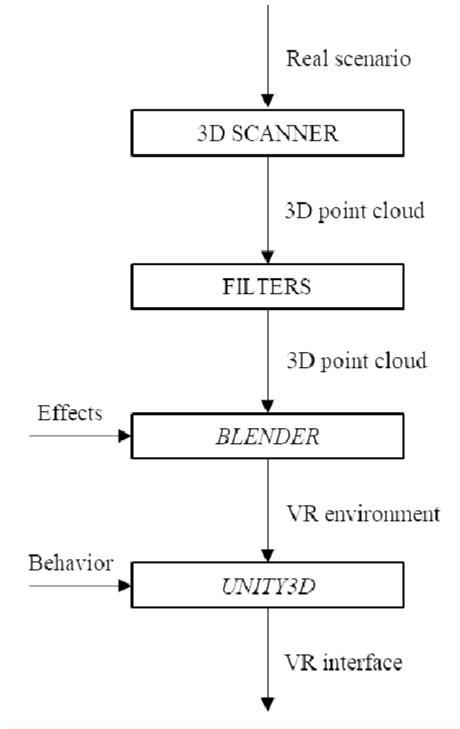

Fig. 4. Process to create the immersive environment and the VR interface.

Fig. 4 and Fig. 5 illustrate the process to create the immersive environment and the VR interface. The scenario of Fig. 5 (a) was firstly scanned using *FARO Focus3D X130 HDR* [36]. The resulting 3D point cloud (Fig. 5 (b)) was processed and filtered with *CloudCompare* [37], and then modelled with *Blender* [38] to render the virtual environment shown at Fig. 5 (c). Comparing Fig. 5 (a) and Fig. 5 (c), the high accurate 3D reconstruction to create the immersive effect can be noticed. The virtual environment is totally accurate to the real one, including the minimum details. Finally, *Unity3D* [39], which offers a wide range of tools and features, was used to implement the human-machine interaction interface through different sets of virtual buttons for the navigation between the menus (Fig. 5 (d)). The user can move along the virtual area with the teleporting function recreating the real environment around the robot. Fig. 6 contains more detailed screenshots of the proposed application, such as the main menu, create a new movement, reproduce a previous movement, etc.

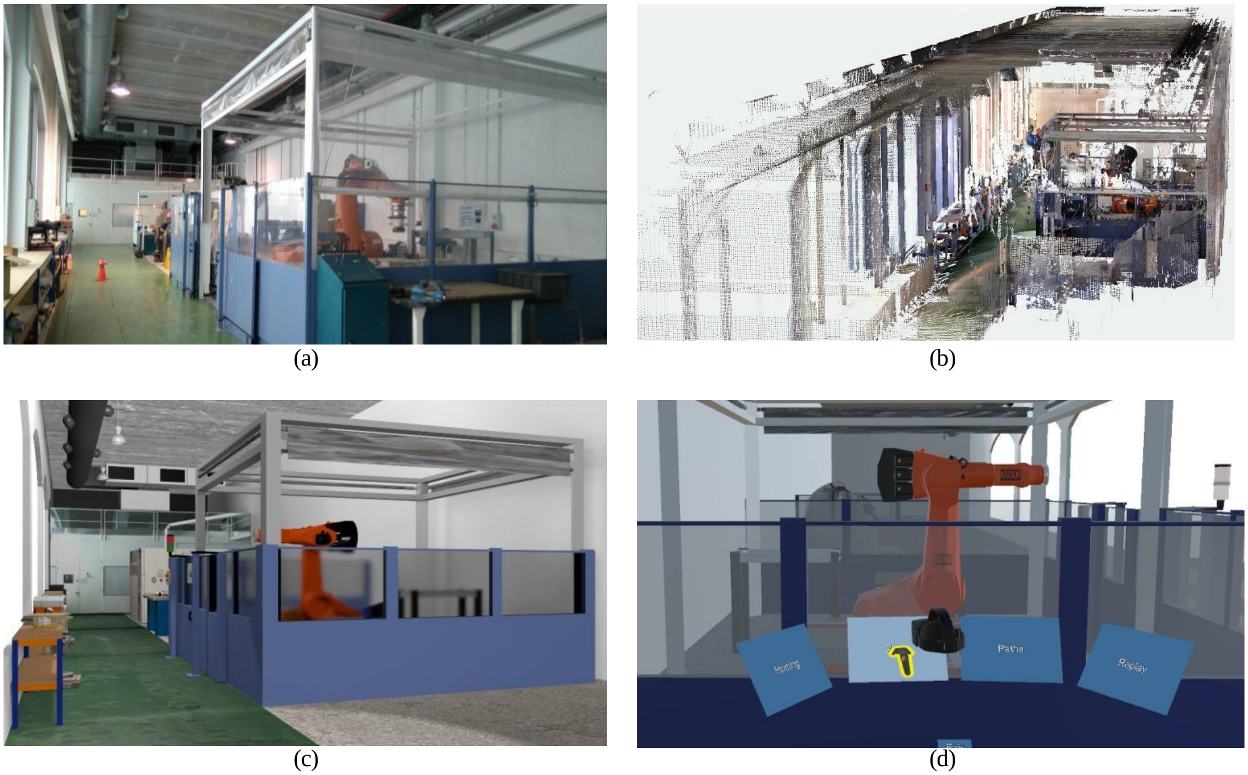

Fig. 5. Real and virtual environments: (a) Real facilities, (b) Point cloud, (c) Virtual environment, and (d) Interaction interface.

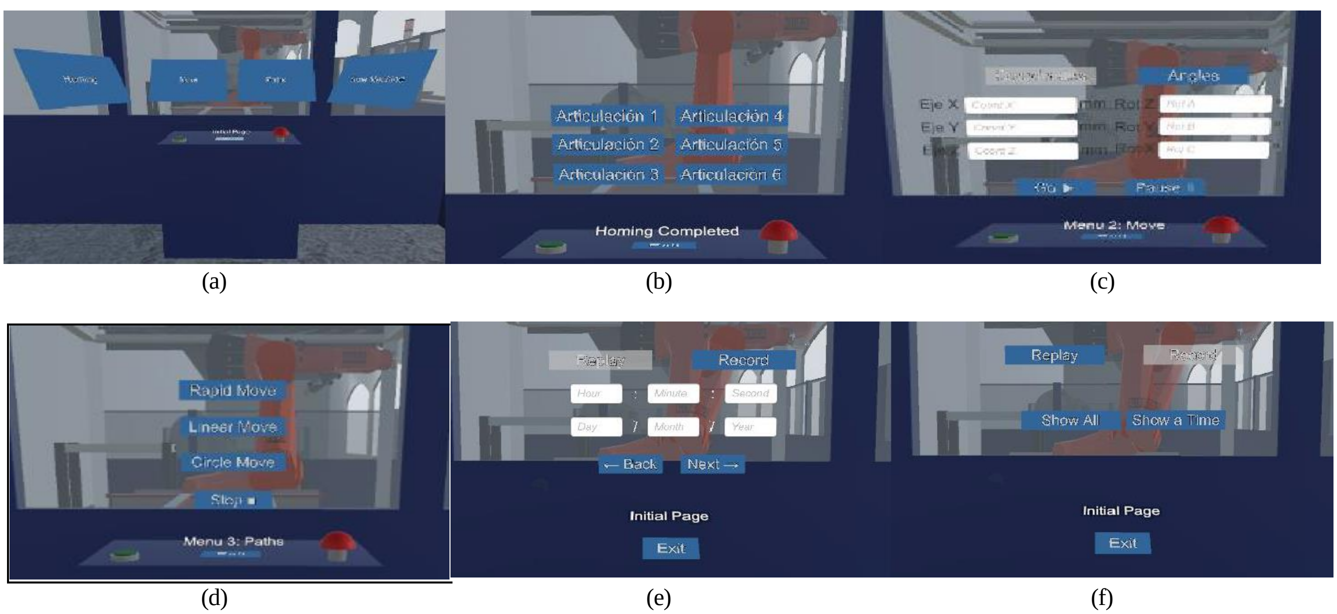

Fig. 6. Virtual interface screenshots: (a) Main menu, (b) Searching the initial position, (c) Move indicating coordinates, (d) Types of movements, (e) Previous movements, and (f) Errors.

6 Results and Discussion

6.1 VR Environment and Interface Validation

Fig. 7 (a) shows the operator in the real scenario using the console to handle the robot to prepare a picking application. Operator and robot are physically separated because of safety reasons. This is the traditional situation. In Fig. 7 (b) the operator is immersed in the VR environment and can move inside the virtual working area of the robot without risks using the glasses with the perception of being really present. Here, he can simulate the different positions, check the singularities, verify the reachability, study the possible collisions of the grippers, etc. This scenario has been created to evaluate the proposed system, including the immersive effect and the VR interface, with operators in a real factory.

(a) (b)

Fig. 7. One of the testers in the scenarios: (a) Working with the real robot, and (b) Working with the virtual robot.

The robot used for the validation of the proposed methodology is the *KUKA KR500-2* [40]. The *Modbus TCP* protocol is used for the communication between the robot controller and the VR system. Among the different available commercial glasses, *Oculus Rift* [41] and *HTC Vive* [42] were selected for testing.

Twelve people of three different profiles and experience (four of each one) have participated in the validation and tests: (a) Robotic application engineers, (b) Robot operators, and (c) Assistant operators. A questionnaire was used to get their feedback:

(1) Have you felt sick during or after the experience?
(2) Have you felt sense of presence and the sensation that events were really happening?
(3) Have you felt the illusion of being in the real facilities?
(4) Have you found the real objects in the virtual environment?
(5) Are colors and textures similar to the real ones?
(6) Are lighting effects appropriated?
(7) Does the robot move like the real one?
(8) Have you perceived any risk?
(9) Is it useful to be virtually inside the robot cell and to move around?
(10) Is the application usable and friendly?
(11) Is it easier to handle the robot with the virtual interface?
(12) Do you find the application time saving as it can be used for training, simulating, and controlling?

Five answers were possible: Very dissatisfied (1 point), Dissatisfied (2 points), OK (3 points), Satisfied (4 points), and Very satisfied (5 points). According to these options, Table 1 shows the punctuations in percentage obtained from the answers. Testers point out that the virtual environment includes all the minimum details of the real scenario giving a sense of total realism. In addition, they consider that the integration of the training, the simulation, and the control of the robot in the same application will increase the efficiency as they are familiarized with the system since the beginning of the process.

Table 1. Questionnaire's scores (%).

Question	Engineer	Operator	Assistant	Mean
(1)	95	85	85	88.33
(2)	100	100	100	100
(3)	100	100	100	100
(4)	100	95	85	93.33
(5)	100	100	100	100
(6)	95	100	100	98.33
(7)	100	95	100	98.33
(8)	100	95	100	98.33
(9)	95	100	100	98.33
(10)	95	90	90	91.67
(11)	100	95	100	98.33
(12)	95	85	95	91.67
Mean	97.92	95	96.25	96.39

6.2 Traditional HMI vs. VR-based HMI

Table 2 shows the comparison between the traditional HMI based on a console and the proposed solution based on VR in terms of acquisition costs, standardization, usability, training time, versatility to include new functionalities, and risks avoidance.

Table 2. HMI comparative.

	Costs	Standard	Usability	Time	Versatility	Risks	Integration
Console	×	✓	×	×	×	×	×
VR	✓	×	✓	✓	✓	✓	✓

Many companies cannot dedicate their robots or purchase a specific one for training purposes. Simulators can be a cost-effective solution for the acquisition of the skills. The VR proposed solution based on commercial gaming hardware is totally affordable as it is a mass consumer product. Related to this, the disadvantage is that this solution requires the creation of the immersive environment in each particular case, thus it is not a standard or plug and play application. However, it is easy to create following the proposed reconstruction procedure, providing a greater versatility to add new features and functionalities.

According to the feedback given by the testers, the new approach is usable and friendly, which reduces the training time. In addition to this, as users are familiarized with the environment, the effectiveness of the training is higher for their real tasks. Finally, testing robot programs and trajectories in VR avoids risks and improves safety in the industrial facilities. The VR-based HMI is an integrated application for training, simulation, and programming.

7 Conclusions

This work presents an immersive human-robot collaborative framework based on virtual reality for intelligent automation and increased productivity. The architecture not only includes training and simulation without risks, but it also proposes the integration of safe and low-cost robot controlling capabilities in an efficient and novel work environment. The tests based on commodity hardware and VR gaming technologies validate the proposed methodology. The realistic behavior of the elements, the avoidance of latencies, and a high quality 3D reconstruction of the real scenario allow a totally immersive experience in the VR environment.

Inside the fourth industrial revolution robots are a core element to improve the competitiveness of the industry. Industrial robots are designed to operate rapidly and repetitively, while humans have the knowledge. The future of manufacturing requires the interaction between humans and robots in the physical and virtual scenarios to make the most of their capabilities and to develop flexible, safe, and efficient applications. For this purpose, advanced interfaces are necessary to achieve a safe and real time interaction, which was not possible in the past, when the human-robot interaction was highly limited.

VR-simulated and VR-operated robotic systems allow humans the possibility to work at scales and in environments which have not been accomplished until today. Thus, it is necessary to exploit the close and growing connections between VR and robotics, taking advantage of the fact that VR is becoming a mass consumer product.

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